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Light propagation in periodic photonic structures formed by photo-orientation and photo-polymerization of nematic liquid crystals

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ABSTRACT

Propagation of linearly polarized light beams in a nematic liquid crystal cell with distinguished regions of different molecular orientation has been analyzed. Specifically, combination of the planar/homogenic and homeotropic alignment, forming thus spatially limited regions characterized by a different LC molecular orientation, has been tested, as achieved by means of the photo-orientation and photo-polymerization processes, independently. An influence of molecular orientation on the light beam propagation has been checked for different directions of the linear polarization. Thanks to the molecular reorientation induced by the low frequency external electric field and also to the reorientational nonlinearity taking place in NLCs, propagation direction of the light beam can be additionally controlled by the electric bias and/or optical power, respectively. Proposed structural solutions and techniques, related to the photo-orientation and photo-polymerization processes described in this communication, give rise to the novel LC geometries and structures. The latter act as promising candidates for new practical photonic applications as they are expected to be of a particular importance for integrated optic elements and devices.

1. Introduction

Liquid crystalline materials are commonly used in photonic applications mainly due to their unique properties combining characteristics of conventional isotropic liquids and solid-state anisotropic crystals [1]. The fluid nature of liquid crystals (LCs) and their compatibility with most optoelectronic substances, polymers and other organic materials allow them to be easily incorporated with other elements in various configurations, forms and geometries, and thus enhance possibilities of potential applications in novel photonic networks. Practical realizations and hi-tech solutions include many photonic elements and devices based on LC technology, such as: liquid crystal displays, spatial light modulators, free-space interconnectors, optical correlators, switchers and routers, optical gates, tunable wavelength filters, sensors, diffractive and reflective elements, adaptive/varifocal lenses, beam/image processing devices, integrated optic waveguide devices, and many others [2–6]. Significant progress in this area of interest, with a high range of possible applications, is mainly due to the high tunability with external fields and factors, relatively simple fabrication process, compact structure, and low power consumption. Taking the above into account one can state that optically active and easily reconfigurable liquid crystalline structures and materials can be considered as a promising medium for the functional optical circuits. It causes that the LC-based photonic devices have been successfully demonstrated in the area of telecommunications, optical data processing, sensing systems, free-space beam steering systems, and optoelectronic neural networks [6].

Nematic LCs (NLCs) are composed of rod-like molecules and due to their anisotropy in molecular structures they exhibit optical and electric anisotropies. In specific range of temperatures, in nematic phase, long axis of molecules are approximately parallel to each other and the averaged alignment direction achieved in such way is characterized by a dimensionless unit vector $\boldsymbol{n}$ called the director (Fig. 1b). Most nematics are optically uniaxial and positive birefringent materials (with an extraordinary refractive index greater than the ordinary one, $n_e > n_0$) with optical axis corresponding to the long axis of molecules. For a linearly polarized light beam one can consider two state lines at which electric field oscillations are perpendicular and parallel to the direction of molecular orientation (characterized by director) and, then an ordinary and extraordinary wave are excited, respectively.

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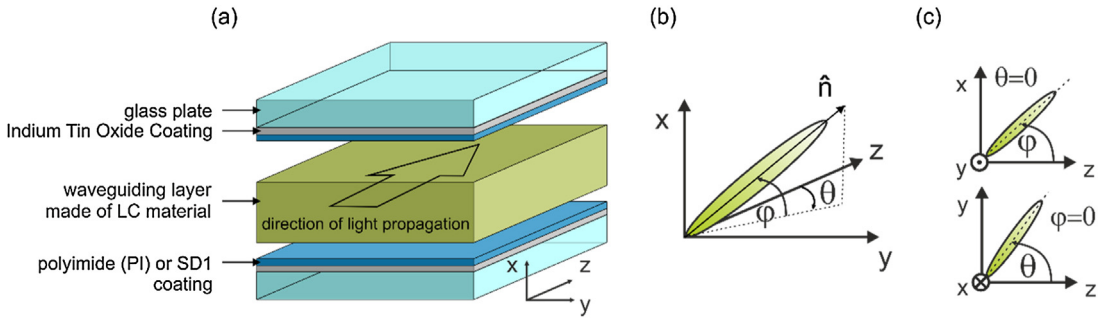

Fig. 1. (a) Typical NLC cell under consideration is composed of liquid crystalline material sandwiched between two glass plates coated both with ITO electrodes and surface alignment layers [e.g., polyimide (PI) or photo-alignment material such as, e.g., SD1]. (b) and (c) Molecular arrangement in NLCs is described by the director which spatial distribution can be defined with use of two orientation angles: θ and φ. (c) When one of these angles is equal to zero, the nonzero one determines molecular (re)orientation in xz- and yz-plane, respectively.

A typical sandwich-type cell with a defined initial NLC molecular orientation and with possibility of a voltage-driven control is shown in Fig. 1a, as a perfect photonic structure to perform electro- and all-optical steering and switching in NLCs. While the interaction between light and NLCs can be used in many ways, the optical properties of photonic devices strongly depend on the particular liquid crystalline structure and/or the material applied. Different structures achieved in nematic LCs, such as, e.g., polymer stabilized LCs (PSLCs) in nematic phase [6–8], may be considered as perfect candidates for LC-based waveguides and other elements for integrated optical circuits. One of the significant technological barriers in terms of development and commercialization of NLC-based devices is to achieve stable and uniform orientation within an NLC layer with liquid crystalline molecules aligned along a desired direction in a steady state. While several approaches have been proposed to improve and stabilize molecular orientation inside an NLC-cell, one of the possible solutions is to engineer the alignment layers obtained with use of, e.g., photo-orientation/alignment methods [8–11].

