All-optically controlled light valve assembled by photorefractive crystal and PDLC hybrid structure

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ABSTRACT

A light-valve device, assembled by Ru–doped $Bi_{12}SiO_{20}$ (BSO) photoconductive substrate and polymer dispersed liquid crystal layer is proposed, in which all the processes are controlled by the near infrared light. Laser beam illumination (Gaussian shape) on BSO:Ru crystal caused charge carriers generation, which migrate and form an inhomogeneous distribution and subsequent space charge field. This surface-localized electromagnetic field penetrates into the PDLC layer and modulate the orientation of the liquid crystals, that caused reverse of the device initial opaque state to the highly transparent one. The proposed structure is simple and easy to fabricate, without requirements of ITO contacts and alignment layers and opens further possibilities for near-infrared applications.

Keywords: photorefractive effect, space-charge field, inorganic crystals, polymer dispersed liquid crystals, hybrid structure, light valves

1. INTRODUCTION

The hybrid structures enable to integrate the excellent properties of organic and inorganic materials into a single device with optimal performance. For instance, combining the large anisotropy and strong birefringence typical for organics with excellent photosensitivity of inorganic materials becomes a challenge issue for the development of non-linear devices for photonic applications. The major advantage of such structures is that they can favorably combine dissimilar properties into single device and in that aspect the device's components can be optimized independently.

Examples of hybrid structures are optically addressed spatial light modulators (SLM) that consists of photoreceptor (photoconductor) and electro-optic material [1]. In general, SLM are liquid crystal light valves (LCLVs) -incoherent to coherent image converters that control the transmittance, reflectance and scattering of light using the electro-optically controlled birefringence of the liquid crystals (LCs) [1,2]. Usually LCLVs are assembled using an inorganic material (offers fast charge carrier mobility, high photoconductivity, band-gap tunability and significant mechanical stability) together with organic compounds (that provide high birefringence, large flexibility and inexpensive cost). Nowadays, LCLVs play an important role in display technology and image processing applications.

$Bi_{12}SiO_{20}$ (BSO) crystals are well known as perfect SLM photoreceptor component due to the remarkable photoconductivity, high dark resistance and fast charge carrier mobility [1-4]. Furthermore, based on the photorefractive properties (refractive index modulation in response to light) several non-linear optical devices have been proposed for non-destructive interferometric testing applications, in precise metrology, image processing, etc. [5]. Moreover, recently it was found that Ruthenium (Ru) is very suitable and effective dopant in BSO crystal structure, which significantly improves the recording speed and sensitivity at 1064 nm [6-9]. This opens many opportunities for near infrared sensitive devices development for non-linear optics.

Particularly, there are two main LCLV structures using BSO crystals as photoconductor. In the first one (proposed earlier by Aubourg [10]), the non-doped BSO is assembled with LC (as electro-optic layer) into an optically addressed transducer, which shows high spatial resolution and low driving voltage. Although several non-linear applications have been demonstrated, the light-valve based on BSO and LC layer requires use of polarizers, which consume significant part of the incident light and also LC alignment procedure makes the fabrication process more complicated. In order this shortcoming to be overcome, Takizawa et al. [11], first proposed simpler light-valve structure, assembled by BSO crystal with polymer dispersed liquid crystal (PDLC) layer. Generally, PDLC consist of micro-sized droplets of liquid crystal (LC) randomly dispersed in a transparent polymer matrix [12]. Since the polymer defines the LC alignment, PDLC do

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not require use of polarizer in contrast to the conventional LCs. The authors demonstrated several examples of high brightness projection displays, showing significant resolution, real-time operation and few ms rise/decay time [13]. However, all the above proposed light-valve configurations work under an external voltage (require ITO contacts deposition) and at visible spectral range. At the same time, requirements to simplify the device structures and to improve the near-infrared sensitivity become of particular technological importance, especially for image processing and bio-medical analysis.

In the present work, a light-valve device based on the excellent photoconductivity of Ru–doped BSO crystal and strong birefringence of PDLC is proposed. Light illumination on BSO:Ru substrate caused charge carriers generation, which migrate and form an inhomogeneous distribution. The photo-induced space charge field penetrates into the PDLC layer, realigning the LCs molecules orientation inside the droplets and change the LCs director, consequently the refractive indexes and transparency of the light-valve device. The proposed BSO:Ru/PDLC device is easy to fabricate, without necessity of ITO layer contacts, alignment layers and no need of polarizers, all the processes are controlled by near infrared light.

