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8th Laser Display and Lighting Conference: Abstract Book

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Yokohama, Japan

The 8th Laser Display and Lighting Conference

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Proc. of SPIE Vol. 11145 1114501-1

SPIE Proceedings Publications

Tetsuya Yagi
Sunao Kurimura
Keisuke Hieda
Editors

23–26 April 2019
Yokohama, Japan

Organized by
Laser Display Technology Group (LDT) of Optical Society of Japan (OSJ)

Sponsored by
The Optical Society of Japan
The Japan Society of Applied Physics

In cooperation with
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Consortium of Visible Laser Diode Applications

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 Boaz Jessie Jackin, NICT (Japan)
- 9 Post Deadline Paper
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SPIE Proceedings Publications

Introduction

The Laser Display and Lighting Conference (LDC) is an international conference on laser displays, laser lighting, and related technologies. The 1st, 2nd, 4th, and 6th, 7th LDC were held in Yokohama, Japan in 2012, 2013, 2015, 2017 2018 respectively, and the 3rd in Taichung, Taiwan in 2014, the 5th in Jena, Germany in 2016. The 8th Laser Display and Lighting Conference (LDC2019) will be held on April, 23th - 26th, 2019 in Yokohama, Japan, at Pacifico Yokohama. The LDC2019 is intended to provide a central forum for the update and review of scientific and technical information on laser display and lighting covering a wide range of fields from fundamental research to systems and applications. The conference is sponsored by the Optical Society of Japan in cooperation with several academic societies and associations.

For details, please come to our web-site;
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Kazuo Kuroda
Hiroshi Murata

SPIE Proceedings Publications

LDC2019

CONFERENCE PROGRAM

Apr. 23rd to 26th, 2019

At Room 301 of Pacifico Yokohama

Poster: Exhibition Hall of Pacifico Yokohama

Day 1, Tue. Apr 23, 2019

OPIC Plenary Sessions <Room 501+502>

Tue. Apr 23, 2019 9:00 AM - 12:00 AM

LEDIA-LDC Joint Session -1- <Room301>

Tue. Apr 23, 2019 1:30 PM - 3:00 PM

Session Chair: Yasufumi Fujiwara (Osaka University), Tetsuya Yagi (Mitsubishi Electric Co.)

1:30 PM - 1:45 PM

[LEDIA-LDC-JS-1-01] Opening Remarks

1:45 PM - 2:00 PM

[LEDIA-LDC-JS-1-02] Opening Remarks

2:00 PM - 2:30 PM

[LEDIA-LDC-JS-1-03, Invited] Reliability improvement in 638 nm broad area laser diode

*Takehiro Nishida¹, Kyosuke Kuramoto¹, Takuma Fujita¹, Masatsugu Kusunoki¹, Tetsuya Yagi¹ (1. Mitsubishi Electric Corp.)

2:30 PM - 3:00 PM

[LEDIA-LDC-JS-1-04, Invited] Recent Advances in GaN-based Laser Diodes for Laser Displays

*Eiichiro Okahisa¹, Yoji Nagao¹, Kazuma Kozuru¹, Yoshitaka Nakatsu¹, Tsuyoshi Hirao¹, Shingo Masui¹, Tomoya Yanamoto¹, Shin-ichi Nagahama¹ (1. Nichia Corporation)

Break (3:00 PM~3:30 PM)

LEDIA-LDC Joint Session -2-

Tue. Apr 23, 2019 3:30 PM - 4:30 PM

Session Chair: Yasufumi Fujiwara (Osaka University), Tetsuya Yagi (Mitsubishi Electric Co.)

3:30 PM - 4:00 PM

[LEDIA-LDC-JS-2-01, Invited] Development of Semiconductors Intra-center Photonics; Manipulation of Eu luminescence in Eu-doped GaN by Control of Photon Fields

*Yasufumi Fujiwara¹, Keishi Shiomi¹, Yutaka Sasaki¹, Tomohiro Inaba¹, Shuhei Ichikawa¹, Jun Tatebayashi¹ (1. Osaka University)

◆This paper is not available due to a copyright issue.

4:00 PM - 4:30 PM

[LEDIA-LDC-JS-2-02, Invited] Characteristics of GaN Tunnel Junction Contacts for LEDs Prepared by Pulsed Sputtering

Taiga Fudetani¹, *Kohei Ueno¹, Atsushi Kobayashi¹, Hiroshi Fujioka^{1,2} (1. The University of Tokyo, 2. JST-ACCEL)

◆This paper is not available due to a copyright issue.

Day 2, Wed. Apr 24, 2019

LDC-Plenary-1 <Room301>

Wed. Apr 24, 2019 9:00 AM - 10:45 AM

Session Chair: Kazuo Kuroda (Utsunomiya University), Hiroshi Murata (Mie University)

9:00 AM - 9:15 AM

[LDC01-02-1] Opening Remarks

9:15 AM - 10:00 AM

[LDC-1-1-01, Plenary] Optical Architectures for Mixed Reality Wearable Systems

*Brian Schowengerdt¹ (1. Magic Leap Inc.)

10:00 AM - 10:45 AM

[LDC-1-1-02, Plenary] Interactive Dynamic Projection Mapping Using High-speed Display and High-speed Image Processing

*Masatoshi Ishikawa¹ (1. University of Tokyo)

Break (10:45 AM ~ 11:00 AM)

LDC-Plenary-2

Wed. Apr 24, 2019 11:00 AM - 11:45 AM

Session Chair: Kazuo Kuroda (Utsunomiya University), Hiroshi Murata (Mie University)

11:00 AM - 11:45 AM

[LDC-1-2-01, Plenary] Visible Lasers for Display and Lighting Applications

*Masahiro Murayama¹ (1. Sony Corporation)

LUNCH (11:45 AM ~ 1:00 PM)

Systems and Applications

Wed. Apr 24, 2019 1:00 PM - 3:15 PM

Session Chair: Satoshi Ouchi (Hitachi), Young-Joo Kim (Yonsei University)

1:00 PM - 1:30 PM

[LDC-2-01, Invited] 360-Degree Tabletop Type 3D Screen System

*Motohiro Makiguchi¹, Hideaki Takada¹ (1. NTT Service Evolution Lab)

1:30 PM - 2:00 PM

[LDC-2-02, Invited] High-speed R/G/B Laser Diode Mixed White Lighting Communication

*Gong-Ru Lin^{1, 2} (1. National Taiwan University, 2. NTU-Tektronix Joint Research Center)

2:00 PM - 2:30 PM

[LDC-2-03, Invited] Laser Projector in Augmented Reality

*Daisuke Iwai¹ (1. Osaka University)

2:30 PM - 2:45 PM

[LDC-2-04] Evaluation of Adaptive Shifted Superimposition Technique for Enhancing the Projector Resolution

*Svein Arne Jervell Hansen^{1,3}, Muhammad Nadeem Akram¹, Jon Yngve Hardeberg²(1. University of South-Eastern Norway, 2. Norwegian University of Science and Technology, 3. Barco)

2:45 PM - 3:00 PM

[LDC-2-05] Wireless Optical Feeding to Remote Moving Object Using Visible Laser Diodes

*Masato Ishino¹, Toshiyuki Kitamura², Akira Takamori¹, Junichi Kinoshita¹, Kazuhisa Yamamoto¹ (1. Osaka University, 2. National Institute for Quantum and Radiological Science and Technology)

3:00 PM - 3:15 PM

[LDC-2-06] Research on Gamut Expansion Mapping Method Based on Laser Display Device

*Ruhai Guo¹ (1. Hisense Electric Co., Ltd.)

Break (3:15 PM ~ 3:30 PM)

Imaging/Lighting Technologies and Devices

Wed. Apr 24, 2019 3:30 PM - 4:45

Session Chair: Hidekazu Hatanaka (Ushio), Fergal Shevlin (DYOPTYKA)

3:30 PM - 4:00 PM

[LDC-3-01, Invited] Homogenization Without Scattering of Laser Illumination

*Fergal Shevlin¹ (1. DYOPTYKA)

4:00 PM - 4:15 PM

[LDC-3-02] High-Speed Operation of Electro-Optic Bragg Deflectors Utilizing Periodically Polarization-Reversed Structures

Yusuke Kato¹, *Hiroshi Murata¹, Kazuhisa Yamamoto² (1. Mie University, 2. Osaka University)

4:15 PM - 4:30 PM

[LDC-3-03] Speckle Suppression for Laser Display Systems Using the N = 11 2-D Barker Code Based Diffractive Optical Element

Seong-Jin Son¹, Do-Kyeong Ko¹, *Nan Ei Yu¹ (1. Gwangju Institute Science and Technology)

4:30 PM - 4:45 PM

[LDC-3-04] Beam shaping for the enlarged diffraction field

*Huan Xiao¹, Qiaofeng Tan¹ (1. Tsinghua University)

■ Reception 18:00 – 20:00

InterContinental Ballroom, 3F InterContinental Yokohama Grand, 1-1-1 minatomirai, nishi-ku, Yokohama

* * Free for OPIC2019 attendees.

Day 3, Thu. Apr 25, 2019

Laser Applications for Automotive -1-

Thu. Apr 25, 2019 9:00 AM - 10:30 AM

Session Chair: Masaru Kuramoto (Stanley Electric), Satoshi Ouchi (Hitachi)

9:00 AM - 9:30 AM

[LDC-4-1-01, Invited] Simulation of Detection Performance by LiDAR Location in Automated Vehicles

*Misako Kamiya¹, Hiroto Ikadai¹ (1. KOITO MANUFACTURING CO., LTD.)

9:30 AM - 10:00 AM

[LDC-4-1-02, Invited] Acousto-optics in headlamps – A new application in automotive laser lighting

*Marcel Bursy¹, Jörg Wallaschek² (1. L-LAB, 2. Leibniz University Hannover)

10:00 AM - 10:30 AM

[LDC-4-1-03, Invited] Current status and future prospects of Automotive Laser Headlamp

*Claus Allgeier¹ (1. OSRAM Continental GmbH)

Break (10:30 AM~10:45 AM)

Laser Applications for Automotive -2-

Thu. Apr 25, 2019 10:45 AM - 12:00 PM

Session Chair: Masaru Kuramoto (Stanley Electric), Satoshi Ouchi (Hitachi)

10:45 AM - 11:15 AM

[LDC-4-2-01, Invited] Technical Challenges in Laser and Lidar Optical Sub-Assemblies for Automotive

*Josh P Kemp¹, Jiamin Zheng¹ (1. Lumentum Inc.)

11:15 AM - 11:45 AM

[LDC-4-2-02, Invited] VCSEL Sensing for Automotive

*Anna Tatarczak¹, Krzysztof Szczepa¹, Chris Kocot¹ (1. Finisar Corporation)

11:45 AM - 12:00 PM

[LDC-4-2-03] Phosphor-in-Glass (PiG) as Wavelength Converter for the Automotive Laser Headlight Application

Kyong-Hyong Kim¹, Deok-Jin Kwon¹, Hye-Bin Yang¹, Tae-Ho Park², *Young-Joo Kim¹ (1. Yonsei University, 2. Bass Co., Ltd.)

LUNCH (12:00 PM ~1:00 PM)

Short Oral Session for Poster

Thu. Apr 25, 2019 1:00 PM - 1:18 PM

Session Chair: Tetsuya Yagi (Mitsubishi Electric Co.)

1:00 PM - 1:03 PM

[LDC-P-01] Optical Surface Error Compensation Based on Freeform Polynomials

*Yuan-Chieh Cheng¹, Wei-Jei Peng¹, Khaled Abou-El-Hossein², Pei-Jen Wang³, Po-Kai Chiu¹ (1. Instrument Technology Research Center (ITRC) National Applied Research Laboratories (NARLabs), 2. Precision Engineering Laboratory, Nelson Mandela Metropolitan University, 3. Department of Power Mechanical Engineering, National Tsing Hua University)

1:03 PM - 1:06 PM

[LDC-P-02] Single-mode fiber coupled compact RGB laser module

*Yusuke Ikeda¹, Junki Sakamoto¹, Akiyuki Kadoya¹, Ichiro Fukushi¹, Koji Tojo¹, Kazuhisa Yamamoto² (1. Shimadzu Corporation, 2. Osaka University)

1:06 PM - 1:09 PM

[LDC-P-03] Holographic Display using Binary Phase Modulation by Image Segmentation Method

*Kento Kurosawa¹, Xiangyu Quan¹, Kouichi Nitta¹, Osamu Matoba¹ (1. Kobe University)

1:09 PM - 1:12 PM

[LDC-P-04] Design of Light Intensity Distribution Control Element for High-Brightness Projectors Using Solid-State Light Sources

*Taro Tsutsumi¹, Ryuichi Katayama¹ (1. Fukuoka Institute of Technology)

1:12 PM - 1:15 PM

[LDC-P-05] Design of freeform progressive addition contact lens for presbyopia correction with schematic eye model

*Wei-Jei Peng¹, Yuan-Chieh Cheng¹, Khaled Abou-El-Hossein², Ming-Fu Chen¹ (1. Instrument Technology Research Center, National Applied Research Laboratories, 2. Precision Engineering Laboratory, Nelson Mandela Metropolitan University)

1:15 PM - 1:18 PM

[LDC-P-06] A Study for Quick and Accurate White Balance Adjustment in Laser Display Production

*Keisuke Hieda¹, Tomoyuki Maruyama, Fumio Narusawa¹ (1. HIOKI E.E. CORPORATION)

Poster Session is held as follows:

Thu. Apr 25, 2019 1:30 PM - 3:00 PM, Hall A (Pacifico Yokohama Exhibition Hall)

Break (3:00 PM ~3:15 PM)

Lasers and Light Sources

Thu. Apr 25, 2019 3:15 PM - 5:00 PM

Session Chair: Tetsuya Yagi (Mitsubishi Electric Co.), Wanhua Zheng (Chinese Academy of Sciences)

3:15 PM - 3:45 PM

[LDC-5-01, Invited] Low vertical divergence angle and low coherence laser diodes for laser display
Yufei Jia^{1,2}, Yufei Wang^{1,2}, Linhua Xu^{1,2}, *Wanhua Zheng^{1,2} (1. Chinese Academy of Sciences, 2. University of Chinese Academy of Sciences)

3:45 PM - 4:15 PM

[LDC-5-02, Invited] High-output-power and high-temperature operation of a blue GaN-based vertical-cavity surface-emitting laser
*Masaru Kuramoto¹, Seiichiro Kobayashi¹, Takanobu Akagi¹, Komei Tazawa¹, Kazufumi Tanaka¹, Tetsuya Takeuchi² (1. Stanley Electric Co., LTD., 2. Meijo University)

4:15 PM - 4:30 PM

[LDC-5-03] Laser-phosphor light source with luminance up to 2000Mcd/m²
*Koji Takahashi¹, Karl Welna², Valerie Berryman-Bousquet², Mattia Signoretto², Toru Kanno¹, Hirokazu Ichinose¹, Hidenori Kawanishi¹ (1. SHARP Corporation, 2. Sharp Laboratories of Europe Ltd.)

4:30 PM - 4:45 PM

[LDC-5-04] Generation of multi-wavelength yellow-orange lasers using chi(2) chirped nonlinear photonic crystals
*To-Fan Pan¹, Kai-Hsun Chang^{1,2}, Jhih-Yong Han¹, Jui-Hung Hung³, Azzedine Boudrioua², Hiroyuki Yokoyama³, Katrin Paschke⁴, Lung-Han Peng^{1,3} (1. National Taiwan University, 2. Université Paris 13, 3. Tohoku University, 4. Leibniz-Institut für Höchstfrequenztechnik)

4:45 PM - 5:00 PM

[LDC-5-05] High-Power 638nm Red Laser Diode with Built-in Lens for Display Applications
*Fumio Shohda¹, Kohei Sakai¹, Kenichi Hirose¹, Yukari Takada¹, Kyosuke Kuramoto², Motoharu Miyashita², Yuji Iwai², Takayuki Yanagisawa¹ (1. Information Technology R&D Center, Mitsubishi Electric Corporation, 2. High Frequency & Optical Device Works, Mitsubishi Electric Corporation)

Day 4, Fri. Apr 26, 2019

Speckle Control and Measurement Methods -1-

Fri. Apr 26, 2019 9:00 AM - 10:30 AM

Session Chair: Junichi Kinoshita (Osaka University), Makio Kurashige (Dai Nippon Printing)

9:00 AM - 9:30 AM

[LDC-6-1-01, Invited] Color Speckle Measurement of Far Field Pattern of RGB Laser Modules

*Junichi Kinoshita¹, Akira Takamori¹, Keizo Ochi¹, Kazuhisa Yomamoto¹, Kazuo Kuroda², Koji Suzuki³, Keisuke Hieda⁴ (1. Osaka University, 2. Utsunomiya University, 3. Oxide Corporation, 4. HIOKI E.E. CORPORATION)

9:30 AM - 10:00 AM

[LDC-6-1-02, Invited] A Study of the Angular Dependence of Chromaticity and Illuminance for Ultra Short Throw Laser Projectors

*Keisuke Hieda¹, Tomoyuki Maruyama¹, Fumio Narusawa¹ (1. HIOKI E.E. CORPORATION)

10:00 AM - 10:15 AM

[LDC-6-1-03] Uniformity of Visual Resolution of Raster-Scan RGB Laser Projector Considering Color Speckle

*Keizo Ochi¹, Junichi Kinoshita¹, Kazuo Kuroda², Koji Suzuki³, Keisuke Hieda⁴, Akira Takamori¹, Kazuhisa Yamamoto¹ (1. Osaka University, 2. Utsunomiya University, 3. Oxide Corporation, 4. HIOKI E.E. CORPORATION)

10:15 AM - 10:30 AM

[LDC-6-1-04] Challenge to Estimate the Equivalent Measurement Conditions of Speckle Contrast

*Makio Kurashige¹, Kazutoshi Ishida¹, Shumpei Nishio¹ (1. Dai Nippon Printing Co., Ltd.)

Break (10:30 AM ~10:45 AM)

Speckle Control and Measurement Methods -2-

Fri. Apr 26, 2019 10:45 AM - 11:45 AM

Session Chair: Junichi Kinoshita (Osaka University), Makio Kurashige (Dai Nippon Printing)

10:45 AM - 11:15 AM

[LDC-6-2-01, Invited] Speckle Reduction in Laser Projector

*Hirotaka Yamada^{1,2}, Kengo Moriyasu¹, Hiroto Sato¹, Hidekazu Hatanaka¹, Kazuhisa Yamamoto² (1. Ushio Inc., 2. Osaka University)

11:15 AM - 11:30 AM

[LDC-6-2-02] Applicability of CIELAB Volume Metric to the Latest Electronic Displays

*Hidefumi Yoshida¹, Keita Hirai², Yoko Mizokami² (1. Sharp Corporation, 2. Chiba University)

11:30 AM - 11:45 AM

[LDC-6-2-03] Color Speckle Measurement for RGB Laser Displays Based on the Current Speckle

Contrast Measurement Instrument

*Koji Suzuki¹, Shigeo Kubota¹ (1. Oxide Corporation)

LUNCH (11:45 AM ~ 1:00 PM)

LDC-IP Joint Session on Emerging Displays 2019

Fri. Apr 26, 2019 1:00 PM - 2:20 PM

Session Chair: Hirotsugu Yamamoto (Utsunomiya University), Boaz Jessie Jackin (NICT)

1:00 PM - 1:05 PM

[IP-LDC-JS-1-01] Opening Remarks

1:05 PM - 1:35 PM

[IP-LDC-JS-1-02, Invited] Integral imaging based large-size see-through head up display for AR applications using DDHOE and projector

*Jackin Boaz Jessie¹, Kenji Yamamoto¹ (1. NICT)

◆This paper is not available due to a copyright issue.

1:35 PM - 2:05 PM

[IP-LDC-JS-1-03, Invited] Analysis on the effect of a finite aperture of the floating lens to the formation of the viewing region in the integral floating display

*Hee-Jin Choi¹, Minyoung Park¹, Junkyu Yim², Sung-Wook Min² (1. Sejong University, 2. Kyung Hee University)

◆This paper is not available due to a copyright issue.

2:05 PM - 2:20 PM

[IP-LDC-JS-1-04] Compact Augmented Reality Near-eye Display Using Geometric Phase Lenses without Chromatic Aberration

Seokil Moon¹, Seung-Woo Nam¹, *Byoungho Lee¹ (1. Seoul National University)

◆This paper is not available due to a copyright issue.

Break (2:20 PM ~ 2:30 PM)

LDC-IP Joint Session on Emerging Displays 2019 -2-

Fri. Apr 26, 2019 2:30 PM - 3:45 PM

Session Chair: Hirotsugu Yamamoto (Utsunomiya University), Boaz Jessie Jackin (NICT)

2:30 PM - 3:00 PM

[IP-LDC-JS-2-01, Invited] Reconstruction of Rays in 3D space using a reverse system of a light field camera or a novel Aerial 3D light field display

*Toru Iwane¹ (1. Nikon Corporation)

◆This paper is not available due to a copyright issue.

3:00 PM - 3:15 PM

[IP-LDC-JS-2-02] Aerial 3D display using combination of a single direction light field display and AIRR

Toru Iwane¹, *Naoto Munemura¹, Masao Nakajima¹ (1. Nikon Corporation)

◆This paper is not available due to a copyright issue.

3:15 PM - 3:30 PM

[IP-LDC-JS-2-03] Aerial Image as a Visual Stimulus for Animal Experiment and Evaluation of its Sharpness

*Masaki Yasugi^{1,2}, Hirotugu Yamamoto^{1,2} (1. Utsunomiya University, 2. JST, ACCEL)

◆This paper is not available due to a copyright issue.

3:30 PM - 3:45 PM

[IP-LDC-JS-2-04] Subjective Super-Resolution Model on Coarse High-Speed LED Display in Combination with Pseudo Fixation Eye Movements

*Toyotaro Tokimoto^{1,2}, Kengo Fujii¹, Shogo Morita¹, Hirotugu Yamamoto^{1,3} (1. Utsunomiya University, 2. DaoApp Technology Co., Ltd., 3. JST ACCEL)

◆This paper is not available due to a copyright issue.

LDC Post Deadline

Fri. Apr 26, 2019 4:00 PM - 4:10 PM

Session Chair: Sunao Kurimura (NIMS), Tetsuya Yagi (Mitsubishi Electric. Co.,)

4:00 PM - 4:10 PM

[LDC-7-01] Colour capability measurements of laser displays

*Johan Bergquist¹ (1. Consultant)

LDC Award Ceremony and Closing

Fri. Apr 26, 2019 4:10 PM - 4:30 PM

Session Chair: Sunao Kurimura (NIMS), Tetsuya Yagi (Mitsubishi Electric. Co.,)

SPIE Proceedings Publications

The 8th Laser Display and Lighting Conference 2019 (LDC'19), Yokohama, Japan, Apr. 23 - Apr. 29, 2019

Reliability improvement in 638 nm broad area laser diode

Takehiro Nishida, Kyosuke Kuramoto, Takuma Fujita, Masatsugu Kusunoki, Tetsuya Yagi
Mitsubishi Electric Corporation, 4-1, Mizuhara, Itami, Hyogo, 664-8641, Japan
+81-72-780-2592, Nishida.Takehiro@eb.MitsubishiElectric.co.jp

Abstract: Reliability of 638-nm broad area laser diode (LD) is basically dominated by catastrophic optical mirror degradation (COMD) at a front facet. The facet and window-mirror structure as a measure to COMD of 638-nm broad area triple emitter were revised to achieve highly-reliable operation under high output power. The improved LD showed very stable operation up to 5,000 hours under operation current of 4.9 A (initial output of 4.75 W), CW without any COMD failure, indicating that the mean time to failure due to COMD exceeding 8,100 hours under the condition. It was approximately 3.3 times of our former LD.

1. Introduction

Laser based displays have gathered much attention, and they are expected to make an alternative huge market for visible laser diodes (LDs), because only the displays may have a wide colour gamut which can express ITU-R BT.2020. Single panel spatial light modulator (SLM) type projectors using broad area (BA) LDs for light sources are most popular so far. BA-LDs in the projectors are operated under the pulse condition with duty around 30-40%. Material of the red LD commonly used is AlInGaP, which has low thermal conductivity compared to AlInGaN, the material of blue and green one. This brings the red LDs not only worse temperature characteristics but also poor mean time to failure (MTTF) due to catastrophic optical mirror degradation (COMD) at a front facet [1, 2]. We already developed a 638-nm high-power triple emitter LD for the single SLM projector, and have improved continuously it to achieve highly reliable operation under the high power output. In this paper, results of reliability improvement in 638-nm triple emitter will be described.

2. LD structure and characteristics

2.1 BA-LD structure

The LDs for this study were the triple emitter LD. The structures are shown in Fig. 1. Details are described in elsewhere [3]. The triple emitter was originally designed for the high power operation under pulse, which consisted of the triple emitters with each width of 60 μm .

It equipped a window-mirror structure made by using Zn diffusion as a measure to COMD. The chip was assembled on $\phi 9.0$ -TO with junction down configuration. An active layers were tuned to lase around 638 nm under the rating.

As mentioned in our previous study [4], there are two causes of power saturation of red LD except for the low thermal conductivity, which are electron overflow from an active layer to a p-type cladding layer, and carrier killer center in the active and guiding layer. The triple emitter used in this study was made by using the improved epitaxial technology and the design to reduce the both mentioned above.

As well known, there are two failure modes in LDs, one is the sudden failure, mainly COMD at the front facet, and the other slow degradation. MTTF of the red BA-

LD is dominated by the former, COMD at the front facet even in the window-mirror structure LD [5]. MTTF due to COMD (MTTF(COMD)) may be improved by adopting some tips to the window-mirror making process and the facet coating one. The triple emitter in this study also equipped the improved facet including the window.

Fig.1 638-nm triple emitter LD structure.

2.2 LD characteristics

The P-I and WPE-I curve dependence on T_c of the improved triple emitter are shown as bold lines in Fig. 2. For comparison, those of the former triple emitter are also plotted in the thin. Both were measured under pulse of 120 Hz with duty of 30 %. Under the operation current (Iop) of 5.0 A at T_c of 25°C, the improved LD emitted up to 5.0 W, although the former did 4.80 W. In other words, the improved had an advantage of 4.1% in the output power at the condition. The improved had the advantage even at high T_c of 55°C, 3.3%. The WPE of the improved LD reached to 41.6% at 25°C, 3.5 points higher than the former. The difference of peak WPE between the improved and the former became small as T_c increased, but it improved still showed 1.5 points higher at 55°C.

Fig.2 P-I and WPE-I dependence on T_c .

3. Reliability estimation

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3.1 Former triple emitter under the over-drive condition
The former triple emitter was originally designed for 2.5W output operation. The aging was performed under the over-drive condition (3.56 A, CW, auto current control (ACC) mode). Initial output was approximately 3.4 W. The result is shown in the left of Fig.3. COMD occurred from 4,000 hours and a half of emitters degraded due to COMD after 7,800 hours. The Weibull chart of the result is shown in the right figure. All plots are on the same straight line with shape factor of 6.35. This means that the degradation after 4,000 hours under the condition was in a wear-out mode. MTTF (COMD) of the LD was estimated approximately 8,000 hours under 3.4 W, CW. This is equivalent to 24,000 hours under 3.4 W output and pulse condition with duty of 30%.

Fig.3 Aging test of former LD under 3.4W, CW.

