Optically addressed liquid crystal light valves for adaptive control of amplitude and phase of laser beam

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ABSTRACT

Space aberration effects which arise in high energy or in high average power laser chains are important parameters to control in order to emit a beam quality close to the diffraction limit. For that purpose we present recent experiments using an original adaptative and programmable module allowing the spatial control of the beam amplitude and the correction of the phase distortions due to the optical components and the gain media of the laser chain. Beam shaping is achieved by an optically addressed photoconductor-liquid crystal light valve. The light valve is addressed in the blue-green spectral range by incoherent projection of a VGA liquid crystal display. This adaptative optics module controls either the amplitude or the phase of near infrared laser beams depending on the liquid crystal operating mode. The other specific characteristics of the module will be detailed: no spurious diffraction effects, up to 10π phase excursion and tri-lateral wavefront sensor. Experimental results of compensation of aberrations introduced on different laser beams will also be presented.

Keywords: Adaptative optics, liquid crystal light modulators, wavefront sensor, adaptative phase correction, spatial beam control, pulse shaping.

1. INTRODUCTION

For many applications involving ultra intense laser system the main features are the focusing ability and the power delivered on the target. These key parameters are directly related to the quality of the beam emitted by such short pulse sources which is mostly limited by spatial and temporal distortions which arise in the laser chain. These distortions lead both to a degraded spot when focusing the beam on a target, due to phase distortions introduced by optical components and amplifiers or to pulse spreading, due to group velocity dispersion effects. Therefore space and time aberrations effects are important parameters to control in order to emit Fourier transform limited short pulses having a beam quality close to the diffraction limit. For that purpose, we have developed a programmable beam shaping module based on the use of an optically addressed light valve (OALV). This module, depending on its operating conditions could be applied in laser chain in order to perform the following adaptative functions on the laser beam:

- amplitude beam shaping for the compensation of spatial non uniformity gain in the amplifiers
- phase beam shaping for the correction of spatial phase distortions as existing in ultrashort pulse laser chains,
- pulse shaping for the compensation of group delay time dispersion of chirped pulse amplification (CPA) laser system.

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2. OPTICALLY ADDRESSED LIGHT VALVE

The different functions of the adaptative beam shaping module are achieved by an optically addressed light valve (OALV) developed at the Laboratoire Central de Recherches of Thomson-CSF. This device is based on the same technology than the liquid crystal display (LCD) used for flat panel display applications as LCD projectors, portable computers,...

The OALV structure is described onto Figure 1-a. It consists in a liquid crystal layer sandwiched between a bulk photoconductive material and a glass substrate. Two alignment layers provide the suitable orientation of the liquid crystal molecules in the volume of the cell. Micro-bowls dispersed in the cell play the role of spacers in order to control its thickness uniformity. The two transparent ITO electrodes on the outside face of the photoconductor and inside face of the glass substrate are used to apply voltage onto the liquid crystal layer.

The device acts as an electro-optic phase plate whose retardation value can be continuously controlled by the voltage applied onto the liquid crystal layer which depends on the conductivity of the photoconductive material.

![Figure 1: (a) OALV structure - (b): OALV operating as a programmable phase plate, liquid crystal layer in the birefringence mode](image)

The OALV which uses a 1mm thick Bi$_2$SiO$_5$ crystal, (BSO), as photoconductor operates as follows and described in Figure 1-b :

- When the photoconductivity is not activated, no illumination or wavelength in the sensitivity range ($\lambda_{\text{w}} > 600$ nm for the BSO), the high dark resistivity, $\rho = 10^{11}$ Ω cm, prevents from any voltage transfer to the liquid crystal layer.
- When locally illuminated with incoherent light ($\lambda_{\text{w}} < 500$ nm) the photoconductive properties of the BSO allow local and partial transfer of the voltage to the liquid crystal layer according to the illumination level. The liquid crystal molecules then exhibit a local change of their orientation leading to a birefringence variation introduced on the reading wavefront at $\lambda_{\text{w}}$.