2. EXPERIMENT

2.1. **Hybrid device preparation**

Figure 1 (a) shows the schematic structure of the device, which consists of Ru-doped BSO crystal and glass substrate, arranged in a cell, filled with PDLC layer (thickness of 10 μm defined by the teflon spacers between two substrates). The BSO:Ru plate was cut from BSO:Ru single crystal [14], with a thickness of 0.5 mm. PDLC film was fabricated by mixing UV-curable monomer NOA65 (n_p= 1.515 at 1064 nm, Norland) in a nematic LC host (E 48, Δn= 0.16 at λ = 1064 nm, Merck) at 30:70 wt. % ratio. LC/monomer mixture was injected into an empty cell at the isotropic state at T = 90°C. After that the cell was exposed with UV light (λ= 365 nm) with an intensity of 60 mW/cm^2 for 15 min at T = 20°C. The average diameter of the LC droplets in PDLC was around 7.3 μm (observed by a polarizing optical microscopy).

A photograph of the PDLC (reference) cell and Ru:BSO/PDLC hybrid structure at their initial (scattering) state are shown at Fig. 1(b,c).

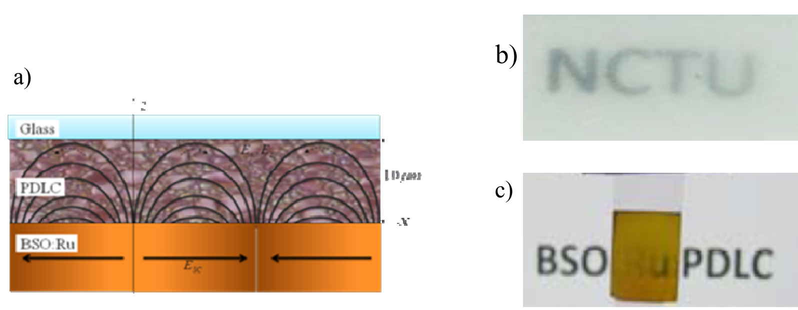

Fig.1 (a) BSO:Ru/PDLC light-valve structure (the lines show the space charge E_{sc} filed distribution) and photographs of (b) PDLC cell and (c) BSO:Ru/PDLC hybrid structure

2.2 **Light-modulation characteristics**

A diode-pumped solid state laser emitting at 1064 nm was used to study the light-valve properties. First, to test the alignment effect of the light-induced space-charge field, the BSO:Ru/PDLC structure was irradiated with laser beam (Gaussian shape). A collimated 633 nm laser beam (several μW power) was used to probe the transmitted beam shape. The time evolution of the Gaussian beam was captured by CCD camera (Fig.2).

Finally, the above optical set-up was slightly modified to 4-f optical system to demonstrate an image pattern evolution through the hybrid structure (Fig.3).

3. RESULTS AND DISCUSSIONS

The main operation principle of the proposed device is based on the photorefractive effect, which arises when the charge carriers, photogenerated by a spatially modulated light intensity are trapped to produce a non-uniform space-charge distribution and consequent space charge field (Esc). First, Tabiryan and Umeton [15] predicted theoretically that the space charge field in inorganic substrates can penetrate into the LC layer and act as a driving force for LC molecules re-alignment and subsequent change of the refractive indexes. Later on, a number of hybrid cells based on ferroelectrics as $KNbO_3$ and SBN:Ce [16,17] and non-doped BSO [18,19] crystals assembled with nematic LC layers has been successfully realized to support experimentally the above prediction at visible spectral range. Until now, only a limited number of near infrared sensitive structures are designed mainly based on semiconductor substrates as CdTe [20] or GaAs [21] and LC layer, which also require precise alignment procedures.

Naturally, PDLC films are opaque due to the refractive index mismatch between the polymer matrix (n_p) and the LC molecules therefore the hybrid structure scatters the light on its initial state (Fig. 1(c)). Generally, PDLC can be switched from the light-scattering to the transparent state by application of an electric field, which support the refractive indices match (between the LC and the polymer). Thus, when the light is incident on the structure, due to the BSO:Ru near infrared absorption and high photoconductivity, the charge carriers become excited and mobile, creating a space charge field. This photo-induced space charge field can rise strong enough to overcome the threshold voltage of PDLC and to penetrate into the layer, re-orienting the LC molecules inside the droplets.

