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kHz-speed optically induced phase gratings with liquid crystal light valves in transient dynamic mode

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Liquid crystal light valves (LCLV) are optically addressable spatial light modulators that allow controlling the phase and amplitude properties of optical beams. We show that submilliseconds phase and amplitude modulations can be obtained when operating the LCLV in the transient dynamic mode by setting the working point close to the saturation of the response. Thanks to the large birefringence of the liquid crystals, this condition provides enough phase shifts to respond to the needs of several methods for, optical measurement, dynamic holography, interferometry and imaging through phase disturbing media, while providing kHz speed. These values of response times also allow foreseeing applications, for example in biophotonics, and for monitoring of the environment.

Liquid crystal (LC) devices have large applications, for example in image displays and light projection [1], and also the LC Spatial light modulators SLM are now extensively used for 2D laser wavefront beam shaping [2]. According to the response time of the LC the typical bandwidth is ~ 100 Hz, corresponding to the large refractive index changes of the order of ~ 0.1 . In LC cell with planar anchoring the index of refraction depends on the applied bias voltage V_b . A full birefringence excursion occurs from a few Volts (Fréedericksz transition [3] voltage V_F) to ~ 10 V when all the molecules tend to align perpendicular to the cell wall. Once the field is removed, the fall time, which is the intrinsic relaxation time of the molecular orientation, is given by

$$T = \frac{\gamma_1 d^2}{K\pi^2}, \quad (1)$$

where γ_1 is the LC rotational viscosity, K the elastic constant and d the thickness of the LC layer. When applying the field, the rise time is related to the applied bias voltage through the equation [1]

$$T_{ON} = \frac{\gamma_1 d^2}{K\pi^2 \left[\left(\frac{V_b}{V_F} \right)^2 - 1 \right]}, \quad (2)$$

Hence, for $V_b \gg V_F$ it can be taken as $T_{ON} \sim T(V_F/V_b)^2$ [4]. A full ON/OFF excursion of the molecular reorientation requires a total switching time $T_{tot} \sim T[(V_F/V_b)^2 + 1]$. To decrease the fall time T , one can act on the LC parameters, for instance approaching the isotropic phase by increasing the temperature [5], or can diminish the LC thickness. However, the rise time T_{ON} can be more simply decreased by increasing the applied voltage $V_b \gg V_F$. Among the various approaches for decreasing the response time of a single LC modulator, the transient dynamics effect has been proposed and

analyzed by ST Wu et al [6]. It is based on the idea of keeping the cell constantly biased at ON with the voltage V_b at an intermediated value of the cell full transmittance response, and by removing the low modulation voltage $\Delta V \ll V_b$ during the OFF part of the cycle [6]. In this transient dynamic mode the modulator exploits the small angle relaxation of a highly-deformed LC director [7,8].

Fig. 1. Schematic structure of the LCLV. ITO : transparent conductive layer. BSO : photoconductive substrate. LC : planar aligned nematic liquid crystal layer, thickness 25 μm . V_0 : externally applied voltage. V_b : LC transferred bias voltage due to V_0 and LCLV green light illumination. P1, P2 : crossed polarizers at $\pm 45^\circ$ with the LC director.

Here, we show that by constantly applying a high bias voltage to a liquid crystal light valve (LCLV), and operating the cell in the transient mode effect, a fast ($\sim$ ms) switching time can be obtained, despite the relatively thick 25 μ m LC layer. In the LCLV the bias voltage V_b is due to the low intensity laser illumination of a photoconductive crystal. In this component the transient mode effect exploits the saturation part of the optical response. Thanks to the reduced molecular excursion of the LC sub-milliseconds response times are achieved when dealing with small amplitude photo-induced phase modulations.

Fig. 2. Two-wave mixing in the LCLV: reference R and signal S at wavelength 532 nm interfere in the LC layer giving rise to a refractive index grating. The red probe beam I_{in} reads the phase grating. I_0 : first diffracted order. EOM : electro-optic modulator. P : polarizer. F : blocking filter for green. PD : photodiode. Beam polarizations are along y axis, parallel to the LC director.