It results that the OALV acts as an adaptative phase plate which can be used in transmission directly for phase control or in combination with a polarizer for amplitude control of the reading laser beam.

Depending on the thickness $d$ of the liquid crystal, the maximum phase excursion $\phi$ can be adjusted according to the following relation:

$$\phi = 2\pi \Delta n d / \lambda$$

Typical value of $\Delta n$ is 0.15 and remains quite constant in a large spectral range from 0.8 to 20 μm.
The transverse resolution which mainly depends on the photoconductor thickness, is about 10 cycles/mm at 50% MTF. A 1 mm thick BSO allows to control a large number of pixels according to the size of the BSO, such crystal being available in quite large diameter up to 2 inches.

Time response $t$ of the OALV depends on the liquid crystal thickness $d$ as shown in the next relation:

$$t = \frac{\nu d^2}{\pi^2 K}$$

where $K$ and $\nu$ are physical parameters of the liquid crystal layer.

Typically $t$ is in the range of 20 to 200 ms if $d$ varies respectively from 4 to 25 $\mu$m.

### 3. ADAPTATIVE BEAM SHAPING MODULE

In order to perform adaptative functions with the OALV, we chose as shown onto the Figure 2, to control the spatial repartition of illumination by imaging an electrically addressed liquid crystal display (LCD), using an incoherent light source. The LCD, used between crossed polarizers, has the VGA format. Interfaced with a computer, it can operate as a programmable mask at video frame rate. Transmission of each pixel is controlled by a lock-up table in order to achieve the required corrections onto the transmitted laser beam. The driving signal is calculated by a processing unit which has been calibrated with respect of the module response, thus taking care from the intrinsic non linearities and non uniformity such as incoherent illumination or residual distortions of the OALV.

![Beam shaping module for adaptative control of laser beam profile](image)

To take fully benefit from the continuous structure of the OALV (large liquid crystal cell with a single uniform electrode), the incoherent LCD image is slightly defocused. Therefore the illumination profile is smoothed and avoids to recreate pixelization.

This technic prevents from limitations encountered with electrically addressed liquid crystal display: spurious diffraction effects due to the pixelized structure of the electrodes and reduced transmission due to the aperture ratio of the black matrix (generally < 50%).

The resulting transmission value is > 70% for an infrared laser operating at $\lambda = 0.8$ or 1.06 $\mu$m, and could be improved by adjusting the thickness of the ITO electrodes to minimize Fresnel losses.
4. AMPLITUDE BEAM SHAPING

The amplitude beam shaping is performed with the module by operating in the following conditions:
- parallel alignment of the liquid crystal molecules at the steady state: birefringence mode,
- reading beam polarized at 45° of the alignment direction for optimum contrast ratio,
- analyzer, to convert birefringence modulation in amplitude modulation.

Amplitude beam shaping has been experimented to ponderate the transmission of a pulsed Nd-YAG laser:
- \( \lambda = 1.06 \mu m \),
- pulse duration: 10 ns,
- repetition rate: 30 Hz,
- beam size : 1 cm²

For the following driving conditions, 10 Volts AC voltage @ 15 Hz , 500 \( \mu \) @ \( \lambda < 500 \) nm, the transmission of the laser beam has been controlled with various profiles within up to 70% and a dimming ratio >100.

The damage threshold has been checked up to 300 mJ/cm² with the same laser pulse conditions but on a reduced size (3 mm diameter size), for the whole device in operation, without any effect either on optical components or on their amplitude profile performances.

5. SPATIAL PHASE CORRECTION

The beam shaping module with the OALV has been used in a pre-compensation configuration, which includes a wavefront sensor, as shown on the set-up given onto Figure 3. The beam shaping module has to operate in the following conditions:
- parallel alignment of the liquid crystal molecules at the steady state: birefringence mode,
- reading beam polarized in the same direction than the alignment direction for pure phase control,
- analyzer is removed.

