PROCEEDINGS OF SPIE

SPIDigitalLibrary.org/conference-proceedings-of-spie

Front Matter: Volume 8272

, "Front Matter: Volume 8272," Proc. SPIE 8272, Advances in Photonics of Quantum Computing, Memory, and Communication V, 827201 (15 March 2012); doi: 10.1117/12.931596

Event: SPIE OPTO, 2012, San Francisco, California, United States

PROCEEDINGS OF SPIE

Advances in Photonics of Quantum Computing, Memory, and Communication V

**Zameer U. Hasan
Philip R. Hemmer
Hwang Lee
Charles M. Santori**
Editors

**23–26 January 2012
San Francisco, California, United States**

Sponsored and Published by
SPIE

Volume 8272

Proceedings of SPIE, 0277-786X, v. 8272

SPIE is an international society advancing an interdisciplinary approach to the science and application of light.

Advances in Photonics of Quantum Computing, Memory, and Communication V,
edited by Zameer Ul Hasan, Philip R. Hemmer, Hwang Lee, Charles M. Santori, Proc. of SPIE
Vol. 8272, 827201 · © 2012 SPIE · CCC code: 0277-786X/12/\$18 · doi: 10.1117/12.931596

Proc. of SPIE Vol. 8272 827201-1

The papers included in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. The papers published in these proceedings reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from this book:

Author(s), "Title of Paper," in *Advances in Photonics of Quantum Computing, Memory, and Communication V*, edited by Zameer U. Hasan, Philip R. Hemmer, Hwang Lee, Charles M. Santori, Proceedings of SPIE Vol. 8272 (SPIE, Bellingham, WA, 2012) Article CID Number.

ISSN 0277-786X

ISBN 9780819489159

Published by

SPIE

P.O. Box 10, Bellingham, Washington 98227-0010 USA

Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445

SPIE.org

Copyright © 2012, Society of Photo-Optical Instrumentation Engineers

Copying of material in this book for internal or personal use, or for the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of copying fees. The Transactional Reporting Service base fee for this volume is \$18.00 per article (or portion thereof), which should be paid directly to the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923. Payment may also be made electronically through CCC Online at copyright.com. Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher. The CCC fee code is 0277-786X/12/\$18.00.

Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.

SPIDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon as they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B ... 0Z, followed by 10-1Z, 20-2Z, etc.

The CID number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID number.

Contents

vii Conference Committee

xi *Spinoptics: Spin degeneracy removal in nanostructures (Plenary Paper) [8269-100]*
V. Kleiner, N. Shitrit, E. Hasman, Technion-Israel Institute of Technology (Israel)

NONBLEACHING AND ULTRASMALL FLUORESCENT TAGS II: JOINT SESSION WITH CONFERENCE 8233

- 8272 05 **Exploring cytoplasmic dynamics in zebrafish yolk cells by single particle tracking of fluorescent nanodiamonds (Invited Paper) [8272-04]**
C.-C. Chang, Academia Sinica (Taiwan) and National Taiwan Univ. (Taiwan); B. Zhang, Academia Sinica (Taiwan); C.-Y. Li, C.-C. Hsieh, Academia Sinica (Taiwan) and National Taiwan Normal Univ. (Taiwan); G. Duclos, Ecole Normale Supérieure de Cachan (France); F. Treussart, Ecole Normale Supérieure de Cachan (France) and Lab. de Photonique Quantique et Moléculaire, CNRS (France); H.-C. Chang, Academia Sinica (Taiwan), National Taiwan Univ. (Taiwan), and National Taiwan Normal Univ. (Taiwan)
- 8272 06 **Use of upconverting fluorescent nanoparticles for bioimaging (Invited Paper) [8272-05]**
D. K. Chatterjee, Y. Zhang, National Univ. of Singapore (Singapore)