The schematic structure of the LCLV is represented in Fig.1. Liquid crystal light valves (LCLV) are optically addressable spatial light modulators, in which a continuous photosensitive layer is used to drive the orientation of a nematic LC layer [2]. Applications include dynamic holography [9], slow light interferometry [10,11] and optical sensing [12]. By using a LCLV fabricated with a semiconductor $\text{Bi}_{12}\text{SiO}_{20}$ crystal (BSO) as a photoconductor, we show that the voltage working point can be set close to the saturation of the optical response, in the conditions where $V_b \gg V_F$ providing a reduced molecular excursion and hence, a faster response time. Here the LCLV operates with small refractive index modulation due to low holographic fringe contrast.

In the LCLV the photoconductive BSO layer is associated with a planar aligned nematic liquid crystal layer of E48 (from Merck). The extraordinary and ordinary index are, respectively, $n_e \sim 1.75$ and $n_o \sim 1.52$ at 589nm, for a total birefringence $n_e - n_o \sim 0.23$. The thickness of the LC layer is $d = 25 \mu\text{m}$. Transparent conductive electrodes of Indium-Tin-Oxide (ITO) are deposited on the outer side of the BSO and inner side of the glass wall closing the cell. An external voltage V_0 is applied across the LCLV and sets the bias voltage V_b across the LC layer. Note that $V_b \ll V_0$ without LCLV illumination due to the high dark resistivity of the BSO crystal, therefore, in the dark the most of the applied voltage is on the BSO [13]. On the other hand, when the BSO is illuminated its resistivity decreases due to the photoconductive effect and, correspondingly, V_b increases across the LC layer.

The BSO is sensitive in the blue-green region of the visible

spectrum. Therefore, a writing light beam in this wavelength range induces a molecular LC reorientation when impinging on the BSO, thanks to the locally reduced resistivity of the BSO and consequent increase of the local bias voltage. Correspondingly, a reading laser beam acquires a phase shift when passing through the LC layer. The phase shift acquired by the reading beam is optically controlled by the writing green beam intensity. Note that phase changes can be converted into amplitude variations by inserting the LCLV in between crossed polarizers at $\pm 45^\circ$ with respect to the LC director. Based on the writing-reading transcription process, phase and/or amplitude modulations can be transferred from the writing beam to the reading beam. For example, phase/amplitude modulations can be transformed at another laser wavelength or at another optical intensity. The dynamics of the process is driven by the LC response time, as expressed in Eq.(1).

The usual way of transferring amplitude/phase information is to perform two-wave mixing. In Fig.2 it is shown the setup to perform two-wave mixing in the LCLV, the main scheme used for holographic interferometry and vibrometry, involving a large reference to signal beam ratio and consequently a low fringe index modulation regime. A plane wave signal S and a reference beams R interfere onto the photosensitive BSO layer of the LCLV. In the experiment here presented the wavelength of R and S is $\lambda = 532 \text{ nm}$ and the grating spacing $\Lambda = \lambda / (2 \sin \theta) \sim 30 \mu\text{m}$. The beam intensity ratio is $\beta = I_R / I_S \sim 20$, with $I_S < I_R$ and the reference intensity $I_R = 8 \text{ mW/cm}^2$.

Fig. 3. Normalized step responses of the LCLV measured for $V_0 = 18 \text{ Vrms}$ (red longer curve) and $V_0 = 60 \text{ Vrms}$ (black shorted curve) by switching ON the signal beam. The intensity of the reference beam is $I_R = 8 \text{ mW/cm}^2$. The curves are normalized to 1 for comparison.