3.2 Improved triple emitter result

The long term aging test with the improved LD was performed under Iop of 4.9 A, CW, ACC. Tc of the LD under aging was tuned to have the same junction temperature (Tj) as that when the LD was operated under Tc of 30°C, 4.9 A in pulse with duty of 30%. It was approximately 15°C. The initial output power at the condition was approximately 4.75 W. The result is shown in the left of Fig.4. All of the LDs under aging kept very stable operation up to 5,000 hours.

The usual single SLM projector has luminosity of a few to a few ten thousand lumen, but the laser light source for this projector is required to emit a few ten to a few hundred watts. The BA-LDs for the single SLM projector are usually used in multiple pieces. Thus it is appropriate to estimate the lifetime of the LD based on each emitter unit, not on an LD (TO-can) unit. The right of Fig.4 shows the Weibull chart of the aging test result, which is shown in the left. There was no failure, thus it was assumed that only one failed right now (at 3,800 hours) and the wear-out failure starts from 3,800 hours with the same shape factor as that shown in Fig. 3. This assumed line is shown as a red line in the figure. Based on this assumption, MTTF(COMD) is estimated 6,200 hours under the injection current of 4.9 A (Po: 4.75 W), CW, and 20,000 hours under the same current pulse with duty of 30%.

As we already reported [5, 6], MTTF(COMD) has strong dependence on Po. The dependence is expressed in the following experimental equation;

$$\text{MTTF}(\text{COMD}) \propto P_o^{-n}$$

n is in the range between 3.2 and 3.4 based on our previous studies. In this study, we used n of 3.2 in a

view point of high margin in the MTTF estimation. MTTF(COMD) dependence on Po under pulse with duty of 30% is shown as bold lines in Fig. 5. MTTF(COMD) longer than 20,000 hours was achieved at Po less than 5.25 W. At Po of 3.5 W, MTTF(COMD) was estimated 72,000 hours. The value was approximately 3.3 times longer than that of our former triple emitter.

Fig.4 Aging test of the improved LD under 4.75W, CW.

Fig.5 Estimated MTTF(COMD) dependence on Po.

4. Conclusion

The improved 638-nm triple emitter LD showed MTTF of 72,000 hours under 3.5 W pulse with duty of 30%, which is approximately 3.3 times of the former. This improved technology may open the new horizon of high bright laser based displays.

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Recent Advances in GaN-based Laser Diodes for Laser Displays

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Abstract: We present latest development results of GaN-based high power blue and green Laser Diodes (LDs). The optical output powers of 455nm blue LDs and 532nm green LDs were 5.25 W and 1.19 W, and the wall plug efficiencies of them were 43.4% and 17.1%, respectively. Applying multiple chip LD package, the optical output power of blue LD reaches over 100 W at 75 °C.

1. Introduction

After we first demonstrated GaN-based LDs in 1995, the characteristics of LDs, such as efficiency, optical output power and reliability, have remarkably improved over the past two decades [1]. Now that our products with GaN-based LDs cover a wide range of wavelengths from UV to green, they have replaced lamps and gas lasers by LDs as light sources for optical disc drives, lithography equipment and flow cytometers. In recent years, LDs in the visible light spectrum have been used more for laser displays, e.g. large laser projectors, digital cinema projectors, projectors for businesses and laser TVs. These displays require the high optical output power of several tens of watts or more. This paper reports the latest device performance of high power blue and green LDs [2]. And we also show a new type of LD package equipped with multiple LD chips.

2. Structure of high power LDs

We optimized the epitaxial and the device structures for high efficiency, high optical power and reliability of LDs. The epitaxial structures of LDs including n-type, active and p-type layers were grown by metal organic chemical vapor deposition (MOCVD) on C-plane free-standing GaN substrates. The structures were separate confinement heterostructure (SCH) which was based on cladding layers, guiding layers and quantum wells. And quantum wells of green LDs were thinner thickness and higher Indium composition than those of blue LDs. And a ridge type structure and electrodes of the n-type and p-type were formed. The ridge widths of blue and green LDs were 45 μm and 15 μm respectively. Dielectric mirrors were deposited on front and rear mirror facets, which were obtained by cleavage at the m-plane surface. Every LD chip was mounted on a heat sink using a junction down mounting method in a TO- ϕ 9 mm package for suppressing thermal resistance. We consider LDs having these structures are suitable for operating at high optical output power.

3. High power blue LDs

We fabricated high power, multi longitudinal mode blue LDs by forming the ridge widths of 45 μm . The peak wavelength of blue LD was 455 nm. Figure 1 shows optical output power-current (L-I) and the voltage-

current (V-I) characteristics of 455nm blue LDs under CW operation at 25°C. The threshold current was 0.3 A. The optical output power and voltage were 5.25 W and 4.03 V at CW 3 A, respectively. The WPE was obtained 43.4 % at CW 3 A. These good characteristics are resulted by optimizing active layer and the suppression of the thermal resistance by adopting the junction down mounting and TO- ϕ 9 mm package.

Fig. 1. L-I & V-I characteristics of a 455nm blue LD

Figure 2 shows the results of the lifetime test. A lifetime test was carried out for 1,000 hours under CW 3A at 65 °C control. The temperature condition of lifetime test fixture includes not only thermal resistance of LD package but also that of heat sink. The lifetime was defined as the expected time when the optical output power of the LDs became the half of initial output power. The lifetime was estimated to be over 20,000 hours.

Fig. 2. Lifetime test results of blue LDs

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4. High power green LDs

We fabricated high power, multiple longitudinal mode green LDs by forming the ridge widths of 15 μm . Figure 3 shows the L-I and V-I characteristics of the 532 nm green LDs under CW operation at 25°C. The threshold current was 0.19 A. The optical output power and voltage were 1.19 W and 4.34 V at CW 1.6 A, respectively. WPE reaches up to 17.1 % at CW 1.6 A. We carried out the lifetime test of green LDs for 1,000 hours at CW 1.6 A and 60 °C control. The estimated lifetime which was calculated in the same way of the blue LDs exceeded 30,000 hours. This result shows these green LDs are sufficiently stable for the light source of the projector as well as blue LDs. Furthermore, we also succeeded in developing 543 nm high power LDs.

Fig. 3. L-I & V-I characteristics of a 532 nm green LD

5. Multi-chip LD package

For high optical output power over several tens Watts, we developed a multi-chip LD package "OctoLas[®]" equipped with multiple LD chips. From the viewpoint of the optical design, beam quality of each LD beam and heat dissipation, we set the dimension of the OctoLas[®] package is H 10.8 mm x W 29 mm (except electrode terminals) x L 47.5 mm in Figure 4.

Fig. 4. Top view of the OctoLas[®] package

Figure 5 shows the L-I characteristics when the module temperature (T_m) of the OctoLas[®] package equipped with 24 blue LD chips is set to 25 °C and 75 °C. T_m was defined at the side of the package. At the T_m 25 °C, the optical output power was 124.0 W at the current of 3 A under CW operation. And even at T_m 75 °C, the optical

output power was 103.9 W at the same current condition of T_m 25°C.

Fig. 5. L-I characteristics of 24 blue LD chips OctoLas[®]

Figure 6 shows the lifetime test results of OctoLas[®] equipped with a conventional type of high power 20 blue LD chips under an operating current of CW 3 A at T_m 75°C for 9,000 hours. The estimated lifetime was over 30,000 hours. OctoLas[®] shows durability for light sources of projectors. In addition, it can easily change the type and number of LDs, which will be further advantages for projector light sources.

Fig. 6. Lifetime test results of OctoLas[®]

6. Conclusions

We succeed in fabricating high power blue and green LDs grown on c-face GaN substrates by adopting the junction down mounting and TO- ϕ 9 mm package. The optical output powers of 455nm blue LDs and 532nm green LDs were 5.25 W and 1.19 W, and the wall plug efficiencies of them were 43.4% and 17.1%, respectively. And we also succeed over 100 W at 75°C using 24 blue LD chips by OctoLas[®] package.

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Optical Architectures for Mixed Reality Wearable Systems

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We are sorry. This paper was not available at time of publication.

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Interactive Dynamic Projection Mapping Using High-speed Display and High-speed Image processing

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Abstract: *Dynamic projection mapping, where dynamically-changing real-world and virtual visual information are completely merged in the level of human visual perception. The technology requires a high-speed projector enabling high-frame-rate and low-latency projection. We have developed a high-speed projector "DynaFlash" that can project 8-bit images up to 1,000fps with 3ms delay.*

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Visible Lasers for Display and Lighting Applications

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Abstract: Visible laser diodes have recently attracted a great deal of attention as light sources for various display and lighting applications. In this paper, recent progress in red, green and blue lasers developed at Sony, which realize watt-class output power operation, are demonstrated.

1. Introduction

Laser diodes have found a wide range of applications in recent years, and it is expected that demand will increase still further. Since our first laser diode product for CD players, Sony has produced many types of lasers, including edge-emitting lasers and vertical cavity surface emitting lasers (VCSELs), for various applications, such as optical discs, laser printers, optical communications, 3D sensors, and laser projectors. Particularly in the field of laser projectors, products such as head-mounted displays, mobile projectors, business and home projectors, and digital cinema projectors, are being developed by exploiting the excellent characteristics of lasers. Projectors using laser light sources have many advantages over conventional lamps and light-emitting diodes (LEDs) in terms of high brightness, high color reproducibility, small size, quick start-up, and long life. Laser projectors mainly use laser sources that can emit visible light. As their projection size increases, so does the demand for high-output lasers. In high-brightness projectors, lasers with watt-level output or higher are used. A typical projector currently on the market, having a luminance of several thousands to tens of thousands of lumens, is equipped with dozens to hundreds of lasers. If laser output power could be further improved, the number of installed lasers could be reduced, which would allow downsizing of light source modules and cost reduction. Moreover, high-power lasers generate a lot of heat owing to the high-power input. This necessitates special cooling mechanisms, which is a major technical challenge. To reduce the load, we need to develop high-efficiency lasers. In this paper, recent progress on high-power and high-efficiency lasers developed at Sony is demonstrated.

2. Watt-class R/G/B lasers at Sony

Sony has developed all three primary-color lasers, i.e. red, green, and blue. Each laser has a broad area stripe and enables watt-class output power operation. In this section, the structures and characteristics of the InGaP-based red laser and InGaN-based green and blue lasers developed at Sony are overviewed.

2.1 Red laser diode

Our InGaP/AlInGaP red lasers are fabricated on GaAs substrates by metal organic chemical vapor deposition

(MOCVD). They have a 1500- μm -cavity and ridge-shaped dual emitters with widths of 70 μm . The facets at both ends have window-mirror structures to improve resistance to catastrophic optical mirror damage (COD).

Figure 1 shows the optical and electrical characteristics of our 640-nm red laser, which is junction-down-mounted on a heat sink in a $\varnothing 9.0$ mm TO package. The output powers and forward voltages are plotted in Fig. 1(a) as a function of injection current under continuous-wave (CW) operation at a case temperature of 25°C. The calculated wall-plug efficiencies are plotted in Fig. 1(b). An output power of 2.9 W and wall-plug efficiency of 41.1% under an operating current of 3.0 A were successfully obtained.

Fig. 1. (a) I-L and I-V characteristics and (b) wall-plug efficiency of our 640-nm red laser measured under CW operation at a case temperature of 25°C.

2.2 Green Laser Diode

We use semipolar {20-21} GaN substrates for our green lasers. InGaN quantum wells on the {20-21} plane were theoretically found to have a piezoelectric field that is only about one-third of that for a conventional c-plane [1]. The piezoelectric field, which becomes larger with In molar fraction of InGaN quantum wells, degrades the luminous efficiency because it reduces the carrier recombination probability. Therefore, using the {20-21} plane makes it easier to fabricate green or longer-wavelength GaN-based light emission devices. The first CW lasing of green laser on the {20-21} plane was reported by Sumitomo's group in 2009 [2], and our

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group reported the first watt-class output power operation [3].

The green lasers we developed have a 15- μm -wide ridge-shaped stripe and 1200- μm -long cavity. The stripe is formed along the $[-1014]$ direction, reported to be an advantageous orientation for semipolar $\{20\text{-}21\}$ GaN [4]. A p-side indium tin oxide (ITO) electrode is deposited on top of the ridge. The transparent ITO layer, which has a much lower refractive index than the active layer, also served as part of the optical cladding layer and ensured good vertical optical confinement. Thanks to the ITO cladding, we could use a thin high-resistance p-type AlGaIn cladding layer and thereby reduce the device resistance.

Figure 2 shows the optical and electrical characteristics of our green laser with a lasing wavelength of 525 nm, which was assembled on a $\varnothing 9.0$ mm TO with a junction-down configuration. An output power of approximately 1.5 W was obtained at an operating current of 2.0 A and a maximum output power of 2 W was reached under CW operation at a case temperature of 25°C. The wall-plug efficiency was calculated to be 17.1% at 2.0 A.

Fig. 2. (a) I-L and I-V characteristics and (b) wall-plug efficiency of our 525-nm green laser measured under CW operation at a case temperature of 25°C.

2.3 Blue Laser Diode

In general, blue lasers have two uses: as pure blue light sources and for phosphor excitation. The former enables R/G/B laser-based projectors and the latter, which can yield white light when used with phosphors such as YAG:Ce, realizes not only projector applications but also lighting.

The blue lasers we developed are fabricated on conventional c-plane GaN substrates. They have a 45- μm -wide ridge-shaped stripe and 1200- μm -long cavity. A p-side ITO electrode is deposited on top of the ridge, as for our green lasers.

Figure 3 shows the optical and electrical characteristics of our 455-nm blue laser, which is junction-down-mounted on a $\varnothing 9.0$ mm TO package. The output power and wall-plug efficiency were approximately 5.2 W and 41.2%, respectively, at an

operating current of 3.0 A under CW operation at a case temperature of 25°C.

Fig. 3. (a) I-L and I-V characteristics and (b) wall-plug efficiency of our 455-nm blue laser measured under CW operation at a case temperature of 25°C.

7. Conclusions

We have presented an overview of watt-class visible lasers developed at Sony for display and lighting applications. Our red laser with a wavelength of 640 nm enables approximately 2.9-W output power operation with a wall-plug efficiency of 41.1%. Our green laser is fabricated on semipolar $\{20\text{-}21\}$ GaN substrate and realizes an output power of 1.5 W and wall-plug efficiency of 17.1% with a wavelength of 525 nm. Our 455-nm blue laser on c-plane GaN achieved an output power of 5.2 W and wall-plug efficiency of 41.2%. Advances in these watt-class visible lasers will further popularize laser displays and lighting.

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360-Degree Tabletop Type 3D Screen System

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Abstract: We propose a 3D screen system with 360-degree smooth motion parallax that utilizes perceptual mechanism of the visual system. We implemented a prototype using 60 projectors, which is about one fifth the number for the conventional method and the display area has a diameter of 1,200 mm.

1. Introduction

Expectations are high for autostereoscopic three-dimensional (3D) screens capable of providing natural 3D viewing without requiring 3D glasses or any other wearable mechanism, as the ultimate display system of the future. In particular, tabletop 3D screen technologies, which can display items as though they were actually on the table, are anticipated for a wide range of applications such as sports viewing in which the whole field can be watched, or for cooperative modelling of products by multiple observers. If multiple observers standing all around the table can watch a sports event from whatever direction they wish, for example depending on the team they are supporting, this experience would dramatically improve the communication environment among viewers. In order to create this sort of experience, it is necessary to use autostereoscopic 3D display technology supporting 360-degree motion parallax without the need for any wearable mechanisms (e.g., 3D glasses, head-mounted displays), which become an obstacle to viewers for making eye contact and seeing the facial expressions of others.

Autostereoscopic 3D display technologies with 360-degree motion parallax have been proposed earlier. Yoshida [1] proposed the system using 288 projectors placed at very small intervals (1.25 deg), projecting onto a special cone-shaped screen. Using multiple projectors to project viewpoint images in this way is advantageous in that the multiple observers can watch 3D video at the same time. On the other hand, many projectors at very close intervals are needed to switch smoothly between video sources as the viewpoint moves, which increases equipment costs and the complexity of the content control system.

In order to reduce the number of projectors, we have focused on a perceptual mechanism of the visual system called “linear blending” [2,3,4]. In linear blending, the luminance of the image from adjacent viewpoints is composed on the basis of the observer’s viewing position, so that the intermediate viewpoints are perceived as being visually interpolated. To apply linear blending to a 360-degree tabletop type 3D screen system and to reduce the number of required projectors, we propose a novel optical configuration with a “spatially imaged iris plane screen” [2] and a circular projector array as shown in the side view of Fig 1.

Side view

Top view

Fig 1. Comparison of conventional super multi-view approach and our linear blending.

2. Linear blending for 3D screen system

When two images overlap with only a small offset to the left or right and the images have different luminance, an image with double edges to the left and right is projected on the human retina. However, in the human visual system, if the distance between these two edges is less than the fusion limit angle [3], it is perceived as one edge instead of two, with the position of the edge varying in accordance with the luminance ratio. This principle, using this image edge perception mechanism to blend viewpoint images from adjacent projectors in accordance with the luminance ratio, is called “linear blending”.

In order to use this mechanism for multiple projector 3D systems, viewpoint images with less disparity than the fusion limit angle are projected. Linear blending enables 3D images to be displayed with binocular disparity and smooth motion parallax, even when using projector intervals that are wider than the spacing between viewers’ eyes. This makes it possible to reduce

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Fig 2. Structure of a spatially imaged iris plane screen.

the number of projectors needed to show intermediate viewpoints.

For changing the luminance ratio in accordance with the viewpoint position for linear blending, an optical luminance distribution is necessary where the luminance peaks at the center position and decreases gradually as the distance from the center increases in the horizontal direction. To achieve this distribution, we have developed a “spatially imaged iris plane screen” [2].

The spatially imaged iris plane screen is composed of a reflective layer, a Fresnel lens layer, and a diffusion layer as shown in Fig. 2. Light from the projectors is reflected by the screen and focuses in the opposing space on the side of the screen. The projector iris plane (the part equivalent to the iris in the projector optical system) forms in the space and the observer can only perceive the projected image within that range. In addition, depending on the diffusion layer characteristics, the luminance distribution of the iris surface peaks at the center and attenuates in accordance with the distance from the center, which is suitable for linear blending.

3. Prototype system

Fig. 3(A) shows our prototype [4]. The screen has a diameter of 1,200 mm and is placed 800 mm above the floor. The projectors have 1280x800 pixel resolution and were placed at 6-degree intervals. On the basis of projection distance, the diameter of the circular projector array was set at about 3,000 mm. The viewpoint images projected from each projector were rendered with real-time synchronization on 60 client PCs, one for each projector. Each client shared the same computer graphics space and rendered the images from a virtual camera in the position of the corresponding projector. Time synchronization of the viewpoint images was done by sending UDP packets from a server PC with information for the 3D model position and the start of animation. This content control system was created by Unity3D.

As shown in the photograph of Fig. 3(B), different images are observed in accordance with the viewpoint position in the horizontal direction. The effect of stereoscopic vision due to binocular parallax can also be confirmed in actual observation.

4. Conclusions

The tabletop type 3D screen technology we propose can reproduce perfect motion parallax in the horizontal

direction of 360 degrees around a table with about one fifth the number of projectors the conventional method [1] requires. This system has a display surface with a diameter six times as large as that of the conventional one. Our method not only reduces the number of projectors required but also enables the screen to be simplified. As a future work, we consider to apply a method to reduce image quality variation by linear blending [5] for our prototype system.

Fig 3. (A) Our prototype. (B) Pictures taken from 8 viewpoints around the screen.

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High-speed R/G/B Laser Diode Mixed White Lighting Communication

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Abstract: In this talk, both the conceptual design and experimental demonstration of the tri-color R/G/B-LD mixed white-lighting source and its directly modulated data transmission performance in a free-space link over 30 Gbit/s will be discussed.

1. Main Text

High-data-capacity visible laser lighting system has become the important issue to be developed for next-generation lighting fidelity (LiFi). In this talk, both the conceptual design and experimental demonstration of the tri-color R/G/B-LD mixed white-lighting source and its directly modulated data transmission performance in a free-space link will be discussed, as shown in Fig. 1. Versatile surface roughened diffusers are employed to

improve the lighting divergence and color aberration. For correlated color temperature (CCT) tunability and color-rendering-index (CRI) enhancement, the assistance with different phosphors or yellow light are also discussed. With such a RGBY based white-lighting transmitter, the visible wavelength division multiplexing (VWDM) can be performed toward beyond 30-Gbit/s data transmission for future applications of smart white-lighting communication.

Fig. 1. The experimental setup of RGB LDs based white-lighting VLC system.

2. Biography

Prof. Gong-Ru Lin received his B. S. degree of Physics from Soochow University in 1988, M. S. and Ph. D degrees of electro-optical engineering from National Chiao Tung University (NCTU) in 1990 and 1996, respectively. He is the Lifetime Distinguished Professor, the Associate Dean of the college of Electrical Engineering and Computer Science, and the Director of the Graduate Institute of Photonics and Optoelectronics, National Taiwan University (GIPO/NTU). Prof. Lin has a broad research spectrum covering visible-lighting and fiber-optic communications, semiconductor laser diodes, ultrafast fiber lasers, and group IV semiconductor nanophotonics. Prof. Lin is the Senior Editor of the IEEE Photonics Journal, the Topical Editor of Optics Letters, and he has served as the associate editor of "Journal of Lightwave Technology", "IEEE Photonics Journal" and "Current Nanoscience". He received three times the outstanding researching awards from National Science Council, and two times the Distinguished Research Awards from Ministry of Science and Technology in Taiwan. To date, Prof. Lin is the Fellows of OSA, SPIE, IET, and IOP and the senior member of IEEE. Prof. Lin is currently the OSA Traveling Lecturer and the SPIE Visiting Lecturer, and the steering committee of CLEO-PR and APMP. Prof. Lin is elected as the Distinguished

Professor in 2015 and becomes the Lifetime Distinguished Professor of National Taiwan University in 2018, he also serve as the President of Taiwan Photonics Society since 2018.

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Laser Projector in Augmented Reality

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Abstract: Projection-based augmented reality (AR), also known as spatial AR and projection mapping, merges real and virtual worlds seamlessly. Because it usually assumes non-planar projection surfaces, laser projector holds an advantage regarding depth-of-field over other types of projectors. This invited talk covers a recent research of introducing laser projector in AR.

Fig. 1. Dynamic projection mapping, or dynamic projection-based augmented reality, of the SPAP (Simultaneous Projection and Positioning) approach: (left) a prototype system of the direct method consisting of a laser projector and photosensors embedded in a projection surface and (right) projection mapping results for different surface poses (rotation and translation) and different textures. The yellow arrow indicates the left edge of the projected image that is horizontally shifted towards right due to the projector's translation [8].

1. Introduction

Projection-based augmented reality (AR), also known as spatial AR and projection mapping (PM), is a technology that controls the appearance of an arbitrarily shaped surface by projecting computer-generated images onto it. One of the recent research trends is dynamic PM where the surface and/or projector is moving [1-3]. Even though multiple systems have been proposed, the projectors applied in the majority of these prior systems, such as DLP (digital light processing) and LCD (liquid crystal display), are not suitable in some dynamic PM applications. In these projectors, a light ray from a light source is spatially modulated on a SLM (spatial light modulator) and then projected through an objective lens. To increase the brightness of the projected imagery, the aperture of the projector is normally designed to be large, which consequently leads to a narrow depth-of-field (DOF). A projection surface is expected to move over a wide area range in a dynamic PM scenario; however, conventional projectors cannot project sharp images over such wide areas.

Previously developed defocus blur compensation or DOF extension techniques can improve this situation but only to a limited extent [4,5]. Conversely, in theory, a

laser projector has an infinite DOF [6] and therefore is suitable for dynamic PM [7]. In a dynamic PM system with a laser projector, it is inevitable to assume a situation where the distance between the projector and the surface varies significantly. Therefore, we need to geometrically register the projector so that the pixel alignment on the surface is consistently accurate with respect to the distance.

2. Simultaneous Projection and Positioning

In this invited talk, I introduce previously proposed geometric registration approach of a laser projector for dynamic PM [8]. Our approach is an extension of the principle of the light pen [9]. The light pen, in which a photosensor is embedded, can measure its position on a CRT (cathode ray tube) screen at each frame while displaying meaningful image content. The pen detects changes in the brightness of nearby screen pixels when the CRT electron beam scans across them and communicates the timing of this event to the computer. Because a CRT scans the entire screen one pixel at a time, the computer can estimate the pen's position from the latest timestamp. The image forming mechanism of the laser projector is also based on raster scanning. A

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MEMS (Micro-Electro-Mechanical Systems) mirror adjusts the direction of a projected beam, and the color of each projector pixel is controlled by modulating the laser diode intensities of different primary colors. Leveraging this mechanism at each frame, we measure the time when a projected beam scanning over a projection surface hits a photosensor that is, for example, embedded in the surface. The time information is then used to estimate the position of the beam in the projector's screen coordinate system when it illuminates the sensor. Because the time information is invariant to the distance from the projector to the sensor, this method does not depend on the distance and therefore meets the requirement for dynamic PM described in the previous paragraph. This principle allows us to measure the position of a photosensor in each frame while projecting meaningful image content and, therefore, is referred to here as *Simultaneous Projection and Positioning (SPAP)*.

The SPAP method estimates the position of a projected beam when it directly illuminates the photosensor. We implement a prototype system as shown in Fig. 1(left) and investigate its geometric registration performance by evaluating the estimation accuracy. The estimation errors are measured by varying the distance from the laser projector to the photosensor, the projected light intensity, and other critical factors. Finally, we implement various dynamic PM applications to show the feasibility of our technique. They include a projector-based texture mapping for a moving 3D surface (Fig. 1(right)) and a drone projection.

3. Drone projection AR

Drone projection is an emerging research topic in which researchers attempt to realize an autonomous projection system that provides SAR anywhere [10,11]. Because a drone on which a projector is mounted generally flies with fluctuations, the geometric registration parameters must be estimated in each frame. In our application, we mounted our projector node on a drone and embedded four sensor nodes in a projection surface (Fig. 2). We applied the wireless system to this application. Estimated pixel positions on the sensors were used to compute the homography matrix used to transform the projection image to align the surface. Fig. 2 shows the result. We confirmed that the wireless system works and that a projection mapping can be achieved even when a projector is flying.

Fig. 2. A prototype of the drone projection [8].

4. Conclusion

Laser projector has a great potential for PM due to its large DOF especially in dynamic situations. This invited talk introduced a geometric registration technique of laser projector in dynamic PM applications. It is expected that laser projectors will be more often applied in PM applications in the near future.

Acknowledgement

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Evaluation of Adaptive Shifted Superimposition Technique for Enhancing the Projector Resolution

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Abstract: Shifted superimposition is a method for increasing resolution by shifting every other frame with subpixel precision. In this work we simulate the possible benefits of shifting in different directions based on the image content. We do find that the directional may be beneficial in some cases, but not necessarily optimal.

1. Introduction

In a projector, the spatial resolution is usually limited by the number of pixels in the Spatial Light Modulator (SLM). If the projector is given a video signal containing a higher resolution than its native SLM resolution, the projector is forced to downscale the video signal and therefore also inevitably lose details in the image.

Resolution enhancement currently has gained some momentum because of the market drive for 4K images and video. Not all SLM technologies have cost efficient 4K modulators available, and for these modulator technologies it is appealing to push the resolution above the native resolution of the SLM using resolution enhancement techniques. Shifted superimposition of projected images is a cost effective way of enhancing the resolution above the native resolution of the spatial light modulator (SLM) in a projector.

2. Technical background

Most projectors that utilize the superimposition method today have an opto-mechanical actuator that spatially shifts every n 'th frame with subpixel precision. The two most common shift configurations are either half a pixel in one diagonal (two positions) or half a pixel in both diagonals (4 positions).

