Nanophotonic Microlens Array

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Abstract—We demonstrate a nanophotonic device fabricated with multiwall carbon nanotubes as electrode sites on a silicon or quartz substrate, covered with nematic liquid crystal. The device acts as a switchable microlens array. Electro optic characterization of the device is presented while discussing potential applications.

Keywords-nanophotonic; carbonnanotube; liquid crystal; microlens array

I. INTRODUCTION

Carbon based nanoparticles are a promising technology because of their excellent electrical properties and strong interaction with the aromatic mesogenic groups of liquid crystals. Jeong et al. [1] showed the formation of unusual double-four-lobe nematic textures in a carbon nanotube-doped liquid crystal under the application of an external voltage. From the hybrid combination of carbon nanotubes and liquid crystals, it has been found that there is a strong interaction between carbon nanotubes and liquid crystals despite the size difference between liquid-crystal molecules (1–2 nm) and carbon nanotubes (a few nanometers to micrometers). This interaction can be interpreted as an optical interaction through the optical anisotropy of the liquid crystal. Hence carbon nanotubes attached to a surface of a substrate in a liquid-crystal cell can be used to form electrodes and defect centers in the medium, and the liquid crystal can be manipulated by applying an external electric field. Based on this technique, an electrically reconfigurable nanophotonic device has been fabricated with light modulation capability [2]. The carbon nanotube electrode arrays were grown on silicon and quartz substrates by plasma enhanced chemical vapor deposition after employing e-beam lithography to nickel catalyst layer into an array. This allowed the growth of a single multiwall carbon nanotube of around 50 nm diameter at each point in the array [2]. Then the nanotubes on the silicon substrate were sputtered with 100 nm thick aluminum and on quartz substrate with 100 nm thick boron oxide for an electric contact between the nanotube array. The nanotube array was then assembled with a top electrode containing indium tin oxide on 0.5-mm-thick borosilicate glass into a cell filled with nematic liquid crystal (BL048) using a 20 um cell gap set by spacer balls in UV glue. The top electrode alone was given a planar alignment by rubbing a thin film of polyimide and hence the resultant alignment of the device was hybrid. The device fabricated on the silicon substrate operated in reflective mode and on quartz functioned in transmissive mode. In this paper we discuss electro optic characterization of the device while explaining potential applications.

II. ELECTRO OPTICS CHARACTERIZATION

Three-dimensional phase recovery from the nanophotonics device is essential for studying the phase modulation capabilities of the device. The phase was retrieved from the device using interference techniques [3]. A Fourier-transform-based fringe analysis [4] was used to retrieve the phase from the device, as it requires only one interferogram and gives higher accuracy by eliminating the background intensity distribution, speckle noise, and optical noise from higher spatial frequencies. The nanophotonic device was characterized using a modified Fourier transform technique. By using the above technique, the microscopic phase profile of each lenslet was recovered using an interference setup constructed with an optical microscope. The microscopic phase profile of each lenslet is of interest as it decides the real modulation capability and applications of the device. The experimental setup consisted of a He–Ne laser along with a beam expander as the illuminating source. An optical microscope was used to detect the beam in reflective mode and for capturing the image. An eye piece having a magnification of ×20 was used in the microscope. The device was mounted on a fine three-axis tilting stage and attached to the microscope. The rubbing direction of the device was kept at 45° to the polarizer. The interference fringes were formed owing to the interference between the ordinary and extraordinary beams being combined by an analyzer that was crossed with polarizer [5]. A rotating diffuser (transparent plastic sheet) was used to average out speckle noise. The fringes were captured by a CCD camera and frame grabber. The interferogram of four lenslets and retrieved unwrapped phase profile of one lenslet at 0Vrms, 1.1 Vrms and 6Vrms of a transparent device with six nanotube group with each nanotube separated by 1μm and a period of 10μm are shown in Fig. 1. It was found that in the absence of an external voltage circular fringes were observed, which showed an alignment deformation of the liquid-crystal molecules near the carbon nanotubes, even though the macroscopic alignment was planar. The change in phase modulation (the phase difference between the center and circumference of lenslet) was bigger at lower voltages than at higher voltages, as shown in Fig. 2. The phase modulation of the hybrid grating lenslet is 3.7 π at 0 Vrms and increased to 4.2 π at 1.1 Vrms because maximum refractive index gradient was created between centre and edge of each hybrid grating lenslet by aligning liquid crystal molecules in response to Gaussian electric field spawned by nanotubes[2]. The phase modulation decreased after 1.1 Vrms as shown in figure 3. The focal length of each hybrid grating lenslet was calculated using the equation $f=\rho^2/ 2OPD$ [5,6] as shown in Fig.3, where OPD is the peak-to valley optical path difference from the centre to the edge of the hybrid grating lenslet and ρ is the radius of the test area 5 µm. The focal length variation was due to the change in phase profile with respect to applied voltage. The focal length was varied from 10 µm (0Vrms) to 36 µm (2.2 Vrms) and hence the micro lens array became more concave in nature with increased applied voltages. The lensing nature of the microlens arrays disappeared after 3 Vrms because the liquid crystal molecules aligned randomly at higher electric fields. The CNT-liquid-crystal nanophotonic device can be used as an electrically reconfigurable optical diffuser. Optical diffusers change the angular divergence of incident light as well as act as a random phase modulator. At the same time the current device acts as a grating because of the periodically arranged CNTs at 10 µm separation and microlenses due to the liquid crystal. Thus the device can be used for homogenous illumination that is reconfigurable with an external voltage. The device has over 1000×1000 lenslets within the 10 ×10 mm area.