The fringe intensity on the photoconductor is given by

$$I_{LCLV} = I_R + 2|S||R| \cos\left(\frac{2\pi}{\Lambda}x + \Delta\phi\right), \quad (3)$$

where the signal intensity has been neglected, $I_S \ll I_R$, $\Delta\phi$ is the phase shift between S and R and the spatial coordinate x is along the LC director axis. Correspondingly, this intensity distribution produces a small angle LC reorientation and a refractive index

$$n = n_2 \left(I_R + 2|S||R| \cos\left(\frac{2\pi}{\Lambda}x + \Delta\phi\right) \right), \quad (4)$$

where n_2 is the Kerr-like coefficient of the LCLV [12]. The light intensity induces a refractive index grating proportional to $2 n_2 |S||R|$. We call Δn the amplitude modulation of this phase grating. Note that the value of n_2 can be evaluated by directly

measuring the light induced phase shift in an interferometer setup or by measuring the two-wave mixing gain. Typical values of n_2 for the LCLV in the green are of the order of $6 \text{ cm}^2/\text{W}$ [12].

The grating amplitude Δn depends on the modulation frequency of the signal beam. In general, the signal and reference beams are themselves self-diffracted by the induced grating and, due to their mutual coupling, exchange phase and amplitude modulation information. This allows transforming the signal phase modulations into intensity variations at the output diffracted beams by the LCLV (see, e.g., [12] and references therein).

Fig. 4. (a) Refractive index change and (b) corresponding LC molecule average orientation angle $\langle \theta \rangle$ vs amplitude of the applied voltage V_0 (in Vrms).

As a first experiment a step response is measured by switching on/off the signal S with a constant bias voltage V_b . The amplitude of the refractive index grating is measured by using a probe beam I_{in} issued from a laser diode, wavelength $\lambda_0=670\text{nm}$. This is done at two different bias voltages, the first one in the usual reorientational regime, $V_0=18 \text{ Vrms}$, the other one in the saturation regime, $V_0=60\text{Vrms}$. These values allows to report across the LC layer a bias voltage $V_b \sim 12 \text{ Vrms}$ and $\sim 54 \text{ Vrms}$, which are, respectively, 8 and 36 times the threshold voltage $V_F \sim 1.5\text{Vrms}$. In both cases the reference to signal ratio is fixed to $\beta=20$. In Fig.3 are shown the step responses obtained by switching ON the signal. For comparison, the diffracted probe intensities I_0 are normalized in between 0 and 1 and are plotted versus time for the two bias voltages, respectively. The corresponding rise time is $T_{on}=43\text{ms}$ ($V_0=18\text{V}$) and $T_{on}=2.9\text{ms}$ ($V_0=60\text{V}$) and the maximum index change reached at the steady state is 7×10^{-3} and 10^{-3} , respectively. The corresponding probe diffraction efficiencies on I_0 are $\eta=0.33$ ($V_0=18\text{V}$) and $\eta=1,3 \times 10^{-2}$ ($V_0=60\text{V}$), respectively. The diffraction

efficiency is related to the grating amplitude through the expression

$$\eta \equiv \frac{I_0}{I_{in}} = \left| J_1 \left(\frac{2\pi d}{\lambda_0} \Delta n \right) \right|^2, \quad (5)$$

where J_1 is the first order Bessel function of the first kind.

When taking into account the fall time T_f , the total switching time can be estimated as $T_{tot} \sim 8\text{ms}$ for $V_0=60\text{V}$ and $T_{tot} \sim 90 \text{ ms}$ for $V_0=18\text{V}$. The gain in the response speed is counterbalanced by a smaller refractive index modulation, because the LCLV operates around different working points on the characteristics of the LC response. However, the maximum index change, as shown in the step response, provides sufficient dynamics for detecting the phase modulation and the efficiency of the induced holographic grating.

Fig. 5. Sub-millisecond amplitude modulations obtained in the LCLV with (a) a sinusoidal and (b) a pulsed signal; $V_0=60\text{Vrms}$.