QUANTUM OPTICS AND SENSING WITH SPINS IN DIAMOND

- 8272 09 **Near-field coupling of a single NV center to a tapered fiber [8272-08]**
T. Schröder, Humboldt-Univ. zu Berlin (Germany); M. Fujiwara, T. Noda, H.-Q. Zhao, Hokkaido Univ. (Japan) and Osaka Univ. (Japan); A. W. Schell, G. Kewes, O. Benson, Humboldt-Univ. zu Berlin (Germany); S. Takeuchi, Hokkaido Univ. (Japan) and Osaka Univ. (Japan)

ULTRASOUND MODULATED OPTICAL TOMOGRAPHY I: JOINT SESSION WITH CONFERENCE 8223

- 8272 0E **Rare-earth-doped materials with application to optical signal processing, quantum information science, and medical imaging technology (Invited Paper) [8272-13]**
R. L. Cone, C. W. Thiel, Montana State Univ. (United States); Y. Sun, The Univ. of South Dakota (United States) and Montana State Univ. (United States); T. Böttger, Univ. of San Francisco (United States) and Montana State Univ. (United States); R. M. Macfarlane, Montana State Univ. (United States) and IBM Almaden Research Ctr. (United States)

ULTRASOUND MODULATED OPTICAL TOMOGRAPHY II: JOINT SESSION WITH CONFERENCE 8223

- 8272 0H **Organic materials for spectral hole burning and non-hole burning optical filters (Invited Paper) [8272-16]**
A. Gorokhovskiy, CUNY, College of Staten Island (United States)

QUANTUM COMPUTING WITH PHOTONS AND COHERENT EFFECTS

- 8272 0J **Realizing physical approximation of the partial transpose (Invited Paper)** [8272-18]
H.-T. Lim, Y.-S. Kim, Y.-S. Ra, Pohang Univ. of Science and Technology (Korea, Republic of);
J. Bae, Korea Institute for Advanced Study (Korea, Republic of); Y.-H. Kim, Pohang Univ. of
Science and Technology (Korea, Republic of)
- 8272 0L **Surprises in fault tolerance and cluster dynamics for quantum computing (Invited Paper)**
[8272-20]
G. Gilbert, Y. S. Weinstein, The MITRE Corp. (United States)
- 8272 0N **Coherent mixed with squeezed vacuum light interferometry: parity detection hits the
Heisenberg limit (Invited Paper)** [8272-22]
K. Seshadreesan, P. Anisimov, H. Lee, J. Dowling, Louisiana State Univ. (United States)

QUANTUM MEMORY AND OTHER QUANTUM PHENOMENA

- 8272 0P **Electromagnetically controlled storage and retrieval for pulses propagating through a line
of atoms (Invited Paper)** [8272-24]
P. M. Leung, B. C. Sanders, Univ. of Calgary (Canada)

DIAMOND NANOSTRUCTURES AND PHOTONICS

- 8272 0W **Suppression of phonon sidebands in the spectrum of nitrogen vacancy centers in diamond
nano-crystals** [8272-31]
H.-Q. Zhao, M. Fujiwara, S. Takeuchi, Hokkaido Univ. (Japan) and Osaka Univ. (Japan)
- 8272 0Y **Towards integrated optical quantum networks in diamond (Invited Paper)** [8272-33]
A. Faraon, C. M. Santori, Z. Huang, V. M. Acosta, P. E. Barclay, K.-M. C. Fu, R. G. Beausoleil,
Hewlett-Packard Labs. (United States)

QUANTUM OPTICS WITH ARTIFICIAL ATOMS IN SEMICONDUCTORS

- 8272 11 **All optical preparation, storage, and readout of a single spin in an individual quantum dot**
[8272-36]
V. Jovanov, F. Klotz, S. Kapfinger, D. Heiss, S. Spiga, D. Rudolph, M. Bichler, M. S. Brandt,
G. Abstreiter, J. J. Finley, Technische Univ. München (Germany)
- 8272 12 **Cavity-QED with quantum dots in oxide-apertured micropillars** [8272-37]
C. Bonato, J. Gudat, E. van Nieuwenburg, M. Bakker, G. Beirne, Huygens Lab., Leiden
Institute of Physics (Netherlands); S. M. Thon, Univ. of California, Santa Barbara (United
States); H. Kim, Univ. of California, Santa Barbara (United States) and Univ. of Maryland,
College Park (United States); T.-A. Truong, T. Suntrup, P. Petroff, M. van Exter,
D. Bouwmeester, Huygens Lab., Leiden Institute of Physics (Netherlands)