Moreover, apart from uniform orientation in which all molecules are oriented along one direction, special attention has been devoted to the cells with spatially modulated NLC structures forming, e.g., domains of a particular orientation or periodically repeated in space (periodic structures). Techniques allowing for an effective creation of the regions with a different molecular orientation inside an NLC layer are still intensively developed and in principle periodic regions of different orientation and interface between different orientational domains can be achieved by, e.g., the spatially structured electrodes (e.g., comb-shaped [12] and partially etched [13] ones) or with a special patterned alignment techniques (e.g., with use of rubbing [14] and photo-alignment [15] technology) to create planar orientation with the director direction changing in different regions. Such specific preparation of the NLC cell allows for the beam launched along the glass plates to interact with the boundaries within two regions of different molecular orientation, as well as for achievement of particular waveguiding effect inside. Specifically, reflection, refraction and separation of the light beams of different polarization have been realized at the interfaces and boundaries of two molecular orientation domains in LC [14,15]. Apart to the waveguide geometry (when LC material form a waveguiding layer), bulk geometry can be considered in an NLC cell when a distance between the glass plates is as much as tens of microns. It has been demonstrated that the self-focusing effect and the soliton-type propagation in such geometry can be obtained for the miliwatts of optical power thanks to reorientational nonlinearity [16–23]. Moreover, such solitary waves, called as nematicons, are able to form a waveguide channel in which, e.g., low-power beams (of different wavelength) can be optically trapped or change direction of their propagation [18]. In addition, interactions between nematicons [20,21], as well as their voltage-driven in-plane steering [22] have been successfully demonstrated, allowing thus for, e.g., optical switches and logic gates to be achieved in NLCs [23].

In this paper, development of the complementary methods based on the photo-orientation and photo-polymerization processes to form required liquid crystalline layers with a particular spatial distribution of refractive index have been presented. In the first method, a polymer material exposed to linearly polarized UV radiation has allowed to achieve sections of planar alignment in an NLC cell with varying angular orientation with respect to the propagation axis. In the second one, thanks to the photo-polymerization process applied, it has been possible to create LC regions with mutually orthogonal molecular orientation (i.e., planar and homeotropic). Both methods can be potentially applied to obtain light guiding structures in planar geometries with an accessible spatial resolution of single micrometers, as well as periodic structures (forming, e.g., waveguide arrays to study discrete light propagation [12] or 2D photonic crystal structures [6]). One of the challenges we aim by introducing photo-alignment and photo-polymerization processes in our liquid crystalline structures, is transformation of photonic elements and circuits with their operation to be practically independent from the electric bias (which was strongly required in our previous works, e.g. [12,21]).

2. Uniform and periodic NLC photonic structures defined by photo-orientation process

Photo-orientation and photo-alignment techniques are extremely important for LC-based photonic elements and applications development [8,24,25]. Initially dedicated mainly to LC displays technology, now feasibilities of forcing specific spatial orientation of NLC molecules are significant when applied for fabrication of functional photonic elements and devices, such as waveplates, phase retarders, polarizers, polarization converters, and polarization gratings [6,7]. Although intensive works on their synthesis are performed in many laboratories worldwide, photo-alignment materials are still practically unavailable commercially with exceptions of same products offered by the Rolic Technologies Ltd with their chemical composition constantly modified and with certain problems with homogeneity and radiation damage threshold. Anyhow, a special class of photo-alignment layers are those based on azo-dye materials as ones providing a uniform defectless alignment with sufficiently high anchoring energies [9,10,26,27]. Importantly, polymerized azo-dye photo-alignment layers are thermo- and UV-stable and can be applied both on glass and on plastic substrates forming NLC cells [27].

In this work we have decided to use one of the most promising photo-orienting material, known as SD1 [26,27]. Photo-orientation

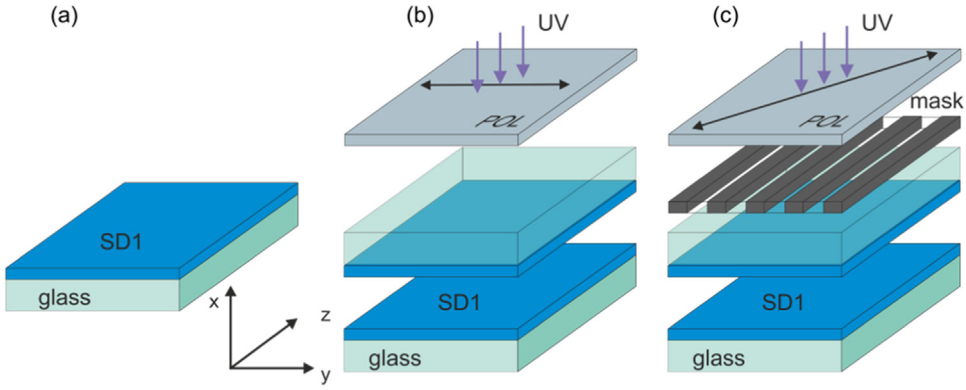

Fig. 2. (a) The azo dye SD1 material can be successfully used as a photo-addressable command layer for liquid crystalline materials when spin-coated on a glass substrate. (b) Photo-alignment with SD1 takes place in the direction perpendicular to polarization direction of the UV light. (c) Re-recording and erasure of previously recorded arrangement allows for variety of sophisticated alignment patterns to be achieved.

of SD1 material takes place in the direction perpendicular to the polarization direction of linearly polarized UV light (used for irradiation), as characteristic for photo-alignment processes taking place in azo-dye material systems [26], whereupon an orientation of NLC molecules follows the direction of alignment enforced by the photo-alignment layer. The main advantages of SD1 include: low exposure energy, extended spectral sensitivity to longer UV and even visible light, possibility of erasing previously recorded alignment pattern and its re-recording (allowing thus for sophisticated orienting pattern to be achieved in multi-step irradiation process), very thin uniform layers of the thickness of single nanometers, no insolubility in liquid crystalline materials. It is important that the orientation obtained with this material is fully reversible and can be cycled many times with no signs of degradation. All these features cause that the SD1 photo-alignment material has been proven as suitable for producing a large variety of NLC-based photonic components. Specifically, while SD1 molecules produce smooth and uniform structure with a thickness as thin as several nanometers (as controlled by the concentration of the azo-dye in an organic solvent), its capability to be effectively used as an orienting layers for NLCs on both glass [9] and plastic PES [28] substrates has been successfully demonstrated. With azimuthal anchoring energies of SD1 spin-coated on both types of substrates greater than 10^{-4} Jm^{-2} [26,28], what is fully comparable to anchoring strength of rubbed polyimide, NLC cells fabricated with the SD1 alignment layers show excellent alignment quality and electro-optical properties.