Fig 1 Two frame grid shifted half a pixel diagonally.

Since the frames are projected at high speed, the two frames at different positions blend together in the human visual system and appear as one frame with a new pixel grid. The new pixel grid consists of a larger number of distinct pixels, approximately doubled both horizontally and vertically, and with a finer pixel pitch, meaning that the distinct pixels are smaller than those in the un-shifted case.

In the analysis in this paper, we look at how the high frequency content in a high resolution source image is preserved when displayed with a projector with a lower native resolution than the source. We have simulated two cases: one where the same subframe is used in both positions, and other where two independent subframes are calculated from the high resolution source image and displayed sequentially.

The same subframe approach is computationally cost effective, but is often not optimal in quality [1]. Another approach is to generate different subframes for each spatial position. Calculating a new subframe for each position is computationally expensive, but it also results in a better quality superimposed image [1].

3. Our approach

We analyze each frame with a histogram of oriented gradients (HOG) analysis. The HOG is divided into predefined bins to calculate in which general direction the image have most high frequency information. We do not discriminate whether the gradient is on an upward or downward slope, so both 0 and 180 degree angles will for instance be placed in the same bin. The 180 degree angle space is then divided into 8 bins, giving us bins for 0-22.5, 22.5-45, 45-67.5, 67.5-90, 90-112.5, 112.5-135 and 135-157.5 degrees.

As subframe generation methods we have used the downsampled superimposed method [1] that use the same subframe in both shifted position, and the Gaussian Sharpened method described in [1]. These methods are compared to the performance of downscaling the source image to the SLM resolution, which will be the case in all displays not utilizing resolution enhancement techniques.

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Fig 2 Gradient preservation shown by HOG analysis.

4. Results

To investigate the benefits of directional superimposition method we have developed a Matlab simulator that explores the different subframe generating methods and how they perform with directional superimposition. This performance is evaluated by calculating the HOG preservation.

For determining the HOG preservation we calculate the HOG for the high resolution source image, and then we calculate the HOG for the resulting superimposed image. The ratio between gradients in the original image and gradients in the superimposed image gives us the gradient preservation for each histogram bin. A preservation of 1.0 means that all gradients in that direction is preserved, while a preservation of 0.4 will mean that 60 percent of the gradients in that particular direction is lost. With this analysis we expect to see that gradients in some directions are better preserved than in other directions, dependent of the direction of the shift.

Fig 2 show the results of a outdoor scene with nature elements as well as a building. The analysis have been done over a broad range of image categories, and the results of all these categories are in general following the same pattern.

As shown in Fig 2 the method that use a single frame for both positions in the superimposition has a very high directivity in their frequency response and therefore also preserve more gradients in the orthogonal direction of the shift. This is because all of the pixels are overlapping themselves and are generating a frequency response which favors the orthogonal direction of the shift. The downside of this approach is that we are losing some details in the direction of the shift.

Fig 2 also shows that both the diagonals have preserved most of their gradients in the different subframe cases.

5. Discussion

The enhanced resolution is a direct consequence of the decreased pixel pitch, giving the display a capability to display smaller details, and a larger amount of these details than would be possible in regular native resolution. Thus it seems logical that the 0 degree and 90

degree shift gives worse results since these shifts only decrease pixel pitch in one given direction.

Since the single subframe method demands less calculation power it is applicable in low cost systems. Hansen et al.⁶ showed that most people prefer the downscaled superimposed method utilized for single subframe over regular downscaling to the SLM resolution. In that study they used a fixed shift in 45 degrees for all scenes and did not take the gradient directions of the image into account. Adding adaptive shift where the system shifts in the appropriate direction based on the image content to the single subframe method would potential increase the quality furthermore since the directions with the most gradients and details would be prioritized.

The different subframe method do not benefit the same way of the directional shifting. The reason for this is that since the two subframes is generated differently based on the spatial position, the different sub-pixels will not necessarily be made up by overlapping pixels of the same strength.

7. Conclusions

These results show that a projection system with enough computational power to generate each subframe based on its spatial position will not benefit much from the directional shifted superimposition. The gradient preservation in the different directions is quite equal when using different subframes.

In a system with less computational power where the system use the same subframe for all positions, the directional shifted superimposition may indeed improve the image quality by shifting in the desired direction based on the content.

Acknowledgement

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Wireless Optical Feeding to Remote Moving Object Using Visible Laser Diodes

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Abstract: Wireless optical feeding to a moving object using visible laser diodes (LD) is successfully demonstrated. The laser beam is kept feeding optical power to a solar cell on the moving object, pinpointedly tracking it by visible 3D LiDAR technology. More than 90% of laser power is expected to be received.

1. Introduction

In recent years, visible LDs have been introduced to in-vehicle devices such as head lamps, head-up displays (HUDs), and in anticipation of automatic operation in future, projection on road surfaces for warning [1]. Also, obstacle detection by LiDAR using an infrared LD [2] has been already introduced in practical use. In addition, laser power supply has attracted attention as a new technology for wireless optical feeding to remote and/or moving objects [3].

If visible LDs are used for multi-purpose lighting systems with a LiDAR and optical feeding, we can use the same light sources for sensing and feeding. This concept is promising in terms of smaller size, lighter weight and lower cost [4-5].

In this paper, we focus on the operating principle of our new optical feeding system using the LiDAR and the visible LDs. We also discuss on the feeding to a moving object.

2. Detection characteristics by visible LiDAR

In the visible LiDAR, a BA (broad area) -LD emitting at 638 nm was used as a light source. The operation conditions were basically the same as our previous work [4-5]. The horizontal scanning angle was 210° at a speed of 20Hz, and the vertical angle was 40° at 1.2 kHz.

Figure 1 shows the maximum detectable distances at typical scanning angles for both black and white targets which have diffusive reflectance of 10% and 90%. The scanning angles are shown on the top of this figure. The detection distance along the center direction was 3 m even for the black targets, and about 10 m for white ones. These would be considered as enough performance necessary for indoor applications. The frame rate is 20 fps, and the resolution is 2590 dots/frame. Interlace (IL) in both horizontal (x20) and vertical (x10) directions can improve the resolution up to 200 times.

Figure 2 shows a comparison between motion scene (a) and 3D-LiDAR image for IL:8 (b) and IL:4 (c). In the case of IL:8, the resolution improves up to 2.1kdots/frame, although the speed can only follow slow motion at 2.5 fps. If IL is lowered to 4, the speed can be detected at 5 fps. However, the resolution degrades to a half (c). Faster and higher resolution can be achieved if

we can limit deflection angle and speed up the optical scanning system in future.

Fig. 1. Maximum detectable distances for both black and white targets at typical scanning angles (Top: scanning angle specifications).

Fig. 2. Comparison between motion scene (a) and 3D-LiDAR images (IL: 8 (b), IL: 4 (c))

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3. Power-supply characteristics by visible LD

For verifying the power-supply performance, the received optical power and the generated electrical power by visible light LD were measured using the system shown in Fig. 3 (a). The red or blue light from a fiber-output of an LD module was used. The light passes through a 10mm ϕ aperture and irradiates a general-purpose Si solar cell. The transmission distance is 1 m. The optical feeding efficiency of laser light was 90% or more, as shown in Fig.4 (b). The energy conversion efficiency were 9% for the red light and 6% for the blue because of poor efficiency of the Si solar cell for visible lights. However, it would be expected to improve conversion efficiency by adopting PV cell matched to visible laser light.

Fig.3. Setup of measurement system for power supply (a), and the graph showing optical power, optical feeding efficiency with respect to laser-power output (red and blue) (b).

4. Wireless optical Feeding to Moving Object

For the laser wireless feeding to a moving object, a system combining visible light LiDAR and variable spot lighting was prepared as shown in Fig. 4 (a). A miniature car with a Si solar cell doing was used as the moving object.

Using this prototype system, we verified the power-feeding performance as shown in Fig. 4 (b).

As a result, it is found that a mobile power source using only visible LDs is expected to realize outstanding cost performance. The development of advanced solar cells using wide-gap semiconductors such as GaN [6], will contribute to greatly improving higher conversion efficiency for visible laser lights. Furthermore, an innovative LiDAR-lighting simultaneous driving technology using the same visible light LD will open the market of a wireless light power feeding.

Fig. 4. Prototype system for feasibility verification of laser power supply to moving body(a), and pictures of laser power feeding to miniature solar car(b).

5. Conclusions

We developed a system of laser power feeding using visible LDs and a visible LiDAR. We verified the highly-efficient optical feeding to moving targets as well as precise tracking using visible LiDAR.

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Research on Gamut Expansion Mapping Method Based on Laser Display Device

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The development of modern traditional liquid crystal display devices is maturing, and at the same time, its color quality is also approaching to the limit. People are constantly pursuing new display technologies such as OLED, QLED, Micro-LED to show better color performance. Laser display technology is one of them because its pure single color spectrum. Therefore, it has a great color gamut coverage and can restore 70% of the natural color. It is 1.7 times more than the exiting TV st-andards. The existing lasere display devices generally use a single color (blue plus phospher) laser source or dual-color laser souse (blue and red plus phospher). Comparing the areas of color gamut with diferent standards with the laser display devices are shown as figure 1.

Fig. 1. Comparing the areas of color gamut among TV, single color laser display device, dual-color laser display device and different standard color gamut

Because the trichromatic coordinates of the laser display devices used in the wide color gamut and are greatly different from the existing television signals. When the TV signal is input to drive the laser display device, color distortion and color deviation may occur to influence the subjective experience.

In order to solve this problem, it is necessary to input signals under a certain rule to expand the small color gamut to the large color gamut for the laser display devices. This means that some colors must be mapped. The extension method of BT 709 color gamut signal to the laser display devices color gamut is

studied based on the basic theory of color science.

Firstly, the Y-xy space color gamut expansion is performed. The high saturation color and the expansion of human eyes to different color perception are formed by adding a correction distortion coefficient. The color gamut mapping expansion in Lab space can achieve a more brilliant color performance than the original small color gamut. The comparing images before and after expansion are shown as figure 2. The extended images are more gorgeous than original ones.

Fig. 1. Before and after mapping of color gamut

However, the gamut boundary calculation is complex and the amount of computation is large. The separation of algorithms and hardware implementation can be achieved by combining the interpolation method to increasing the calculation speed. In addition, the over-rendering and gradation patching of extended image can be solved by constructing a non-linear expansion function with the hue as the foundation.

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Homogenization Without Scattering of Laser Illumination

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Abstract: Our innovative deformable mirror technology is shown to be effective for homogenization of illumination intensity and for speckle reduction. Performance is similar to approaches that use moving diffusers but with much improved optical efficiency.

Fig. 1: [Left] Surface structure of an engineered diffuser. Although it is smooth piecewise, its slopes are discontinuous such that diffraction occurs. [Center] Typical homogenization optical system: laser diode, collimating lens, diffuser, coupling lens, integrating rod. Losses arise due to scattering by diffuser at angles higher than are accepted by coupling lens. [Right] Aperture of a beam trap positioned to accept laser light diverged approx. 6 deg by a cascade of two engineered diffusers. Plot of mean intensity in the neighborhood of the center line shows losses.

Fig. 2: Regions of field illuminated from exit face of integrating rod, with $150\times$ magnification by $f/2.4$ projection lens, into which light from a multimode laser diode is coupled. [Left] With cascade of two engineered diffusers before light guide. [Center] Moving one of the two diffusers improves homogeneity through spatiotemporal averaging. [Right] With no diffusers before light guide, mean intensity is approx. $1.5\times$ higher but homogeneity is poor due partially to the structure of multimode emission.

1 Introduction

The low étendue of laser diode emission facilitates efficient coupling into optical systems. However, in display or illumination optical systems, étendue may need to be increased to homogenize intensity and to shape the illuminated field. A moving diffuser is typically used despite the consequences for optical efficiency since even those with relatively smooth surfaces scatter light at angles such that it exits the optical system, see Figures 1 and 2.

DYOPTYKA has developed an innovative phase-randomizing deformable mirror technology [1], see Figures 3 and 4. It reduces speckle and other unwanted

Fig. 3: [Left pair] Small deformable mirror in inactive and active states. Elliptical central region of $3\text{mm} \times 4.5\text{mm}$ is actuated at hundreds of kHz to excite randomly-distributed surface deformations for angular divergence without diffraction. Reflection efficiency is approx. 99% and damage threshold is approx. 6 W. Power consumption depends on application requirements but is typically $\leq 100\text{mW}$. [Right] Contour plot of simulated surface wave heights showing smooth transitions between regions of convex and concave curvatures. As heights change over time the curvature of each region is reversed such that directions of reflection are changed.

Fig. 4: [Left] Typical deformable mirror configuration for illumination. Light from one or more laser sources is directed into an area of several tens of mm^2 , for example. Reflected light can be directed into a larger area with a smaller angle or vice-versa, in accordance with the optical invariant. [Right pair] Regions illuminated using the same deformable mirror actuated for different surface wave amplitudes such that divergence angles are approx. 2 deg and 3 deg respectively. No light is scattered outside these regions.

interference effects with excellent optical efficiency in comparison with diffusers, see Figure 5.

2 Objectives

To demonstrate how our phase-randomizing deformable mirror technology can be used for intensity homogenization without scattering for improved optical efficiency; and for the reduction of speckle contrast.

3 Apparatus

Powerful laser diodes have different structures of multimode emission and different coherence characteristics that can ef-

Fig. 5: [Left pair] Low-gain matt painted surface and high-gain rough metallic surface (of polarization-preserving cinema screen) illuminated with moving diffuser apparatus similar to schematic in Figure 1. Speckle contrast ratios are approx. 6% and 16% respectively. [Right pair] Same surfaces illuminated by same apparatus but without diffusers—a deformable mirror is used instead. Speckle contrast ratios are the same as with diffusers yet mean intensities are approx. $1.5\times$ higher.

Fig. 6: Elements of experimental homogenization and projection apparatus. [Left] Prototype large deformable mirror with approx. 200 W damage threshold, oriented at 45° , reflecting approx. $\varnothing 15$ mm beam expanded from 532 nm DPSS laser; $f = 50$ mm, $\varnothing 30$ mm lens positioned close to deformable mirror to collect light from approx. $\varnothing 15$ mm region. [Center] $f = 20$ mm, $\varnothing 25$ mm aspheric lens positioned to direct light into 6×8 mm² entrance face of integrating rod. [Right] Exit face of integrating rod and DLP[®] projection lens with stop added to approximate $f/2.4$.

fect homogenization performance. Hence a highly coherent laser source with a near-Gaussian beam profile was chosen for the purposes of experimentation. Its beam was expanded to approx. $\varnothing 15$ mm such that it was similar in diameter to the combined emission from multiple powerful laser diodes.

A prototype large deformable mirror with a high laser damage threshold was used. Due to a fabrication error it had a distorted surface figure—the effect of which is seen in the following section. Large diameter lenses were used to couple into an integrating rod of length 50 mm. In an alternative configuration, three such rods were positioned next to each other for length 150 mm.

A projection lens was used to form a magnified image of the exit face at a distance of approx. 2 m. See Figure 6 for further details.

4 Homogeneity

The homogeneity of intensities shown Figures 7 and 8 are certainly improved through the action of the deformable mirror. That their mean intensities are the same supports the assertion that no light is scattered from the system.

It can be seen in Figure 8 that intensity distribution across the field is not perfect. Likely explanations include mirror surface figure distortion and misalignment of the aspheric lens used for coupling into the integrating rod.

Fig. 7: Regions of field illuminated through integrating rod of length 50 mm. Mean intensities are approximately the same. [Left] Prototype large deformable mirror inactive. Distortions of its surface result in highly irregular intensity distribution. [Right] Deformable mirror active. Its surface wave amplitudes are insufficient for good homogeneity.

Fig. 8: Regions of field illuminated through integrating rod of length 150 mm. Mean intensities are approximately the same. [Left] Prototype large deformable mirror inactive. Longer light guide achieves more global distribution of irregularity. [Right] Deformable mirror active. Its surface wave amplitudes are sufficient for good homogeneity.

Although it was not measured with this particular apparatus, we are confident from previous experimentation that speckle contrast ratio is reduced by the deformable mirror to the same level as by a moving diffuser, see Figure 5.

5 Conclusions

Homogenization without scattering has been demonstrated. Our understanding is that surface waves on the deformable mirror result in spatially-distributed randomized angular divergence that makes the illuminated region appear as an extended source that fills the entrance face of the integrating rod better than point-like sources. The smooth transitions between surface waves, whose wavelengths are longer than those of the light, do not result in diffraction. Movement of surface waves further improves homogenization by directing light along different optical paths such that standing interference patterns do not arise. This movement also acts to reduce speckle contrast.

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High-Speed Operation of Electro-Optic Bragg Deflectors Utilizing Periodically Polarization-Reversed Structures

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Abstract: A high-speed operation of electro-optic (EO) Bragg deflectors based on polarization-reversed structures of ferro-electric crystals was experimentally demonstrated. Owing to its simple electrode structure for the deflection operation, it is possible to control a laser beam at ~GHz with a high-contrast, which is suitable for future IoT systems.

1. Introduction

Semiconductor laser diodes (LD) operating in the visible wavelength ranges are promising for future display and lighting owing to their excellent characteristics of wide colour gamut, high colour reproduction range, small extendue, and low power consumption [1].

LDs are also attractive for IoT applications with high-speed data communications. The simplest way to use LDs for data communication applications is to superpose data signals over the DC bias signal for LDs; which enables us to have a simple circuit configuration for modulating laser beams for communication applications. However, the data signal frequency is approaching to GHz ranges, the frequency chirping effect may be caused by the superposition of the high frequency signal. In addition, since the relaxation oscillation frequency of standard LDs is in the GHz frequency band, drastic spectrum broadening and temporal waveform changes could be caused with the superposition of a narrow spectrum signal [2]. Therefore, for the applications to high-speed communications, it is desirable to use an external laser beam control/modulation device of the visible laser beams emitted from LDs.

Recently, we have proposed a visible laser beam control device based on the Bragg diffraction by use of the first-order electro-optic (EO) effect in periodically polarization-reversed ferro-electric crystals (LiNbO₃, LiTaO₃, KTP, etc.) [3]-[5]. This device can control a visible laser beam with a high-speed (~GHz) and a high contrast ratio owing to electrically-controllable Bragg diffraction in EO crystals. The basic operations of the proposed device up-to the radio frequency ranges (< MHz) have been experimentally demonstrated. However, verifications of the operation in the microwave frequency range was a remained issue.

In this paper, high-speed operation of the EO Bragg deflectors by use of the polarization reversed structures of ferro-electric crystal was experimentally demonstrated for the first time as far as we know. Owing to the simple electrode structure for the Bragg deflection operation, it is possible to control a laser beam at ~GHz with a high-contrast, which is suitable for future IoT systems.

2. Basic structure

The basic device structure of the proposed EO Bragg deflector is illustrated in Fig. 1. The key point for the high-speed operation is its simple electrode structure, that is, just a pair of planar electrodes on the both side of the ferro-electric crystal with a periodically polarization-reversed structure. Therefore, this device can be considered as a simple capacitor from the electrical circuit point of view, and it can be operated in the high-frequency range, which is limited by its RC constant [4]. Another limitation factor for high-speed operation is the transit time of the light beam through the device. However, the transit time effect will become significant at the frequency range of over 10 GHz when the grating thickness L in Fig. 1 is within 10 mm long.

1 mol%-MgO-doped stoichiometric LiTaO₃ crystal was adopted for the device substrate material. The substrate thickness was set as 500 μm from the view point of the fabrication process. The photograph of the microscopic image of the fabricated polarization-reversed structure is shown Fig. 2, where the spacial period of the polarization-reversed structure was set at 20 μm for the operational wavelength of 635 nm. The deflectors for the green and blue wavelengths can be also obtained by changing the period of the polarization reversed structures. The device design details and fabrication process details of the EO Bragg deflector are described in [3]-[5].

Fig. 1. Basic structure of the EO Bragg deflector.

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Fig. 2. A photograph of the fabricated polarization-reversed structure in the LiTaO₃ crystal substrate.

3. Experiments

To verify the operational characteristics of the fabricated EO Bragg deflector in detail, a micro-strip line (MSL) was prepared for the signal feeding to the device. Since this device can be considered as a capacitor element with a pair of parallel electrodes from the electrical circuit point of view, it is easy to obtain an impedance matching condition by connecting an appropriate lumped circuit element to the feeding MSL line.

Figure 4 show the measured output signal driven by use of a large amplitude sinusoidal signal at 100 Hz. From this result, the operational voltage for switching a 635 nm laser beam completely was measured as 83 V. Figure 5 shows measured examples driven by use high-frequency signals. The high-speed operation of the EO deflector was verified experimentally up-to 150 MHz.

Fig. 3. Photograph of the fabricated EO Bragg deflector with an MSL feed line.

Fig. 4. Measured output signal from the EO Bragg deflector driven with a large amplitude signal at the frequency of 100 Hz. ($\lambda = 635$ nm)

4. Conclusions

The high-speed operation of the EO Bragg deflector with periodically polarization-reversed structures have been verified. The operational voltage of this deflection device can be lowered over 10 times by introducing an

optical slab waveguide structure [3]. Now, the experiments for the data transfer by using the EO Bragg deflector are underway. The details will be presented in the conference.

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Fig. 5. Measured high-frequency output signals from the EO Bragg deflector driven at the frequency of (a) 50 MHz and (b) 100 MHz. ($\lambda = 635$ nm)

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Speckle Suppression for Laser Display Systems Using the N = 11 2-D Barker Code Based Diffractive Optical Element

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Abstract: we design and fabricate 2-dimensional barker code DOE with code length N = 11. We demonstrate speckle reduction by the barker code doe with vibration

1. Introduction

The laser projection display is a promising the compact device. The Laser light source projector system has a lot of advantages such as wide color gamut, high brightness, contrast, resolution, life time, mercury free and low power consumption [1]. However, the laser light source causes the speckle noise problem because of the coherent. The speckle noise appears a coherent beam is scattered by a rough surface at screens. The speckle noise decreases image quality and inhibit the application of laser source display systems. There are several methods for reducing the speckle noise: moving screen, polarization mixture, inserting diffuser, spectrum broadening [2]. The speckle noise reduction approaches are based on averaging of the speckle pattern. The moving diffractive optical element (DOE) is one of the most effective methods of speckle noise reduction. In this study, the 2-dimensional barker code DOE for speckle reduction is fabricated by the e-beam lithography. We demonstrate speckle reduction using 2-dimensional barker code DOE with vibration.

2. Experiments and Result

The amount of speckle noise determined by the speckle contrast ratio C which is defined by

$$C = \frac{\sigma_I}{\langle I \rangle} \quad (1)$$

Where σ_I is a standard deviation of the intensity distribution in the image, $\langle I \rangle$ is an average value of the intensity in the image. The speckle contrast ratio can transform in 1-dimensional scanning projection display systems: [3]

$$C_{1D,x}^2 = 2 \int_{-\infty}^{\infty} \left| \frac{A(Dx)}{A(0)} \right|^2 Q(x) dx \quad (2)$$

$$= \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \left| \frac{A(Dx)}{A(0)} \right|^2 \left(\frac{1 - \text{Sinc}(4\pi x)}{x^2} \right) dx$$

Where $A(Dx)$ is autocorrelation function of the complex optical amplitude incident upon the screen, $Q(x)$ function represents the effect of the image sensor aperture, and D is eye resolution size on the screen. If $A(x)=1$, then speckle contrast ratio will be $1/\sqrt{2}$. The speckle contrast ratio can derive in 2-dimensional scanning projection display systems [4]:

$$C_{2D} = C_{1D,x} * C_{1D,y} \quad (3)$$

Equation (2) gives the expression for the calculation of the speckle contrast in a scanning projection display. From the equation (2), the narrow autocorrelation function can provide the large speckle suppression. One of the best approach for obtaining use the Barker code based DOE. The Barker code design provides the narrow autocorrelation function with the small side lobes amplitude which is $1/N$. Where N is the Barker code length. We designed the $N = 11$ 2-dimensional barker code DOE structures for speckle noise reduction and fabricated the DOE by e-beam lithography.

Figure 1. Scanning electron microscope image of 2D Barker code DOE

Figure 1 (a) shows the SEM image of the Barker code DOE. The pixel size is 6.4 micron with 11 primitive cells. The depth of Barker code DOE pattern is about 560 nm that similar to the center wavelength of the primary colors. In order to demonstrate speckle reduction, we perform the experiment. The Barker code DOE is placed at the object plane in the experimental setup. The screen is placed at the plane conjugate to DOE plane. The Baker code DOE is on the piezo stage for vibration. The Barker code DOE vibration reduced the spatial coherence of laser light and reduce the speckle noise. Figure 2 shows the experimental result. Figure 2 left shows laser beam image on screen without the Barker code doe. This figure shows the spatial modulation of beam intensity because HeNe laser

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coherence cause the strong speckle noise. In contrast, figure 2 right obtained with the vibrating Barker code DOE. We achieve the strong suppression of speckle noise. The speckle contrast ratio decreased about 7 times by the barker code DOE

Figure 2 Speckle pattern image without and with the Barker code DOE.

In addition, the moving Barker code DOE method has a dependence of angle which is between the direction of the DOE vibration and DOE and vibration speed.

Figure 3. Scheme of the Barker code DOE vibrating along the x-axis with inclination angle θ .

If the angle between vibration axis and Barker code DOE Axis is special angle (α) which is $\alpha = \arctan(1/NM)$ provides theoretically maximum speckle

reduction [5]. Where N is barker code length and M is an arbitrary integer. We will be presenting about not only speckle reduction by the Barker code DOE but also speckle contrast dependence of the angle and velocity of the Barker code DOE.

7. Conclusions

In Conclusions, we design and fabricate 2-dimensional barker code DOE with code length $N = 11$. We demonstrate speckle reduction about 7 times by the barker code doe with vibration.

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Beam shaping for the enlarged diffraction field

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Abstract

In this paper, we use a diffractive optical system with spherical wave incident, and calculate a larger diffraction field range by a double-sampling algorithm to obtain the target field distribution of arbitrary shape. The large-angle diffraction field obtained by this method has problems such as uneven light intensity. We have obtained a good beam shaping effect by optimizing the algorithm. We also performed machining error analysis on binary optics designed with optimized algorithms. The results show that the optimization algorithm can effectively improve the uniformity of the light intensity of the target light field, and can also effectively control the local light intensity of the target light field.

Keywords: diffractive optical element, beam shaping, algorithm optimization, large diffraction pattern

1. Introduction

Since its appearance in the 1960s, laser technology has been widely used in many fields such as industry, medical, and defense because of its good directionality, high brightness, and good monochromaticity [1]. In applications such as laser processing holographic projection, laser radar, etc., beam shaping is required to obtain the required intensity distribution [2].

Binary Optical Elements (BOEs) are two or more stepped relief structures based on materials such as glass [2]. They are pure phase diffractive optical elements. The binary optical elements are thin and light, and diffracted. High efficiency, unique dispersion performance, and the ability to achieve beam shaping in any shape, so it has important research value and broad application prospects.

