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Optical induction of Bessel-like lattices in methyl-red doped liquid crystal cells

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A B S T R A C T

The optical induction of annular photonic lattices by a traveling Bessel beam has been investigated in Methyl-red (MR) doped nematic liquid crystal (LC). Non-diffracting Bessel beams were formed by an axicon. The induced Bessel-like lattice had a ~15 μm period in the radial direction. The lattice was tested by measuring the forward diffracted power of the recording Bessel beam. The dependency on the angle between the polarization of the laser beam and the director of the LC and on the axial position of the LC cell had been investigated. A diffraction efficiency of 14% had been obtained. Investigations have been performed for different MR dye doping concentrations. An erasure time of the lattice of 60 s has been determined by a 532 nm probe Gaussian beam of 2 mW in a LC cell with MR dye concentration of 1.15 wt%. The induced periodically varying refractive index in the LC medium is analogous to microstructured fibers and allows the study of light localization and soliton behavior in highly nonlinear waveguide arrays.

1. Introduction

Photonic materials with artificial spatial periodic structures offer new possibilities to route, control, and steer light in all-optical information processing and nanophotonic devices. Therefore, materials with periodic refractive index modulations have become the subject of extensive research [1,2]. While different fabrication methods, such as lithography or direct laser writing, have been utilized to produce permanently fixed periodic structures (photonic crystals), some future applications certainly require increased flexibility and the possibility to tune and adapt photonic lattices in real-time. The optical induction of photonic lattices in photosensitive materials (holographic technique) is relatively simple, flexible and very promising [3–8]. The illumination of a photorefractive medium by an optical beam with spatially modulated intensity leads to a refractive index modulation, thus creating refractive lattices, with relatively lower refractive index contrast compared to solid-state photonic crystals.

Some of the most promising materials for refractive lattices formation by holographic techniques are photorefractive crystals [3,4,9], liquid crystals (LC) [10,11] and composite polymer materials, including polymer dispersed [12] and polymer stabilized liquid crystals [13–15], photopolymerizable sol–gel glass [16] and its modifications [17–19], as well as atomic vapor [20]. The light-induced material structuring on the one hand and the influence of structured media on the propagation characteristics of the light on the other hand lead to the concept of optically induced photonic refractive lattice structures (photonic lattices) [8]. Recently suggested non-diffracting Bessel traveling and standing wave methods have been used for the formation of 1D Bessel-like and 2D complex photonic lattices in photorefractive crystals [21]. Non-diffracting optical beams appear as a special class of linear waves propagating in the free space without any distortion [22]. In particular, the non-diffracting Bessel beams with transverse intensity distribution, expressed by the zero-order Bessel function are very promising for the formation of annular photonic lattices. Such lattices, in turn, are very promising for spatial soliton formation. The presence of a periodically varying refractive index in a medium affects the propagation and localization of the optical beams, and many recently observed new effects are associated with the soliton dynamics in periodic waveguide arrays [23]. Many novel effects have been predicted to occur in non-diffracting Bessel-like ring optical lattices [24], and the first experimental results on soliton formation in ring lattices have been obtained in Ref. [25]. Due to their annular symmetry, such lattices represent a good analogy to microstructured fibers and allow the study of the light localization and soliton behavior in highly nonlinear ring-type fibers.

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LC is a convenient material for optical induction of rewritable photonic lattices due to their high nonlinearity. These materials have mostly been used in input devices suitable for supplying images or bit-pages into displays or holographic optical systems [26,27]. However, their role may be wider, in particular, for the formation of refractive lattice structures. The illumination of a LC medium by intensity modulated light can lead to the corresponding refractive index change due to high nonlinearity of LC.

The optical nonlinearity due to optical induced reorientation of the director can be enhanced drastically when absorbing dye molecules are dissolved in liquid crystal [28–31]. A small amount (less than 1%) of dye dissolved in nematic LC can enhance the reorientation by almost two orders of magnitude and, in some cases, even change its sign [30]. Simoni and co-workers have pointed out that the observed huge reorientation effect in a LC–dye mixture is due to light-induced modifications at the aligning surface [31].

It has been shown that methyl red (MR)-doped nematic LCs exhibit a nonlinear optical response that is several orders of magnitude larger than in other organic and inorganic materials. A nonlinear coefficient n_2 of the order of 1 cm^2/W or even higher can be observed in these materials without application of a dc bias field [32–34]. This extraordinarily large nonlinear response opens new opportunities for the application of nematic LCs, in particular, in the field of adaptive optics.

While the Bessel traveling and standing wave techniques for the formation of annular and complex refractive lattice structures in photorefractive media have been studied in details for doped $LiNbO_3$ crystals in [21], the application of this method to LC media is promising due to numerous applications of structured LC medium with extra-high nonlinearity.