In order to obtain specific alignment of NLC molecules we have used a 0.5 wt.% solution of SD1 material in *N,N*-dimethylformamide (DMF) spin-coated on a glass substrates, dried on a hot-plate and then exposed to a linearly polarized UV light (@$\lambda = 450$ nm with the calcite Glan polarizer applied to get the desired direction of linear polarization) [26]. Specifically, for the NLC photonic structures shown in this section two different photo-orientation procedures have been applied. In order to obtain uniform and unidirectional alignment along *z*-axis, the glass substrates spin-coated by the SD1 solution have been illuminated with the linearly polarized light at the angle of 45° (in *yz*-plane) with respect to input facet of the NLC cell for 15 min at the 30 mW/cm^2. In order to create a periodic modulation of orientation a two-step irradiation process have been applied. In the first step, the glass substrate with the SD1 layer has been exposed to UV radiation to get uniform and unidirectional alignment along *z*-axis and thereafter, in the second step of irradiation process, the same substrate has been irradiated again trough an amplitude mask of desired (rectangular) pattern with a specific period (Fig. 2). In the second step the direction of a linear polarization of UV radiation has been rotated by the angle of 45° and the substrate has been illuminated for 25 s at the 700 mW/cm^2. This allows for creation of alternating regions with LC molecular orientation of 0° and 45° with well-defined widths and thus for creation of periodic waveguide structures in NLC layer, as described below.

After infiltrating the sample with a liquid crystalline material by a capillary action, when placed in between two crossed polarizers, it indicates uniform molecular orientation for one-step process (structures shown in Figs. 3 and 4) and areas of two states of orientation when two-step process has been applied, while the second UV exposure realigns the molecules at 45° with respect to the first irradiation (periodic structures shown in Figs. 5 and 6). Please note that the pattern photo-alignment has been previously demonstrated as performed with UV light [27,29] and also with visible radiation [27] for LC polymers (LCPs) and for NLCs.

In the first stage of an experiment nematic liquid crystal cell of the thickness of 30 μm with uniform molecular orientationof LC have been applied. The alignment layers, obtained by the proper irradiation of the SD1 material with UV light, ensure planar orientation in *yz*-plane (i.e., $\phi = 0$) with the initial molecular anchoring at $\theta = 45°$ with respect to the *z*-axis (Figs. 1 c, 3 a). Indium tin oxide (ITO) thin transparent electrodes deposited on the inner sides of an NLC cell have been applied to provide an adjustable low-frequency electric field for out of *yz*-plane reorientation of LC molecules. The NLC cell under consideration has been infiltrated with 6CHBT NLC [30]. The light beam from a linearly polarized laser source, operated at the wavelength of 1064 nm, has been focused to the waist of several micrometers and then launched into the NLC cell with its ***k*** vector oriented along *z*-axis. The CCD camera has been used to collect a light scattered above the NLC cell when the laser beam is launched inside. This part of the experimental setup (as marked by the horizontal rectangle in Fig. 3a) has been applied to analyze light beam propagation along the NLC cell, while its second part (framed by the vertical rectangle in the same scheme) allows for observation of the changes in light intensity when the NLC cell is placed between two adjustable polarizers and illuminated by the white light. The latter has been applied to check direction and quality of the molecular orientation in an NLC cell under consideration [31]. By using a high resolution CCD camera combined with a microscope lens it is possible to record the images of the NLC sample obtained in both parts of the experimental setup described above. Exemplary results achieved in this way in the analyzed NLC cell with particular alignment are presented in Fig. 3b–d. Firstly, photos of the top-view of the NLC cell taken for either TE- (with electric field parallel to *y*-axis) and TM- (with electric field parallel to *x*-axis) polarized low power (<1 mW) beam launched with the wavevector (***k***) aligned to *z*-axis are shown in Fig. 3b. As one can see, both light beams clearly diffracts and TE-polarized beam propagates at the angle of 5° with respect to ***k*** vector (what corresponds to walk-off [32]),

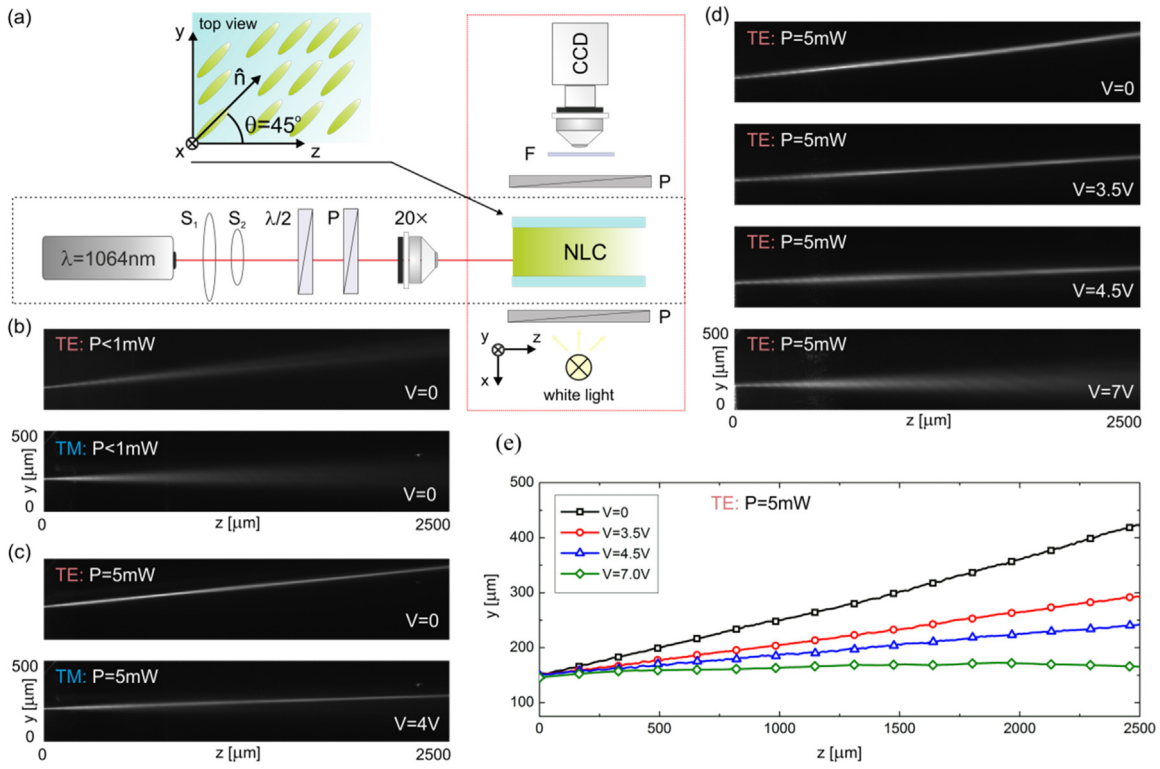

Fig. 3. (a) Scheme of the experimental setup composed of one section related to the characterization of the laser beam propagation along an NLC cell (bordered by a black dotted line) and the second one used to test white light transmittance through the LC cell placed between two polarizers (framed in red); (b) top-view of the NLC cell with low power (<1 mW) TE- and TM-polarized light beams launched along z-axis, respectively; (c) top-view of the NLC cell with TE- and TM-polarized light beam forming nematicons for the optical powers of 5 mW and in assistance of external bias of 4 V for TM-polarization, respectively; (d) top-view of the NLC cell with a voltage controlled soliton steering and (e) corresponding beam trajectory as a function of external bias.