The numerical calculation of the diffraction field is the basis for the optimal design of the diffractive optical element. In many beam shaping applications, such as laser processing, game entertainment, holographic projection, etc., it is necessary to obtain a relatively large diffraction pattern at a relatively close distance. So far, researchers have proposed a variety of methods to increase the size of the diffraction pattern. Shpunt A et al. used a Daman grating to extend the three-dimensional projection spot pattern implemented by DOE into a plurality of spot pattern matrices of the same size and closely spaced, thereby expanding the projection area of the spot pattern [3, 4]. However, this expanded diffraction pattern is cyclically extended and cannot be applied to beam shaping of any shape. The diffraction angle can be physically expanded by diverging spherical wave illumination diffractive optical elements [5]. MasD, Ma Jian, et al. also proposed numerical calculation formulas for diffraction fields under spherical wave illumination conditions [6, 7]. However, these numerical calculation formulas do not expand the sampling area of the diffraction field, and the enlarged diffraction pattern cannot be optimized by these formulas.

Weidong Qu *et al.* used a divergent spherical beam to illuminate the DOEs to increase the maximum size of the diffraction patterns, and a double-sampling algorithm was adopted to realize the design of such DOEs[8]. By this way, The calculation range of the diffraction field can be effectively expanded, and the amplification of the diffraction pattern is independent of the cell size of the diffractive optical element, thereby relaxing the requirements on the size of the DOE unit and reducing the difficulty of DOE processing.

However, when the diffraction field is beam-shaped by the above method, a phenomenon in which the target pattern light intensity is uneven occurs. By optimizing the double-sampling algorithm, this paper expands the calculation range of the diffraction field and improves the uniformity of its light intensity. At the same time, it analyzes the errors caused by phase quantization and device processing.

2. Design of DOE

When the DOE is illuminated by a divergent spherical wave, the propagation of the optical field from the diffractive optical element to the output surface is shown in Figure 1.

Figure 1. Principle of the double-sampling algorithm

Taking the plane of the vertical axis of the spherical wave as the intermediate plane, the numerical calculation of the diffraction field on the output surface can be carried out in two steps.

The first step is the diffraction (reverse) from the DOE to the middle plane. Since the incident light wave is a spherical wave, the diffraction can be regarded as a reverse diffraction[5]. The process can be expressed as

$$U_1(x_1) = \exp\left(\frac{ikx_1^2}{-2r}\right) F^{-1}[U_0(x_0)] \quad (1)$$

$U_0(x_0)$ is the complex amplitude distribution of the DOE, $U_1(x_1)$ is the complex amplitude distribution of the intermediate plane, and r is the divergent spherical wave radius. The constant term is omitted in the formula.

The second step is the diffraction from the intermediate face to the output face. This diffraction is a forward Fresnel diffraction as shown in the formula (2).

$$U(x) = \exp\left[\frac{ikx^2}{2(z+r)}\right] F\{U_1(x_1) \exp\left[\frac{ikx_1^2}{(z+r)}\right]\} \quad (2)$$

Thus, we can infer that the light field distribution of the output surface is

$$U(x) = \exp\left[\frac{ikx^2}{2(z+r)}\right] F\left\{\exp\left(\frac{ikx_1^2}{-2r}\right) F^{-1}[U_0(x_0)] \exp\left[\frac{ikx_1^2}{(z+r)}\right]\right\} \quad (3)$$

Using the double-sampling algorithm, we are able to calculate a larger diffraction field range as follows

$$L_z = \frac{z+r}{r} L_0 \quad (4)$$

L_z is the sampling range on the output surface.

Then, we optimize the GS algorithm. Add the initial phase to the weighting factor to jump out of the local optimal solution and find the global optimal solution.

$$\varphi = m_1 + (1 - m_1) * \varphi \quad (5)$$

Weighted correction of expected output

$$C(i,j) = m_2 * C(i,j) + (1 - m_2) * C(i,j) / U(i,j) \quad (6)$$

3. Results and Discussion

By optimizing the algorithm, the light intensity uniformity of the target pattern is effectively improved.

Figure 2. Simulation result of original algorithm

Figure 3. Simulation result of Optimized algorithm

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Simulation of Detection Performance by LiDAR Location in Automated Vehicles

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Abstract: LiDARs are drawing attention for automated driving. We simulated a number of important traffic scenes and compared the detection performance among different LiDAR installation locations. It indicated the LiDAR units in the lamps could detect front and rear objects in a wide range even if there were obstructions.

1. Introduction

Automated driving is being developed around the world with the aim of reducing traffic accidents and congestion. Automated driving requires many sensors including LiDARs, cameras, millimeter-wave radars, and ultrasonic sensors. Among these, LiDARs are drawing attention because of their ability to measure the surrounding environment in detail in three dimensions. Various mounting locations on the vehicle are being considered for LiDARs, including the roof, bumper, front grille, headlamps/rear lamps, and others, and our company has proposed to build a LiDAR unit into the lamps. If the LiDAR location changes, the LiDAR's field of view would also change as would the performance to detect surroundings. We explore the difference in the LiDARs field of view and performance caused by the difference in the LiDAR's location by using 3D and 2D simulations.

We also presented this report at the SIA VISION 2018 CONGRESS.

2. 3D Simulation

In the 3D simulation, 16 traffic scenes were selected. If there is an obstacle between a host vehicle and an object in a traffic scene, a blind spot is created which makes LiDAR unable to detect the object. In order to define the relationship between the LiDAR location and a detectable area, this simulation focused on traffic scenes with obstacles.

2.1 Setting of LiDAR simulation conditions

The simulation replicated a rotational LiDAR which is frequently used in test vehicles for automated driving.

3 LiDAR locations were simulated: on the roof, in the bumper and in the lamps. The roof and bumper are the places where LiDAR is mounted in typical test vehicles for automated driving. The lamps were added to these locations because they are located at the corners of the vehicle. The detailed horizontal field of view and locations of the LiDAR units are shown in Figure 1. LiDAR has 16 or more horizontal layers.

In the 3D simulations, point clouds hitting on a target object are obtained. In this report, detection means a state in which there is at least a single point hitting a target object. In order to perform automated driving safely, it seems to be important to detect a target object

as soon as possible and for as long a period of time as possible. We analyzed it in consideration of the above.

Fig. 1. Detailed field of view and locations of LiDAR

2.2 Result

Among the 16 scenes, differences were observed in 11 scenes resulting from the locations of the LiDAR. These scenes were examined by classifying them into three types.

A. Advantage of corners

Fig. 2. Difference between LiDAR in the lamps and bumper when there is a preceding vehicle

The lamps are located near the corners of the vehicle, while the roof and front bumper are located at the center between the right and left of the vehicle.

When the LiDAR units were near the corners of the vehicle, there were few blind spots created by preceding and following vehicles, as shown in Figure 2. Under these circumstances, the LiDAR unit in the lamps seemed to detect the target objects more rapidly and for a longer time than in other locations.

B. Advantage of height

The LiDAR unit on the roof was mounted at a height 30 cm higher than the roof and therefore was able to detect

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a target object over adjacent vehicles (having the same height as the host vehicle) as shown in Figure 3.

Fig. 3. Roof LiDAR detecting the object over adjacent vehicles

C. Other scenes

In a certain scene, the largest amount of beams from the bumper LiDAR was blocked by the guardrails set on the roadside. In other scene, LiDAR beams travelled through the space under the truck and detected the legs of the pedestrian. The beams in the simulation were perfectly linear with no cross-sectional area. However, since actual LiDAR beams have divergence, the same results as in the simulation may not be obtained. This verification is a future issue.

3. 2D simulations

The results of the 3D simulations demonstrated that detection performance varies depending on the LiDAR location. To investigate this result further, we examined changes in a detectable area by varying the LiDAR position continuously in the horizontal and vertical directions.

3.1 Horizontal direction

To examine changes in the horizontal detectable area of the pedestrians, traffic scenes as shown in Figure 4 were set. The LiDAR was mounted between the right and left edge of the host vehicle's front. The pedestrian was located on the pedestrian existence line. P is a boundary between a detectable area and an undetectable area caused by the preceding vehicle, we use the position P for changes in a detectable area.

Fig. 4. 2D scenes for examining in the horizontal direction

The results are shown in the Figure 5. When the LiDAR position was closer to the pedestrian, the detectable range of the pedestrian increased. In particular, the detectable range steeply increased around the corners of the vehicle.

3.2 Vertical direction

As shown in Figure 6 vertical traffic scenes in which a pedestrian was located in front of the host vehicle was set. The LiDAR was mounted on the host vehicle's front. We compare areas that were detectable or undetectable by the heights of P1 and P2. Furthermore, we analyzed it in the case of a child or an adult.

Fig. 5. Changes in position P caused by the LiDAR position

Fig. 6. 2D scenes for examining in the vertical direction

Fig. 7. Changes in the height of P1 and P2 caused by the LiDAR's height

The results are shown in the Figure 7. If the LiDAR position was high, P2 exceeds 1 m and the LiDAR was unable to detect a child. On the other hand, the adults were detectable from any LiDAR heights, but, as seen in Figure 7, the detectable range differed.

4. Conclusions

Verification was conducted on how LiDAR's detection performance changes with the position of the LiDAR mounted on the vehicle through 3D and 2D simulations. It was confirmed that the LiDAR units in the lamps could detect front and rear objects in a wide range even if there were obstructions in the surrounding area because the LiDAR units were located at the corners of the vehicle. If the LiDAR was located at a higher position such as on the roof, it was able to detect objects over surrounding obstructions in some cases. On the other hand, it was confirmed to be difficult for the LiDAR on the roof to detect a child near the host vehicle.

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Acousto-optics in headlamps – A new application in automotive laser lighting

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Abstract: Automotive lighting demands technological solutions to generate adaptive light distributions. For laser scanning headlamps, acousto-optic deflectors offer promising characteristics. Most important is their high deflection speed and precision. The deflector's capability to implement arbitrary scanning patterns in combination with an RGB laser offers great potential for innovative lighting functions.

1. Introduction

Future automotive lighting evolves more and more into a beneficial assistance system for the driver's safety and comfort. This demands technological solutions to generate adaptive light distributions with high angular resolution. A competition between various technological approaches is currently carried out, demanding a decision for the most advantageous system. [1]

Laser scanning headlamps offer great potential in this competition and are therefore part of the ongoing research. A light beam is dynamically deflected by a deflection device for illuminating the wanted area. This deflection process opens the possibility to guide and redistribute generated light. It forms adaptive distributions with any wanted variation of intensity. The available laser light can be distributed widely to illuminate a desired field of view or it might be concentrated to form areas with high luminous intensity. Having this capability laser scanners also offer excellent characteristics as projection systems for displaying symbols in the vicinity of the car.

2. Acousto-optic deflectors

The functional principle of a laser scanning headlamp shows that its performance strongly depends on the used deflection device. Since this device can form and vary the resulting intensity distribution, its functionality is crucial for the whole system. As the deflection device has a great impact on the system's performance, the requirements on its capabilities are quite demanding. While conventional laser scanners mostly rely on rotating or swivelling mirror systems to deflect the beam, acousto-optical deflectors offer exciting new possibilities.

2.1 Operating principle

The acousto-optic effect is based on the implementation of a diffraction grating inside a transparent material, usually a crystal. Incident light with sufficient coherence is diffracted with the Bragg angle, depending on the light's wavelength and the grating's spacing. In case of an acousto-optic device, this grating is applied by acoustic waves travelling through the material. These longitudinal waves periodically change the material's refractive index by mechanical rarefaction and compression.

Acoustic waves are launched by a piezo electrical transducer serving as the "loudspeaker" for the crystal inside the deflector. By changing the frequency of the acoustic waves, the spacing is changed, leading to a changed diffraction angle. This inertia-free principle enables acousto-optic devices to steer light into a determined angle and to perform high dynamic laser scanning. [2]

2.2 Applications in automotive lighting

The integration of acousto-optic deflectors in automotive lighting systems depends on the intended use-case, tolerable system complexity and safety considerations. The most flexible setup with full use of acousto-optics is sketched in Fig. 1. It consists of an RGB laser light source combining the three lasers to one output beam, which is then deflected by a set of two acousto-optical deflectors. They are arranged perpendicular to each other and are therefore deflecting the beam in two axes. This design takes full advantage of the deflector's capability to form any desired intensity distribution and can provide every high-resolution function from one headlamp system.

Fig. 1. Possible utilisation of acousto-optic deflectors in automotive lighting systems. A conceivable use-case is a standard light distribution, combined with a coloured symbol projection.

3. Experimental setup

To investigate and develop the use of acousto-optics further, an experimental setup is built in the laboratory. It is to prove the concept, demonstrate technological options and reveal further challenges. The setup's principle is shown in Fig. 2.

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Fig. 2. Sketch of the laboratory setup, which was built up to evaluate the acousto-optic deflectors.

3.1 Optical design

The light's path starts at an RGB laser light source with three independently controllable channels. The laser light, being emitted in a single beam, is deflected by two acousto-optic deflectors. They are specially optimised for their use in the visible wavelength range of the RGB laser. After passing through the deflectors, secondary optics are used to enlarge the field of view.

3.2 Electronics

Most important for the successful usage of the setup is the proper electronic control. Two components are fixed a priori: the laser driver, which is controlling the current for driving the laser diodes and a two channel RF power generator with voltage-controlled oscillators as a signal source for the deflectors. Both components work with analogue control voltages. The laser driver's output power linearly follows an input voltage and the RF frequency can be equally controlled. Because this frequency directly influences the diffraction grating's spacing inside the deflector, changing this frequency means scanning the laser beam. The analogue control voltages are formed by assigned digital-to-analogue converters. Digital signals are provided by the output ports of one central element, which is an FPGA board.

3.3 Serial deflection

One challenge when designing the control mechanism of the described setup arises from the acousto-optic effect itself. Since steering the laser beam relies on diffraction, it is wavelength selective. This means that for a certain acoustic frequency, different laser wavelengths will be deflected into different angles. Therefore, it is not feasible to deflect all laser colours at the same time, but they must be scanned one after the other. This serial deflection is implemented by turning one laser wavelength on, deflecting it two-dimensionally to form the desired intensity distribution and after that switching the setup to the next colour. All laser wavelengths form exactly the same intensity distribution and are deflected only into their common angular range, causing a precise spatial overlap of the colours (Fig. 3).

Fig. 3. Simultaneous RGB deflection (left) versus synchronised serial deflection (right).

3.4 Scanning patterns

On the one hand the scanning must happen fast enough to ensure a flicker-free performance in dynamic situations. For this a frame rate of 200 Hz or more is desired, leaving approximately 1.6 ms for the deflection of a single wavelength. On the other hand, it is desirable to have a high degree of freedom concerning the light distribution's composition. On the electronics side, the light distribution's resolution is limited by the precision of the signal converters, while optics and the deflectors also limit the angular resolution. Pursued is a resolution of 200 steps in the overlapping angular range for each axis. These 40,000 "pixels" must be addressable in the mentioned period of time, requiring a clock frequency of 25 MHz or more. Since acousto-optic deflectors can follow a changing control signal quickly, it is possible to implement arbitrary scanning patterns. A wanted light distribution can be changed by implementing a different deflection pattern, which has no impact on the laser modulation.

4. Conclusion

Acousto-optic deflectors offer exciting capabilities for utilisation in scanning lighting systems. Their operating principle, which is virtually mechanism free, allows high dynamic scanning and adaption to the wanted intensity distribution. Combined with an RGB laser light source a wide range of applications in lighting and projection can be covered. This requires an electronic control which is synchronising lasers with deflectors and is operating the scanning process. Experimental investigations show promising results and prove the concept. But there is further work to do: the next generation of control electronics offers more degrees of freedom to implement any deflection pattern. Furthermore, a software solution will be developed to calculate the optimum scanning pattern for generating any desired light distribution.

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Current status and future prospects of Automotive Laser Headlamp

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Abstract: In the year 2014 blue high power lasers have been introduced into automotive headlamps via modules converting the blue laser radiation by ceramic phosphors into non coherent white light with very high luminance. In the meantime major progress has been made to reduce the complexity and size of these laser activated remote phosphor light modules. An overview on the progress of the technology and the current status will be given. Some results of our investigations to extend its application range will be presented. It will also be pointed out, which major technical challenges will need to be solved in future to allow a wider usage of this technology for automotive front lighting.

1. Introduction

In 2014 the laser activated remot phosphor (LARP) technology was introduced in automotive headlamps of the BMW i8 and the AUDI R8 for an auxiliary high beam to increase the viewing range up to 600m [1, 2]. Subsequently its use is extended in the meantime to various car models [3]. One of the major trends in automotive forward lighting is the size reduction of headlamps in general, and the reduction of the optical aperture of the beam shaping optics at the surface of the headlamp for styling purposes in particular. Another important trend is the digitization and increasing resolution of the front light distribution on the road. For both trends the high luminance of the LARP technology does offer some benefits.

2. Size reduction

To allow a size reduction of the module more powerful laser diodes were introduced. Size and complexity of the

Fig. 1. Laser modules used in 2015 BMW 7series (left) & in 2019 BMW 7series (right).

laser safety system were reduced considerably by introducing a new technology directly proving the

Fig. 2. The laser safety system used in the first laser modules via an optical sensing system requires complex calibration methods, a laser beam dump in the headlamp and substantial construction space.

Integrity of the ceramic converter by an electrical resistance measurement with high dynamics.

Fig. 3. The new laser module introduced recently in 2019 BMW 7series does no longer require a beam dump in the headlamp and saves a considerable amount of construction space.

3. Reduction of the optical aperture

The high luminance of laser activated emitter surfaces of currently typically 600 – 800cd/mm² does in principle allow the reduction of the diameter of the beam shaping optics as shown in Fig. 4 for a High Beam application. For comparison: standard LEDs typically achieve luminance values of about 100cd/mm² and LEDs optimized for high luminance may reach values of 200 - 250cd/mm² in future.

Fig. 4. Illustration of the dependence of a High Beam optics diameter from the emitter luminance, under the assumption of an emitter size of 0,5mm².

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This opens possibilities to use Laser modules for very thin aperture stylings of headlamps as has been shown in different demonstration vehicles, e.g. in [4, 5].

4. Laser based dynamic and adaptive light control

The high luminance and thus low etendue of the white converted laser light is physically very well suited to enable technologies like laser scanning or laser illuminated DMDs to be used for dynamic, high resolution front lighting.

Laser Scanning

Fig. 5. Laboratory set up of a Laser scanning converter.

On one side it was shown in the iLaS project that LARP based laser scanning allows a power neutral dynamic control of the luminous intensity, and that a light accumulation can be done together with a very smooth analogous, high resolution light center positioning [6]. On the other side we could demonstrate in a concept study, that already with a 0,3'' DMD the emitter luminance of a LARP module does allow high resolution ($0,02^\circ$) projections with 1000 lumen on the road and an $E_{\max}$ of 120 lux with a horizontal field of view of $\pm 10^\circ$.

Fig. 6. Demonstrator of a projector unit allowing a high resolution light distribution & projection via the illumination of 0,3'' DMD with a LARP module.

5. Major Challenges

Despite the technologically very exciting possibilities of laser based high luminance light sources some major challenges remain, which need to be solved in the future to enable this technology for a broader use in automotive applications beyond the auxiliary high beam application.

Fig. 7. Progress of the energy conversion efficiency of blue laser radiation as published by OSRAM Semiconductors [3].

First of all the conversion efficiency of the electrical energy into blue light of high power blue laser diodes need to be improved and in parallel their optical output power. Forward lighting applications beyond auxiliary high beam do require life times of the laser diodes beyond 4000h under automotive conditions. The material properties and thermal durability of the phosphor converters need to be improved substantially to achieve emitter luminance greater 1000cd/mm^2 with a lumen output of more than 2000 lumen [7]. And finally, of course in addition, the cost per lumen will need to be lowered considerably to make this technology commercially sustainably attractive.

6. Conclusions

Great progress has been achieved in the laser active remote phosphor technology and its usage for auxiliary high beam applications in headlamps. Despite that still substantial technological and commercial challenges need to be solved to allow for this exciting technology a broader penetration in the different applications of automotive forward lighting.

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Technical Challenges in Laser and Lidar Optical Sub-Assemblies for Automotive

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Abstract: Lidar systems are undergoing significant changes to reduce both the size and cost for volume deployment in automobiles. We show that MEMS based FMCW Lidar has similar design requirements of telecom equipment and will require the same types of manufacturing techniques to obtain the reliability and performance over temperature.

1. Introduction

Recent advancements in self-driving vehicles has resulted in significant research into developing smaller and cost effective Lidar systems with greater than 200m range. One of the leading approaches to achieving this is Frequency Modulated Continuous Wave (FMCW) Lidar using solid state lasers and Micro-Electro-Mechanical (MEMS) steering elements. Lidar systems present significant design challenges for manufacturing a reliable free-space optical system capable of withstanding the demands of the automotive industry. The design requirements are comparable to those found in the telecom industry for MEMS-based wavelength-selective switches (WSS).

2. Laser Considerations

MEMS-based FMCW Lidar systems have many design challenges. Highly-integrated solid state components are required to achieve an acceptable cost structure for mass adoption. Designing a solid-state laser that is rapidly tunable in frequency, maintains constant power during tuning, generates high power and has low phase noise are key requirements.

The requirement to couple the laser source into the receive path to create a local oscillator (LO) increases the demands on the output power requirements and complexity of Lidar Optical Sub-Assembly (LOSA). One solution is to create a "Lidar Engine" that integrates the transmitter and receiver into a single chip. This limits the need for free space coupling of the LO and thereby enabling a compact design.

Achieving the output power requirements with the low phase noise needed for FMCW can be achieved with Master Oscillator Power Amplifier (MOPA) based designs. The high laser output powers required for ranges >200m place significant cooling demands on the LOSA design to maintain reliability. Telecom lasers have 20+-year reliability requirements. The same design methodologies used for telecom lasers can be applied to design reliable automotive-grade lasers which are efficient over wide temperature ranges (-40°C up to 125°C) experienced in automobiles.

3. LOSA Manufacturing Requirements

Designing a LOSA to meet the demanding environment of an automobile creates many technical hurdles. Components need to meet the performance requirements as well as the vibrational and environmental operational ranges.

The vibrations MEMS-based Lidar need to tolerate are demanding for the automotive industry. MEMS need to survive jarring impacts of 1500G [1]. This requirement is not different for MEMS-based WSS in the telecom industry. Also, forces of 200G during operation [2] can be tolerated with little impact on performance. Proper orientation of components and vibrational isolation are key design elements that need to be incorporated into the product to comply with reliability requirements.

It has been shown that in order to maximize the range of a system it is desired that the beam waist be increased as large as reasonably possible [3]. In order provide a quality image it is desired that the MEMS have a large FOV. Typical targets range from 40° to 60° for horizontal axis and ~20° for the vertical axis for long-range automotive Lidar. The technical requirement for a large mirror MEMS and the requirement for a large FOV are competing elements in MEMS design. Resolving both requirements can be done with either strong hinges or utilizing resonant operational modes.

The extreme temperature environments in automotive applications ranging from -40°C to temperatures greater than 85°C [1] present the additional challenges for the LOSA. Again these requirements do not significantly differ from that of the outside plant requirements in telecom [4]. These large temperature ranges necessitate an optical mechanical system that is rigid and does not change the optical alignment over the desired temperature range. The process capabilities of the LOSA manufacturer to maintain this alignment limit the Lidar range and hence the mirror size. As the mirror size is increased the requirement for maintaining a narrow optical alignment (i.e. more rigid optical train) increases (Figure 1). The loss introduced into the optics system is not unlike the optical misalignments created by a turbulent atmosphere [5]. Figure 1 illustrates the

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alignment tolerances needed for 1dB of performance margin to ensure compliance over the operational temperature range. This means that not only is the range of the Lidar system limited by the achievable size of the MEMS but also the opto-mechanical design and manufacturing capabilities of the LOSA manufacturer.

Fig. 1. Angular miss-alignment between TX and RX paths that creates 1dB of loss in the system.

Angular alignment sensitivity of the transmitter and receiver paths is similar to those seen in MEMS-based WSS [2]. These switches can be made to operate reliably over large temperature ranges and the same manufacturing techniques can be used to create stable free-space optical systems for FMCW Lidar for use in automotive applications.

A large MEMS aperture improves photon capture at the expense of increased sensitivity to angular misalignment and the corresponding impact to manufacturing yield. In summary tradeoffs must be

made to optimize the system around the process capabilities, technical requirements and cost.

7. Conclusions

We have discussed the manufacturing challenges associated with creating MEMS-based FMCW Lidar. There are several aspects of the design that bear strong similarity to the free-space optics systems found in telecom components and equipment. Leveraging the manufacturing techniques from the telecom industry can provide a path to creating a cost-effective FMCW Lidar system for automotive applications.

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VCSEL Sensing for Automotive

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Abstract: Vertical cavity surface emitting lasers (VCSELs) are a primary candidate for emerging optical 3D sensing applications for automotive due to their high bandwidth, reliability, cost and energy efficiency. In this paper, VCSEL based optical time-of-flight (TOF) sensors and their main characteristics are examined.

1. Introduction

As vehicles become more autonomous, they require a range of reliable sensors that can provide accurate, real-time information about the driver and the environment. Rapid development of sensors and computer vision algorithms is bringing us closer to fully autonomous and safer vehicles. Widely implemented sensors such as cameras and radars are being complemented more with active optical sensors that are used for both in-cabin and outdoors automotive applications, such as light detection and ranging (LIDAR). A key component of active optical sensor is a laser diode. In this work, we specifically address VCSEL-based sensing systems. The maturity of VCSEL technology makes them attractive for the emerging optical 3D sensing and previous experience can benefit automotive applications. In the data communication context, VCSELs were demonstrated to be: reliable [1], cost- and energy-efficient (WPE) [2] and fast [3], and to also support high-power density in the arrays [4]. In the following paragraphs, we will review the main components of the VCSEL-based 3D sensing system.

2. Optical Time of Flight

Depth information required by the environmental perception systems can be obtained using various optical methods including interferometry [5] and triangulation [6], but in the following sections, we focus on the more cost efficient and lower complexity technique that also supports larger scanning range, namely time of flight (TOF) [7]. The two main ToF types are direct and indirect. The direct time of flight (d-ToF) uses the round-trip time of the pulse generated by the source and reflected from the sensed target to calculate the distance. Higher accuracy is obtained when the laser pulse is shorter, and the system bandwidth is higher. The indirect time of flight (i-ToF) requires continuous wave modulation or pulsed light modulation. It is best to use the pulsed solution in the automotive application to ensure eye safety. Pulsed i-TOF uses the phase delay between the transmitted and received pulse in the calculation of the distance [8].

3. Optical ToF System Components

The components of the ToF system include a pulsed light source, optical element and an imager with a decision algorithm on the receive side. Distance supported by this

technology can range from cm for smartphone devices to ~300m for automotive LIDARs. To support each of these distances, one must choose a suitable component configuration and power level.

3.1 Transmitter

A transmitter in the ToF system comprises a high-speed driver, an optical source and an optical element. An optical element is typically a diffuser, which ensures a uniform spatial illumination. The main parameters of the transmitter from the system perspective that need to be considered in a ToF design include wavelength (eye safety requirements and absorption in water are different for 940nm and 1550nm windows); reliability; power and beam uniformity (crucial for a uniform field illumination); speed (bandwidth needs to support ~ns pulse width with short rise and fall time); eye safety (average power from the optical system needs to be within safety requirement); noise; emitter density and location in the array (to ensure uniform illumination); power efficiency; thermal stability; and cost efficiency. VCSELs and edge emitters are the two main laser types that are currently implemented for optical sensors.

