Current Applied Physics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Current Applied Physics

journal homepage: www.elsevier.com/locate/cap

# Tunable optical vortex arrays using spontaneous periodic pattern formation in nematic liquid crystal cells

L.K. Migara, Cheon-Myeong Lee, Keumcheol Kwak, Heesu Lee, Jang-Kun Song*

*School of Electronic & Electrical Engineering, Sungkyunkwan University, Jangan-Gu, Suwon, Gyeonggi-do 440-746, South Korea*

ARTICLE INFO

*Keywords:*
Optical vortex array
Liquid crystals

ABSTRACT

Controllable liquid crystal (LC) defects can provide an effective approach to creating tunable optical vortices. We develop a method to create tunable matter vortex arrays in an LC cell, in which $+1$ and $-1$ defects are periodically arranged in a square grid lattice. Spontaneous formation of the periodic defect array is achieved using a spontaneous standing pressure wave without using any patterned electrode or patterned alignment layer. The $+1$ and $-1$ defects in the array can induce optical vortices with opposite handedness, and the matter vortex array produces a periodic optical vortex array with orbital angular momenta of $-2\hbar$ and $+2\hbar$ in the same grid lattice. Because the pitch of the grid can be controlled, the method can provide a useful pathway to producing tunable optical vortex arrays for various applications such as advanced optical communication and quantum computation.

## 1. Introduction

Interestingly, traveling monochromatic light can possess not only spin angular momentum but also well-defined orbital angular momentum (OAM) [1–4]. The spin angular momentum is related to the circular polarization of the light, and the OAM is related to the spatial phase profile on the plane orthogonal to the k vector. The OAM of a beam, which is denoted as $m\hbar$, has a spatial helix with $|m|$ intertwined surfaces [2,5]; thus, the beam is called an optical vortex and has a topological phase singularity along the helix axis [6]. $|m|$ is referred to as the orbital helicity of the beam or the charge of the vortex. Optical vortices have attracted increasing interest owing to their potential applications in various fields, such as optical tweezers [3,7,8], the search for extrasolar planets [9], wave front sensors [10], quantum computation [11], and, in particular, optical communication [12,13].

There are many methods to generate optical vortices, and one of easiest is to use a q-plate, which converts circularly polarized light to an optical vortex with OAM [2]. A liquid crystal (LC) film with a point defect can serve as an excellent q-plate for generating optical vortices owing to the anisotropic nature of LCs [2,6,14]. Because defects in an LC medium are usually unstable and uncontrollable [15], intensive effort has been made to create stable and controllable defect structures in LCs using various methods including photo-alignment, holography, and LC droplets [16–18]. An LC light valve can be used to create well-controlled nematic director profiles to manipulate dense arrays of optical vortices with arbitrary and reconfigurable geometric distributions [19]; however, this requires an expensive spatial light modulator. Self-assembled defect arrays in smectic LCs were used to induce an array of optical vortices [20] in which the smectic defect array is stationary rather than electrically controllable. Thus, finding a way to easily and precisely control LC defects can be a promising technology to produce controllable optical vortex arrays. Our group recently developed a novel technology to induce a periodic LC vortex array using mechanical standing waves by applying pulse train signals in a vertically aligned LC cell [21]. The periodic pitch of the nematic vortex array depends on the frequency of the electric field and thus can be used to induce controllable optical vortex arrays.

In this study, we demonstrate that a mechanical-standing-wave-mediated nematic LC vortex can produce an optical vortex array. We clarify the director distribution in the LC vortex array, in which three types of LC defects are spontaneously formed: two types of $+1$ defects with left and right circular director orientations and a $-1$ defect. The $+1$ defects produce an optical vortex with $m = -2$ for the right circularly polarized input beam, and the $-1$ defect creates one with $m = +2$ for the same input beam. The experimental results accord well with theoretical simulation results. The LC vortex arrays are stable and reconfigurable, which makes them useful in potential applications using an optical vortex.

## 2. Experimental

An LC mixture, MLC7026 (Merck Co., Korea) having a negative

* Corresponding author.
*E-mail address:* jk.song@skku.edu (J.-K. Song).

https://doi.org/10.1016/j.cap.2018.04.005
Received 6 February 2018; Accepted 6 April 2018


Please cite this article as: Migara, L.K., Current Applied Physics (2018), https://doi.org/10.1016/j.cap.2018.04.005

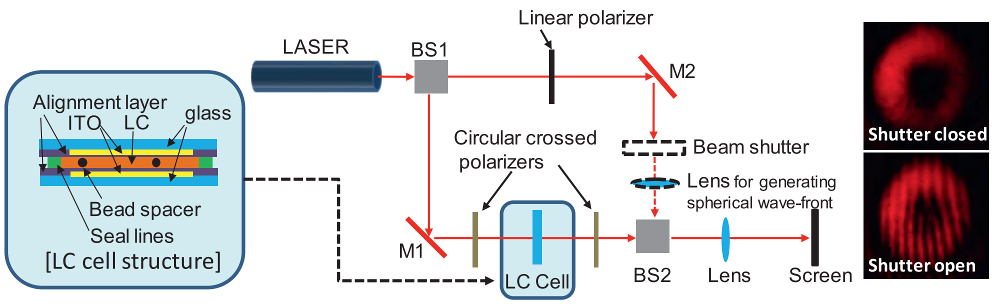


**Fig. 1.** LC cell structure (left) and experimental set-up (right) for optical vortex generation using an LC cell. BS and M indicate beam splitters and mirrors, respectively. Opening the beam shutter induces the interference pattern of the vortex under linear polarized light.