whereas TM-polarized beam propagates parallel to ***k*** vector. When optical power increases to the value of 5 mW, TE-polarized beam is self-trapped to the form of nematicon (i.e., spatial soliton in NLC) while TM-polarized beam requires an assistance of the external electric field to form a self-focused beam. When a sufficiently high voltage is applied to the ITO electrodes the LC molecules are reoriented in *xz*-plane, changing thus the director orientation. Indeed, by applying an electric bias of 4 V (@1 kHz) it is possible to obtain a self-trapped beam of TM-polarization (Fig. 3c). It is worth noting that for TE-polarization, the electro-optical response of NLC makes the molecules to reorient out of *yz*-plane, correspondingly changing the principal plane (defined by ***k*** and ***n*** vectors) in which the Poynting vector lies, inducing thus the changes in the walk-off angle. It means that by increasing an electric bias applied to the NLC cell one can progressively reduce the walk-off angle (which goes to zero when the Poynting vector is collinear with the wavevector) observed in *yz*-plane for a TE-polarized beam, as it was previously reported by G. Assanto and co-workes [33]. It is equivalent to the modification of propagation direction of nematicons, as demonstrated in Fig. 3d, where experimental results for an extraordinary (i.e., TE-polarized) beam of the power of 5 mW and for different values of electric bias applied to the NLC cell are shown. The same results are presented comparatively in Fig. 3e, where the walk-off angle observed as a function of electric bias turns into a voltage-controlled nematicon trajectory. As one can see, the apparent walk-off angle decreases with the voltage until the latter reaches the value of 7 V for which the nonlinear response of NLC becomes too weak to form nematicon and the light beam propagates without the walk-off in a linear manner (i.e., it is diffracting).

To prove again that the light beams of the orthogonal linear polarizations behave in a different way when propagate trough the NLC sample prepared with the use of the photo-orientation technique, two parallel light beams of TE- and TM-polarization have been launched into the cell with their initial spatial separation of 100 μm (Fig. 4a and b). When no bias is applied, TE-polarized beam is self-trapped in a form of nematicon propagating at the angle with respect to direction of ***k*** vector as determined by the spatial walk-off effect, whereas the TM-polarized beam diffracts. In accordance to results shown in Fig. 3c–e, an increase in the electric bias allows for the self-focusing of the TM-polarized beam (Fig. 3c) and leads to the changes in trajectory of TE-polarized beam (Fig. 3d and e). When launched to the LC cell together, for the bias of 4.5 V, the orthogonally polarized beams propagate as nematicons (i.e., self-trapped beams) parallel to each other. It means that in the present configuration with properly adjusted value of applied voltage it is possible to observe both TE- and TM-polarized nematicons propagating independently in a NLC cell.

In order to create an array of the planar waveguide structures in an NLC layer we have decided to use a two-step irradiation process of an SD1 layer with linearly polarized UV light, as described above. By both changing the direction of linear polarization of UV radiation and using an amplitude mask of the comb shape with the predetermined pattern in the second stage of irradiation, it has been possible to obtain permanent domains of different molecular alignment with the easy axes mutually inclined at the specific angle. Importantly, creation of the optical waveguides in NLC layer requires the formation of relatively narrow region with the width of several tens of micrometers, characterized by a higher refractive index when compared to adjacent regions, acting here as a waveguide cladding. Specifically, in order to get photonic structures shown in Figs. 5 and 6, the two-step exposure has been applied as follows: first, the homogenous illumination with the linearly polarized light has been applied to specify the direction of azo dye alignment to be parallel to *z*-axis (green arrows in Figs. 5 and 6) and then the cell

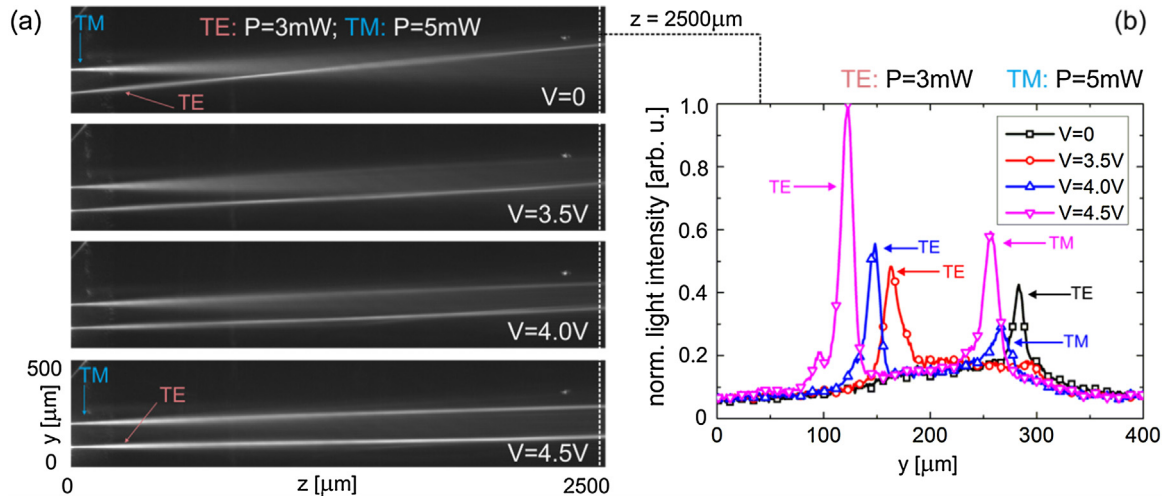

Fig. 4. (a) Top view of the NLC cell with two parallel laser beams of orthogonal polarizations for different values of electric voltage applied across the cell. (b) Normalized light intensity profiles at the output facet of the cell (i.e., for z = 2.5 mm) as a function of electric bias. For the voltage of 4.5 V beams create nematicons propagating in parallel to each other.

