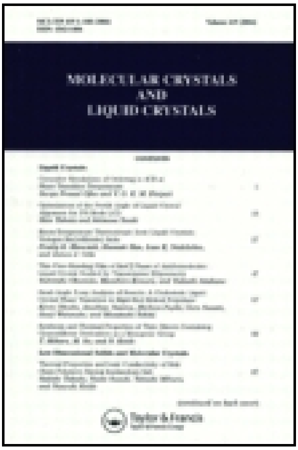

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Optically Addressed Liquid Crystal Light Valves and their Applications

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Optically Addressed Liquid Crystal Light Valves and their Applications

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The beams delivered by high energy laser chains suffer from spatial and temporal aberrations which degrade the performances of the source. These aberrations araise from thermal lensing and group delay dispersion effects which reduce the available peak power density when focusing the beam on a target. To increase the laser brightness to a value close to the diffraction limit in the space and time domains we propose to use a liquid crystal spatial phase modulator. It consists of an optically addressed light valve which permits to control the phase of a wavefront and the phase of each spectral component of an ultrashort femtoseconde pulse. We present the technology and the characteristics of the device and demonstrate the following applications: wavefront correction, compensation of group delay dispersion and dynamic holography with gain.

Keywords: adaptive optics; liquid crystal light valve; solid-state laser; two-wave mixing; aberration compensation

INTRODUCTION

Ultra intense laser chains exhibit large amounts of spatial and temporal aberrations which degrade the quality of the beam delivered by the source. These aberrations arise from the thermal lensing due to the efficient pumping of the gain media. Also, the aberrations of the optical components as well as the group delay dispersion effects due to ultra short pulse propagation in a femtosecond laser are major parameters which degrade the spatial and temporal properties of the beam. In such conditions the beam spot size after focalization and the pulse duration are far from their ultimate Fourier transform limit (1-2-3). Since now most of the applications require optimum source brightness and ultra high peak power, it is of particular importance to introduce new programmable optical components which can compensate for the spatial and temporal aberrations of the chain (4-5). The technology developed at TH-CSF/LCR consists in using an optically addressed liquid crystal spatial light modulator (OASLM) which exhibits very interesting characteristics for the control of temporal and spatial signals. After the presentation of the device operating principle, technology and performances, we highlight the following applications:

- Correction of the spatial aberrations of a 100 TW laser
- Correction of the group delay dispersion in a femtosecond laser
- Dynamic holography for image amplification.

OASLM: OPERATING PRINCIPLE AND TECHNOLOGY

The early work on optical information processing at TH-CSF/LCR lead to the development of an original structure of an optically addressed spatial light modulator used as input transducer for incoherent to coherent image conversion in a parallel Fourier processor (6). This is the same device structure that we now use in adaptive optics for high energy lasers and dynamic holography. The OASLM which acts as an electro-optic 2D programmable phase plate is based on the liquid crystal technology. The OASLM uses bulk monocrystalline $Bi_{12}SiO_{20}$ (BSO) both as the photoconductive material and as one of the substrate supporting a liquid-crystal layer (see Fig.1). When addressed optically with incoherent light ($\lambda_{Writing}$ < 500nm), the photoconductive properties of BSO locally transfer the voltage to the liquid-crystal layer. Then, over the entire valve aperture, the liquid crystal exhibits spatial-index variation proportional to the incoherent-light spatial distribution. An IR (λ_{Read} > 600nm) beam passing through this active phase plate will have its wave front controlled according to the voltage distribution. Depending on the thickness of the liquid crystal, phase deformation of several wavelengths can be generated. Transverse resolution of the OASLM ensures the control of more than 300 x 300 pixels over the beam aperture. The optical addressing of the device is performed by means of imaging a programmable mask on BSO. In our experiments the mask is generated by a PC and displayed on an electrically addressed liquid-crystal television active matrix made of an array of 640 x 480 pixels used between crossed polarizors (see Fig.2). The addressing light originates from an incoherent low-voltage arc lamp. To avoid to create a pixelization on the valve when we are imaging the active mask, we add a slight defocusing. Following this operating principle of the OASLM, any analog light pattern generated on the mask is transferred into a spatial phase modulation of a wave front passing through the device.

Some specific characteristics of this BSO-LC SLM are given hereafter:

- Aperture size: 10 x 10 → 30 x 30 mm^2
- BSO thickness: 1 mm typical
- Liquid crystal: d = 8 to 10 μm - Δn = 0.2 typical
- Phase excursion: $\Delta\varphi = 4\Pi$ at λ = 1,06 μm
- Writing illumination: blue spectral range λ_W = 450nm
- Laser readout: λ_R > 650nm
- Operating voltage: 15 V – AC – 10 to 100 Hz
- Rise / decay time: 50 ms.