3.1.1. VCSELs

VCSELs are mature and cost-effective laser sources that are manufactured in high quantities. For ToF applications, they are usually implemented as arrays, which allows for flexibility and scalability of output power. This allows for the ability to achieve a larger sensing distance [4] and due to the redundancy, the reliability of an array is greater than that of a singlet. Additionally, single VCSEL's reliability expressed as time to 1% failure (TT1) is more than 10 years of continuous operation at 80C [1]. VCSELs are highly energy efficient, which is evident in their wall-plug efficiency of ~30% [2]. Single VCSELs demonstrate modulation bandwidth up to 30GHz [3], which is sufficient to support <100ps rise and fall time and <1ns pulse width required by ToF applications. Laser noise expressed as relative intensity noise (RIN) is <140 dB/Hz [9]. The wavelength of VCSELs currently used for high power ToF applications is 940nm. They typically do not require active temperature control due to small thermal wavelength drift (0.06nm/K). In terms of manufacturability, the vertical structure of the device allows for on-wafer testing, which further reduces cost.

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Some of the VCSEL parameters that are critical for the ToF system include the turn-on delay, pulse width and rise/fall time. The turn-on delay is a function of the threshold carrier density and the injection current magnitude. The risetime is usually determined by the gain switching, while the fall time is usually limited by the driver.

3.1.2. Edge Emitters

Edge emitters support higher power per individual device, which means they can achieve the longest sensed distance (~300m). They can also be designed at 1550nm, allowing them to operate in the regime of better eye safety, and have bandwidths higher than VCSELs so they can be pulsed faster. However; as edge emitters are both more expensive and more difficult to parallelize, VCSEL arrays can be a better candidate.

3.2 Channel

The path between the transmitter and receiver can be approximated as a free-space channel. The channel characteristics differ depending on the application and include two main types for automotive applications: in-cabin and outdoor. The in-cabin sensors are typically used for monitoring driver's engagement and gesture recognition. They need to cover short range (~1m) with high resolution (1cm) and are prone to highly varying light conditions that require a large system dynamic range.

The outdoor channel characteristics include long free-space path (100m-300m) with varying ambient light and atmospheric conditions, such as rain or snow. Additionally, an outdoor channel includes objects with different types of reflection characteristics, different absorption and scattering. Due to these factors, dynamic range of the reflected signal is 1: 100 000 in an outdoors traffic application [9]. To keep the vehicle safe in such a challenging environment, LIDARS should be complemented by radar (lower spatial resolution, long range) and camera systems (low range, 2D object identification, relies on external light).

3.3 Receiver

The in-cabin and outdoor applications require different receiver characteristics. For i-TOF, the light reflected from the target is integrated at the receiver in several time windows and the receiver algorithm uses a single photon counting method to retrieve information on mean intensity. Each pixel at the receiver sensor of ToF is typically comprised of a single-photon avalanche diode (SPAD) [7]. It is followed by the quenching circuit, which generates a pulse when at least one photon is detected in the gate time. SPADs employ time correlated photon counting (TCPC), which is a method that results in statistical uncertainty. The SPAD based receiver parameters that must be considered during the design include internal noise and dead time.

4. Eye Safety

The eye safety requirement is expressed as a wavelength dependant parameter M.P.E. (Maximum Permissible Exposure) on the cornea and on the skin [10]. The field of view and numeric aperture of the system must be included for its calculation, the eye safety regulations dictate pulse conditions, i.e. pulse power, width and the duty cycle. In the automotive applications, higher duty cycles are preferred as an accuracy of the environment mapping depends on how often the information is collected. The pulse power must be high enough to be distinguishable from background light. Hence, to assure the eye safety, the pulse width is constrained to be as short as possible. It is, however, limited by the laser source characteristics.

5. Conclusions

Optical ToF applications for automotive require high volumes, cost- and power-efficiency, reliability and flexibility. These are design factors where VCSELs have an advantage over other laser technologies and prove to be a promising candidate for the new emerging automotive applications.

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Phosphor-in-Glass (PiG) as Wavelength Converter for the Automotive Laser Headlight Application

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Abstract: The phosphor-in-glass (PiG) was applied as a wavelength converter for the automotive laser headlight. Through the measurement of optical characteristics of PiG with high internal quantum efficiency of 92%, we proposed and designed the geometric structure of laser headlight using the PiG and MEMS scanner to maximize the optical and thermal characteristics.

1. Introduction

Recently, there have been many attempts to apply a laser as a light source in the fields of display and automotive headlight. Since phosphor-in-glass (PiG) has lower price and higher efficiency than ceramic phosphor and has better thermal characteristics than epoxy/resin phosphor, it is getting a spotlight as a wavelength converting material of lasers in the display applications [1, 2]. However, a PiG-based laser headlight system has not been completely commercialized in the automotive application due to severe requirements for thermal stability such as thermal shock by temperature deviation which may cause the physical damage on PiG [3].

In this study, we proposed the application of PiG as a wavelength converter for the laser automotive headlight after measuring basic characteristics of PiG. Furthermore, we designed new geometric structure of laser headlight with the MEMS scanned laser on PiG to improve the optical characteristic of color deviation as well as the thermal stability of PiG.

2. Phosphor-in-glass

2.1 Basic properties of phosphor-in-glass

In this study, a PiG composed of YAG:Ce phosphor particles and borosilicate glass were used. These two materials are mixed in a powder state at first then pressed and sintered to form as a single plate with a thickness of 100 μ m. In order to verify the color conversion efficiency according to the PiG thickness, we measured the intensity of converted light by changing the thickness. As shown in Fig. 1, our PiG plate resulted in best conversion efficiency in 2 layer configuration with a thickness of 200 μ m. Compared to that from a single layer plate, the enhanced conversion in yellow range was obtained in the 2-layer-PiG with the increased optical power of 22.5%. Thus, all studies have been based on the double-layer configuration for highest color conversion efficiency.

2.2 Quantum efficiency measurement

After the fabrication of PiG plate, internal quantum efficiency (IQE) was measured with the measurement set-up, as shown in Fig. 2.

Fig. 1. Wavelength spectrum of converted yellow light by PiG and microscopic view of PiG plate

Fig. 2. Quantum efficiency measurement set for PiG film

PiG plate was placed in the bottom place of the half integrating sphere and a light source of 450nm was inserted to the PiG plate from top surface. In addition, a reflector was placed under the PiG to confirm that most of converted light could be absorbed by detector.

Through this measurement, we confirmed that our PiG plate had an IQE of 92%. This value indicates that PiG shows excellent performances among various types of phosphor materials. Therefore, this study aims to improve both the color deviation and thermal stability on PiG plate with the optimized geometric design for the laser headlight application.

3. Design concept and experimental results

3.1 The scanned laser beam based on MEMS scanner

We first decided to use a microelectromechanical (MEMS) scanner for the improved optical and thermal properties on PiG plate. The concept of scanning laser beam on PiG plate with MEMS scanner is shown in Fig. 3. A scanning beam with the MEMS allows the laser

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Fig. 3. Light spreading mechanisms of structure applying MEMS scanned beam and TiO_2 layer

entering PiG at wider angle, which means blue light can be spread more evenly on the PiG surface. We expected that the scanned beam would result in lower angular color deviation than that of the single beam incidence. In addition, it is expected that the temperature deviation on the PiG plate would be decreased by uniformly laser scanning on the PiG surface.

3.2. Additional scattering effect by TiO_2 layer

For the additional improvement on the angular color deviation and optical intensity distribution, the TiO_2 nanoparticle layer was located under the PiG plate as shown in Fig. 3. Thus, a scanned laser beam can be scattered effectively to increase the color conversion efficiency by meeting more phosphor particles and decrease the angular color deviation by emitting the converted light uniformly at a wider angle.

3.3. Experimental results

MEMS scanner which oscillates in both x and y axis is located between the laser source and reflective type PiG plate. Then, the laser beam is reflected by the MEMS scanner then enters on the PiG plate to convert the wavelength of input laser for producing white light. Angular characteristics of white light are measured by a detector rotating around the PiG plate. Then the correlated color temperature (CCT) and optical intensity were measured as a function of angle distribution. In addition, TiO_2 layer was embedded on the PiG surface for the additional scattering effect. TiO_2 layer of $50\mu\text{m}$ thickness was fabricated with the concentration of 10wt% using the size of 300nm TiO_2 nanoparticles. As a result, it is proved that the scanned beam and TiO_2 layer effectively reduces the angular color deviation of white light, as shown in Fig. 3. The case of both scanned beam and TiO_2 layer shows the best improvement with the decreased ΔCCT (color deviation) up to 50%.

Fig. 3. Angular (a) CCT (b) intensity results

4. Structural design of laser headlight

Based on proposed concept and its experimental result, we designed the geometrical structure of laser headlight with the PiG plate as a wavelength converter as shown in Fig. 4. It is consisted of blue laser, scanning MEMS scanner or actuator, reflective type PiG plate with additional TiO_2 layer. This structure would secure the lowest color deviation of the illuminated white light as well as improve the thermal stability of PiG plate. Also, the scanned beam enters on PiG plate in the normal direction which keeps the symmetry in the intensity of the emitted white light.

Fig. 4. The schematic design of laser headlight structure

5. Conclusions

A high efficient phosphor-in-glass (PiG) as a wavelength converter was applied for the automotive laser headlight in this study. With the use of PiG plate having high internal quantum efficiency of 92%, we can improve both optical and thermal characteristics of laser headlight by combining with MEMS scanned laser beam and TiO_2 scattering component. Based on experimental evaluation results, we proposed and designed a geometric structure of automotive laser headlight using the PiG and laser scanning concept to maximize both optical and thermal performance. Finally, we have confirmed that PiG plate can be used as an appropriate wavelength converter with an aid of laser scanning concept for various laser application fields, including the automotive.

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Optical Surface Error Compensation Based on Freeform Polynomials

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Abstract: Recently, freeform surface widely using to the optical system; because it is have advance of optical image and freedom available to improve the optical performance. In this study, the freeform compensate method of Zernike polynomials results successfully verified; it is correction the form deviation of freeform surface.

1. Introduction

Optical lenses have a long history. Lens are used in many fields, including mobile phones, computers, automobiles, and medical services. With the rapid development of the technology industry and the improvement of the technical level, optical lenses are used more and more widely, and precision. Mirrors have evolved from traditional spherical mirrors to aspherical mirrors and even complex freeform lenses. Since the free-form optical element has a large surface freedom and can provide different on-axis or off-axis errors in a targeted manner, it satisfies the requirements of high performance, light weight and miniaturization of modern optical systems. Free-form lenses have been widely used in optics in recent years, such as LED source optics, laser beam shaping, AR, VR, Human Vision, AR Head up display, Lighting Technologies, 3D imaging Devices,. Hence, freeform optics are becoming increasingly important in optical systems, as they make extra degrees of freedom available in the design of optical systems [1-2].

In the present research, the slow tool servo technique was applied on an ultra-precision diamond turning machine in conjunction with the tool path generating algorithm for freeform surface fabrication. And the form error compensation method via Zernike polynomial fitting will be investigated. The form accuracy and surface roughness of freeform surface were examined by Zygo interferometer.

2. Freeform Surface for Machining

Freeform optical surfaces are already state of the art. Freeform surfaces can be machined by fast tool servo (FTS), micro-milling, fly-cutting or raster milling, and slow tool servo (STS) [3]. Ultra-precision diamond turning is capable of generating various flat, spherical, aspherical, and freeform optical components to sub-micrometer form accuracy and nanometer surface finish. Three ultra-precision machining processes, slow tool servo (STS), are frequently used to produce optical freeform surface. The development of slow tool servo and fast tool servo techniques has made the fabrication of freeform optics such as toric not just possible but feasible and economically viable. For a facing operation,

the cut-depth (Z-axis) is a function of radial (X-axis) position and work spindle angular position (C-axis) in both slow tool servo and fast tool servo. As the work-piece rotates, the diamond tool oscillates in and out of Z-axis motion to generate the required surface. In comparison to slow tool servo, fast tool servo can offer better frequency response and can run at faster spindle speed. However, extra attachments and investments need to be put in place before the fast tool servo process. Slow tool servo, on the other hand, does not have this drawback and can be applied on a standard precision turning machine for turning operation directly as shown in Fig. 1 with the basic configuration of the STS function [4].

Fig. 1. Machine configuration for STS [4]

3. Freeform Surface with Zernike Polynomials Description

In this study, Optical Surface error Compensation using the Zernike Polynomials Description. Zernike polynomials are a complete set of orthogonal polynomials based upon polar coordinates expressed in a unit circle. The Zernike Standard Sag, based on a conical surface plus Zernike coefficients in Zemax, was employed for the perturbed surface deformation, as shown in Eq.

$$Z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum_{i=1}^N A_i Z_i(\rho, \phi) \quad (1)$$

where Z is the sag of the polynomial, c is the curvature, r is the radial coordinate of the lens, k is the conic constant, A_i is the coefficient of the Zernike Standard polynomial, ρ is the normalized radial ray coordinate, and ϕ is the angular ray coordinate.

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4. Surface Measurement

We use 3D Optical Profiler instruments to measure the error surface after the injection process. Fig.2. shows the measurement results, the surface form error is $2.75\mu\text{m}$ with 2.8mm in diameter range after the surface alignment analysis, it could be output the X Y Z and Zd (Z deviation) information. That can Curve fitting the form error Zd of error surface to become Zernike polynomials.

Fig. 2. Optical surface error

5. Correction the Form Error

In this study, we generated the Zd data by Zernike description imported the data into DIFFSYS. DIFFSYS is the software for analyzing and generating tool path to manufacture optical surfaces in the ultra-precision CNC (Computer Numerical Control) machines. Fig.3. is the surface form deviation Zd, therefore a typical radius diamond tool can be used to fabricate the Zd of error surface. Fig.4. shows the example of the tool path point data by giving rough feed per revolution and constant arc length in the peripheral region of the mold. The parameters for the fine finish cutting are given as: 0.004mm/rev feed, 0.1mm arc increment (for peripheral region), and 0.5 degree maximum C-axis increment (near the center region). The Spline function of the FF705XG is activated for reducing the vibrations of the X, Z, and C axes during machining.

Fig. 3. Surface error form deviation Zd

Fig. 4. Spiral tool path with X-axis stable moving

In this study, we used a diamond tool with 0.3mm in radius, 10 degree in front clearance angle, and 120 degree in window angle. The tool path is planned to follow the spiral path of the Zd surface. The tool path

with tool radius compensation could be calculated simply by offset the tool radius along the surface normal direction, i.e. the tool path is compensated in X- and Z-direction simultaneously. The 6061 aluminum alloy was used as the material of the sample. Fig.5. shows the reference mark of aluminum sample orientation for the Zd of error surface. The freeform compensate result of the Zd surface was approximately $-2.75\mu\text{m}$, We can correction the form error Zd. Finally we can use the Zernike polynomial to correction the form error (Z-Zd). Fig.6. shows the form accuracy over the using region of 2.8 mm in diameter is less than $0.984\mu\text{m}$.

Fig. 5. Orientation identification of sample

Fig. 6. Surface after correction form accuracy

6. Conclusions

In this study, we have established the manufacture processes of compensation in form errors of freeform surface. using the Zernike polynomial expression, the form error compensation of freeform surfaces (namely Z-Zd) was finally completed at region of 2.8 mm in diameter from $2.75\mu\text{m}$ down to smaller than $0.984\mu\text{m}$. More importantly, the profile errors of freeform surfaces have been controlled with minor residual errors, they are possibly caused by the irregularity of diamond tool, the system errors of servo control and the ambient temperature variations in long time machining.

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Single-mode fiber coupled compact RGB laser module

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Abstract: Single-mode fiber coupled compact RGB laser module which can be applied to head-mounted display and pico-projector was developed. It has characteristics such as a small size, focus free, flexibility and color variation by adopting wavelength multiplex system and single-mode fiber coupling.

1. Introduction

Recently, three primary colors of laser diode have become available by developing the AlGaInP based red laser diode and the GaN based blue and green laser diode. Currently, a demand for laser diode is increasing as a light source of display instead of LEDs and lamps. If those light source replace with a laser beam, the depth of focus (DOF) of projection can be deeper and quality of images can be much higher than LEDs and lamps [1]. Then, a head-mounted display that can be set on user's head to provide information and pico-projector that can project high quality images with portable size are developed. In case of using laser diodes for above application, it is necessary to make the laser module size compact. Generally, when a laser beam couples into a fiber, a fiber combiner or a wavelength multiplex system are used as a system of fiber coupling. However, if using fiber combiner, the module size becomes large because this system needs to provide for several fibers. Therefore, the wavelength multiplex system which uses only one fiber can make the installation area of the module small.

In this paper, the technology and specification of developed RGB laser module is shown.

2. Development of RGB laser module

2.1 Wavelength multiplex system

To realize compact RGB laser module, the wavelength multiplex system was adopted. As shown in Fig. 1, this is a system to combine laser beams of different wavelengths with optical devices like a dichroic mirror. By making the laser beams of different wavelengths coaxial, it is possible to achieve simple design, high luminance and high output. It is difficult to converge laser beams having different wavelengths at the almost same position and direction on single-mode fiber facet.

In addition, a fiber coupled compact RGB laser module is especially required in portable applications. The rigidity of the structure was designed with care because it is so important to maintain the fiber coupling efficiency in product lifetime.

Fig. 1 Wavelength multiplex system.

2.2 Single-mode fiber coupling

Coupling a laser beam into a single-mode fiber need to adjust precisely. The experiment was done to estimate how much the fiber coupling precision is required. The coupling efficiency was examined when the pointing of laser beam was shifted from the center of the fiber along the x, y, z axes shown in Fig. 1, respectively. Fig. 2 and 3 are the relation between displacement from x, y and z axes and coupling efficiency. As a result, it was found the coupling efficiency declined half with the displacement of only 1 μm .

It is important to fix each parts of RGB laser module for productization. After obtaining optimal fiber coupling efficiency, the parts are attached by laser welding. However, the parts are easily shifted from submicron to a few micron during the process of laser welding. The technique to compensate the shift is needed.

Fig. 2 Relation between displacement from x, y axes and coupling efficiency.

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Fig. 3 Relation between displacement from z axis and coupling efficiency.

2.3 Specifications

Table 1 shows the main specifications of the RGB laser module. The RGB laser module can provide over 40 mW laser output in each wavelength from a single-mode fiber with core diameter 3 μm and NA 0.12. The smaller that the value of the product of fiber core diameter and NA is, the better beam quality is. Since the quality of single-mode laser beam is ideal, for that reason, the RGB laser module has excellent characteristics such as high DOF and condensing the light to the diffraction limit. Moreover, as shown in Fig. 4, the laser size: W 11.7 × H 8.0 × L 30.7 mm is compact.

Fig. 5 and 6 shows the spectra of the RGB laser module and the relation of output power and input current, respectively. The narrow spectra width derives from laser diode, and the output power of RGB 3 colors are in proportion to the input current.

The RGB laser module was applied on “RETISSA® Display”: head-mounted display of the glasses which projected on the retina [2]. This product has a unique characteristic which the user can see clear images without paying attention wherever the user is focusing on because the DOF of the single-mode laser beam is deep.

Table 1. Main Specifications of the RGB laser module.

	Red	Green	Blue
λ [nm]	640 ± 5	515 ± 5	455 ± 5
Power [mW]	> 40		
Fiber	Core Diameter: 3 [μm] NA: 0.12 Single-mode Fiber		
Size [mm]	W 11.7 × H 8.0 × L 30.7 (Fiber is not included.)

Fig. 4 Appearance of the RGB laser module.

Fig. 5 Spectra of the RGB laser module.

Fig. 6 I-L characteristics of the RGB laser module.

3. Conclusions

We developed the compact single-mode fiber coupled RGB laser module. It provides over 40 mW laser output power for each color.

The module was adopted by the glasses typed head-mounted display that can be projected on the retina directly.

By controlling the laser output power of each wavelength, this compact laser module can be applied not only to a head-mounted display but also to a small type display device such as a pico-projector and a laser microscope.

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Holographic Display using Binary Phase Modulation by Image Segmentation Method

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Abstract: Binary-phase-only reconstruction for holographic 3D display has a problem that degrades the image quality by enhancing the speckle. Image segmentation method is applied to reduce the speckle effect. Numerical and experimental results are presented to verify the proposed method.

1. Introduction

One of the problems of the holographic three-dimensional (3D) display is the degradation of image quality due to the presence of speckle. Especially, when the phase-only distribution is used for holographic 3D reconstruction, image degradation and speckle enhancement occur. In the gray-scale phase modulation, the optimization of the phase distribution is achieved by using the error diffusion method and the iterative phase retrieval method. We proposed a holographic 3D display system using binary phase-mode spatial light modulator (SLM) [1]. In this system, binarization of the phase pattern enhances the image degradation and the speckle. However, the optimization of the binary phase pattern using a modified Fresnel ping-pong algorithm and the intensity addition to average the speckle patterns, are effective to improve the image quality. In our simulation and experiments, the good reconstruction is obtained when the number of iterations for phase optimization is 100 and the number of intensity addition is 50. The optimization process of the binary phase pattern can be implemented in off-line in advance. However, the number of intensity addition requires high-speed SLM for real-time reconstruction. Reduction of calculation time of the binary phase pattern or decrease of the number of intensity addition is important to build a real-time 3D display system.

In this paper, we investigate a method to reduce the speckle by using the segmentation of the original image. An original image is divided into sub-images where pixel values at adjacent pixels are blank as presented in Refs. 2 and 3. In Refs. 2 and 3, the time-division multiplexing of segmented images reduces the speckle because the destructive or constructive interference is avoided in blanked pixels. In the numerical simulation and experiments, the reconstructed image quality is compared with that of our previous method in Ref. 1.

2. Binary phase modulation using image segmentation for 3D display

Figure 1 shows the proposed method of calculating binary phase patterns for a holographic 3D display with time-multiplexing. First, an original image is divided into several images in which there are no overlapped pixels. In Fig. 1(a), an original image is divided into four

sub-images. In each sub-image, one-fourth pixels have pixel values and the other pixels are blanked. Owing to the blanked pixels, destructive interference that is the main reason of the speckle is avoided. By using these sub-images, binary phase patterns are optimized by a modified Fresnel ping-pong algorithm described in Ref. 1. Numerical process is described in Fig. 1(b). In this case, the object is a two-dimensional (2D) image. There are two planes. One is the object plane and the other is the display plane. Two constraints are satisfied to obtain the optimized binary phase pattern. In the object plane, the ideal amplitude distribution is the amplitude of the original object to be reconstructed. In the object plane, a random phase distribution is added to the amplitude distribution in the initial step. After the Fresnel propagation to the display plane, a binary phase distribution is extracted. This is the second constraint. After another Fresnel propagation to the object plane, the reconstructed wave is obtained. When the error is less than the threshold, iteration process is terminated.

Fig. 1. Numerical process of binary phase optimization of segmented images. (a) image segmentation and (b) iterative process of optimization of binary phase pattern.

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Otherwise, the optimization process of the binary phase pattern is repeated. In each sub-image, the optimized binary phase pattern is obtained and the reconstructed intensity patterns are added to get the whole reconstructed image.

3. Numerical and experimental results

First, numerical results are presented. Fig. 2 shows the reconstructed images when the optimization of binary phase patterns was used. By increasing the number of iterations, the image quality of the reconstructed images becomes better. Next, the comparison between the previous method in Ref. 1 and the proposed method is given. In Fig. 3(a), the contrast of the reconstructed image is low when the whole image is used for the optimization. Here, 10 intensity addition and 10 iterations in each binary phase pattern are used. Figs. 3(b) and (c) shows the reconstructed images by applying the proposed method with two and four divided images, respectively. It is clearly seen that the image quality is better than that of the previous method.

Fig. 2. Reconstructed images of the previous method described in Ref. 1. The numbers of iterations are (a) 1, (b) 10, and (c) 100.

Fig. 3. Reconstructed images of the previous method and the proposed method: (a) previous method with 20 iterations and 10 intensity addition, (b) two divided images with 10 iterations and 10 intensity addition in each image, and (c) four divided images with 10 iterations and 10 intensity addition in each image.

We implemented the experimental verification. The experimental setup is presented in Fig. 4. A He-Ne laser light at a wavelength of 632.8 nm is used. After the beam expansion, the collimated light incidents on a ferroelectric liquid crystal SLM. This SLM, developed by Citizen Watch Co., Ltd., is used as a high-speed SLM. This SLM operates as binary phase mode. The maximum frame rate is 5,000 frames per second. The number of pixels is 2048×2048 and the pixel pitch is $7.8 \mu\text{m}$. After the elimination of the DC term, a Galvano mirror is used to change the propagation direction to extend the observation field.

Figures 5(a) and (b) show the reconstructed images when two and four divided images are used. There is no big difference between the two images. However, in Fig. 5(b), more clear image is obtained in four divided images.

Fig. 4. Experimental setup.

Fig. 5. Experimental results of reconstructed images when (a) two divided images and (b) four divided images are used.

4. Conclusions

We have applied the image segmentation method in a holographic 3D display using binary phase patterns to suppress the speckle effect. Numerical and experimental results reveal that the proposed method is effective in enhancing the image quality in 3D displays.

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Design of Light Intensity Distribution Control Element for High-Brightness Projectors Using Solid-State Light Sources

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Abstract: A light intensity distribution control element based on the computer-generated hologram for projectors in which blue lasers and yellow phosphors are combined was designed. This element improves the light utilization efficiency by transforming the shape of the light beam from circular to rectangular and makes the light intensity distribution uniform.

1. Introduction

In conventional projectors, mercury lamps are used as the light source. Meanwhile, in recent years, projectors using solid-state light sources have been put into practical use due to their long life, mercury-free, instantaneous lighting, and high color rendering characteristics. However, they are still inferior to the conventional projectors in terms of brightness.

The projectors using solid-state light sources that are currently the mainstream have a configuration in which blue lasers and yellow phosphors are combined, and the phosphor plane and screen are conjugate with each other. In this configuration, if the blue laser beam is focused on the phosphor plane, the light emission efficiency of the phosphor is deteriorated. One method to avoid this is to expand the blue laser beam on the phosphor plane circularly by using a diffusion plate. However, in this case, the light utilization efficiency on the phosphor plane is deteriorated because the light beam outside the screen area becomes a loss as shown in Fig. 1(a). Moreover, the light intensity distribution in the screen area becomes non-uniform.

To solve this problem, the objective of this research is to design a light intensity distribution control element (LDC element) that can be used instead of the diffusion plate. The LDC element has two functions. One is to improve the light utilization efficiency on the phosphor plane by transforming the shape of the light beam from circular to rectangular as shown in Fig. 1(b). The other is to make the light intensity distribution in the screen area uniform.

Fig. 1. Shape of light beam and screen.

2. Methods

Figure 2 shows the optical configuration used in this research. The light beam is emitted from a laser. A computer-generated hologram (CGH) having two-level phases (0 and π) was used as the LDC element. To compare the simulation and proof-of-principle experiment, the following parameters were chosen. The wavelength of the laser was 520 nm. The shape of the light beam on the CGH was circular with the diameter of 15 mm. The pixel size of the CGH was $64 \mu\text{m} \times 64 \mu\text{m}$. The focal length of the lens was 300 mm. The target shape of the light beam on the phosphor plane was rectangular with the size of 1.92 mm x 1.08 mm corresponding to the screen.

The shape of the light beam on the phosphor plane can be calculated as the Fourier transformation of that on the CGH. We used MATLAB to design the CGH. Among several kinds of optimization algorithms for designing the CGH, we chose the Gerchberg-Saxton algorithm [1].

In the proof-of principle experiment to verify the design, a liquid crystal spatial light modulator (SLM) was placed at the position of the CGH and the CGH was displayed on the SLM. A polarizer was placed in front of the SLM and an analyzer was placed behind the SLM. Moreover, a CCD image sensor was placed at the position of the phosphor plane and the light intensity distribution on the phosphor plane was captured by the image sensor for further analysis.

Fig. 2. Optical configuration.