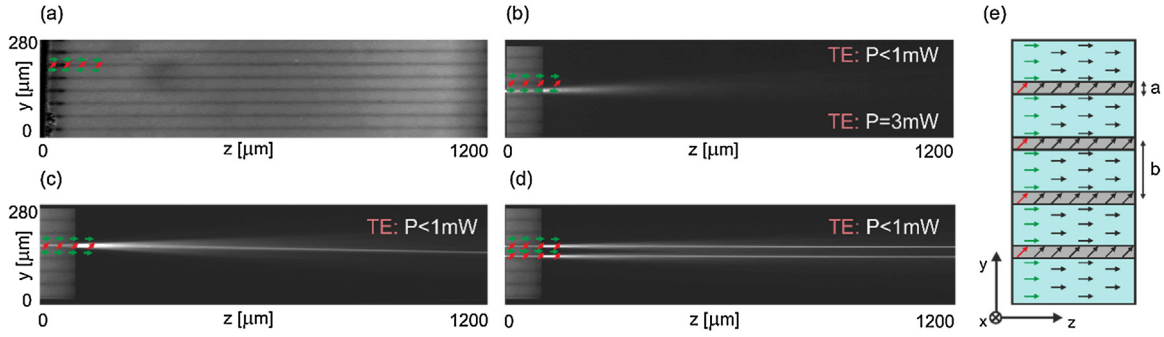

Fig. 5. (a) Periodic photonic structure made by the regions of different molecular orientation in a liquid crystalline material obtained thanks to a two-step irradiation of the orientation layer. Red and green arrows indicate molecular orientation direction (with orientation angle of 0° and 45° with respect to *z*-axis in *yz*-plane, respectively). (c) and (d) Propagation of the low power (<1 mW) TE-polarized beams launched into waveguide channel formed by regions in which molecules are oriented at the angle of 45° with respect to *z*-axis experiencing the waveguiding effect. (b) Low power light beam launched in between the channels diffracts, similarly to a TM-polarized beam launched in any place of the input facet of the sample (not shown here as it is exactly the same as presented in Fig. 3b). By increasing the input power up to 3 mW in this case does not change the propagation effect. Photos of the structure and the arrows indicating molecular orientation are presented in each case, while the scheme of the specific structure under consideration is shown in panel (e), where a = 15 µm, b = 65 µm, and the cell thickness is 17 µm.

has been additionally illuminated with the UV linearly light polarized with the angle of 45° (in *yz*-plane) with respect to previous orientation (what resulted in the orientation of 45° with respect to *z*-axis, as marked by red arrows in Figs. 5 and 6). It is worth to remind that in uniaxial birefringent medium, as it is in a case of NLC material considered here, the effective refractive index (n_{eff}) for linearly polarized light beam takes a value from the set limited by the ordinary (n_0) and extraordinary (n_e) refractive index which are characteristic for a particular liquid crystalline material at specific wavelength and temperature. The exact value of the effective refractive index depends on the angle between the director and the direction of the electric field vector of the electromagnetic wave. In particular, by assuming changes in molecular orientation taking place in *yz*-plane (i.e., for $\phi = 0$), the effective refractive index for TE-polarized beam can be determined in accordance to the following formula: $n_{eff} = n_o n_e [n_o^2 \sin^2\theta + n_e^2 \cos^2\theta]^{-1/2}$, where θ is an angle between molecular long axis and *z*-axis (here direction of $\boldsymbol{k}$ vector). By implementing the difference in the orientation angle of 45° for different regions, as achieved in two steps of irradiation process described above, it is possible to form a 1D periodic planar waveguide structure for TE-polarized light beam with the spatial refractive index modulation introduced in photo-orientation process (Fig. 5a). When the transverse dimensions of the region with higher refractive index is comparable with the wavelength and cell thickness, the linear polarized light beam guiding is ruled by a total internal reflection, like in classical waveguide. The huge anisotropy of NLC molecules combined with variable orientation in transverse direction obtained in the photo-orientation process enable to create described waveguide structures, which can oparate in both linear and nonlinear regime. In such a structure, low power (<1 mW) TE-polarized beam diffracts (Fig. 5b) when it is launched into the region with 0° molecular orientation (marked with green arrows) as it experiences ordinary refractive index, whereas it is confined in the waveguide channel formed in the area with higher refractive index (Fig. 5c) when it is launched into the region with a 45° molecular orientation (red arrows in Fig. 5). In general the independent propagation of two (or more) TE-polarized light is possible in such structure when the beams are launched into neighbouring channels independently (see e.g., Fig. 5d). It is worth noting that the NLC layer in an analyzed structure is considered as one with uniform effective refractive index distribution for TM-polarized light beam as the electric field of EM wave is perpendicular to the director orientation in whole region (i.e., orientation angle changes in *yz*-plane and thus the TM-polarized beam experience only ordinary refractive index in a whole NLC layer). However, it is worth noting that in a uniform structure of this form, waveguides can be

formed due to the nonlinear effects while nematicon creation that represents a fundamental mode of the self-induced waveguide, as presented above.

As it was in the case of the NLC cell with uniform orientation (Fig. 3), also here an external voltage applied to the NLC sample can be used as an additional factor to tune light propagation in the analyzed structure. External electric field applied along *x*-axis reorients molecules across the NLC cell. Fig. 6 shows experimental results obtained for 2.9 V, where this specific voltage have been chosen to be above Freedericksz threshold ($V_{th} \approx 1.3$ V) and also to be low enough to prevent coupling of the TE-polarized beam into the TM-polarized one. In this way, similarly to the case previously demonstrated (Figs. 3 and 4), TE-polarized light beam launched into the region with a 45°-orientation is confined in a waveguide channel due the higher refractive index in this area for both low (<1 mW) and high (3 mW) power, showing thus that there is almost no difference between linear and nonlinear beam propagation in such configuration (Fig. 6a and b). For a TM-polarized light beam with the power of 3 mW it is possible to create a self-trapped beam in assistance of external bias (2.9 V) both for the light beam launched into the region of 0° and 45° orientation with respect to *z*-axis (Fig. 6c and d). Fig. 6e and f presents a joint propagation of TE- and TM-polarized light beams when launched into regions of 45° and 0° orientation, respectively. When the optical power of a TE-polarized beam increases to the value of 5 mW, the changes in the molecular orientation induced by the beam modifies the refractive index distribution in such a way that the TM-polarized beam changes direction of its propagation (Fig. 4f).