The present device exhibits a damage threshold resistance higher than 300mJ cm^{-2} with pulsed Nd-YAG laser at λ = 1,06 μm. An attractive alternative solution consists in replacing the bulk photoconductor by an organic thin film, in particular if larger aperture size are required. Also, a larger phase dynamic range is possible by choosing a LC material having a birefringence close to Δn = 0,3.

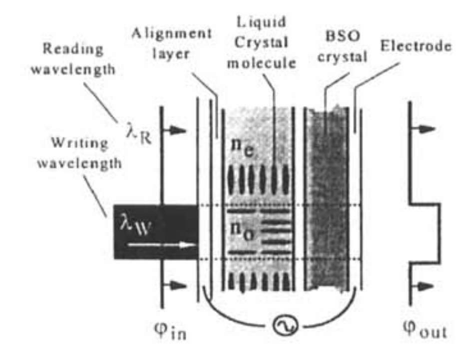

Fig. 1 Operating principle of the liquid crystal OASLM.

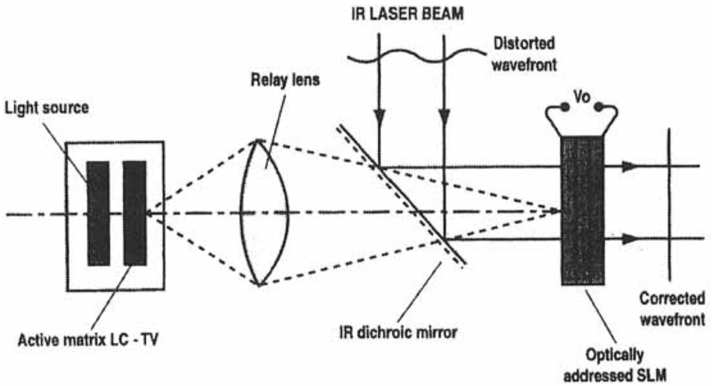

Fig. 2 Optical module for adaptive control of the phase of a laser beam.

2D spatial phase modulation could also be achieved by using a bulk material with a large third order non linearity typically a photorefractive like crystal or polymer. However a determinant advantage of the light valve approach relies on the fact that each function respectively, the photoconductive and the electrooptic properties of the device can be optimized with different materials. In such conditions, the OASLM technology can exhibit better and much more flexible characteristics in comparison to a single nonlinear medium for adaptive phase control applications as presented in the following paragraphs.

CORRECTION OF THE WAVEFRONT OF A HIGH ENERGY LASER

For testing the capabilities of the programmable LC OASLM to correct for phase distortions of a laser beam we tested the set-up shown in Figure 3a using a CW low power Nd-YAG laser. It consists of the following elements :

a) an achromatic wavefront sensor : a three beams lateral shearing interferometer.
b) a CCD camera for beam analysis.
c) the OASLM.
d) a processing unit.

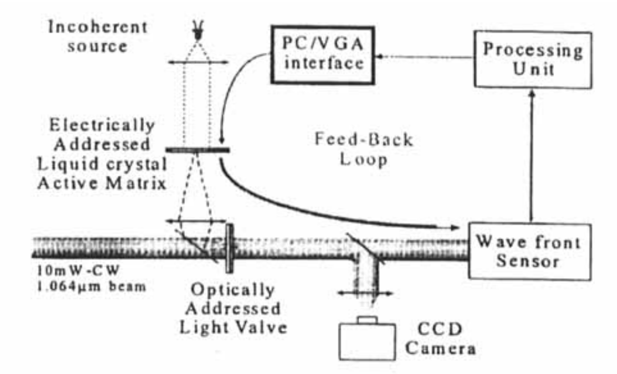

Fig. 3a Experimental set-up showing the OASLM module in a feedback-loop.

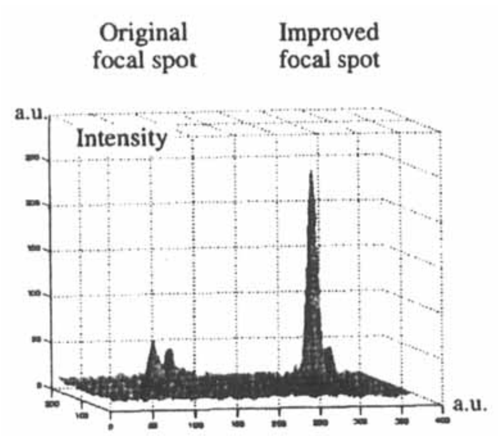

Fig. 3b Experimental result after adaptive phase correction by the OASLM.