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3. Results

Figure 3 shows the target shape of the light beam on the phosphor plane. Figure 4 shows the calculated shape of the light beam on the phosphor plane using the CGH with a random pattern (random CGH), which corresponds to the diffusion plate. It can be seen that a circular light beam was obtained. Figure 5 shows the calculated shape of the light beam on the phosphor plane using the CGH with the designed pattern (designed CGH). It can be seen that a rectangular light beam similar to Fig. 3 was obtained. The light intensity inside the rectangular area for Fig. 5 was 2.1 times higher than that for Fig. 4. Moreover, the difference in the average light intensity between the center and periphery of the rectangular area for Fig. 5 was smaller than that for Fig. 4.

Fig. 3. Target shape of the light beam.

Fig. 4. Calculated shape of the light beam using random CGH.

Fig. 5. Calculated shape of the light beam using designed CGH.

Figure 6 shows the measured shape of the light beam on the image sensor when the random CGH was displayed on the SLM. Figure 7 shows the measured shape of the light beam on the image sensor when the designed CGH was displayed on the SLM. The measurement results agreed well with the calculation results.

Fig. 6. Measured shape of the light beam using random CGH.

Fig. 7. Measured shape of the light beam using designed CGH.

4. Discussion

In both the simulation and experimental results, a minute fluctuation of the light intensity was observed. However, in an actual case, multiple lasers are aligned two-dimensionally and the light beams from the multiple lasers are combined by the lens. Therefore, the fluctuation might be averaged and reduced.

Moreover, in the experimental results, a high-intensity 0th order light (non-diffracted light) was observed, which made the quantitative analysis difficult. This might be minimized by optimizing the angle of the polarizer and analyzer sandwiching the SLM.

Anyway, the simulation and experimental results have proved that the light utilization efficiency can be improved and that the average light intensity distribution can be uniform by using the LDC element.

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Design of freeform progressive addition contact lens for presbyopia correction with schematic eye model

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Abstract: The design of the freeform progressive addition contact lens for myopic presbyopia correction based on the schematic eye model is presented in this paper. The additional power is 2D between the near and far zone.

1. Introduction

The design and optimization of a freeform progressive addition contact lens for presbyopia correction using schematic eye model is presented in this paper. Contact lenses (CLs) and spectacles are two primary types of the ophthalmic lens for correction of the refractive error of the eye. In recent years, the occupation of the CL is increasing steadily because of appearance, fitness, and convenience. The presbyopia is a phenomenon of the loss of accommodation with the growth of ages, and the multifocal lens design is required for clear vision at near and far distance. Multifocal lenses [1] include bifocals, trifocals, and progressive addition lenses. However, the disadvantage of conventional multifocal lenses is the image jump produced by the prismatic effect of the vision line, and the progressive addition lens (PAL) [2] can provide a smooth power change to avoid the differential image displacement. The PAL has the far-view zone, intermediate zone and near-view zone for presbyopia patients with clear vision at all distances. The far-view zone is at the upper part with the minimum curvature, and the near-view zone is at the lower part with the maximum curvature. The intermediate zone in the center portion, where the curvature varies gradually and smoothly, connects the far-view zone and the near-view zone. Unfortunately, the variation of the curvature results in the unwanted surface astigmatism, also called astigmatic error or cylinder error. The astigmatic error in the peripheral region is defined as the maximum difference of optical power along two orthogonal axes, and it should be minimized to avoid the wearer's blur vision and uncomfortable feeling. Therefore, the PAL design should meet the power distribution of three zones and the low astigmatic error in the peripheral region. There are different numerical methods for PAL design, including the method of parametric design, optimization for the nonuniform rational B-spline surface [3], and the mathematical model, etc. Although these indirect methods can control the distribution of the power and astigmatism independently, the performance in real condition, such as the designed ophthalmic lens combined with the human eye model, was not verified. In this study, the schematic eye model is not only applied to the PAL design for optimal power distribution

and minimum astigmatic error but also used to simulate the optical performance on the retina. In general, many presbyopic patients accompany the myopia; therefore, the freeform surface design must correct both presbyopia and myopia. The myopia is typically corrected by the power of the far-view zone, and then the power of the near-view zone is decided based on the sum of the addition power of the presbyopia and the degree of the myopia. The addition power (ADD) is defined as the power difference between the near-view and far-view zone, and the value of ADD depends on the optical power accommodation ability of the patient's crystalline lenses. Finally, the freeform progressive addition CL is designed and verified by the schematic eye model for both presbyopic and myopic correction.

2. Optical design

In this study, the freeform progressive CL with the myopia of -2D and the ADD of +2D is designed with the schematic eye model. First, a schematic eye model for the CL design should be selected. There are many research about the schematic eye model, the Liou's schematic eye model [4] based on the ocular anatomy extensively applied to the ophthalmic lens design is selected for the CL design in our study. Subsequently, the myopic model should be constructed according to the conjugate with the far point of the -2D myopia. Because the addition power (ADD) is +2D, the object distance are 1160 mm, 600 mm and 350 mm for the far view, middle view and near view, as shown in Table 1. The looking down angles for the far view, middle view and near view are designed as 0°, 10° and 20° respectively, as shown in Fig. 1. Figure 2 shows the layout and MTF of the far view distance, the average MTF at 100 line pair per mm (lp/mm) is 0.31. Figure 3 shows the layout and MTF of the middle view distance, the average MTF at 100 lp/mm is 0.22. Figure 4 shows the layout and MTF of the near view distance, the average MTF at 100 lp/mm is 0.22. The limiting resolution of the emmetropic eye is approximately 100 lp/mm on the fovea, which is also corresponds to the resolvable angle of 1 arc minute. The designed MTF is enough for resolving this spatial frequency. The footprint on the freeform surface of the CL is shown in Fig.5. The power maps of the spherical

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and cylinder power are shown in Fig. 6. It is found that the lowest diopter on the center region for the far view, and the largest diopter on the lower region for the near view. The variation of the power between the far and near view regions is gradually smooth. The cylinder power, which is the astigmatic error, occurs in the peripheral region of the CL, it affects the used region slightly.

Table 1. Specification of myopic presbyopic contact lens

Myopic presbyopia contact lens	
Myopia	-2D
ADD of Presbyopia	+2D
Far view distance	1.16 M
Middle view distance	60 cm
Near view distance	35 cm

Fig. 1 The layout of the far, middle and near view

Fig. 2 Far view: (a) Layout (b) MTF

Fig. 3 Middle view: (a) Layout (b) MTF

Fig. 4 Near view: (a) Layout (b) MTF

Fig. 5 Footprint on the freeform surface of the CL

Fig. 6. Power map of freeform surface: (a) spherical power (b) cylinder power

3. Conclusions

The myopic presbyopia contact lens with the -2D myopia and +2D ADD is successfully designed with the schematic eye model. The MTF of the far, middle and near view is enough for the clear vision. The variation of the diopter from the far to near view on the freeform of the CL is gradually smooth, and the cylinder power affects the used footprint region slightly.

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A Study for Quick and Accurate White Balance Adjustment in Laser Display Production

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Abstract: White balance adjustment is crucially important but time-consuming work in display production. In this paper, we point out challenges in white balance adjustment process and discuss how they can be resolved using the Discrete Centroid Wavelength Method, which was newly developed for laser-display measurement.

1. Introduction

Currently, more and more displays such as head up displays (HUD) and head mount displays (HMD) are employing lasers to make use of their high color reproducibility, enhanced energy efficiency and small size. [1]. As laser displays are becoming more common, the demand for accurate measurement of their chromaticity and photometric quantity is also rising. In our previous study, reflecting this situation, we suggested a new measurement method called the Discrete Centroid Wavelength Method (DCWM) to precisely measure these two parameters using the centroid wavelength λ_c and the power P of RGB lasers as follows [2].

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = K_m \begin{pmatrix} x(\lambda_{cr}) & x(\lambda_{cg}) & x(\lambda_{cb}) \\ y(\lambda_{cr}) & y(\lambda_{cg}) & y(\lambda_{cb}) \\ z(\lambda_{cr}) & z(\lambda_{cg}) & z(\lambda_{cb}) \end{pmatrix} \begin{pmatrix} P_r \\ P_g \\ P_b \end{pmatrix} \quad (1)$$

Subscripts r, g and b denote red, green and blue, respectively, and capital X, Y and Z are tristimulus values. $x(\lambda)$, $y(\lambda)$ and $z(\lambda)$ are the color-matching functions stipulated in a CIE international standard. The coefficient K_m is 683lm/W so that tristimulus value Y is equal to the photometric quantity, and the chromaticity x and y are easily obtained from the tristimulus values. Another important process in display production is white balance adjustment. Display manufacturers assign each display with different adjustment factors that fix the balance of RGB lasers aimed at ensuring homogeneity of the displays' brightness and color. For the purpose of finding the adjustment factors, production-line workers adjust the displays' color to reference white by changing the output of RGB lasers. In this paper, we will discuss how white balance adjustment can be done more quickly and accurately using the DCWM in order to further accelerate the prevalence of RGB laser displays.

2. Challenges in White Balance Adjustment

White balance adjustment is often done using an optical power meter and a highly accurate spectrometer. A common flow of the adjustment work is shown in Fig.1.

Fig.1 Common Flow of White Balance Adjustment

The wavelength of each of RGB lasers is needed to calculate their power (P_r, P_g, P_b) that generates the target chromaticity (x, y) and photometric quantity E for white balance adjustment as follows.

$$\begin{pmatrix} P_r \\ P_g \\ P_b \end{pmatrix} = \frac{1}{K_m} \begin{pmatrix} x(\lambda_r) & x(\lambda_g) & x(\lambda_b) \\ y(\lambda_r) & y(\lambda_g) & y(\lambda_b) \\ z(\lambda_r) & z(\lambda_g) & z(\lambda_b) \end{pmatrix}^{-1} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (2)$$

$$= \frac{1}{K_m \cdot \det} \begin{pmatrix} y_g z_b - y_b z_g & x_b z_g - x_g z_b & x_b y_r - x_r y_b \\ y_b z_r - y_r z_b & x_r z_b - x_b z_r & x_r y_g - x_g y_r \\ y_r z_g - y_g z_r & x_g z_r - x_r z_g & x_r y_b - x_b y_r \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

$$\det \equiv x_r y_g z_b + x_g y_b z_r + x_b y_r z_g - x_r y_b z_r - x_g y_r z_b - x_r y_b z_g$$

$$X = \frac{x}{y} E$$

$$Y = E$$

$$Z = \frac{1 - x - y}{y} E$$

The symbols of the color-matching functions in Eq.2 are simplified. For instance, x_r in Eq.2 means $x(\lambda_{cr})$ in Eq.1. Eq.2 is obtained by calculating the inverse matrix of Eq.1. In many cases, a spectrometer with a very narrow spectral bandwidth is used to precisely measure the laser spectrum so that an accurate wavelength can be obtained. In other cases, the wavelength shown in the datasheet is used without spectral measurement. After (P_r, P_g, P_b) is calculated from Eq.2 using the wavelengths, the power of each laser is adjusted to these values while measured by a power meter. Since a power meter is generally designed for single laser measurement and not capable of

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wavelength measurement, you need to set to it the wavelength of your laser and measure the power one by one as shown in Fig.1. Although this adjustment method seems to work well, it actually has a few problems. First, wavelength measurement with a highly accurate spectrometer takes much time. Since wavelength varies from one laser to another, typical values shown in their datasheet are not reliable. Therefore, wavelength measurement is indispensable. However, spectrometers such as an optical spectrum analyser are mostly slow, which hinders quick adjustment work. Second, wavelength varies depending on the laser power. That is because a higher-power laser has a higher temperature, which causes wavelength shift particularly in red. Even if (P_r, P_g, P_b) is calculated based on the wavelengths measured in a certain power condition, they are no longer correct once their wavelengths change during power adjustment work. If you would like to conduct white balance adjustment very accurately, you need to repeat the process shown in Fig.1 while inspecting the chromaticity and photometric quantity of the RGB lasers (Fig.2). However, it requires even longer time for the adjustment work.

Fig.2 Work Flow for More Accurate White Balance Adjustment

3. Quick and Accurate White Balance Adjustment with the DCWM

The DCWM is characterized by simultaneous measurement of the centroid wavelength and radiometric quantity of RGB lasers. Their chromaticity and photometric quantity are also calculated using the color-matching functions. In this chapter, we would like to explain how the DCWM can overcome the above challenges regarding white balance adjustment. Unlike spectrometers, it doesn't require laser spectrum

measurement to obtain centroid wavelength as shown in [2]. Because of this characteristic, the necessary time for wavelength measurement has been sufficiently shortened. For instance, HIOKI's RGB laser meter TM610x, which adopts the DCWM for laser display test, takes 460ms or shorter to obtain the centroid wavelength of RGB lasers. Besides, the TM610x can internally carry out the calculation of Eq.2 based on the measured centroid wavelengths and continuously update (P_r, P_g, P_b) . Therefore, even if the wavelength of RGB lasers changes as their power increases or decreases, the TM610x can instantly recalculate correct values. Production-line workers simply need to adjust the power of RGB lasers to the one offered by the TM610x without any concern over wavelength shift. A typical flow of white balance adjustment with the DCWM is shown in Fig.3.

Fig.3 A typical flow of white balance adjustment with the DCWM

5. Conclusion

In this paper, we have made clear the challenges in conventional white balance adjustment work and suggested how this process can be improved with HIOKI's RGB laser meter TM610x, which employs a new measurement method called the DCWM. We conclude that the TM610x can make the time-consuming work much quicker and more accurate, which can help with a stable supply of high-quality laser displays.

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Low vertical divergence angle and low coherence laser diodes for laser display

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Abstract: In this work, we demonstrate a red laser with low vertical divergence angle 18.3° and low coherence with speckle contrast of 5.2% to achieve reduction of speckle, showing a bright prospect for the laser display.

1. Introduction

Lasers have the natural advantages over other sources in color gamut, big screen and long lifetime. However, lasers also have the inherent drawbacks to affect the display quality like speckle owing to the high coherence of the conventional lasers. There are many methods presented to reduce the speckle [1-3]. The above methods all introduce the independent speckle patterns on the light path. The fundamental method to reduce speckle is the light source, and we do some research about it [4].

In this paper, we provide the red laser with the low vertical divergence angle and low coherence. We realize the small vertical divergence angle from 42.2° to 18.3° by adopting the large optical cavity (LOC) wafer structure and the low coherence by the chaotic cavity.

2. Theory of the speckle suppression

The speckle is characterized by the speckle contrast C . It is defined as [5]:

$$C = \frac{\sigma}{\langle I \rangle} \quad (1)$$

The σ is the standard deviation of intensity and $\langle I \rangle$ is the mean intensity. Assume that the surface height fluctuations and the spectrum of the light source both are Gaussian-shaped, the speckle contrast C is [5]:

$$C = \left[1 + 8\pi^2 \left(\frac{\delta\lambda}{\lambda} \right)^2 \left(\frac{\sigma_h}{\lambda} \right)^2 \right]^{-\frac{1}{4}} \quad (2)$$

Where $\delta\lambda$ represents the 1/e width of the spectrum and the σ_h is the standard deviation of screen height. According to Eq. (2), we can realize the speckle suppression by broadening bandwidth of the illumination source. It also means the low coherence source can reduce the speckle contrast.

3. Design and device fabrication

We adopt the chaotic cavity to obtain many pseudo-random spatial modes for low coherence [4,6]. As is shown in Fig. 1, the laser consists of a D-shaped section for realizing multimode lasing and a stripe area for higher power. The parameters is $R=500 \mu\text{m}$, $d=0.5R$ and $L=1000 \mu\text{m}$. By the standard photolithography and the

inductively coupled plasma (ICP) process, the laser can be well fabricated.

Fig. 1 Schematic of the low coherence red-emitting laser.

4. Results

Fig. 2 shows the vertical divergence angles of the low coherence lasers using standard epitaxy structure and LOC structure, respectively. The measured vertical angle of LOC structure is 18.3°, while the former is 42.2°.

Fig. 2 Vertical divergence angles of the low coherence lasers using standard epitaxy structure (blue line) and LOC structure (red line), respectively.

Fig. 3(a) shows the spectra of low coherence red-emitting laser using LOC structure at different currents from 5A to 10A (40 μs 40 Hz and TEC 20°C), which results in the normalized intensity emission and the spectrum width at full-width-at-half-maximum (FWHM) shown in Fig. 3(b). It is worth noticing that the spectrum

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emission intensity increases superlinearly and the FWHM decreases with the current. These phenomena provide the evidences for lasing. The FWHM is about 7.9 nm at 10A, thus in principle (Eq. (2)) the laser source should lead to the low coherence. The maximum output power reaches 120mW@20A.

Fig. 3(a) Emission spectra collected at different currents and (b) Spectrally integrated emission intensity and emission bandwidth as a function of the current for the low coherence red-emitting laser using the LOC structure.

Fig.4 shows the speckle patterns of the low vertical divergence angle and low coherence laser and the conventional FP laser using the same LOC wafer structure. The width and length of FP laser are 90 μm , 2 mm, respectively. The speckle contrast C is calculated by using the same size and location of sample areas, with the results of 5.2% for the low vertical divergence angle and low coherence red-emitting laser and 12.8% for the FP laser according to Eq. (1).

Fig. 4 Speckle patterns of the low vertical divergence angle and low coherence laser (a) and the conventional FP laser (b) using the same LOC wafer structure

5. Conclusions

We have demonstrated the low vertical angle and low coherence red-emitting laser diode, which has a bright prospect for the laser display.

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High-output-power and high-temperature operation of a blue GaN-based vertical-cavity surface-emitting laser

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Abstract: High output powers of 22.2/2.6 mW at 20/140°C were obtained from a blue GaN-based VCSEL by introducing lateral optical guide and long cavity structures, and by adjusting the front cavity mirror reflectivity. A single-lobe far-field pattern with a narrow divergence of 5.1° was observed at 5 mW output.

1. Introduction

GaN-based vertical-cavity surface-emitting lasers (VCSELs) are of significant importance in numerous applications, including adaptive laser headlamps [1], retinal scanning displays and visible light communication systems. These devices have numerous advantages, including the avoidance of catastrophic optical damage (COD), ready integration with two-dimensional arrays, minimal temperature dependence and circular output beams with limited divergence. It is especially important to avoid COD in the case of automotive headlamp laser diodes to ensure safety, and it is also preferable that the lasing wavelength not be affected by temperature so that a stable beam color is obtained. Based on these requirements, a combination of blue VCSELs and phosphors is the most attractive light source for next-generation laser headlamps. Recently, some research groups have achieved continuous-wave (CW) operation of GaN-based VCSELs [2] and reported light output power (LOP) values of mW order [2]. However, further improvements to GaN-based VCSELs are required for applications such as laser headlamps. In this summary, we report a high output power of 22.2 mW from a blue GaN-based VCSEL under CW operation, owing to the introduction of a SiO₂-buried lateral optical confinement (LOC) structure [3] and a long-cavity (10λ) structure, and to a reduction of the reflectivity of the front cavity mirror [4].

2. Device structure

Schematics of simple SiO₂-aperture (device A) and SiO₂-buried (device B) VCSELs are shown in Fig. 1. The basic structure consisted of a 46-pair AlInN/GaN distributed Bragg reflector (DBR), a 4.5λ cavity and a 10.5-pair SiO₂/Nb₂O₅ DBR. The epitaxial structure between the DBRs was composed of an n-GaN layer, a 5-pair GaInN/GaN multiple quantum well, a p-AlGaIn electron blocking layer and a p-GaN layer. In device A, the thickness of the SiO₂ layer was 100 nm and the diameter of the aperture was 8 μm. Assuming that a local shift of the resonance wavelength produces a corresponding change in the effective index [5], calculating the resonance wavelength difference

demonstrates that a normalized effective index difference ($\Delta n_{\text{eff}}/n$) of -0.025 is obtained from this structure, resulting in an anti-guiding structure. On the other hand, the SiO₂-buried structure was formed by etching an area of the p-GaN layer having a diameter of 8 μm to a depth of 20 nm using reactive ion etching, after which a 20 nm SiO₂ thin film was deposited and lifted off. In this case, $\Delta n_{\text{eff}}/n$ was calculated to be 2.6×10^{-3} . In this work, the number of AlInN/GaN DBR pairs was also varied from 42 to 46 to tune the reflectivity. Herein, we define the substrate side as the front side.

Fig. 1. Schematics of the fabricated blue VCSELs with (a) a simple SiO₂ aperture and (b) a SiO₂-buried lateral optical confinement structure.

3. Results and discussion

Figure 2(a) shows the reflectivity and slope efficiency (η_s) from the front side as functions of the number of AlInN/GaN DBR pairs. The open and closed symbols indicate the results obtained from VCSELs with a simple SiO₂ aperture and a SiO₂-buried LOC structure, respectively. From these data, it is evident that lower reflectivity values resulted from reducing the number of DBR pairs from 46 to 42, corresponding to a change in the reflectivity from 99.8% to 99.5%. This drop in reflectivity approximately doubled the mirror loss for the front side, and therefore resulted in a higher η_s . Compared to the efficiency of a 46-pair AlInN/GaN DBR VCSEL with a conventional SiO₂ aperture (0.13 W/A), the efficiency was increased by a factor of 4.7 (to 0.61 W/A) upon introducing the LOC structure, and was further improved by a factor of 6.7 (to 0.87 W/A) by additionally tuning the front cavity mirror reflectivity.

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Figure 2(b) shows the inverse of the total external differential quantum efficiency (η_d^{total}) as a function of the inverse of the mirror loss. The value of α_i can be obtained from the slope of a linear fit to the data. For the conventional GaN-based VCSEL without an LOC structure, α_i was calculated to be 73 cm^{-1} . In contrast, α_i for the VCSEL incorporating an LOC structure was significantly lower, 23 cm^{-1} . It was experimentally found that the impact of transverse radiation loss was extremely high, 50 cm^{-1} , which accounts for more than 2/3 of the entire internal loss in conventional VCSELs. In addition, a maximum η_d^{total} of 32% was obtained from the SiO₂-buried VCSEL with a 42-pair AlInN/GaN DBR under pulsed operation.

Fig. 2. (a) Reflectivity and slope efficiency under pulsed conditions as functions of the number of AlInN/GaN DBR pairs. (b) Inverse of external differential quantum efficiency as a function of the inverse of the mirror loss.

Fig. 3. (a) I-L/I-V characteristics of the fabricated VCSEL (device B) from 20 to 140 °C. (b) Full width at half maximum (FWHM) of the far-field pattern (FFP) of the 5λ-cavity and 10λ-cavity VCSELs with a 5.5 μm aperture as a function of LOP. Insets are the FFP images around 1 mW and 5 mW, respectively.

In order to improve the thermal resistance, a long-cavity structure (10λ) was introduced in the blue VCSEL with an LOC structure [4]. Figure 3(a) shows the I-L/I-V characteristics of device B with a 10-λ cavity structure in the temperature range from 20 to 140 °C. A maximum

LOP of 22.2 mW at 20 °C and high temperature lasing operation up to 140 °C were obtained. Owing to the reduced thermal resistance provided by the long-cavity structure, this VCSEL also exhibited a high slope efficiency of 40% and a wall-plug efficiency of 10%. This VCSEL essentially operated with multimode lasing. Because the 8 μm aperture was relatively large, higher-order modes were possible even with an extremely low $\Delta n_{\text{eff}}/n$ value. Figure 3(b) shows the FWHM divergence angle of the 5λ-cavity and 10λ-cavity VCSELs with a 5.5 μm aperture as a function of their LOP. The insets show FFP images around 1 mW and 5 mW, respectively. An extremely small divergence angle of 4.2° was observed for the 10λ-cavity VCSEL around 1 mW. Furthermore, a narrow beam of 5.1° in FFP angle was observed even at a relatively high LOP of 5 mW.

4. Conclusions

We have demonstrated a blue GaN-based VCSEL featuring a SiO₂-buried LOC structure, in which the reflectivity can be tuned by varying the AlInN/GaN DBR. Internal loss measurements revealed an extremely high transverse radiation loss in the case of a conventional GaN-based VCSEL without an LOC structure. This internal loss was significantly reduced by introducing the SiO₂-buried LOC configuration. This decrease in the internal loss, in combination with an adjustment of the cavity mirror reflectivity and introduction of the long-cavity structure, resulted in the high output power of 22.2 mW at 20 °C and 2.6 mW at 140 °C. In view of transverse mode control, the 10λ-cavity VCSEL with a 5.5 μm aperture exhibited a very narrow divergence beam of around 5° even at approximately 5 mW output power. These technologies and superior performances may open the door to practical use for VCSEL eyewear display. In the future, we will continue to explore W-class high-power VCSEL arrays in the blue wavelength range with the goal of achieving highly functional automotive headlamps.

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Laser-phosphor light source with luminance up to 2000Mcd/m²

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Abstract: A compact laser-phosphor light source is demonstrated. Newly-developed YAG:Ce phosphor plate showed very high luminance before saturation. This light source is suitable for long-distance laser lighting applications with a narrow beam divergence.

Keywords: laser lighting, blue laser, phosphor, luminance

1. Introduction

In recent years, various laser-phosphor lighting technologies using high power blue or blue-violet laser diode and phosphor light converter have been reported [1-4]. It was proven to be promising for applications that require high luminance light sources and small optics. Due to the focusing capability of a laser diode, the emission size on the phosphor plate can be very small. A small light source with high luminance is desirable in applications such as long distance illumination [4], automotive headlight [3], etc that require propagation of light with small divergence angle.

We reported the advantages of laser lighting in 2011 [1,2]. In 2015, we reported a laser-phosphor light source module with a luminance of 700 Mcd/m² and a flux of 2000 lm, in which multiple high power blue lasers were coupled into a fibre to excite the phosphor converter [4].

In this paper, we describe a compact and high power laser phosphor lighting module with newly developed phosphor plate whose saturation luminance is shown to be as high as 2000 Mcd/m².

2. Experimental

A reflective-type laser-phosphor lighting configuration was used for phosphor evaluation and fabrication of a demonstrator. The demonstrator, as shown in Figure 1, is composed of a single watt-class multimode blue laser mounted in a 9mm TO-can. The phosphor plate is mounted away from the blue laser with a tilted angle of 60 degree. Special care was taken to control the laser beam shape on the phosphor by using collimation and focusing lens as well as beam shaping optics. The new phosphor plate was made from a thin phosphor layer consisted of Cerium doped Yttrium Aluminium Garnet (YAG:Ce) powder and matrix material on an aluminium substrate. A heatsink is included at the bottom and the back of the demonstrator as well as a small fan to allow for efficient heat dissipation of the watt-class blue laser and for maintaining an operating temperature below 50 degC. A parabolic reflector was designed specifically for the emission light source using ray tracing and was attached over the phosphor plate to collect and to project the converted light.

Fig. 1. Laser lighting demonstrator

3. Results and Discussion

3.1 Phosphor luminance

Figure 2 shows the peak luminance from our new phosphor plate when varying the power density using a commercially available bench top blue laser module. For this experiment, the laser beam was shaped to achieve a top hat intensity distribution.

The maximum luminance was achieved for a laser power density of 47 W/mm² and reached 2000 Mcd/m² before starting saturation and roll over. This saturation is due to thermal quenching of the phosphor conversion caused by heating of the phosphor particle, due to the absorption of the blue laser light. This improved phosphor performance was achieved following optimisation of several parameters such as phosphor powder characteristics, matrix material and thickness of the phosphor film.