- 8272 13 **Optical properties of fluorine implanted ZnMgSe/ZnSe quantum-well nanostructures**
[8272-38]
Y. M. Kim, Univ. Paderborn (Germany); D. Sleiter, Stanford Univ. (United States); K. Sanaka,
Y. Yamamoto, Stanford Univ. (United States) and National Institute of Informatics (Japan);
J. Meijer, Ruhr-Univ. Bochum (Germany); K. Lischka, Univ. Paderborn (Germany); A. Pawlis,
Univ. Paderborn (Germany) and Stanford Univ. (United States)

QUANTUM OPTICS WITH ATOMS IN SOLIDS

- 8272 16 **Single-atom absorption imaging** [8272-49]
E. W. Streed, A. Jechow, B. G. Norton, D. Kielpinski, Ctr. for Quantum Dynamics, Griffith Univ.
(Australia)
- 8272 17 **Quantum memory in warm Rb vapor with buffer gas** [8272-42]
M. Bashkansky, F. K. Fatemi, I. Vurgaftman, U.S. Naval Research Lab. (United States)

POSTER SESSION

- 8272 19 **UV laser beam switching system for Yb trapped ion quantum information processing**
[8272-44]
D. R. Scherer, J. M. Hensley, K. R. Parameswaran, D. J. Bamford, Physical Sciences Inc.
(United States); E. Mount, S. Crain, J. Kim, Duke Univ. (United States)

Author Index

Conference Committee

Symposium Chair

Klaus P. Streubel, OSRAM GmbH (Germany)

Symposium Cochairs

David L. Andrews, University of East Anglia Norwich (United Kingdom)
Liang-Chy Chien, Kent State University (United States)

Program Track Chair

Zameer U. Hasan, Temple University (United States)

Conference Chairs

Zameer U. Hasan, Temple University (United States)
Philip R. Hemmer, Texas A&M University (United States)
Hwang Lee, Louisiana State University (United States)
Charles M. Santori, Hewlett-Packard Laboratories (United States)

Program Committee

Dmitry Budker, University of California, Berkeley (United States)
Alan E. Craig, Montana State University (United States)
Jonathan P. Dowling, Louisiana State University (United States)
Gurudev Dutt, University of Pittsburgh (United States)
James D. Franson, University of Maryland, Baltimore County (United States)
David Hughes, Air Force Research Laboratory (United States)
Fedor Jelezko, Universität Stuttgart (Germany)
Seth Lloyd, Massachusetts Institute of Technology (United States)
Aleksander K. Rebane, Montana State University (United States)
Selim M. Shahriar, Northwestern University (United States)
Alan Eli Willner, The University of Southern California (United States)
Jörg Wrachtrup, Universität Stuttgart (Germany)
Horace P. Yuen, Northwestern University (United States)
M. Suhail Zubairy, Texas A&M University (United States)