In this paper we report the optical induction of annular photonic lattices by traveling Bessel beam method in MR-doped LC cell. The recording and the testing of the Bessel-like lattice is performed simultaneously with the use of a single mode 532 nm laser beam.

The lattice was tested by the same recording Bessel beam by measuring the forward diffracted power during the optical induction. The dependency of the diffraction efficiency on the beam polarization direction with respect to the LC cell alignment direction and the dependency on the LC cell position along the axial direction in the Bessel beam zone during the recording process have been studied. The investigations were performed for different MR dye doping. The erasure time of inducted lattices was also measured.

2. Experimental part

2.1. Sample preparation

The liquid crystal employed in our experiments is the nematic E7 LC mixture from Merck which consist of a blend of 50.6% 4-pentyl-4′-cyanobiphenyl, 25.2% 4-heptyl-4′-cyanobiphenyl, 17.8% 4-octyl-4′-cyanobiphenyl, and 6.4% of 4-pentyl-4′-cyanoterphenyl with a clearing point of about 58 °C. The mixture is doped with methyl red at different concentrations: 0.85 wt%, 0.996 wt% and 1.15 wt%. Glass substrates are cleaned thoroughly. A thin film of nylon 6-6 is spin-coated and then unidirectionally rubbed to align the LC.

Finally, the cells are filled by capillary force. One of the prepared cells filled by LC–dye mixture is shown in Fig. 1. Fig. 2 shows the absorption spectra for light polarized parallel or perpendicular to the LC alignment direction. The strong anisotropy arises from the high degree of alignment of the dye molecules in the liquid crystal.

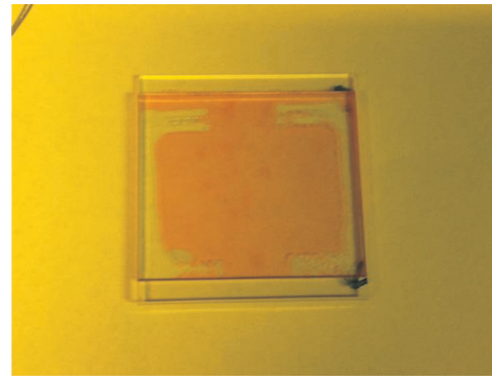

Fig. 1. Cell with spacers of 20 μm filled with E7 LC mixture doped with MR.

2.2. Bessel beam formation by an axicon and optical induction of Bessel-like lattices

A Bessel beam represents a particular solution of the wave equation such that the beam transverse intensity distribution remains invariant along the propagation direction z. A Bessel beam can be formed by superposition of an infinite number of plane waves lying on a cone. In past years, a number of practical ways to generate Bessel beams have been suggested including the use of ring apertures [35], Fabry–Perot interferometers [36], programmable phase modulators based on the phase-imprinting technique [37], and holographic diffractive elements [38]. One of the simplest methods of Bessel beam formation is the use of an axicon [39]. It is worth to mention also some recent 3D lithography approaches for the generation of micro-axicon lenses [40–42].

In our experiments, a beam from a diode pumped green laser (532 nm) with 59 mW power was expanded and transmitted through the axicon (Del Mar Photonics AX-BK-7-175) with an aperture cone angle of 175° (Fig. 3a). The Gaussian beam after passing through the axicon was transformed into a Bessel beam (Fig. 3b and c).

The distance from the axicon apex where beams are overlapped and form the Bessel beam (Fig. 3a) was measured Z_{max} ~20 cm. The beams become divergent behind the overlapping zone Z_{max} and form a ring pattern (Fig. 3d).

The Bessel structure was enlarged by a microscope objective and projected onto the screen. The enlarged pattern was recorded using a digital camera with 8 Megapixels resolution.

The spacing between the concentric rings is equidistant, except for a few central rings. The spacing between the concentric rings can be varied by moving the output lens of the beam expander back and forth thus varying the convergence angle of the beams behind the axicon. The number of rings depends on the Z distance in the overlapping zone.

Fig. 3b and c shows the experimentally obtained transverse intensity distribution of the Bessel beam in the overlapping zone at $z=3$ cm (b) and a fragment of the Bessel distribution at $z=13$ cm (c) distance from the axicon apex. The size of the Bessel beam at the half-distance $Z_{max}/2=10$ cm, where the number of rings is maximum, is equal to 6 mm and the spacing between the concentric rings was measured to be ~15 μm. This results in a maximum number of rings up to 400.

The recording was performed at different positions of the MR doped LC cell along the Z axis inside the Bessel beam zone.

The intensity distributions formed by a traveling Bessel beam (Fig. 3b and c) can be imparted into the LC medium via the optical nonlinearity. A quasi-local reorientation of the director results from this modulation. The dye-enhanced interaction exhibits a very high nonlinear coefficient. The duration of recording is