To characterize the full response of the LCLV we have measured the index change and derived the corresponding LC average orientation angle $\langle \theta \rangle$ when varying the applying bias voltage V_0 . The resulting curves are plotted in Fig.4 (a) and (b), respectively. Here the threshold voltage for the LC molecular orientation to occur is $V_{on} \sim 8 \text{ Vrms}$ corresponding to the Fréedericksz transition voltage $V_F \sim 1.5 \text{ Vrms}$ across the LC layer. The external voltage at which the LC molecules are at half of their total excursion ($\theta=45^\circ$) is $V_0 \sim 15\text{Vrms}$. For $V_0=60\text{V rms}$ the saturation of the LC orientation process is almost reached. Therefore, the changes of the molecular orientation around this working point are small, but allowing a fast response time. The reduced LC excursion provides a small phase

modulation due to a limited angular excursion of the LC molecules induced by the low grating fringe contrast. However, this provides enough index variations for efficient detection and grating diffraction. The main advantage of working in this regime of transient dynamic is a short response time, hence a frequency bandwidth larger ($\sim$ kHz) with respect to the usual operating conditions of the LCLV.

For a bias voltage at which a large Δn excursion occurs ($V_0=18\text{Vrms}$), the usual cutoff is at ~ 100 Hz. For a large bias voltage ($V_0=60\text{Vrms}$), a smaller Δn is obtained, but still detectable diffractive efficiency. Note that the spatial resolution is also improved at high bias voltage, this because only the regions close to the cell boundaries contribute to the refractive index change, resulting in a reduced effective thickness of the LC layer.

We now introduce an amplitude modulation of the signal S by using an electro-optic modulator (EOM) followed by a linear polarizer with its axis parallel to the LC director (Fig. 2). The modulated signal intensity has the form $I_S(t) = I_p(1 + \sin 2\pi ft)$, with I_p the peak value, and the grating amplitude follows at the modulating frequency, $\Delta n = \Delta n(f)$. By setting f in the kHz range we verify that the LCLV responds in a large frequency band, with sub-millisecond response time. A phase grating of amplitude $\Delta n \sim 10^{-3}$ is observed at 2kHz signal modulation. As an example we show in Fig. 5 (a) a sinusoidal phase modulation at 2.4kHz, which is clearly detected by measuring on the probe first order diffraction I_0 . As a second example, we show in Fig. 5 (b) a sequence of pulses with 1.2 kHz modulation and 60 Hz repetition rate. The sub-millisecond temporal resolution can be appreciated as well as a fairly good grating amplitude Δn .

Fig. 6. Frequency response of the LCLV measured for two different working points, $V_0=18\text{Vrms}$ and $V_0=52\text{Vrms}$. The grating amplitude Δn is plotted versus the modulating frequency in log-log scale.

Finally, we have measured the frequency response around the two working points, full span of the LC orientation ($V_0=18\text{Vrms}$) and saturation regime ($V_0=52\text{Vrms}$). The results are shown in Fig.6. By varying the frequency of a sinusoidal amplitude modulated signal we measure the amplitude Δn of the induced phase grating. It is interesting to note that for the bias voltage at which the full LC orientation is exploited ($V_0=18\text{Vrms}$) the Δn is maximum or $f < 10\text{Hz}$ but the frequency response decreases rapidly beyond $\sim 180\text{Hz}$, where the crossover with the saturation regime ($V_0=52\text{Vrms}$) occurs. On the contrary, in the saturation regime the

dynamics is stretched but the response time decreases only of a factor 10 after the crossover, allowing the detection of phase modulations in the kHz frequency bandwidth. Note that extension of the method to the near infrared (NIR) can be implemented for LCLV using a NIR sensitive photoconductor, for example a semi-insulating GaAs, which has a high dark resistivity and, therefore, allows applying high bias voltages.

In conclusion, by working in the transient dynamic mode, close to the saturation regime of its response, the LCLV provides sub-milliseconds phase/amplitude modulations with $\Delta n \sim 10^{-3}$ grating amplitudes. This provides sufficient dynamics for the detection and processing of the diffracted optical signals. Moreover, the LCLV is a spatially extended optically addressed modulator allowing the detection on large size laser beam and working with low intensities of the addressing beams, $< 10\text{mW/cm}^2$. These unique properties allow applications in two-wave mixing, dynamic holography and optical phase conjugation with kHz frequency bandwidth. The conditions of small index modulations where a sub-millisecond response is required may also be well suited for coherent imaging through biomedical tissues or turbid media [14,15].

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