Session Chairs

- 1 Nonbleaching and Ultrasmall Fluorescent Tags I: Joint Session with Conference 8233
Ramesh Raghavachari, U.S. Food and Drug Administration (United States)
Philip R. Hemmer, Texas A&M University (United States)
- 2 Nonbleaching and Ultrasmall Fluorescent Tags II: Joint Session with Conference 8233
Ramesh Raghavachari, U.S. Food and Drug Administration (United States)
Philip R. Hemmer, Texas A&M University (United States)
- 3 Quantum Optics and Sensing with Spins in Diamond
Charles M. Santori, Hewlett-Packard Laboratories (United States)
- 4 Ultrasound Modulated Optical Tomography I: Joint Session with Conference 8223
Lihong V. Wang, Washington University in St. Louis (United States)
Philip R. Hemmer, Texas A&M University (United States)
- 5 Ultrasound Modulated Optical Tomography II: Joint Session with Conference 8223
Lihong V. Wang, Washington University in St. Louis (United States)
Philip R. Hemmer, Texas A&M University (United States)
- 6 Quantum Computing with Photons and Coherent Effects
Charles M. Santori, Hewlett-Packard Laboratories (United States)
Hwang Lee, Louisiana State University (United States)
- 7 Quantum Memory and Other Quantum Phenomena
Hwang Lee, Louisiana State University (United States)
- 8 Quantum Spatial: Joint Session with Conference 8274
Enrique J. Galvez, Colgate University (United States)
- 9 Quantum Imaging: Joint Session with Conference 8274
Philip R. Hemmer, Texas A&M University (United States)
- 10 Diamond Nanostructures and Photonics
Alan E. Craig, Montana State University (United States)
- 11 Quantum Optics with Artificial Atoms in Semiconductors
Charles M. Santori, Hewlett-Packard Laboratories (United States)

- 12 Quantum Optics with Atoms in Solids
 Elizabeth A. Goldschmidt, National Institute of Standards and
 Technology (United States)

Spinoptics: Spin degeneracy removal in nanostructures

Vladimir Kleiner, Nir Shitrit, and Erez Hasman*

Micro and Nanooptics Laboratory, Faculty of Mechanical Engineering, and Russell Berrie
Nanotechnology Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel

*mehasman@technion.ac.il

web site: www.technion.ac.il/optics

ABSTRACT

Spin-symmetry breaking in nanoscale structures caused by spin-orbit interaction, leading to a new branch in optics – *spinoptics* is presented. The spin-based effects offer an unprecedented ability to control light and its polarization state in nanometer-scale optical devices, thereby facilitating a variety of applications related to nano-photonics. The direct observation of optical spin-Hall effect that appears when a wave carrying spin angular momentum (AM) interacts with plasmonic nanostructures is introduced. A plasmonic nanostructure exhibits a crucial role of an AM selection rule in a light-surface plasmon scattering process. A spin-dependent dispersion splitting was obtained in a structure consisting of a coupled thermal antenna array. The observed effects inspire one to investigate other spin-based plasmonic effects and to propose a new generation of optical elements for nano-photonics applications.

Keywords: nanoaperture, plasmon-polariton, spin-orbit interaction, geometric phase, optical spin-Hall effect

1. INTRODUCTION

The interaction of light with metallic subwavelength structures exhibits various anomalous effects such as extraordinary optical transmission and beaming. These effects have been elegantly explained by a mechanism involving the coupling of light to collective surface-confined electronic oscillations known as surface plasmon-polaritons (SPPs). Extensive research has been carried out in the field of electromagnetic surface waves due to its technological potential and fundamental implications. Apparently, the handedness of the light's polarization (optical spin up/down) may provide an additional degree of freedom in nanoscale photonics. The dynamics of spinning light was investigated, and the effect of spin on the trajectories of polarized light beams (spin-orbit coupling) was experimentally observed, with results that agree with the predictions of Berry's phase theory¹. We examine the spin-orbit coupling effects that appear when a wave carrying intrinsic angular momentum (spin) interacts with a nanoscale structures. The Berry's phase is shown to be a manifestation of the Coriolis effect in noninertial reference frame attached to the wave. The theory is supported by experiment demonstrating the spin-orbit coupling of electromagnetic waves via a surface plasmon anisotropic inhomogeneous nanostructure. The measurements verify the unified geometric phase, demonstrated by the observed polarization-dependent deflection (spin-Hall effect) of the waves^{2,3}.