The experimental set-up uses a feedback loop between the wavefront sensor and the OASLM. The procedure is thus the following.: after measuring the wavefront aberration, delivered by the wavefront sensor, and according to this information, to generate the mask displayed on the LC-TV. Then the resulting focal spot is analyzed on a CCD camera. The experimental results firstly obtained by J.-C. Chanteloup et al in reference 7 and shown in Figure 3b clearly demonstrate the improved beam quality due to the operation with the LC light valve (Strehl ratio increases from 25% to 96%). Most recently B. Wattelier et al in reference 8 demonstrate the integration of the device in the LULI – 100 TW – 400fs. Nd-Glass laser chain whose schematic, including pulse stretchers, amplifiers, and pulse compressors, is shown in figure 4a. 3D views of wavefronts before and after correction highlight that the peak to peak values is reduced from 0,48 λ to 0,2 λ while the rms value decreases from 0,13 λ to 0,04 λ (see Figure 4b). Also an important point to notice in figure 4b is that the OASLM does not introduce spurious diffraction effects on the beam: it is a non pixelated structure which only affects the phase of the laser wavefront.

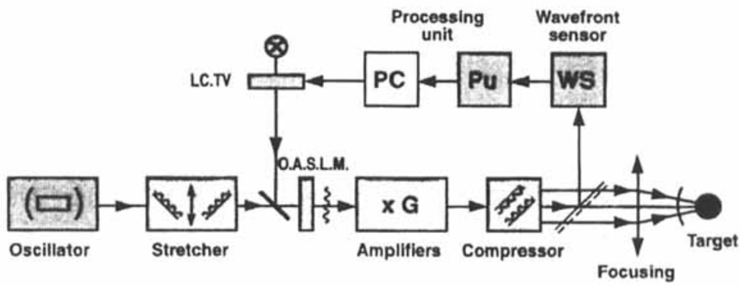

Fig. 4a Integration of the OASLM Adaptive optical loop for spatial phase correction of a high peak power laser: 100 TW LULI laser

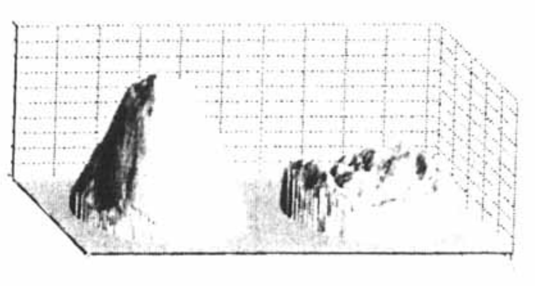

Fig. 4b 3D views of wavefront before and after corrections.

CORRECTION OF SPECTRAL DISPERSION EFFECTS OF A FEMTOSECOND LASER

Remarkable breakthroughs have occured recently in the field of ultrafast laser technology in particular with Ti-Saphir crystals which have a wide spectral gain bandwidth ($\Delta\upsilon > 100nm$). Self mode locking and chirped pulse amplification techniques (CPA) are used with success for the production of fs pulses with focused intensities exceeding $10^{20}Wcm^{-2}$. However, to attain the maximum peak power requires to deliver a gaussian pulse whose duration τ is as close as possible of the ultimate Fourier limit $\tau = 0.44/\Delta\upsilon$ with high contrast ratio. In CPA systems the chirp induced by the grating stretcher and the high order dispersion effects in gain media and optical components cannot be perfectly compensated by the grating compressor. Any uncompensated dispersion prohibits pulse compression to the Fourier transform value. Therefore, as in the space domain, there is a need of a programmable 1D spatial modulator to control the phase of the each spectral component of the pulse. For that purpose, several technologies were tested such as, pixelated LCD, acousto-optic modulators or flexible piezo mirrors. In general, these devices either suffer of limited spatial resolution, or introduce parasitic diffraction due discrete pixel sampling. C. Dorrer et al in reference 9 firstly demonstrated the use of the non pixelated LC-OASLM for controlling the temporal aberrations of an ultra short pulse. The procedure described in detail in the reference 9 is the following. Before operating with the OASLM the relative phase of the spectral components of the pulse are measured by a classical spectral interferometric technique. Then, to achieve a precise control of the phase for high order dispersion compensation, we implement a feedback loop to converge toward the required phase value. In such conditions, a frequency chirped laser pulse can be recompressed by the use of a OASLM whose major characteristics have been presented in section 2.