Fig. 2. Luminance of phosphor plate

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3.2 Laser lighting demonstrator: Luminance

The laser excitation beam used in this demonstrator exhibits an elliptical shape and has a Gaussian-like distribution. If this beam was used directly to excite the phosphor, this would cause non-uniform light excitation. As shown in Fig. 2, performance of the phosphor varies with laser power density. In order to maximise the luminance and flux, it is therefore desirable that the excitation area is as uniform as possible. If this was not improved, early phosphor saturation by thermal quenching would occur at different area in the phosphor emission zone.

We have used beam shaping optics and a focusing lens to achieve a nearly top-hat laser excitation on the phosphor (as shown in Fig.3). The phosphor emission (Fig.3a) corresponds to the laser beam size at the phosphor surface and has a full width at half maximum of $350\text{ }\mu\text{m} \times 650\text{ }\mu\text{m}$. In this demonstrator the laser beam shape was designed to be rectangular. The luminance distribution in the x direction shows a plateau at about 1500 Mcd/m^2 whereas it is slightly less uniform in the y direction but still reaches the same luminance value.

Fig. 3. Distribution of luminance of Laser-phosphor demonstrator. (a) Phosphor emission image, (b) Distribution of luminance in x-direction and (c) in y-direction.

3.3 Laser lighting demonstrator: Projected beam

Narrow angle projection at long distance was demonstrated as shown in Fig. 4.

The demonstrator projected a luminous intensity of 540,000 cd and projected light beam angle was as narrow as 1.9 degree in vertical direction and 1.2 degree in horizontal direction.

Fig. 4. Laser-phosphor lighting narrow angle projection demonstration. (a) light beam image, (b) illumination of a house placed over 200m away from the light source.

4. Conclusions

Compact laser-phosphor lighting was demonstrated. The saturation luminance of phosphor plate was shown to be as high as 2000 Mcd/m^2 due to the newly developed YAG:Ce phosphor plate. The demonstrator has reflective-type laser-phosphor lighting configuration. A narrow angle projection of $1.9\text{deg}/1.2\text{deg}$ was obtained from the demonstrator with a small reflector.

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Generation of multi-wavelength yellow-orange lasers using chi(2) chirped nonlinear photonic crystals

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Abstract: Yellow-orange multi-wavelength laser source is demonstrated by utilizing chi(2) nonlinear photonic crystals cascaded of tri-parallel IR-OPO segments with chirped design for frequency up-conversion. This intra-cavity pump scheme allows 1~3 groups of NIR signal/idler generation depending on the relative beam position onto the crystals, enabling frequency-converting up to 5-peak wavelengths in the 585~595nm band.

1. Introduction

Laser is one of the important light sources in biomedical application, especially in bio image. It is now possible to see vivo image with properly exciting fluorescent proteins [1]. Also in recent year, the Stimulated emission depletion (STED) microscopy technique enables us to see image over diffraction limit. Both techniques enable us to have better image application. For STED technique to excite the green or yellow fluorescent proteins, the yellow-orange band light source is needed [2]. It is reported that the yellow-orange light source can be produced by sum frequency of 1064 nm and near 1300 nm [3, 4]. However, since the sum frequency generation (SFG) depends on the control of two different laser sources, its spectrum will always be narrow and only single peak. So, we proposed another way to achieve yellow-orange spectral range with tunable multi-peak wavelengths in yellow-orange spectral range.

2. Experimental setup and results

In our experiment setup, we use green pump intra-cavity second harmonic process to produce yellow-orange band laser source. And since the conversion efficiency of SHG is usually proportional to the intensity of the fundamental wavelength. So, we decide to confine the NIR inside the cavity to achieve high intensity.

Fig. 1. Experimental setup of yellow-orange laser

As show in the Fig. 1, we first convert the narrow band 1064 nm to narrow 532 nm by KTP crystal as our OPO pumping source. Then we choose mirrors with high

reflectance from 1160 nm to 1180 nm. In this way, the energy of IR will be stored in the cavity. Our periodically poled lithium tantalate (PPLT) design is based on two different quasi-phase-matching (QPM) segments in cascade. The first segment of the PPLT is to produce IR by difference frequency generation (DFG) with 532 nm pump. The other segment is chirped design for second harmonic generation of the IR produced from previous segment. The chirped design enables us to increase the temperature bandwidth and acceptable fundamental wave bandwidth, but with compromise on the conversion efficiency. Except for the cascade design, we also design the tri-QPM period of DFG section in the parallel direction. In this way, a tunable and multi-peak IR light source will be available. The Fig. 2 shows the idea of design.

Fig. 2. The design example of PPLT

As showed in the Fig. 1, we confine almost all the IR energy inside the cavity, but only leak some of them into the optical spectrum analyzer (OSA). The Fig. 3 shows the NIR measurement result of the idler part of the three signal/idler groups which are generated from tri-parallel DFG segments.

Fig. 3. The spectrum of idler part of the IR

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This situation is showed up when we choose the proper beam waist and pump onto the proper PPLT position. If we choose the improper experiment conditions, there will be single peak or two peaks. The corresponding yellow-orange spectra are also depending on spectra of the IR or the position of the PPLT. When the yellow-orange laser is operating at single peak position, i.e. only one peak in 585~595 nm band, the single-side slope efficiency is about 17% and the threshold is about 40 mW. Fig. 4 shows the OPO output power versus input green power and the spectrum when we operate it in the single peak situation.

Fig. 4. The OPO output power and spectrum when operating at single peak position

If we shift the position of the PPLT we can control the number of output peaks in yellow-orange band from single peak to two peaks. At the two-peak wavelengths situation, the single-side slope efficiency is about 14.2 % and the threshold is about 54 mW. Fig. 5 shows the OPO output power versus input green power and the spectra when we operate it in the two peaks position.

Fig. 5. The OPO output power and spectrum when operating at two peaks position

If we further shift the position of the PPLT, the number of yellow-orange laser peaks increases from two peaks to three peaks. At this position, the OPO single-side slope efficiency is about 7.1 % and the threshold is about 61.9 mW. The OPO output power and the corresponding spectrum are showed in Fig. 6.

Fig. 6. The OPO output power and the spectrum at three peaks position

Now, if we tune the PPLT such that the pumping green beam can cover all of the tri-parallel QPM periods. Then, the output spectrum of the oscillator will produce five peak wavelengths in 585~595 nm band as showed in Fig. 7.

Fig. 7. The OPO spectrum of five peak wavelengths in yellow-orange band

3. Conclusion

We successfully design and build an OPO to produce yellow-orange laser source with tunable number of peak wavelengths in 585~595 nm band. By designing QPM periods into two segments in cascade, the first segment is the DFG part which produces IR laser source, and the other part is the SHG part which is chirped design to produce yellow-orange visible laser source. Also in the DFG part, we design tri-parallel QPM periods, in this way, a simultaneous three groups of the IR signal/idler pairs was observed. It is possible to tune the output NIR spectra from single peak wavelength to three peak wavelengths by moving the PPLT in transverse direction. The corresponding number of peaks of output yellow-orange light is also changed from single peak to five peaks.

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High-Power 638nm Red Laser Diode with Built-in Lens for Display Applications

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Abstract: We realized compact light sources with built-in lens for display applications by exploiting beam expander configuration in Slow-axis. It's embedded in 9.0mm TO-package and emits collimated beam of 638nm pulsed 2.5W with divergence angle of 3.6° (Slow-axis) and 0.4° (Fast-axis).

1. Introduction

Laser based displays have gathered much attention, and they are expected to make an alternative huge market for visible laser diodes (LDs), because only the displays may have a wide color gamut which can express ITU-R BT.2020. We have already developed a high-power 638nm triple emitter LD with pulsed output power over 2.5W for display application [1-2]. In that laser, since the divergence angle is extremely large, the larger collimating lenses which can make small spot size are necessary to efficiently illuminate the display. However, optical design would be so complicated that application range is limited because of the large Fast-axis divergence angle and triple emitter LD structure.

In this work, we developed the high-power red LD with built-in lens in order to simplify optical design and optical system configuration. In the triple emitter direction (Slow-axis), it applied the principle of beam expander which reduces the divergence angle by enlarging the beam size. In this paper, we show the performance of the high-power collimating beam realized with 9.0mm TO-package.

2. Lens Design

The high-power red LD has Broad Stripe (BS) structure in which emitters and insulators are alternately arranged. An active layer consists of AlGaInP material. We carefully designed the emitter structure in order to ensure high output performance and high reliability and the details are described in elsewhere [1]. Each stripe width of emission regions is $60\ \mu\text{m}$, total effective width of all three emission regions is $270\ \mu\text{m}$ and the transverse mode oscillates in multi modes. The cavity length is $1500\ \mu\text{m}$. In Far Field Pattern (FFP), the beam divergence full width (FW1/e²M) at which the light output becomes $1/e^2$ of the peak value were typically 8.0° (Slow-axis) and 69.0° (Fast-axis) respectively.

When collimating the emitting light in Slow-axis, a focal length of the collimating lens needs to be relatively lengthened because the equivalent emitting spot size in Slow-axis becomes larger size $270\ \mu\text{m}$ by considering three lights as a single light source. On the other hand, when collimating the emitting light in Fast-axis with the

same focal length as Slow-axis, it is necessary to widen the effective aperture of the lens in order to increase the transmittance because the divergence angle is relatively larger as 69.0° compared with 8.0° . Given these conditions, it is difficult to collimate with one smaller lens having an axisymmetric structure for two axes. Therefore, we adopted an axially asymmetric lens structure and applied the principle of beam expander which reduces the divergence angle by enlarging the beam size in Slow-axis. Fig. 1 schematically shows each collimating functions for both axes.

Fig. 1. Collimating functions for each axis.

The principle of beam expander is as follows. When two different lenses with focal lengths f_1 and f_2 are located at a distance d apart, the beam size of transmitted light expands at magnification $m (= -f_2 / f_1)$ determined by the ratio of focal lengths. The relationship between the incident light (divergence angle θ_0 , beam diameter ω_0) and the emitted light (divergence angle θ_1 , beam diameter ω_1) is expressed the following equations by using the distance d , the focal lengths f_1 and f_2 .

$$\omega_1 = (-f_2 / f_1) \omega_0 = m \omega_0 \quad (1)$$

$$\theta_1 = (-f_1 / f_2) \theta_0 = \theta_0 / m \quad (2)$$

$$d = f_1 + f_2 \quad (3)$$

By using both input and output surfaces of the lens, we applied this principle of beam expander only for Slow-axis and realized the collimating beam. On the other hand, in Fast-axis, we collimated at output surface by employing the conventional way. Since the divergence angle of Slow-axis does not depend on the distance between LD emitting surface and lens for beam expander, the position of lens was determined by the target focal length of Fast-axis. The calculation results of the beam profile after transmitted the lens are shown in

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Fig. 2. The beam diameter (FW1/e²M) just after passing through the lens (z = 0m) was 1.0 mm (Slow-axis) and 1.7 mm (Fast-axis), and the divergence angle (FW1/e²M) of FFP is 3.5° (Slow-axis) and 0.2° (Fast-axis).

Table 1 shows a comparison of lens configuration between conventional axisymmetric type and this work. Since we adopted an axially asymmetric lens structure in this work, the size of lens can be reduced and the lens was built-in the cap which seals LD package. Regarding this package, we adopted TO-CAN package with the diameter of 9.0mm in order to reduce a contact thermal package. Furthermore, there is a margin in Slow-axis assembly tolerance compared with conventional one. Therefore, it also can be realized to manage easily the position of the emitter with respect to the LD chip outline.

Table 1. Comparison of lens configuration.
(In case the divergence angle of slow-axis is constant.)

Item	Conventional (Axisymmetric)	This work
Configuration		
Size	×	○
Assembly tolerance	Fast: ○ Slow: ○	Fast: ○ Slow: ◎

3. Laser characteristics

Fig. 3 shows the optical power-current characteristics of this proposed LD package when driving at 30% duty pulse. This temperature indicates the stem's temperature of TO-CAN package. In the case of output power 2.5 W at 25°C, the driving current was 2.77 A and the driving voltage was 2.35 V. The slope efficiency was 1.17 W/A. The transmittance of the lens was over 98%. It realized the equivalent optical performance as the case of conventional configuration. We also confirmed the equivalent optical performance all over temperature between 0 °C and 45 °C. In the output power 2.5W under 25 °C, the peak wavelength is around 638 nm, and the full width at half maximum of the spectrum is about 1.0 nm. The FFP images in Slow-axis (FFP //) and the Fast-axis (FFP ⊥) at this proposed one are shown in Fig. 4. The divergence angle was 3.6° (Slow-axis) and 0.4° (Fast-axis), respectively. Considering the assembling

tolerance of the lens cap, reasonable measured values were obtained for the design value.

Fig. 3. P-I characteristics of LD in this work.

Fig. 4. FFP characteristics of LD in this work.

4. Conclusion

We developed the red LD with built-in lens which is very suitable for display applications. The compact light source was realized by applying the principle of beam expander to the built-in lens which enlarges the beam in Slow-axis and reduces the divergence angle. A pulsed 2.5W collimating beam with divergence angle of 3.6° (Slow-axis) and 0.4° (Fast-axis) was realized with 9.0mm TO-package.

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Color Speckle Measurement of Far Field Pattern of RGB Laser Modules

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Abstract: Color speckle of a fiber-output white laser beam of an RGB laser module is measured. The output beam is projected on the standard screen. Both speckled and un-speckled far field patterns are obtained. Speckle contrast can be successfully obtained by conversion into a homogeneous background using the un-speckled data.

1. Introduction

RGB laser modules are of great interest because they are applied for various laser displays and lighting products. The laser modules often have a fiber-output of white laser beam combining the R, G, B LD (laser diode) outputs, for user's convenience.

For display and lighting applications, photometric and colorimetric measurements are very important, whereas only radiometric measurements have been carried out for long history of other laser applications.

Regarding the international standardization of display measurements, IEC TC110 WG10 has already published three IS documents related to monochromatic and color speckles. The new item on visual quality under effects of color speckle has already started. Furthermore, the committee draft of electro-optical measuring methods of laser modules is also discussed in IEC TC110 PT 62595.

The above activity in IEC TC110 are based on remarkable academic works on monochromatic and color speckles [1-5].

The goal of this work is to establish more advanced measurement methods of monochromatic and color speckles for the RGB laser modules. Their output from fibers, waveguides, lightguides, or even laser beam itself, has a specific field pattern (a.k.a., "projected speckle", or "far field pattern (FFP)").

We can analyze such a mixed-up measured data as they are. However, speckle contrast, C_s must be determined by statistically calculating the measured data obtained in a relatively large projection area on a homogenous background. The C_s measurement method by eliminating such FFP background was proposed in our previous work [4]. This method uses a little tricky statistical post-process for picking up a smoothed background field profile by averaging local area data.

In this work, we propose an advanced method for obtaining speckle contrast C_s and color speckle distribution more easily and precisely.

2. Measurement setup

The measurement setup layout is shown in Fig.1. A standard diffusive screen (Diffuse Reflectance Target, SRT-99-120 by Lasphere Inc.) was used. Speckle measurement equipment SM01VS11 with a color speckle display function was provided by Oxide

Corporation [2]. A compact RGB laser module with a single mode fiber output was provided by Shimadzu Corporation [6].

The distance between the screen and the fiber-output, L was 810mm, and the distance between the screen and the speckle measurement equipment, D was 760mm. The observing angle between the laser beam, θ was 9.1° .

The basic module performance such as RGB wavelengths, irradiance/illuminance and so on was measured precisely using an RGB laser meter, TM6102 which is particularly designed for measuring narrow spectral linewidth by HIOKI E.E. CORPORATIN [7].

Fig. 1. Measurement setup.

3. Results

The measured results of the basic module performance are listed in Table 1. The fiber-output was set near the light receiving aperture of the RGB laser meter.

Table 1. Basic module performance

	B	G	R
$\lambda(\text{nm})$	455.7	520.3	636.9
Power ratio	0.260	0.278	0.462
White chromaticity	x		y
	0.3003		0.2740

The captured color speckle data (512×512) of the FFP projected on the screen is shown in Fig.2. The colored image (upper left) was obtained by post-processing the 2D data. The actual data plot along the horizontal center

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line is also shown (lower left). The un-speckled image (upper right) and the un-speckled horizontal plot (lower right) were obtained by widely opening the aperture of the speckle measurement equipment. By opening the aperture, speckle grains become smaller un-noticeably to human eyes. That is, the un-speckled data which are almost equivalent to the background FFP can be easily obtained.

Fig. 2. Measured color speckle data (upper: colored images, lower: line-plot, left: speckled, right: un-speckled)

The monochromatic and photometric speckle contrast, C_s and C_{ps} must be measured in a homogeneous background area. Therefore, the speckled data are divided by the un-speckled data for converting the FFP background to the homogeneous one. The result of the homogenized conversion is shown in Fig.3. The obtained values of C_s for the RGB colors and C_{ps} for the white are listed in Table 2

Fig. 3. Homogenized background speckle (right).

Table 2. Measured of C_s and C_{ps}

C_s			C_{ps}
B	G	R	W
0.247	0.224	0.229	0,173

The center area of the FFP is reddish and the periphery is bluish due to wavelength dependence of the fiber NA. The color speckle distributions in the chromaticity diagram are shown in Fig.4 (left: FFP background, right: homogenized). The spreading toward red obviously shrinks after homogenized conversion.

Fig. 4. Color speckle distributions in CIE 1931 chromaticity diagram (left: measured data on FFP, right: homogenized)

4. Summary

Color speckle of the white laser beam of a single mode fiber output of an RGB laser module is measured. Speckle contrast and photometric speckle contrast, C_s , C_{ps} etc. can be successfully obtained by conversion into a homogeneous background using the un-speckled data.

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A Study of the Angular Dependence of Chromaticity and Illuminance for Ultra Short Throw Laser Projectors

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Abstract: The photometric and colorimetric evaluation of ultra short throw laser projectors is vitally important. Since the light from them enters optical meters with a large angle, the angular dependence of optical meters plays a significant role. We developed RGB laser meters and confirmed they have a proper angular dependence.

1. Introduction

In recent years, an increasing number of displays have been adopting lasers to benefit from their high color reproducibility, enhanced energy efficiency, and small size [1]. One rapidly growing application is ultra short throw laser projectors, which also function as a television (TV), because lasers can allow high brightness and a big display. As ultra short throw laser projectors are becoming popular, the demand for accurate measurement of their chromaticity and photometric quantity is also rising. In our previous study, we reported XYZ-filter illuminance color meters, which have been widely used to test the two parameters of displays in production lines so far, are not accurate enough for laser displays, and our RGB laser meter is a better fit for the optical evaluation of laser displays because of its new measurement method named the Discrete Centroid Wavelength Method [2]. In addition, ultra short throw laser projectors are positioned very close to a screen, and the incident angle of the light to optical meters are very large as shown in Fig.1. Therefore, the incident angle dependence of optical meters plays an important role for accurate measurement. In order to achieve a proper evaluation of ultra short throw laser projectors, the RGB laser meter is designed to have an ideal angular dependence by putting a diffusional optical system ahead of photo sensors. We experimentally tested its incident angle dependence and confirmed the RGB laser meter has no problem with the measurement of ultra short throw laser projectors.

Fig.1 Incident Angle of the light from projectors

2. Diffusion Optical System

Figure 2 shows a schematic diagram of a typical optical structure in illuminance color meters. Because of their

reasonable price, their optical system usually has only one diffuser before the sensors.

Fig.2 A Schematic Description of Incident Angle Dependence of an Illuminance Color Meter

In this case, the ratio of light intensity detected by each sensor is different between vertical incidence (the left illustration in Fig.2) and oblique incidence (the middle illustration in Fig.2) because the incident light is not fully diffused or mixed with the diffuser. As a result, the chromaticity value largely depends on the incident angle. In the same way, the ratio also changes when the illuminance color meter is rotated (the right illustration in Fig.2), which means the measurement results depend on how the illuminance color meters are set on the screen.

Fig.3 A Schematic Description of Incident Angle Dependence of the RGB laser meter

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As shown in Fig.3, the RGB laser meter has an integrating sphere behind a diffuser. The incident light is fully diffused and mixed in the integrating sphere, and the ratio of light intensity detected by each sensor remains unchanged regardless of the incident angle or how it is set on the screen. In short, the chromaticity value measured by the RGB laser meter is not affected by the incident angle or the direction of installation on the screen.

3. Experiment

We conducted an experiment where the chromaticity and photometric quantity of RGB lasers was measured at different incident angles to the RGB laser meter as shown in Fig.4. In this experiment, three lasers (red, green and blue) were mixed in a bundle fiber, and irradiated to the RGB laser meter. It was set on a rotation stage, and the stage rotated at 5-degree interval. The chromaticity and photometric quantity at each angle were recorded. This experiment was done in two different setups as shown in Fig.5.

Fig.4 A Schematic Description of the Experiment for the Incident Angle Dependence of the RGB laser meter

Fig.5 Two Directions of installation of the RGB laser meter in the Experiment

4. Results

We calculated the variation of chromaticity value x and y using the results measured under vertical incidence as a reference and found that its incident angle dependence is smaller than 0.0030 at 80 degrees in both setups as shown in Fig.6.

Fig.6 The Incident Angle Dependence of the RGB laser meter in Chromaticity from -80 to 80 degrees

As for illuminance, since the effective light detection area of the RGB laser meter decreases in accordance with the cosine law, Illuminance should also follow the cosine law. Figure 7 shows that the measured illuminance is consistent with the cosine law and it is comparable to the JIS precision class stipulated in JIS C 1609-1.

Fig.7 The Incident Angle Dependence of the RGB laser meter in Illuminance from -80 to 80 degrees

5. Conclusion

The incident light from an ultra short throw laser projector to an optical meter has a large angle. We created a diffusional optical system in our RGB laser meter using an integrating sphere in order to achieve an ideal angular dependence. Its angular dependence has been experimentally proved to be good enough to measure the chromaticity and illuminance of ultra short throw laser projectors.

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Uniformity of Visual Resolution of Raster-Scan RGB Laser Projector Considering Color Speckle

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Abstract: Visual resolution of a raster-scan RGB laser projector was measured. Color speckle effects were clearly examined using a new comparison method with un-speckled measurement. Uniformity of speckle contrast and the resolution on the projected plane were also investigated. Different results were obviously observed between the center and the both sides.

1. Introduction

Laser displays using laser light sources are beginning to spread. There are two types of laser displays: a full frame type that projects a surface and a scanning type that scans an irradiation beam. Since the scanning type is low power, small size and light weight, it is expected to be widely used as a mobile application in the future. Therefore, it is necessary to establish measurement items and measurement methods for evaluating the image quality of the scanning laser display.

As the image quality evaluation items, illuminance, chromaticity, and resolution are cited, and it is particularly important to evaluate in-plane uniformity. Because of the scanning method of the irradiation beam, the change of the scanning speed influences the image quality. The left and right ends where the beam folds are affected because the scanning speed is slower than the center of the screen.

Moreover, chromaticity and resolution are considered to be affected by speckle noise peculiar to the laser.

The degree of speckle can be expressed by speckle contrast C_s , and it is necessary to evaluate in-plane uniformity as well as illuminance, chromaticity, and resolution. If the speckle state is not uniform, the graininess of the speckle pattern also becomes non-uniform, and it is predicted that the resolution will change.

It is predicted that chromaticity will also change due to color speckles with overlapping speckles of each wavelength.

Therefore, in-plane uniformity of the speckle state is also important as an item of image quality evaluation.

2. Measurement setup

The measurement setup layout is shown in Fig. 1. A standard diffusive screen (Diffuse Reflectance Target, SRT-99-120 by Lasphere Inc.) was used. Speckle measurement equipment SM01VS11 was provided by OXIDE Corporation. A raster-scan type laser mobile projection display was used.

The distance between the screen and DUT, L was 390mm, and the distance between the speckle measurement equipment, D was 710mm. The observing angle θ was 20.6° .

The performance such as RGB wavelengths, irradiance/illuminance etc. was measured precisely using an RGB laser meter, TM6102 particularly designed for measuring narrow spectral linewidth by HIOKI E.E. Corporation.

A nine-point resolution measurement pattern is shown in Fig. 2, and a nine-point speckle measurement pattern is shown in Fig. 3.

Fig. 1. Measurement setup (resolution & speckle)

Fig. 2. Resolution measurement pattern (9 points)

Fig. 3. Speckle measurement pattern (9 points)

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3. Results

Fig. 4 shows the comparison Image of the resolution with and without the speckle pattern. The presence or absence of speckle is controlled by the presence or absence of pinholes. When the speckle pattern overlap, the outline of the image is blurred and the resolution is slightly lowered. The graph of Fig. 4 is the illuminance distribution of the image, and it shows the influence of speckle on resolution well.

Fig. 4. Comparison of resolution with / non speckle (Graph: illuminance distribution)

Fig. 5 is the comparison of the resolution in horizontal direction, and the speckle pattern is superimposed on the image. When comparing the left, middle, and right of the nine-points on the resolution chart, there is not much difference in resolution. On the other hand, there is clear difference in the narrowest line-pair marked in red. This is presumed to be a problem of the light control system corresponding to the scanning speed, not due to the influence of speckle. Around the both sides of the nine patterns, scanning speed becomes slow and the irradiation time becomes long. It seems to be caused by control to correct illuminance change.

Fig. 5. Comparison of resolution in horizontal direction

Fig. 6 is the comparison of C_s of nine-points on the screen. There is hardly any difference in the vertical direction, whereas C_s at both ends in horizontal direction, which is the scanning direction, is larger than at center. This is considered to be caused by the change in the scanning speed, and details will be validated in future.

Fig. 6. Comparison of speckle contrast in nine-point

4. Conclusion

Speckle contrast and the resolution are found to be different between the center and the both sides.

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Challenge to Estimate the Equivalent Measurement Conditions of Speckle Contrast

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Abstract: Various measurement conditions of speckle contrast were analysed in terms of the equivalent area of the amplitude point-spread function of the imaging system on the screen. The results shows the possibility to achieve the equivalent measurement conditions among different measurement distance, f-number and focal length of imaging lens.

1. Introduction

The perception of speckle with green or red laser is significant, thus the importance of the accurate speckle measurement methods is much higher in the field of electronic displays and lighting, to estimate the influence to the human. Speckle contrast varies according to the measurement distance and other measurement variables. If there is an equivalent measurement condition among the different measurement parameter sets, it will be able to increase the freedom of choice, e.g. measurement distance, f-number and focal length of the imaging lens. In this report, various measurement conditions were analysed in terms of the equivalent area of the amplitude point-spread function of the imaging system (resolution element) on the screen, and the averaging effect of speckle contrast by the sensor pixel size.

2. Theory

2.1 Averaging effect in unsuppressed speckle

In case of unsuppressed speckle [1], which means highly coherent state, speckle contrast does not depends on the aperture angle (angle from the imaging aperture to the screen). This is because the coherent area of the illumination system is so large. However, the average speckle size R is dependent on the f-number of the imaging system [2], which can be written as,

$$R = \frac{4}{\pi} F\#_{\text{image}} \lambda \quad (1)$$

where, $F\#_{\text{image}}$ is an effective f-number of the imaging lens, λ is wavelength of the laser. The speckle pattern is integrated over some finite area of detector element. This is called "integrated speckle" [3], and the mathematical formula was described as

$$C_s = 1 / \sqrt{M} \quad (2)$$

$$M = \left(\sqrt{\frac{A_c}{A_m}} \operatorname{erf} \left(\sqrt{\frac{\pi A_m}{A_c}} \right) - \left(\frac{A_c}{\pi A_m} \right) \left[1 - \exp \left(-\frac{\pi A_m}{A_c} \right) \right] \right)^{-2} \quad (3)$$

where, C_s is speckle contrast, M is integration parameter, A_c is the coherent area on the sensor (equivalent to R), A_m is the size of square, uniform detector element, and $\operatorname{erf}(x)$ is a standard error function. So, in this case, only the averaging effect on the detector elements is dominant for the imaging condition of speckle contrast.