The flexibility and tunability of the optical system under study combined with nonlinear response of NLC molecules have been checked by changing the linear polarization direction of the UV light used in the second step of irradiation process and by modifying thus the index contrast in the waveguiding structure. In the tests, starting from the initial orientation along *z*-axis, the orientation angle has been brought to different orientations using 15° increments. Fig. 7 shows the dynamics in the light propagation for two beams launched in parallel to different periodic structures formed in a NLC layer.

Specifically, propagation of nematicons created by two TE-polarized light beams launched independently to the waveguide channels formed in the regions of 45° orientation for a different NLC molecular orientation in the space between them (with the orientation angle varying from 0° to 30° with respect to *z*-axis, as marked by green arrows) has been analyzed. As already demonstrated for spatial solitons in nematic liquid crystals, their "interaction" – in sense of changing in propagation trajectories experienced during their joint propagation trough the liquid crystalline material – may result in the collision (crossing the paths) when initial separation is small enough and for proper distribution of refractive index ina NLC layer [21,34]. This interaction highly depends on the coupling between neighbou ring waveguides and refractive index profile deformations and is limited by the range of the nonlocal reorientational nonlinearity. In this sense, the distance (measured along *z*-axis) between input facet of the NLC cell and the first collision point may be used to indicate the strength of the interaction between two nematicons (i.e., shorter the distance stronger the interaction). This characteristic length of the NLC response can be modified by changing the voltage [35,36] or via a beam optical power [21]. Specifically, a voltage controlled interaction between nematicons has been demonstrated in planar NLC cells, both with uniform voltage applied across it [35], as well as in one with comb electrodes [36]. In the first case, the interaction between nematicons has been controlled by a degree of nonlocality modulated by the electric voltage applied, while in the second case the in-plane solitons interactions vs. nonlinearity (while keeping nonlocality constant) has been investigated by taking advantage of periodic electrodes used in the system.

In this work we have decided to take advantage of the periodic photonic structure in an NLC layer obtained in a two-step photo-orientation process ensuring thus easy modification in depth and width of the refractive index profile, influencing thus the interaction between solitons in NLCs. Fig. 7 shows exemplary experimental results obtained for interaction of two nematicons in a periodic structure under consideration. The initial separation of two beams, with an optical power of 30 mW each, is defined by the grating period and it is equal to 50 μm and it is larger than a cell thickness which is of 30 μm in this case. When the angle of the molecular orientation in a region between two waveguide channels is set to 0° (what corresponds to the molecular orientation along *z*-axis), the "attraction" between two nematicons is almost absent and the beams propagates independently (Fig. 7a). For an angle of the molecular orientation in the regions surrounding the waveguide channels is changed to 15°, a decrease in the refractive index contrast (for TE-polarization) causes the interaction between two nematicons to be observed, while two beams attract each other (Fig. 7b). By further decreasing the index contrast (i.e., due to change in molecular orientation in the cladding region) it is possible to get stronger beam interaction (Fig. 7c).

3. Periodic structures obtained due to photo-polymerization

The second possible option to get periodic photonic structures in NLCs is to take an advantage of a photo-polymerization technique in order to achieve regions with different molecular orientation. Specifically, LC polymer (LCP) composites which are in principle composed of LC material and monomer mixed with it, are an important modification of LC assemblages while offering higher flexibility and functionality than achieved in pure LC systems. Recently, polymer dispersed/stabilized NLCs and polymer-stabilized blue phase liquid crystals are appearing as very promising candidates for new applications in photonic systems. Depending on the monomer concentration one can categorize LC polymer composites as: (i) polymer-dispersed LCs [37], (ii) polymer-stabilized LCs [38], and (iii) polymer-network LCs [39], with monomer percentage of: (i) more than 20 wt.%, (ii) less than 10 wt.% and (iii) between 10 and 20 wt.%, respectively. The anchoring effect achieved in such polymer networks allows for some practical photonic applications in a form of, e.g., micro-lenses with relatively fast response time (when compared to pure NLC micro-lenses) [39–43], but the domains size in the networks has to be carefully adjusted (e.g., by changing monomer concentration) to avoid high light scattering [44]. Moreover, polymer network stabilized LCs have attracted increasing interest due to their potential applications in photonic devices such as displays and light shutters [4].

In this work we have decided to use a polymer-stabilized NLC to form distinguished regions of different molecular orientations in an NLC cell, while using comb-shaped photo-mask during UV irradiation. Specifically, a diacrylate monomer, namely RM257 [43], with a rod-like structure (similar to this of LCs) and with reactive double bonds at both ends of the chain, has been applied with its concentration kept to be 10 wt.% or less. RM257, as a liquid crystal monomer, exhibits optical and electrical anisotropies as it is for NLCs and thus by combining it with nematic LC one can expect increase in the birefringence of the resultant mixture.

Fig. 8a shows the schematic structure of an NLC cell with initial planar orientation of LC molecules determined by the polyimide (PI) alignment layers rubbed in anti-parallel directions, forcing thus the director to be aligned along the substrates, i.e., parallel to *y*-axis. While the inner surfaces of the glass substrates are properly