dielectric anisotropy ($\Delta\varepsilon = -3.9$) was used, and 0.2 wt% of a chiral dopant, R811 (Merck Co., Korea) with a helical twisting power of ~11 $\mu m^{-1}$ was added to the mixture. LC cells were prepared by sandwiching the LC mixture between two glass substrates with square indium tin oxide electrodes ($2 \times 2$ $cm^2$). The substrates were coated with a commercial vertical alignment layer, AL60101 (JSR, Japan) but were not treated by a rubbing process. The cell thickness was maintained at 3.5 μm by bead spacers that were randomly distributed within the cell, and the LC layer was sealed by a surrounding polymer seal lines (Fig. 1).

The experimental setup is illustrated in Fig. 1. To create an optical vortex, a circularly polarized laser beam was sent to an LC cell with defects and then passed another circular polarizer with opposite handedness. The beam shape was observed on a screen after the beam size was magnified using a lens. To analyze the phase geometry of the beam, the vortex beam was interfered with a reference Gaussian beam having linear polarization. By opening or closing the beam shutter in the experimental set-up, the beam profiles of the optical vortex and the interference pattern were selectively observed.

## 3. Results and discussion

When square-wave electric fields were applied across the LC layer, random textures appeared because the LC directors in the cell without rubbing treatment were likely to be randomly oriented (Fig. 2(a)). Microscopic observation showed that umbilical defects were present, but the densities and positions of the defects were random and uncontrollable (inset in Fig. 2(a)). When the electric field signal was changed to a pulse train signal, two-dimensional periodic patterns were spontaneously formed (Fig. 2(b)).

The phenomenon is caused by a series of chain reactions between molecules and a standing pressure wave. The pulse train signal (20 V, 15 Hz, pulse width:off time = 1:7) induces periodic collective motion of the molecules; the periodic molecular motion induces periodic backflow, which causes pressure waves in the LC cavity. The pressure waves form a periodic standing pressure wave owing to the square boundary condition, and finally, the standing pressure wave reorients the director profile to form a periodic circular vortex arrangement, as shown in Fig. 2(c). The use of chiral dopant eliminates the creation of some of micro domains and helps to create uniform and regular defect arrays [21]. This is a unique phenomenon; the details of the underlying mechanism will be discussed elsewhere [21], and here we focus on the director profile in the cell and its use for optical vortex formation.

During application of the pulse train signal, the LC directors periodically fell and rose, causing periodic blinking, which makes it difficult to use the defect array as a stable optical vortex inducer. When the pulse train signal was switched back to a square-wave electric field (usually 6 V), the periodic pattern was stabilized without vibrational motion of the directors. Although the square wave does not have any driving force to reinforce the LC defect array, the defect array itself is in

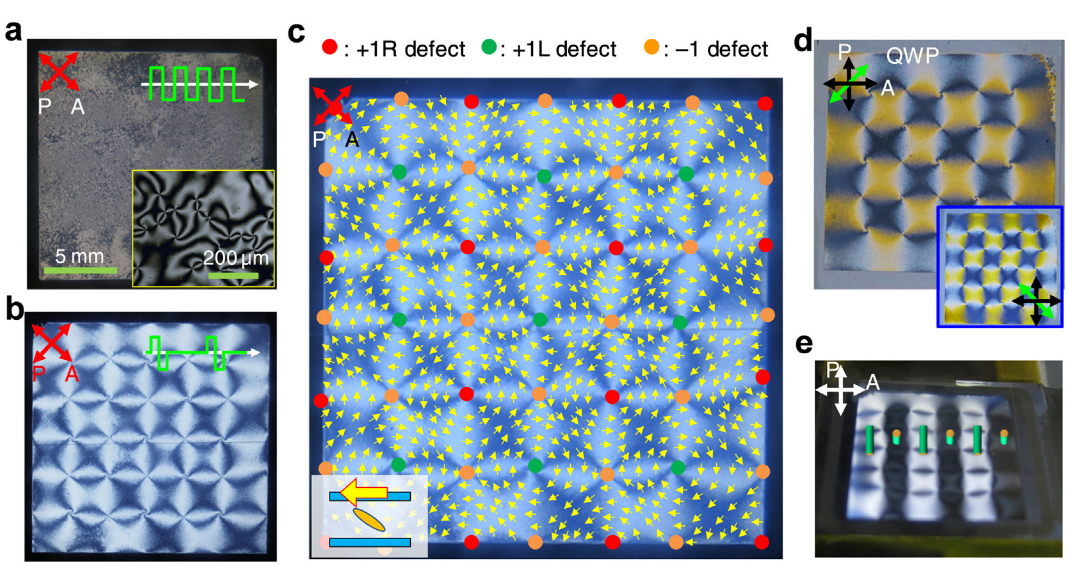


**Fig. 2.** Periodic defect array and director profile determination. (a) Random texture under square-wave electric fields and umbilical defects (inset). (b) Periodic defect array and (c) director profiles under pulse train signals. The yellow arrows indicate the mean director tilt direction (see the inset at the bottom). +1R and +1L defects represent +1 defects with right-handed (anticlockwise) and left-handed (clockwise) vortex orientations, respectively. (d) Determination of director profile in top view using optical compensation film and (e) director tilt direction obtained by oblique observation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)