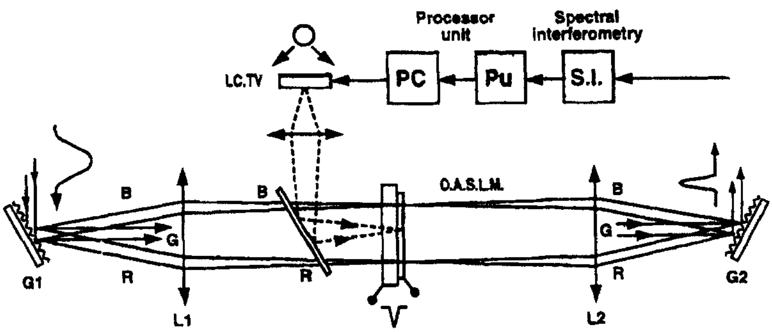

Fig. 5 OASLM in the spectral plane of a zero dispersion line: correction of group delay dispersion in a CPA for laser chain.

The OASLM has the flexibility of classical LC modulators but it is non pixelated and it displays a spatial resolution higher than 10 ℓmm^{-1}. Its operating principle for spectral phase modulation is shown in Figure 5. The device is placed in the focal plane of a zero dispersion line including two highly dispersive gratings 1000 ℓmm^{-1} and Fourier transform lenses $L_1 - L_2$. The spectral components are spatially dispersed over the 10 mm aperture of the light valve. Depending of the light pattern projected onto the BSO by the LC-TV, it turns into a spectral modulation of the phase of the local spectral components of the pulse delivered by the Ti-Saphir oscillator. When operating with the LC light valve, the spectral phase is rendered nearly constant over the spectral bandwidth 795-835nm and as a consequence the autocorrelation shows that the pulse is recompressed close to the Fourier limit (see Figure 6). Also it results a significant reduction of the wings of the 50fs pulse.

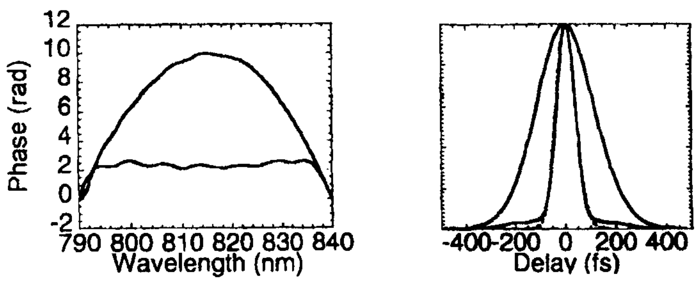

Fig. 6 Spectral phase and pulse autocorrelation without correction (a) and with correction due to OASLM (b).

The integration of the module in a CPA Ti-Saphir laser follows the schematic of Figure 4a where the module of the figure 5 is placed before the pulse stretcher. After measuring the spectral phase of the chain by spectral interferometry, the OASLM then permits to compensate the high order group delay dispersion due to propagation of the pulse through the active and passive components of the chain.

DYNAMIC HOLOGRAPHY FOR IMAGE AMPLIFICATION

Degenerate two-wave mixing (TWM) of two optical beams in a nonlinear medium has been extensively investigated for real time holography and wavefront amplification in particular using photorefractive materials. In a similar manner to photorefractive materials, A. Brignon et al have shown in reference 10, that an OASLM can also be used for dynamic holography with a high TWM gain as experienced in the interaction geometry of figure 7a. A low intensity signal and a pump beams interfere on the light valve and it results a periodic variation of the index of refraction of the form:

$$n(x) = n_0 + \Delta n \cos \frac{2\Pi x}{\Lambda}$$

where Λ is the grating period. When the light valve operates at the correct bias point shown in Figure 7b, we can achieve optimum diffraction efficiency and index modulation Δn. In such conditions, the self diffracted beam will contribute to the coherent two wave interaction and the signal beam experiences a gain G given by the following relation

$$G = 1 + \left[\frac{2\Pi}{\lambda} n_2 I_1(0) \right]^2 . L^2$$

where $n_2 = \frac{\partial n}{\partial I}$ is the slope of the SLM characteristics, i.e. the index versus incident pump intensity. L: interaction length in the liquid crystal. The gain equation shows that even without a phase shift between the grating and the incident interference pattern an energy redistribution is achievable, but the energy transfer is always from the strong wave to the weak one. By comparison, in conventional TWM interactions in a nonlinear medium the refractive-index grating changes in amplitude and position during the propagation of the waves in the medium. In this case it is well known that energy transfer occurs only when the induced grating is shifted with respect to the interference pattern. In the experiments, the laser used the 514nm line of a linearly polarized Ar laser. The beam was divided into two coherent beams, A_1 and A_2, and then recombined on the OASLM by a Mach-Zehnder interforemeter with the condition $A_2 << A_1$.