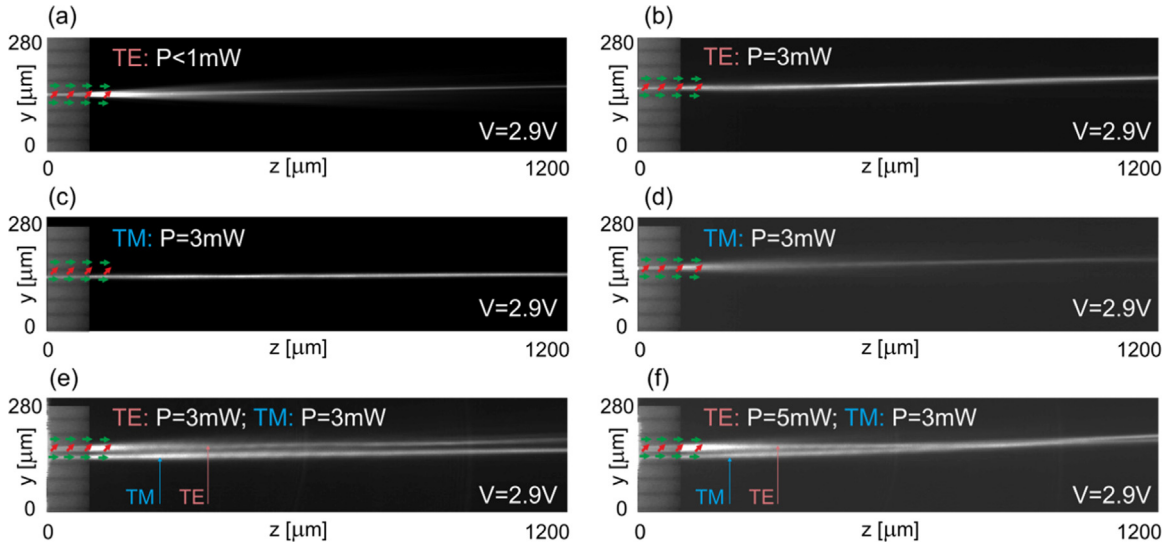

Fig. 6. Propagation of low (a) and 3 mW (b–e) power beams of TE- and TM-polarization in periodic photonic structure in assistance of electric bias of 2.9 V. In all cases beams do not diffract due to waveguiding phenomenon and/or nonlinear effect related to reorientational nonlinearity in NLC. The periodic photonic structure formed in an NLC layer is the same as in Fig. 5e.

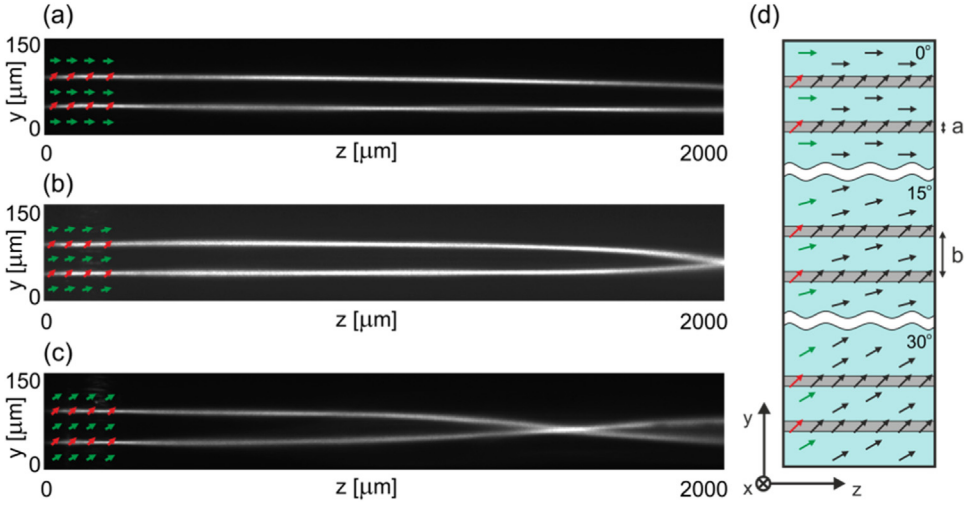

Fig. 7. Two beams of TE- polarization launched to the waveguide channels formed in NLC material. Changes in molecular orientation in the region between the channels, with the orientation angle varying from 0° to 30° (with the step of 15° as indicated by green arrows), leads to change in index contrast and thus to different effects of nematicons "interaction". In all cases geometrical parameters of the photonic structures are the same and characterized by the channel width a = 15 µm and the distance between channels b = 50 µm. The thickness of NLC layer is equal to 30 µm.

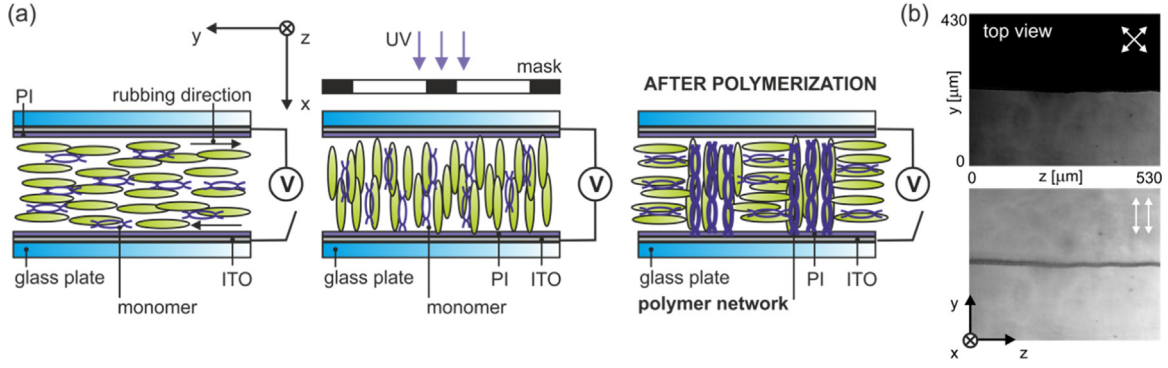

Fig. 8. (a) Scheme of the photo-polymerization process in an NLC layer leading to the periodic structure creation: (i) glass cell with planar orientation (introduced by the rubbing in the polyimide layer) is infiltrated with NLC mixed with monomer; (ii) after molecular reorientation taking place due to the high electric bias applied to the cell, the NLC/monomer mixture is illuminated (trough the periodic mask of desired geometry) with unpolarized UV radiation; (iii) thanks to the photo-polymerization process it is possible to "freeze" molecules in fixed orientation – in this way it is possible to obtain two separated regions with orthogonal orientations of NLC molecules. (b) Two domains of different molecular orientation formed in NLC thanks to the photo-polymerization process schematically described above, when the mask covers the lower half of the sample section shown in the photo. NLC cell of the thickness of 10 µm (as determined by teflon spacers placed between the glass substrates) has been analyzed between two crossed and parallel polarizers when illuminated by the white light, respectively.