2. OBSERVATION OF THE SPIN-BASED PLASMONIC EFFECT IN NANOSCALE STRUCTURES

The proposed anisotropic inhomogeneous plasmonic structure was produced on top of a thin metal film evaporated onto a glass plate. The element consisted of a cavity (a spiral Bragg grating with a central defect), surrounded by a coupling grating (Fig. 1(a)). The structure was illuminated by circularly polarized light (**R** – right-handed, **L** – left handed). The intensity in the plasmonic cavity was measured by a Near-field Scanning Optical Microscope (NSOM). The measured intensity distribution exhibits a strong dependence on the incident spin (see Fig. 1(a)). An annular ring structure with a dark spot in the center for **R** illumination and with a bright spot for **L** illumination indicates coupling to different spiral plasmonic modes. The origin of the spin-dependent change in the near-field intensity distributions lies in the geometric phase of the excited plasmonic mode. In the most general case, when a wave carrying an arbitrary spin angular momentum changes its direction of propagation and polarization state, the geometric phase is given by a simple expression stemming from the Coriolis effect². The Coriolis effect is a result of the rotation of the reference frame, represented by the local direction of the grating grooves. Accordingly a spiral geometric phase with spin-dependent helicity arises in a circular grating³. In the spiral structure, (see Fig. 1(a)) an additional dynamic phase arises as a result of a space-variant path difference. The overall phase in the spiral cavity is the sum of the geometric and dynamic phases, which is manifested by different spiral modes that are obtained in the cavity for different polarizations.

One of the possible technological implementations of the plasmonic geometric phase could be a spin-dependent plasmonic focusing lens. The proposed structure is presented in Figure 1(b). This structure was illuminated from the bottom with **R** and **L**-polarized plane waves and the near-field intensity distribution was collected by the NSOM. A spin-

Figure 1. (a) The scanning electron microscope image of the spiral nanostructure and the scheme of the optical setup. Intensity distribution in the cavity measured by a NSOM for **R** and **L** illumination. (b) Spin-dependent plasmonic lens based on a plasmonic spin-Hall effect. The intensity distributions measured by a NSOM for **R** and **L** illumination and the corresponding transverse cross-sections of the measured intensity distributions in the focal plane of the lens (**R** - blue squares, **L** - red circles) Calculated cross-sections are plotted for each polarization (solid blue line -**R**; dashed red line - **L**). The SEM picture of the element is depicted in the inset.

dependent transverse shift of the focus is observed by comparing the spots (Fig. 1(b)). This shift can be regarded as a manifestation of the optical Magnus effect (optical spin-Hall effect) which arises in our system due to a spiral geometric phase. The observed effects inspire one to investigate other spin-based plasmonic effects and to propose a new generation of optical elements for nano-photonics applications.

3. OBSERVATION OF OPTICAL SPIN SYMMETRY BREAKING IN NANOAPERTURES

Observation of a spin symmetry breaking effect in plasmonic nanoscale-structures due to spin-orbit interaction is presented. We demonstrate a nanoplasmonic structure which exhibits a crucial role of an angular momentum (AM) selection rule in a light-surface plasmon scattering process. In our experiment, the intrinsic AM (spin) of the incident radiation is coupled to the extrinsic momentum (orbital AM) of the surface plasmons via spin-orbit interaction. Due to this effect, we achieved a spin-controlled enhanced transmission through a coaxial nanoaperture⁴.

In our experiment the spin-orbit interaction mechanism and the AM selection rules were experimentally verified by investigating the effect in a circularly symmetric – *achiral* – nanostructure. For this purpose we induced an external

Figure 2. Removal of the spin-degeneracy in circular corrugation by use of externally induced OAM. (a) experimental setup. A laser beam is modulated by a Spatial Light Modulator (SLM) to obtain a spiral phase and then incident through a Beam Splitter (BS) onto a coaxial aperture with circular corrugation. The transmitted light is captured in the image plane by the camera. The spiral phase with $l_{ext} = 2$, the measured intensity distribution across the incident beam, and the SEM picture of the element are presented in the figure. (b) intensity distribution cross-sections captured by the camera for different l_{ext} .