![Figure 3](image)

Figure 3: Integration in a chirped pulsed amplification laser system including the wavefront sensor which collects the phase information, the feed-back loop is active when the LCD addresses the OALV.

The measurement of the phase profile of the wavefront is achieved via a three-wave lateral shearing interferometer (TWSI). This sensor allows to recover the three derivatives of the phase by using a 2D grating which replicates three
tilted copies of the wavefront. This method is well adapted for short laser pulse applications for the following reasons: it allows a very large dynamic range from $\lambda/100$ to $100\lambda$ and the measure keeps a precision of $\lambda/10$ even for distortions as large as $10\lambda$; it is free from any limitations due to the coherence length or pulse duration (like broad spectral bandwidth); a self-error estimation is provided by the measure itself.

The operating principle for phase correction is based on a feedback loop between the wavefront sensor and the light valve. Depending on the shape of the output of the laser system, a conjugate adaptive phase plate is generated by optically driving the OALV through an interactive process involving a PC. The role of the computer is first to recover the phase from the interferogram and secondly, according to this information, to generate a mask to be displayed on the LCD. Finally, the focal spot pattern is monitored on a CCD camera.

Figure 4: From CCD camera analysis. 3D views and top views, on the left of original (Strehl ratio = 25%) and on the right of the corrected (Strehl ratio = 96%) intensities distribution in the focal plane.

Figure 4 shows the results of an experimental test performed with the following conditions: the laser light source is a Nd:YAG laser running in a CW mode at the wavelength of 1.06 μm with 10 mW output power. The distorted wavefront is
recorded by the ATWLSI giving the measurement of the spatial phase repartition leading to the focal plane shown on the left of Figure 4: peak to peak distortions is 1.7λ over an 6 mm aperture size. The corrected wavefront with λ/5 peak to peak residual distortions leads to the improved focal spot shown on the right of the same figure. The corresponding Strehl ratio of 0.96% shows that the corrected wavefront is nearly diffraction limited.

Same type of corrections have been also demonstrated in the ns regime with a Q-switch YAG laser emitting at 1.06 μm at 15 Hz repetition rate and delivering an energy of 100mJ/cm².

6. TEMPORAL PULSE SHAPING

The same beam shaping module has been implemented for compensation of the temporal aberrations due to group velocity dispersion in a CPA laser chain, in the experimental set-up shown onto the Figure 5. For that purpose the OALV is placed in the Fourier plane of the stretcher, where the spectral components of the pulse are spatially separated, thus leading to an adaptative control of the pulse duration.

![Figure 5](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Figure 5: Operating condition for pulse beam shaping by placing the OALV in the Fourier spectral plane of a stretcher.

To validate the operation of the module a Ti-Sapphire oscillator delivering 40 fs pulses was sent in a « zero dispersion line ». Due to the group velocity dispersion in the optical components, the initial pulse duration at the output of the « zero dispersion line » is 150 fs. In the Fourier plane, each spectral component of the ultrashort pulse are independently and
continuously phase shifted by the OALV. By projection of a calculated pattern on the OALV which generates a quadratic phase distribution over its aperture (8 mm wide), it was able to recompress the pulses at 50 fs\(^6\).

7. CONCLUSION

To conclude, the different experiments presented, using our programmable beam shaping module based on the use of a non-pixelized optically addressed light valve, open new attractive potentialities for adaptative control of laser beam wavefront. Performances demonstrated in term of efficiency, contrast ratio, phase excursion, damage threshold show the compatibility with CW or ultra-intense or/and ultra-short pulse laser for which spatial corrections of phase or temporal distortions are necessary but critical. The use of spatial light modulators, like optically addressed light valves, is well adapted to produce programmable, smooth and continuous laser beam wavefront profile, reduces the constraints on quality of the optics and introduces flexibility on the design of the high energy laser chain.

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9. REFERENCES

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