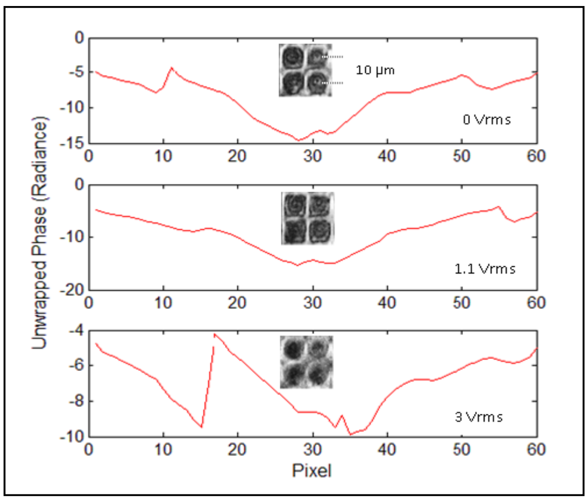

Figure:1 Interferograms of four lenslets along with unwrapped phase profile across one lenslet at 0Vrms, 1.1 Vrms and 3 Vrms. The phase profile is smooth and parabolic like at 1.1 Vrms.

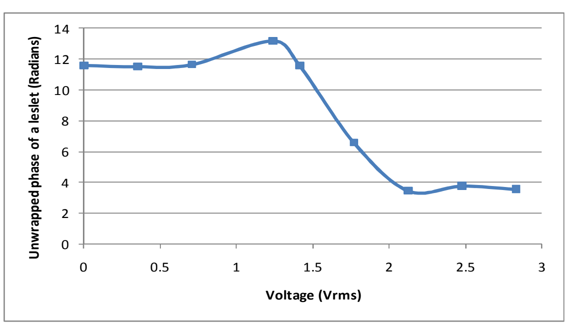

Figure:2 The variation of unwrapped phase of one lenslet with respect to applied voltage

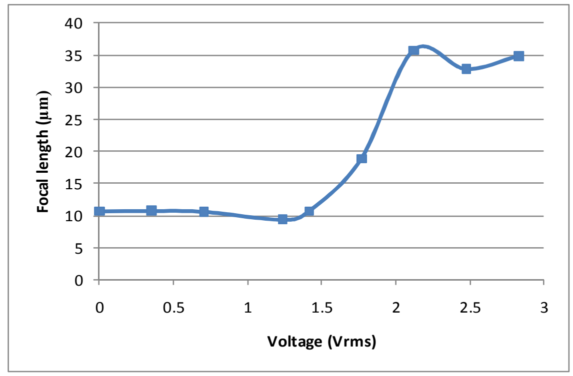

Figure:3 Focal length variation of one lenslet with respect to applied voltage.

III. Conclusion

We present a nanophotonic device functioning as a voltage reconfigurable micro lens arrays. The device was fabricated using conducting multiwall carbon nanotubes and liquid crystals. An interference set up attached to a microscope was used to recover the interference fringes. The phase profile was retrieved using Fourier transform techniques and the phase profile of the device was more or less parabolic at 1.1 Vrms, but distorted the parabolic profile at higher voltages. The focal length of the device varied from 10 µm to 36 µm. The device performance was elaborated while explaining the potential applications.

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References

[1] Seok Jin Jeong, Palanivelu Sureshkumar, Kwang-Un Jeong, Anoop K. Srivastava, Seung Hee Lee, Seok Ho Jeong, Young Hee Lee, Ruibo Lu, and Shin-Tson Wu, "Unusual double four-lobe textures generated by the motion of carbon nanotubes in a nematic liquid crystal," Opt. Express , vol. 15, pp. 11698-11705 , 2007.

[2] T. D. Wilkinson , X. Wang, K. B. K. Teo and W. I. Milne, "Sparse Multiwall Carbon Nanotube Electrode Arrays for Liquid-Crystal Photonic Devices, " Adv. Mater. (Weinheim, Ger.) , vol. 20, pp. 363 - 366, 3 Jan 2008.

[3] Mitsuo Takeda, Hideki Ina, and Seiji Kobayashi, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," J. Opt. Soc. Am. , vol. 72, pp. 156-160, 1982.

[4] Claude Roddier and François Roddier, "Interferogram analysis using Fourier transform techniques," Appl. Opt., vol. 26, pp. 1668-1673 ,1987.

[5] Hongwen Ren and Shin-Tson Wu, "Variable-focus liquid lens," Opt. Express, vol. 15, pp. 5931-5936, 2007.

[6] Ranjith Rajasekharan-Unnithan, Haider Butt, and Timothy D. Wilkinson, "Optical phase modulation using a hybrid carbon nanotube-liquid-crystal nanophotonic device," Opt. Lett., vol. 34, pp. 1237-1239 ,2009