OAM carried by the incident beam. We fabricated the element, which consisted of an individual coaxial aperture, surrounded by an annular coupling grating (see Fig. 2a). This aperture was illuminated by a green laser light at a wavelength 532nm whose phase was modulated by a spatial light modulator (to achieve a spiral phase with topological charges $l_{ext} = 0, \pm 2$). We obtained a spin-dependent enhanced transmission by controlling the behavior of the device with external orbital AM, (see Fig. 2(b)).

4. PLASMONIC AHARONOV-BOHM EFFECT

A circular nanoslit was used to excite an out-propagating plasmonic wavefront. We measured the scattered plasmonic-wave dislocation strength by its interference with an additional plasmonic reference wave (see Fig. 3). The dislocation strength was shown to be equal to the incident optical spin (polarization helicity) in a manner similar to the Aharonov-Bohm wavefunction dislocation strength being equal to the magnetic flux parameter. Moreover, we experimentally demonstrated that the surface plasmon-polariton wave dislocation is independent on the incident wavelength and the nanoslit diameter, therefore verifying the geometric nature of the phenomenon. This effect is attributed to the optical spin-orbit interaction – coupling of the intrinsic angular momentum - spin and the extrinsic (orbital/linear) momentum of the electromagnetic field⁵. Our experiment was analyzed using a rotating reference frame, which leads to a spin-dependent correction of the momentum term in the wave equation. The experiment and analysis presented in this letter elucidate the significance of the optical spin in the scattering of surface plasmon-polaritons from

Figure 3. Experimentally measured near-field intensity for (a) $\sigma = 1$ polarization (right circular polarization) and (b) $\sigma = -1$ polarization (left circular polarization) at wavelength 800 nm. The measured fringe maxima are presented in (c) for $\sigma = 1$ and (d) for $\sigma = -1$ states. The black circle in (c) and (d) represents the location of the circular nanoslit. The inset in (b) with a dark spot in the center (marked with an arrow) is the measured intensity distribution inside the circular slit.

5. OPTICAL SPIN-HALL EFFECTS IN PLASMONIC CHAINS

Spin-Hall effect is a basic phenomenon arising from the spin-orbit coupling of electrons. In particular, the spatial trajectory of the moving electrons is affected by their intrinsic angular momentum. More generally, the dispersion relation of the particles is modified in a spin-dependent manner.⁶ The spin-Hall effect is regarded as intrinsic when it arises due to Rashba coupling (Berry curvature), while the extrinsic effect occurs due to the spin-orbit-dependent scattering of electrons from impurities. The optical spin-Hall effect (OSHE) – beam displacement and momentum shift

Figure 4. The OSHE-LI and OSHE-LA for circular chains. The measured far-field intensity distribution of the spin-flip component scattered from a circular chain of ordered (a) and disordered (c) coaxial apertures at a wavelength of 780 nm, and rotating nanorods with $m = 2$ at a wavelength of 730 nm (b); bottom, SEM images of the chains with radii of 5 μm . The spin-Hall momentum deviation is accompanied by a spiral phase-front with the topological charges $l=2$ and $l=4$, for the OSHE-LI (a) and OSHE-LA (b), respectively. Note that no spin-Hall momentum deviation is observed from the disordered chain (c).

due to the optical spin (polarization helicity) – was recently presented.^{1,7} The effect was attributed to the optical spin-orbit interaction occurring when the light passes through an anisotropic and inhomogeneous medium. Here, we present and experimentally observe the optical spin-Hall effects in coupled localized plasmonic chains⁸. The *locally isotropic* optical spin-Hall effect (OSHE-LI) is regarded as the interaction between the optical spin and the path of the plasmonic chain with an isotropic unit cell. In contrast, the *locally anisotropic* optical spin-Hall effect (OSHE-LA) occurs due to the interaction between the optical spin and the local anisotropy of the unit cell, which is independent on the chain path. This latter mechanism expands the scope of the OSHE and provides an additional degree of freedom in spin-based optics.