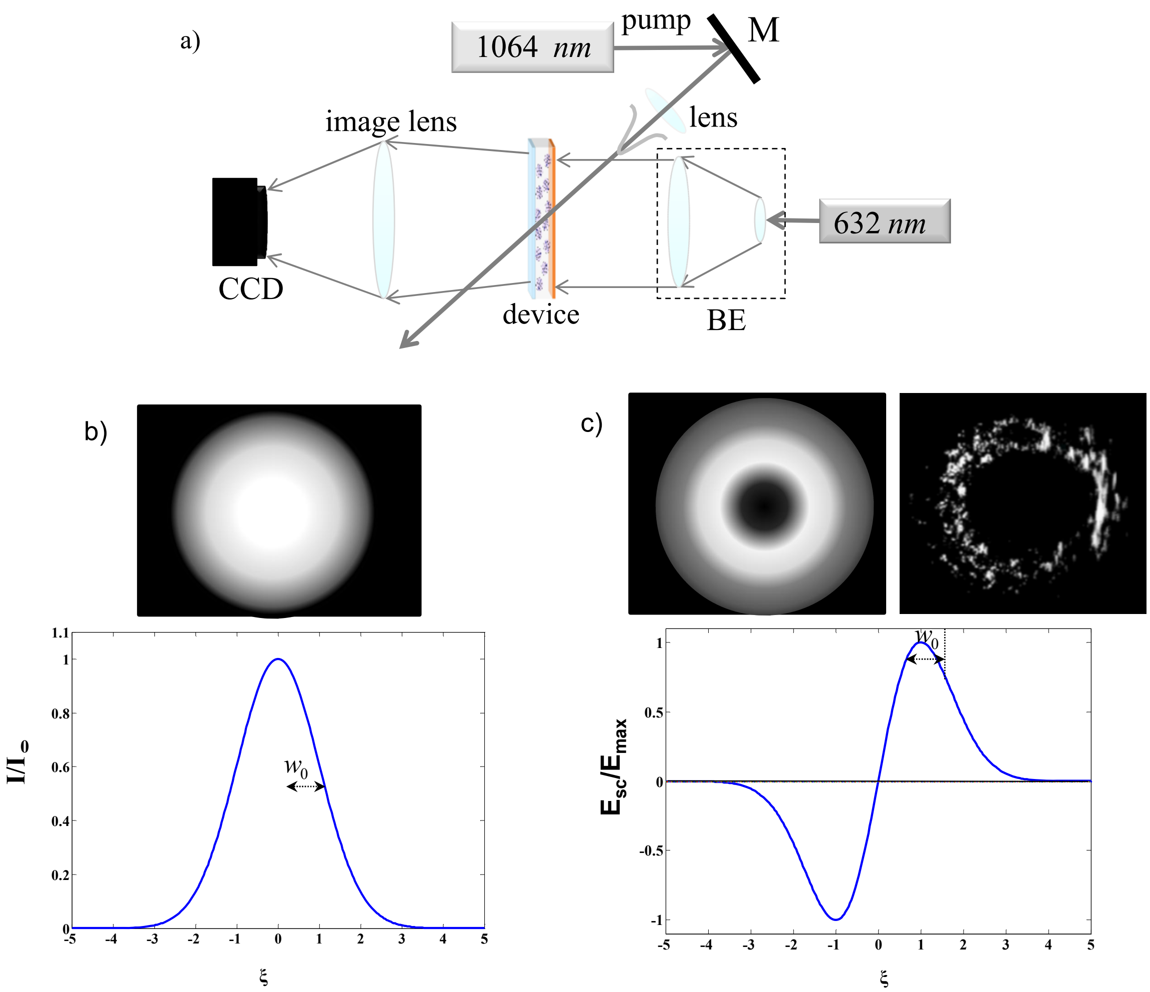

Fig. 2. (a) Experimental set-up for a Gaussian beam propagation through BSO:Ru/PDLC structure; (b) light intensity numerical distribution and (c) E_{sc} numerical distribution (left) and experimental propagation of the Gaussian beam (right) through the BSO:Ru/PDLC device.

In our previous research [9] we briefly estimated the space charge field E_{sc} induced in BSO:Ru crystal plate (supposing sinusoidal charge density distribution [2]) as a value of $E_{sc(BSO:Ru)}$=1.5x10^5 (V/m). Assuming the threshold voltage of PDLC layer about 20 V and 7.3 μm droplet size, the PDLC's threshold electric field is $E_{th(PDLC)}$= 2x10^6 (V/m). Therefore, for the space-charge field in PDLC layer we found $E_{sc(PDLC)}$ = 2x10^6 (V/m). Evidently, the space charge field created in BSO:Ru can be strong enough to penetrate into the PDLC layer and modulate the LCs director. This is a sign that Ru addition in BSO crystal structure generates enough density of charge carriers.