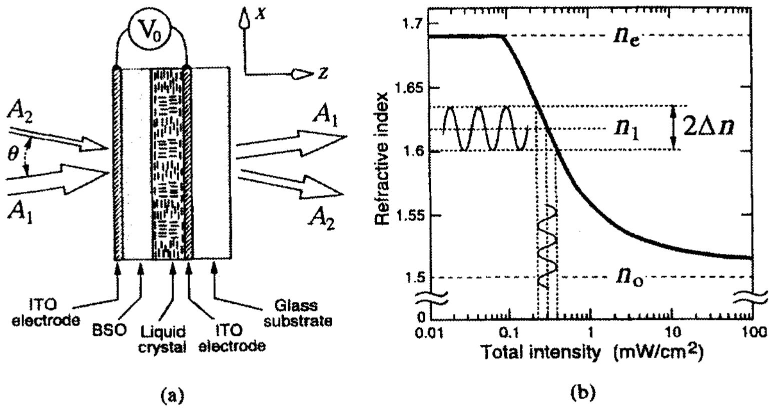

Fig. 7 Schematic of the TWM interaction geometry in a BSO liquid crystal OASLM (a). Refractive index as a function of the incident intensity (b).

For an applied voltage frequency of F = 25 Hz a maximum gain of 10 was obtained for I_0 = 210 μW/cm² and V_0 = 5,5 V. When we take into account the overall transmission of the OASLM, this result corresponds to a net gain of 6. According to the gain equation the equivalent nonlinear index coefficient n_2 is thus as large as 220 cm²/W. Using a beam shutter in the arm of the pump beam and with I_0 = 210 μW/cm², we measured a response time of 150 ms for the gain to reach 90% of its steady-state value. Signal-beam amplification depends on the grating period of the induced index grating and is limited by the resolution of the OASLM. Figure 3 shows the experimentally observed TWM gain as a function of the grating period Λ in the weak-signal regime (pump to probe beam ratio β = 225). For Λ < 80 μm no gain was observed. The gain then increases with Λ and reaches a constant value for a grating period larger than 400 μm. This moderate spatial resolution is attributed to the thickness of the BSO crystal. It is known that a thinner crystal or a thin film of photoconductive polymer material would certainly permit higher spatial resolution. Figure 8 illustrates the capabilities of the OASLM for image amplification when an object binary chart is inserted on the signal beam. Amplified images are due to energy transfer from the pump beam to the signal. In both cases we obtained a stationary 5X amplification of the signal wavefront in the image plane and a net gain factor of 3. These results demonstrate amplification of a laser beam by two-wave mixing in a BSO liquid crystal light valve with very low input intensities and driving voltage. Since OASLM can be designed for various ranges of wavelengths, it is also expected that this newly observed effects will be observed in spectral regimes that are not easily achieved with current nonlinear materials.

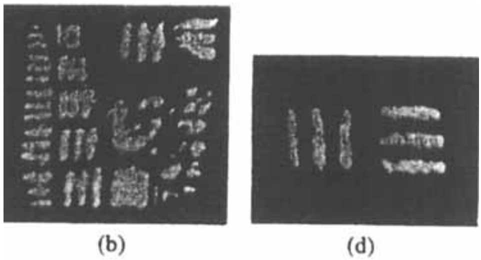

Fig. 8 5X-amplified image in the presence of the pump beam.

CONCLUSIONS

The different experiments presented, based on the use of a non pixelated optically addressed liquid crystal light valve, open new attractive issues for adaptive control of laser beams. Performances demonstrated in term of optical efficiency, contrast ratio, phase excursion and damage threshold show the capabilities of the device to control and to correct the spatial and temporal aberrations araising in high energy lasers or in femtosecond chirped pulse amplification laser chains. The SLM technology permits to attain the ultimate performances of the chain while it relaxs the constraints on the quality of the optical components of the laser.

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