2.2 Averaging effect in suppressed speckle

In case of suppressed speckle [1], e.g. by using moving diffuser, the averaging effect of speckle pattern from the different coherent area occurs. Speckle contrast C_s is,

$$C_s \propto \sqrt{\frac{1}{K}} \propto \frac{NA_{\text{image}}}{NA_{\text{illumination}}} \quad (4)$$

where K is the factor of spatial diversity, NA_{image} and $NA_{\text{illumination}}$ is numerical aperture of both illumination and imaging system against the screen. The averaging effect by the integrated speckle occurs at the same time. To find out the equivalent measurement condition, now we focus on the resolution element of imaging system, which is interpreted as the average speckle grain (close to the airy disc) projected on the screen through the imaging system. Since the speckle contrast depends on the incoherent phasor within the resolution element, it is important to select each parameters so as to keep the same resolution element size. The diameter of resolution element S can be expressed as (5), with using equation (1) and magnification of imaging system; m ,

$$S = \frac{R}{m} \propto \frac{F\#_{\text{image}}}{m} = F\#_{\text{screen}} \quad (5)$$

where $F\#_{\text{screen}}$ is the f-number of the imaging lens on the screen side, i.e. it represents the aperture angle. The other expression of (5) is

$$S = \frac{R}{m} \propto \frac{F\#_{\text{image}}}{m} = F\#_{\text{image}} \frac{L}{f} \quad (6)$$

where L is a measurement distance, and f is an effective focal length of imaging lens.

3. Experiments

3.1 Measurement of unsuppressed speckle

The measurement setup is shown in Fig.1.

Fig.1. Measurement configuration of speckle contrast under unsuppressed speckle condition.

To achieve highly coherent illumination, He-Ne laser of 543.5nm was used. The beam was passed through the spatial filter, and illuminated the diffuse reflectance target, SRT-99-050 (Labsphere, Inc.). The measurement

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distance was fixed at 0.4m. The imaging f-number was changed from 3.2 to 42. Speckle contrast measurement system (SM01VS09, Oxide corporation) with the CCD pixel size of 6.45 μ m was used.

As shown in Fig. 2, measured speckle contrast was fit well with the calculated results. The both measured speckle contrast were normalized at the f-number of 42. The measured speckle contrast was 0.92 at the f-number 42. It was verified that only the integration effect on the detector occur under the unsuppressed speckle condition.

Fig.2. The effect of integrated speckle on the unsuppressed speckle contrast measurement.

3.2 Measurement of suppressed speckle

Fig.3. Measurement setup and parameters for the suppressed speckle condition

Setup for suppressed speckle contrast measurement is shown in Fig.3(a). SHG laser (wavelength 533 nm) illuminated the rotating diffuser, making a spot about 1 cm diameter at 1.2m away from the diffuse reflectance target. The first trial was to change the f-number of imaging lens and the measurement distance, holding the aperture angle according to equation (6). Parameters are shown in Fig. 3 (b). Same measurement system was used.

Fig.4. The effect of integrated speckle on the suppressed speckle contrast measurement.

The results are shown in Fig. 4. Measured speckle contrast was 0.11 at the f-number 42, and it was normalized same as 3.2. Thus, it could be concluded that as long as the aperture angle was kept same, same speckle contrast can be reproduced by the appropriate combination of the f-number and the measurement distance, while the effect of integrated speckle still should be considered carefully to compare the results among the different conditions.

The second trial was to change imaging lens with different focal length. In this measurement, the different imaging camera, of which CCD pixel size was 9 μ m was used. The focal length of the imaging lenses were 35mm and 50mm. According to the equation (6), the measurement distance was set at 0.42m for the 35mm lens, and 0.62m for the 50mm lens. The measurement configurations were same as Fig.3.

Fig.5. The speckle contrast under the equivalent conditions.

The results were shown in Fig. 5. Even if the measurement conditions were different, the each speckle contrast curve was almost same. In this case, the contribution of the integrated speckle on the speckle contrast was same at the same f-number, so the results could be comparable through the whole range of f-number.

4. Conclusion

The equivalent, exchangeable measurement conditions of speckle contrast were investigated with considering the size of the resolution element of the imaging lens on the screen. Indeed there was some limitation caused by the finite detector size (integrated speckle), it could be useful when the focal length of the imaging lens is changed.

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Speckle Reduction in Laser Projector

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Abstract: Speckle is one of the most serious problems of laser projectors. To suppress speckle, the combinations of angular diversity, wavelength diversity and polarization diversity are widely used. In this paper, speckle reduction effect by these speckle reduction methods is investigated on matte and silver screens.

1. Introduction

Recently, laser projectors have been rapidly developed along with the development of visible laser diodes. Because of the coherence property of lasers, laser projectors suffer from the image deterioration due to speckle, which is interference patterns created on the viewer's retina. The most popularly used methods to suppress speckle include angular diversity, wavelength diversity and polarization diversity. In order to suppress speckle to the acceptable level, combinations of some or all of these speckle reduction methods are used.

There are various methods to change each of angular, wavelength, and polarization diversity in a projector. In this paper, we investigated the speckle reduction effect by angular, wavelength, and polarization diversity achieved by various methods. Angular diversity was changed by changing the angular distribution of incident light or speckle measurement condition. Wavelength diversity was changed by changing the spectral width of a light source with broad spectrum or changing the number of wavelengths. Polarization diversity was achieved by using the polarization state of the incident light or the depolarization on screen.

2. Speckle reduction by angular diversity

According to Goodman [1], speckle reduction by angular diversity can be written as:

$$C = 1/\sqrt{MK/(M + K \pm 1)}, \quad (1)$$

where M is the temporal diversity, K is the spatial diversity, $+$ and $-$ signs are chosen depending on the condition of the illumination light. The M value can be changed by using a moving diffuser [2], using a multimode fiber [3], or increasing the number of independent lasers. In the case of cinema projectors, it is often the case that M is much larger than K because of the use of moving diffusers or large number of independent lasers. In that case, the speckle contrast is approximated as $C \approx \sqrt{1/K}$.

The K value depends on Ω_p and Ω_d , which are the solid angles subtended on the screen by the illuminated area of the projection lens and the camera aperture for speckle measurement, respectively. Therefore, we changed both Ω_p and Ω_d to change angular diversity and compared the

results. It was confirmed that the speckle contrast depends on the ratio of Ω_p and Ω_d .

3. Speckle reduction by wavelength diversity

One way to reduce speckle by wavelength diversity is using light source with multiple wavelengths [4,5]. By using lasers with N different wavelengths, speckle can be reduced by a factor of $\sqrt{N}$ when the wavelength interval is large enough. When the wavelength interval is not large enough, a factor of speckle reduction becomes less than $\sqrt{N}$. The wavelength interval required to reduce speckle depends on various parameters, such as effective surface roughness of screen, illumination condition and measuring condition [5].

Another way to reduce speckle by wavelength diversity is using a light source with broad spectrum [1]. In the same way as the speckle reduction by multiple wavelengths light source, speckle reduction by using a light source with broad spectrum depends on the illumination and measuring conditions, and screen characteristics.

In order to compare the speckle reduction by using multiple wavelength light source and light source with broad spectrum, we measured the speckle contrast of multiple wavelength lasers and Xe lamp with bandpass filters using the same DLP projector on matte and silver screens. Fig. 1 shows the schematic diagram of a Xe lamp projector and a laser projector. To measure the speckle reduction by light source with broad spectrum, the spectral width of Xe lamp was narrowed from 86 nm to 13 nm using bandpass filters as shown in Fig. 2. The same DLP projector was used to measure the speckle reduction by multiple wavelength lasers. Instead of Xe lamp, 1-5 lasers with wavelength interval of about 6 nm were used. In addition, a rod integrator and a ground glass diffuser were inserted in the projector.

Fig. 3 shows the measured speckle contrast on matte and silver screens. On silver screen, the speckle contrasts of lasers and Xe lamp were nearly the same when the spectral width was the same. On matte screen, the speckle contrast of lamp was smaller than that of lasers. The difference between matte and silver screens comes from the effective surface roughness of screen. Since the effective surface roughness of matte screen is larger than

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that of silver screen, wavelength interval needed to reduce speckle is smaller for matte screen [5]. Thus, 6 nm interval was not large enough for matte screen and the speckle contrast of lasers was larger than that of Xe lamp.

(a)

Fig. 1. Schematic diagram of (a) a Xe lamp projector and (b) a laser projector. The same DLP projector was used in both cases. When using lasers, a rod integrator and a ground glass diffuser were inserted in the projector instead of Xe lamp.

Fig. 2. Spectra of Xe lamp with various bandpass filters.

Fig. 3. Speckle contrast of lasers and Xe lamp on matte and silver screens.

4. Speckle reduction by polarization diversity

Speckle reduction effect by polarization diversity depends on the polarization state of the incident light and the depolarization on screen [1,6]. When the incident light is polarized and depolarization occurs upon scattering on

screen, the resulting speckle patterns become the sum of two independent speckle patterns and speckle is reduced by a factor of $\sqrt{2}$. In addition, if the incident light is unpolarized or the sum of orthogonal polarization states, each of two polarization states results in two independent speckle patterns. As a result, there are four independent speckle patterns and the speckle reduction factor becomes 2, instead of $\sqrt{2}$.

Here, we investigated the speckle reduction effect by polarization diversity on matte and silver screens. On matte screen, speckle reduction due to both polarization state of the illumination light and depolarization on screen was confirmed. On the other hand, on silver screen, there was no speckle reduction by polarization diversity.

5. Conclusions

In this paper, the effect of speckle reduction by angular diversity, wavelength diversity, and polarization diversity was discussed.

Angular diversity was changed by changing both the solid angle Ω_p subtended by the illuminated area of projection lens and the solid angle Ω_d subtended by the camera aperture. It was confirmed that the speckle reduction by angular diversity depends on the ratio of Ω_p and Ω_d .

Wavelength diversity was achieved by using multiple wavelength lasers or Xe lamp with bandpass filters. The speckle reduction effect by multiple wavelength lasers and Xe lamp were compared. On silver screen, the speckle contrasts of lasers and Xe lamp were nearly the same when the spectral width was the same. On matte screen, the speckle contrast of lamp was smaller than that of lasers.

The speckle reduction by polarization diversity was investigated on matte and silver screen. On matte screen, speckle was reduced due to both polarization state of the illumination light and depolarization on screen. On the other hand, on silver screen, there was no speckle reduction by polarization diversity.

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Applicability of CIELAB Volume Metric to the Latest Electronic Displays

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Abstract: We evaluated the colour performance of the latest self-emissive displays based on the CIELAB colour volume metric. The white reference point was set at (1) white with a 25% window, (2) absolute value, (3) white with a 100% window. None of the reference whites resulted perfectly satisfactorily on its own, but the combination of these results was reasonable. The CIELAB volume metric with the appropriate normalization can be a great tool for evaluating the latest self-emissive display.

1. Introduction

In CIE168, there is a section that denotes that CRT displays can be evaluated by CIELAB gamut volume (CGV) [1]. In ISO 11664-4, there is a part that says that CIELAB is usable if the value is appropriately normalized [2]. Nowadays, display luminance is very high, and equipped with boosting function. Is CIELAB applicable to the latest electronic display? What is the appropriate normalization? We investigated these issues.

2. Subjective evaluation

We conducted subjective experiments. As the latest display, we picked up display with white boosting and that with WRGB boosting.

2.1 Displays with white boosting

We picked up (1) Display A without white boosting and (2) B with white boosting (Table 1). Total luminance of RGB was the same (670 cd/m²), but the white luminance of B (1060cd/m²) is much higher than A (680cd/m²). We asked the subjects to give scores; very bad, bad, good, very good. Display B with white boosting had the higher score in both of the cases that displays were shown next to each other and was shown alone (Fig. 1).

2.2 Display with white RGB boosting

Figure 2 shows the performance of displays we used. The x axis shows the APL (white window ratio), and the y-axis shows the luminance of white. We compared three types of displays; C: white luminance is high and does not depend on APL, D: white luminance is low and does not depend on APL, E: white luminance depends on APL and the luminance is high with low APL and the same as that of display C and the luminance is low with high APL and the same as that of display D. We located two of three displays side by side. We asked the subjects; which is apparently better (+2), better (+1), worse (-1), apparently worse (-2). Figure 3 shows the result. Display E was a little better than high luminance display C and much better than low luminance display D.

2.3 Results

The subjective results clarified; 1) Display with higher luminance is better, 2) Display with white boosting is better, 3) Display with WRGB boosting is better.

Table 1 Displays for subjective experiment.

	Total luminance of RGB	White luminance
Projector A without boosting	670 cd/m ²	680 cd/m ²
Projector B with white boosting	670 cd/m ²	1060 cd/m ²

Fig. 1 Subjective experiment for displays with/without white boosting

Fig. 2 Luminance dependence on white window size of displays.

Fig. 3 Subjective experiment for displays with various luminance and WRGB boosting.

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3. CIELAB

Figure 4 shows the situation when displays with different white luminance and the same pure red (B1-B4) are displayed next to each other. The higher the luminance of the display is, the more colorful the displayed red is. The red color with high luminance looks red (B1 in Fig. 4), but that with lower luminance looks almost dark brown instead of red (B4 in Fig. 4). Figure 5 shows the red color with several luminances and chromaticity coordinates. Display B1 in Fig. 4 has the larger volume (Blue area in Fig. 5) than B3 (green area in Fig. 5). CIELAB shows that the color with lower lightness is less colorful. CIELAB seems very effective and powerful.

Fig. 4 Displays with different peak luminance.

Fig. 5 Cross-section view of CIELAB volume.

4. Color Gamut Volume with several normalization white level for some typical virtual displays

Figure 6 shows the characteristics of virtual displays for evaluation. We prepared basic displays with different luminance (B1 – B4), display with white boosting (C), and displays with WRGB boosting (D1, D2). We adopted the same typical color coordinates for them. Figure 7 shows the calculated Color Gamut Volume (CGV). If the white peak of 25% window is adopted, only type C has the inferior point. This seems unreasonable. If the absolute value of 1000cd/m² is adopted, the points for the displays are almost satisfactory. However, the score for D1 is the same as that for B1. This is different from the subjective experimental result (D1 should be better than B1). If the full-screen white is adopted as the reference white, the point for D1 is raised up. However, in this case, display D2 has the maximum point because it has especially low full-screen white compared to 25% screen white. This also seems unreasonable.

Any white reference does not seem reasonable to utilize solely. We tried to have a weighted average value. We first set the weighted average as $CGV(4) = (CGV(1) \times N1 + CGV(2) \times N2 + CGV(3) \times N3) / (N1 + N2 + N3)$
 CGV(1): Reference at peak white with 25% window
 CGV(2): Reference at 1000cd/m²
 CGV(3): Reference at peak white with 100% window
 Considering the result in section 2.3, the volume for C should be better than that for B3 and D1 should be better than B1. We set N1 =0, N2=7, and N3=1 initially (Fig. 7). We realized that the calculated CGV(4) matches the subjective evaluation result.

5. Conclusion

The result with sole reference white was not perfectly satisfactory. The combination of the results with several white references gave a reasonable one. CIELAB volume metric with the appropriate normalization can be a great tool for evaluating the latest self-emissive display

Fig. 6 Several artificial displays with different luminance without boosting (B1-4), white boosting (C), WRGB boosting (D1, 2)

Fig. 7 Color gamut volume of displays with various normalization white reference.

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Color Speckle Measurement for RGB Laser Displays Based on the Current Speckle Contrast Measurement Instrument

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Abstract: Color speckle measurement system is constructed from the current measurement instrument. RGB filters are included in the instrument and the algorithm based on the international standard is introduced in its dedicated measurement software to calculate color speckles. One of laser displays was measured using this improved instrument.

1. Introduction

In recent years, the study of speckle has been advanced for practical use in laser displays. Quantitative measurement and reduction of speckle are major issues. Since the speckle is the interference pattern of scattered laser light formed on a human eye retina, it is essential to construct an optical system to simulate the human eye. We have already established a measurement method of speckle contrast and released some commercial measurement instruments in which the MTF of camera is optimized to approximate the human eye using an attached pinhole [1]. This method was subsequently published as the international standard of Ref.[2] in 2016.

A new method called “color speckle measurement” is attracting a great deal of attention. The overlaid RGB speckle pattern is seen as tiny separate spots with various colors shown in Fig. 1, because the speckle pattern generated by RGB lasers is spatially uncorrelated with each other. Therefore, the speckle of white has a spread around the white point on the chromaticity diagram.

The color speckle theory was introduced by Kuroda et al. [3]. After that, two actual measurement methods were verified in SID 2016. The first method directly measured the color speckle using a 2-D colorimetric luminance meter including XYZ filters with attached the pinhole [4]. The second calculated the color speckle from the monochromatic speckle spatial distribution patterns measured in each color using the above speckle contrast measurement instrument [5]. Both results were compared with the color speckle simulated by using the measured speckle contrasts and well matched with the simulated results. These methods were published as the international standard in Ref.[6] in 2018.

Based on the second method, the color speckle measurement system is constructed by modifying the current instrument. The improved system and its measurement results on an RGB laser display are reported.

Fig.1. Color speckle photograph (laser TV).

Fig.2. Measurement unit. (a) Color filter wheel (without the front panel), (b) Internal structure.

2. Modification of measurement instrument

The speckle contrast measurement instrument model SM01VS09 of Oxide Corporation is modified. A color filter wheel with red, green and blue dielectric multilayer filters is built in the measurement unit shown in Fig.2.

The wheel on a motor is controlled by the dedicated measurement software installed on a PC. The software gives instructions of the measurement unit to capture each monochromatic speckle distribution pattern in the order of red, green and blue. It calculates the relative CIE tristimulus values X , Y , Z in each pixel of camera from the monochromatic distributions and the measurement conditions (the RGB wavelengths and the chromaticity coordinates of white point) and calculates the CIE 1976 chromaticity coordinates u' , v' given by $u' = 4X/(X+15Y+3Z)$ and $v' = 9Y/(X+15Y+3Z)$ [6]. It can plot the color speckle on the chromaticity diagram and calculate the standard deviations and the covariance of u' , v' . It can also calculate a photometric speckle contrast which is equivalent to a speckle contrast of white measured by a Y -filtered imager.

Fig.3. Color speckle measurement configuration.

3. Experimental Method

Figure 3 shows the configuration in which the pinhole diameter was fixed at 1.2 mm. We measured a full-frame projection laser TV (rear-projection type) model 75-LT1 of Mitsubishi Electric Corporation. The projection image was a uniform circle of white. The measurement conditions were set using a spectroradiometer model SR-UL1R of Topcon Technohouse Corporation.

4. Results

Figure 4 shows the measured color speckle which plots the 300×300 pixel data. For comparison, the simulated color speckle using the measured speckle contrast values is shown in Fig.5. From these results, the calculated standard deviation $\sigma(u')$, $\sigma(v')$, the covariance $\mu(u', v')$ and the photometric speckle contrast C_{PS} are summarized in Table 1, where a correlation coefficient $\rho(u', v') = \mu(u', v') / \{\sigma(u') \cdot \sigma(v')\}$ is shown instead of $\mu(u', v')$. Although the shape defined by the color speckle varies slightly, the values in Table 1 are well matched with the error of 3% or less.

Fig.4. Measured color speckle of the laser TV.

Fig.5. Simulated color speckle of the laser TV. The speckle contrasts are 0.075, 0.065 and 0.028 measured in red, green and blue, respectively.

Table 1. Values of the laser TV.

	Measured	Simulated	Δ
$\sigma(u')$	0.0069	0.0068	1.7%
$\sigma(v')$	0.0064	0.0063	1.3%
$\rho(u', v')$	- 0.539	- 0.556	3.0%
C_{PS}	0.054	0.053	1.9%

5. Discussions

We have tried to display the color speckle photograph. At first, we attempted to synthesize the normalized monochromatic speckle distributions in proportion to the RGB power ratio, but the photograph was bluish overall. According to Ref.[7], it is necessary to calculate colors on the display using the XYZ - RGB conversion method which consists of the 3×3 transformation matrix and the gamma correction formula. Figure 1 shows the photograph of white image with a text of “Speckle” projected by the laser TV, in which the digital values of RGB is calculated from the relative tristimulus values X, Y, Z using this method. This pseudo color photograph helps us to explain the degree of color speckle.

6. Conclusions

The color speckle measurement system is constructed from the current speckle contrast measurement system. The laser TV, which is one of laser displays, was measured and well matched with the simulated results. We hope that this instrument is useful for evaluating the color speckle of various laser displays.

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Colour capability measurements of laser displays

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Abstract: Colour additivity and gamut volume of direct-emitting RGB and blue laser-pumped phosphor displays were measured as functions of input grey value and sample size, respectively. Correlation between chromaticity area and colour gamut volume could not be found, but measurements of the latter were shown to be both fast and accurate.

1. Introduction

Lasers are attractive light sources for displays because of their large electro-optic conversion efficiency and narrow emission linewidth, which ensures high colour saturation. An LCD with a diffusive RGB laser backlight unit (BLU) has already been demonstrated [1], but the large polarization contrast and collimation make lasers suitable also for patterned diffractive BLUs [2] that can increase the LCD's optical efficiency 10-fold. So far, RGB lasers have been deployed commercially in front- and rear projection, near-eye, and head-up displays. Another class of laser displays uses blue light-emitting lasers to optically pump yellow and optionally green phosphors, from which red and green are generated by filters.

Field-sequential colour (FSC) laser displays render the primary RGB colour planes rapidly in a sequence, thus making the colours fuse temporally in the human visual system. By combining the RGB laser outputs in *each* colour field (or subfield) it is possible to tune the chromaticities and adaptively trade colour saturation for higher luminance [3]. This can be used to maximise the luminous efficacy of slow LCD FSC devices by shortening and aligning the laser pulses to the end of each colour field where transmission is highest. A drawback of this approach, however, is that saturated primary colours (RGB) become dimmer due to the shorter duty. This trade-off is similar to white light-illuminated RGB displays with *degenerate* white subfields or subpixels [4].

Some blue laser-pumped phosphor FSC displays have an extra yellow field, the chromaticity of which can lie either inside or outside the triangle defined by the RGB primary colours. In the former case, the yellow is *degenerate* because 1) it is derived from the orthogonal RGB input and 2) it can be rendered solely by the RGB emitters. In the latter case, the *non-degenerate* yellow is more saturated and therefore helpful for compensating the shift in white point caused by the highly saturated blue pump laser. However, neither the blue nor the yellow has any representation in the input RGB colour space so expanding the RGB gamut along the blue-yellow axis will compromise colour fidelity.

Displays with additional, non-RGB emitters are sometimes referred to as “multi-primary” displays but this term is incorrect since the only primaries of additive colour are RGB. A better term is “multi-chromatic”. Adding these extra colours inevitably reduces the RGB output since their fraction of the frame time (FSC) or pixel area decreases. While the luminance of unsaturated

colours can be boosted by adding white or yellow, images with saturated colours appear dimmer compared to RGB-only displays. This trade-off can be expressed by the simple metrics of colour- and white light output,

$$CLO/WLO = (Y_R + Y_G + Y_B) / Y_W \quad (1)$$

where Y_x is the luminance at input colour x . Since (1) is neither a colour capability nor a fidelity metric, and because the trade-off is not evident from the uncoupled white luminance and chromaticity area metrics, CIE $L^*a^*b^*$ colour gamut volume (CGV) was proposed and its measurement feasibility was verified [5] for various display technologies, but not for RGB laser displays.

This study reports CGV of three commercial laser displays under test (DUT); A) RGB FSC, B) raster-scanning RGB, and C) blue laser-pumped RGBY FSC.

2. Experimental setup

A spectroradiometer generally provides the best accuracy but it is in many cases too slow for CGV measurements. The colorimeter used in this study (Konica Minolta CA-VP427) had previously [5] been calibrated [6] for displays A and C against a spectroradiometer (Konica Minolta CS-2000). Displays A and B were additionally measured with an RGB laser luminance meter (Hioki TM6103, [7]) using the same diffuser and test images as [5]. Its lower sensitivity required the projected image height to be reduced from 1 to 0.3 m. Due to the non-Lambertian diffuser, the absolute luminance did not agree between the two instruments but, since CGV is based on adaptation to display white, this is not a problem. Prior to the experiments, the absence of luminance dependence on average pixel level (APL) was confirmed, because it could affect the result. Display B exhibited some luminance loading for higher APLs so an APL of 4% was used throughout the measurements.

All instruments in the experiment exhibited excellent repeatability so measuring the DUTs synchronously with the vertical synchronization signal of the video source or setting the internal sampling rate to the frame rate (at six significant digits for TM6103) allowed for frame-wise averaging and hence the total measurement time could be kept short. Display B had a large optical peak power, so a neutral density (ND) filter was applied to prevent saturation of the colorimeter. The laser meter did not saturate even without ND filter.

The rule-of-thumb number of patches for *a priori* unknown CGV hulls is 602, for which the measurement

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Fig. 1. Additivity by input grey level for the three laser displays

Fig. 2. Normalized CGV as a function of number of grid points for display A and C compared to a previous study [5] of OLEDs and LCDs (display B was not measured)

took 5-10 minutes depending on the DUT and instrument. This time is much shorter compared to a spectroradiometer and can be reduced further by sorting the patches to minimize automatic gain adjustments.

3. Results and discussion

To determine the applicability of the interpolation method [8] for CGV, it is helpful to first measure the DUT additivity. Generally, each optical output channel of a modern display can depend on *all* RGB inputs via a 3D look-up table (LUT), and this LUT can change dynamically depending on the input image histogram and/or DUT operational mode. Standardising the test images and measurement methods is therefore of utmost importance.

Measuring and calculating additivity for all entries in such a general LUT is not a practical task so here the additivity a is simplified to

$$a(n) = (Y_R(n) + Y_G(n) + Y_B(n)) / Y_W(n) \quad (2)$$

where n is the input grey level, $Y_x(n)$ the measured luminance of input colour x at grey level n , and $n = n_r = n_g = n_b$. The constancy of $a(n)$ determines how the CGV should efficiently be measured and calculated.

As shown in Fig. 1, neither of the displays exhibited constant additivity so 602 patches evenly distributed on the RGB cube were used as input. The XYZ tristimulus response was measured, transformed to D50 using the

Bradford chromatic adaptation transform, and converted to CIE $L^*a^*b^*$ before calculating the absolute CGV and reference space (BT.2020) coverage. CGV convergence by number of grid points (Fig. 2) was faster for display A, but 602 grid points were used in all cases in order to compare the results. The CGV value differed between the two instruments for displays A and B by 1.9% and 3.3%, respectively.

Table 1. Colour capability in terms of ratio to BT.2020

DUT	area, xy	coverage, xy	CGV	coverage, CGV
A	110.2%	94.0%	55.6%	51.5%
B	111.2%	95.4%	111.8%	92.5%
C	58.6%	57.6%	24%	22.9%

Table 1 summarizes the results and compares with the CIE 1931 xy chromaticity area. The lack of correlation found in the previous study [5] was confirmed. Interactive 3D hull visualization and colour difference mapping of real images provide [9] further aspects of the results.

4. Conclusions

Lack of chromaticity area/CGV correlation demonstrated the necessity of a CGV metric. It was shown that high-speed, colour-filter based instruments can replace a spectroradiometer in CGV measurements of laser displays.

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