The OSHE-LI was studied on a coupled plasmonic chain of annular apertures, whose local orientation varies linearly with the x coordinate. The local orientation of the curved chain induces local anisotropy variation in the scattered field. Polarization analysis shows that the scattering from the curved chain contains a spin-flip component, which is experience a spin-dependent beam deflection. Similar beam deflection was observed in scattering from linear chain of rectangular apertures (nanorods) with orientation linearly varied along the chain (OSHE-LA). In other experiment the circular chains of coaxial apertures and rotating nanorods demonstrate scattered wave with an orbital angular momentum as result of spin-orbit interaction between light and anisotropic inhomogeneous structure (see Fig. 4). The observed OSHEs are due to the collective interaction of the localized modes within the periodic plasmonic chains. Emergence of spiral phase front with orbital AM was then directly verified by interference experiment and strength of phase singularity was measured.

6. SPIN SYMMETRY BREAKING IN THERMAL EMISSION

When light is emitted or scattered from a revolving medium, it exhibits a dispersion splitting – angular Doppler effect (ADE) – which depends on the circular polarization handedness (the photon's spin)⁹. The dispersion splitting is attributed to a spin-dependent correction of the momentum term in the wave equation due to rotation of the emitting medium. This splitting is the manifestation of the spin-orbit interaction, which is the basis for optical spin-Hall, Magnus, and Coriolis effects. Here, we report on a *geometric Doppler effect* manifested by a spin-dependent dispersion splitting of thermal radiation emitted from a structure whose local anisotropy is rotated along x-axis. The observed effect is attributed to the dynamics of the thermally excited surface wave propagating along the structure¹⁰.

In our experiment deepenings ("thermal antennas") with the subwavelength size of $1.2\mu\text{m} \times 4.8\mu\text{m}$ (Fig. 5, inset(i)) were etched to a depth of $1\mu\text{m}$ on a SiC substrate forming isolated thermal antenna and coupled thermal antenna array (Fig. 5, inset(iii)) with a period of $\Lambda = 11.6\mu\text{m}$. The upper plot in Fig. 4 is the emission spectrum of the isolated thermal antenna, which shows local resonances at frequencies 890 cm^{-1} and 945 cm^{-1} . These modes exhibit strong linear

Figure 5. Spectral emission from the isolated thermal antenna (top, SEM image in inset (i)), and for homogeneous coupled oriented antenna array (bottom, SEM image in inset (iii)); red and blue curves correspond to polarization along the short axis and long axis of the antenna respectively, and black for the total intensity. Inset(ii) presents a FDTD simulation of the intensity distribution in vicinity of an isolated antenna at 890 cm^{-1} , white line indicates the location of the antenna. Black arrows point to the local resonances.

polarization along the direction of the small axis of the antenna. The same polarization of local modes is observed in the emission from the coupled antenna array (Fig. 5, inset (iii)). However, in this case the spectrum at normal incidence, contains an additional narrow peak at 830 cm^{-1} , which is also strongly linear polarized along the same direction (Fig. 5, bottom). By measuring the emission dispersion from the array of identically oriented antennas, we have found that the narrow spectral peak contains two extended dispersive modes - a fast mode and a slow mode, attributed to coupled, localized surface phonon-polaritons (Fig. 6 (a)). By applying polarization measurements, we verified that the polarization direction of the slow mode follows the antennas' orientation.

Different and very intriguing polarization properties were observed in an array of antennas whose orientation was gradually rotated along the x -axis (Fig.6(b), inset). In the measured dispersion of thermal radiation¹⁰, the slow mode exhibits a clear splitting in the momentum of the emitted waves. The above phenomenon can be elucidated when considering surface waves propagation. As surface phonon-polaritons travel along the superstructure, they radiate a linearly polarized field that rotates at a spatial rate $\Omega = d\phi/dx$ (ϕ - local antenna's orientation). This rotation induces coupling between the intrinsic and the extrinsic momentum – spin-orbit interaction – which leads to a spin-dependent perturbation of the momentum $\Delta k = \sigma\Omega$, where $\sigma = \pm 1$ is the spin state. By solving the perturbed Helmholtz equation we derive the dispersion shift $\omega = \omega(k_x + \sigma\Omega)$ in the momentum dimension. Therefore, the original dispersion of the homogeneous structure is split into two emitted modes with opposite spin states. We found the spin-projected dispersion of the thermal emission (Fig. 6(b)) by measuring the Stokes' polarization parameter S_3 , which represents the circular polarization portion. This measurement reveals that the slow mode is split in the momentum by 2Ω between the two opposite spin-states.