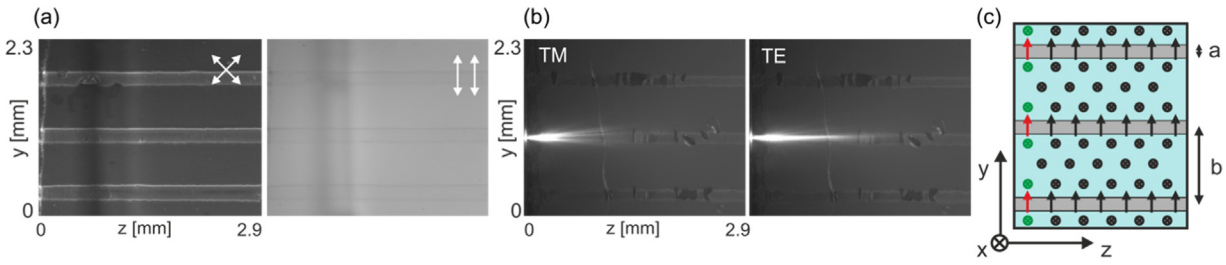

Fig. 9. (a) Periodic structure obtained in an NLC cell for the special mask applied when irradiating the cell with UV light, as observed trough two (crossed and parallel) polarizers. (b) Propagation of low power beams with orthogonal polarizations when launched in the channels of planar orientation. (c) The scheme of photonic structure obtained thanks to the photo-polymerization process taking place in NLC layer. Geometrical parameters are of: a = 180 μm and b = 740 μm.

prepared by the rubbing technique, one can assume that for the LC/monomer mixture filled to the cell (with its thickness kept in the range of single microns as determined by the spacers) both LC molecules and monomers are aligned along the same direction. Thanks to transparent ITO electrodes deposited on the glass plates and for high enough values of applied voltage (much above the threshold value, i.e., with the AC square amplitude of 30 V in the 10 μm-thick NLC cell used here) it is possible to get the molecular reorientation from the initial planar to the vertical one. In this specific configuration UV irradiation trough the photo-mask has been performed. In the analyzed case, the NLC/monomer mixture has consisted of 4.16 wt.% of RM257 monomer and 94.88 wt.% of E7 nematic LC [45], as well as a small amount of photo-initiator (0.97 wt.%). When the mixture has been exposed to unpolarized UV irradiation, its highest intensity in unblocked region initiates the polymerization process in this region (please note the gradient of the light intensity close to the edges of the amplitude mask). During irradiation the double bonds of the monomer are opened and the molecules, which are linked together, may form a stable polymer network.

It means that after UV stabilization (performed when external bias is on) the NLC domains are tightly sealed in the film due to the cross-linking of the monomer, forming thus the regions of different molecular orientation. The photo-polymerization process performed with use of the amplitude mask of desired geometry allows to “freeze” some NLC molecules in a given position even when the voltage is off, whereas the initial planar alignment in the adjacent region (covered with the mask during irradiation) is retained. In this way, taking the advantage of the anchoring effect in a polymer network formed in an NLC layer, it is possible to create neighbouring regions having the orthogonal (planar and homeotropic) molecular orientation. Such specific section of the NLC cell examined under crossed and parallel polarizers is shown in Fig. 8b.

Fig. 9b shows the propagation of the linearly polarized light beams within an NLC layer with desired periodic distribution of refractive index as obtained after polymerization process. Specifically, the light intensity for TE (*y*-polarized) and TM (*x*-polarized) light beams are presented. For both beams the effective refractive indices in two domains in NLC are different as determined by the relative angle between LC director and the electric vector of the electromagnetic wave and the index contrast for two regions distinguished in the NLC layer is as high as optical birefringence of the LC mixture. In a case of the structure presented in Fig. 9 only TE-polarized beam can be trapped in the channel where it is launched while it experiences extraordinary refractive index in this region.

4. Conclusions

In this work we study changes in a linearly polarized light beam propagation as an effect of passing through the regions of a liquid crystalline layer with different molecular orientation. The latter can be successfully created thanks to particular boundary conditions achieved via photo-orientation or to photo-polymerization process allowing for stabilization of LC orientation in a particular direction. These two techniques allow to create distinguished regions of different molecular orientation in which effective refractive indices for light beam with particular direction of linear polarization are different. The advantages of an LC photo-alignment and photo-polymerization technologies described here when compared with typical rubbing alignment methods applied so far, suggest that proposed techniques are suitable for research development in the subject of LC-based photonic devices. In particular, as demonstrated here, such periodic waveguiding structures can be easily applied to change the effect of solitons interactions. Specifically, by slightly changing the molecular orientation in the neighbouring regions (which are in micrometers range), what is well-controllable when proposed photo-orientation process is applied and cannot be so easily achieved with use of a standard rubbing technique, full control on the range and strength of the solitons interactions can be achieved. It means that by a proper adjustment of the LC cell parameters – in sense of differences in effective refractive indices in the adjacent sections of the LC layer – fully controllable and predictable effect of the solitons interactions can be achieved. It results in a specific position of the light beams at the output of the liquid crystalline cell what is crucial for further potential applications even if not strictly demonstrated in this paper. However, an example of effective refractive index difference dependent x-junction performing a power controlled interchange of the input channels for soliton propagation is presented in Fig. 7. As far as results of the solitons interactions in nematic liquid crystals are well-known and already demonstrated as suitable for practical photonic applications in form of, e.g., all-optical steering, switchers, x-junctions, AND and NOR gates [23], it has to be underlined that so far they have been shown mainly in LC cells with molecular orientation defined by means of the rubbing technique and with an assistance of the electric field (with electrodes of sophisticated shapes and geometries often required) [16]. Such standard technique of an LC cell preparation has its obvious limitations and in principle does not allow to achieve complex structures (with spatial periodicity in the range of micrometers) of the molecular arrangement in such easy way as provided here. In particular, proposed molecular orientation of 45° with respect to transverse *y*-direction gives an additional degree of freedom which allows for forming waveguide arrays without assistance of the external electric field. In addition, photo-polymerization technique (commonly applied to stabilize liquid crystalline materials in so-called blue-phase) and its application to create waveguiding structures in liquid crystalline material can be also interesting from applicative point of view. Regions of polymerized LC can potentially act as relatively easily achieved waveguide arrays that can be used for many purposes in photonic structures, e.g., for trapping solitons in the regions where their power is too low to allow for their further propagation. What has been proven in this paper is that proposed technologies, leading to creation of well-defined micrometer-scale regions with specific molecular orientation in a liquid crystalline layer, are reliable and

worth to be developed. Certainly, their practical applications in a form of functional devices such as couplers, switchers, junctions, etc. must be carefully designed, fabricated and examined before their actual demonstration. In this sense, proposed solutions allow for further miniaturization and simplification of the design, as well as its possible independence from an external electric bias.

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