To demonstrate the feasibility of LC reorientation by a spatially inhomogeneous electric field localized on a BSO:Ru photorefractive plate, the time evolution of the Gaussian beam passing throughout the device is shown. The experimental set-up, the numerical simulation of the Gaussian beam distribution

$$I(\xi) = I_0 e^{-\left(\frac{x}{w_0}\right)^2} = I_0 e^{-\xi^2} \quad (1)$$

and the space-charge field distribution

$$E_{SC}(\xi) = E_{\max}\xi \cdot e^{-\xi^2} \quad (2)$$

(where: I-light intensity, E_{sc}-space-charge filed, w_0 –half beam width, ζ-normalized dimension) as well as experimental time evolution of Gaussian beam shape passing through the hybrid device are displayed at Fig. 2 (a,b,c). When 1064 nm pump light is off because of the PDLC scattering state (mismatch between the refractive indices of the LC and polymer binder), the light passing through the device is almost scattered and quite weak intensity pattern is captured by CCD. After the pump light is switched on, the charge carriers generated in BSO:Ru become homogeneously distributed, creating a space charge field which spread out into the PDLC surface and realign the LCs molecules. Obviously, the BSO:Ru/PDLC structure becomes more transparent in the area where the space-charge field is stronger (Fig. 2(c)). The presented experimental results are in very good agreement with the numerical calculation about the electric field and the charge density distribution of Gaussian beam intensity effect on BSO photorefractive crystal by Stevens et al [21]. The author's numerical results show that Gaussian illumination creates notch width that is proportional to the width of the

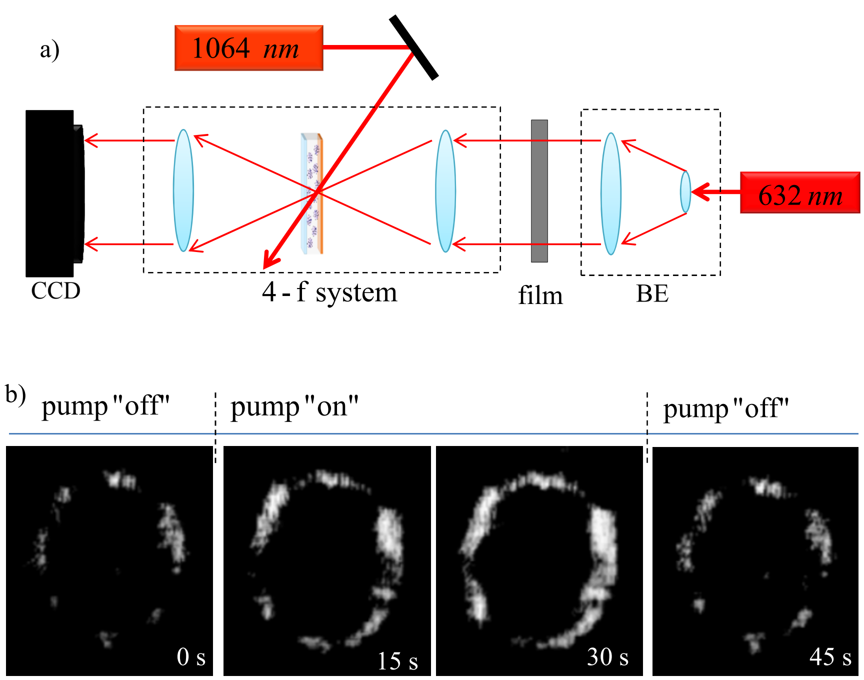

Fig.3. (a) 4-f optical system for pattern evolution through the BSO:Ru/PDLC light-valve (b) time-sequential images of letter "o" when the pump light is off /on/off position.

high intensity beam, created by the charge accumulation at the interface between the dark and spurious illumination, also confirmed in our case.

Next, an image pattern (letter "o") was placed into the input plane of 4-f optical system and BSO:Ru/PDLC device was illuminated by Gaussian beam (0.5 mm width). Since the light-induced transparent area is limited by the Gaussian beam width, we calculated the Fourier spectrum width of the pattern. Taking into account the film (image pattern) resolution of 100 dpi, the probe wavelength 632 nm and the focal length of f =10 cm, the full spectrum width is $\frac{\lambda f}{\Delta x} x2 \sim 0.48$ mm, where Δx is the minimal feature size of the film. Clearly, the width of the spectrum is smaller than the Gaussian beam size, so the Fourier spectrum of the image can pass through the device without strong scattering. The lack of the full brightness of the image can be related to the PDLC uniformity.

Apparently, by changing the orientation of the liquid crystal molecules by the space-charge field, it is possible to vary the intensity of transmitted light through the device. This temporal evolution shows that the all optically induced switching property of the proposed BSO:Ru/PDLC light valve could be used for further dynamic near-infrared photonic applications.

4. CONCLUSIONS

In conclusion, we have demonstrated near infrared sensitive light valve assembled by PDLC layer on BSO:Ru substrate, where all the processes are controlled by light. The space-charge field, induced by photogenerated charge carriers inside the BSO:Ru substrate act as a driving force for the LC molecules realignment. As a result by varying the transmitted light intensity through the device it can work as near infrared light valve in transmission mode, allowing an easy implementation of classical wave-interaction scheme and further practical applications at near infrared spectral range.

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