Figure 6. (a) The measured emission dispersion of the coupled thermal antenna array (Fig. 5 inset (iii)). Dashed lines highlight the dispersion of the slow and the fast modes. (b) Spin-projected dispersion of the rotating antenna array, obtained by S_3 measurement. Dashed/dotted lines highlight the dispersion of the spin-split slow mode (red/blue color corresponds to a positive/negative spin projection, respectively). The observed dispersion shift is $\Delta k = \sigma\Omega$, signs of $\sigma = \pm 1$ correspond to two opposite circular polarizations; in the inset - SEM of the antenna array rotating along the x -axis with a period $a = 6\Lambda$; ($\Omega = \pi/a$).

7. CONCLUSION

The spin of photons can provide an additional degree of freedom in nanoscale photonics leading to a new branch in optics – *Spinoptics*^{11,12}.

REFERENCES

- [1] Bliokh, K. Y., Niv, A., Kleiner, V. and Hasman, E., "Geometrodynamics of spinning light", *Nature Photonics* 2, 748-753 (2008).
- [2] Bliokh K. Y., Gorodetski Y., Kleiner V., and Hasman E., "Coriolis effect in optics: unified geometric phase and spin-Hall effect", *Phys. Rev. Lett.* 101(3), 030404-1 – 030404-4 (2008)
- [3] Gorodetski, Y., Niv, A., Kleiner, V. and Hasman, E., "Observation of the spin-based plasmonic effect in nanoscale structures", *Phys. Rev. Lett.* 101(4), 043903-1 – 043903-4 (2008).
- [4] Gorodetski Y., Shitrit N., Bretner I., Kleiner V., and Hasman E., "Observation of Optical Spin Symmetry Breaking in Nanoapertures", *Nano Letters*, 9 (8), 3016–3019 (2009).
- [5] Gorodetski Y., Nechayev S., Kleiner V., and Hasman E., "Plasmonic Aharonov-Bohm effect: Optical spin as the magnetic flux parameter", *Phys. Rev. B* 82, 125433-1 - 125433-4(2010)
- [6] Bychkov Y. A., Rashba E. I., "Oscillatory effects and the magnetic susceptibility of carriers in inversion layers", *J. Phys. C*, 17(33), 6039-6045 (1984).
- [7] Leyder, C., Romanelli, M., Karr, J. Ph., Giacobino, E., Liew, T. C. H., Glazov, M. M., Kavokin, A. V., Malpuech, G., Bramati, A., "Observation of the optical spin Hall effect", *Nature Phys.* 3, 628-631, (2007).
- [8] Shitrit, N., Bretner I., Gorodetski Y., Kleiner, V. and Hasman E., "Optical Spin Hall Effects in Plasmonic Chains", *Nano Letters* 11, 2068 (2011).
- [9] Garetz, B. A., "Angular Doppler effect", *J. Opt. Soc. Am.* 71, 609-611 (1981).
- [10] Dahan N., Gorodetski Y., Frischwasser K., Kleiner V., and Hasman E., "Geometric Doppler Effect: Spin-Split Dispersion of Thermal Radiation", *Phys. Rev. Lett.* 105(13), 136402-1 - 136402-4 (2010).
- [11] Frischwasser, K., Yulevich, I., Kleiner, V. and Hasman, E., "Rashba-like spin degeneracy breaking in coupled thermal antenna lattices", *Opt. Express* 19, 23475-23481 (2011).
- [12] See additional references at www.technion.ac.il/optics