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Theoretical modeling on the laser induced effect of liquid crystal optical phased beam steering

Xiaoxian He [a], Xiangru Wang [a,b,e,*], Liang Wu [c], Qinggui Tan [d], Man Li [b], Jiyang Shang [f], Shuanghong Wu [a], Ziqiang Huang [a]

[a] School of Optoelectronic information, University of Electronic Science and Technology of China, Chengdu 610054, China
[b] Science and Technology on Electro-Optical Information Security Control Laboratory, Sanhe 065201, China
[c] School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054, China
[d] National Key Laboratory of Science and Technology on Space Microwave, Xi'an 710100, China
[e] Zhejiang Sci-Tech University, Hangzhou 310018, China
[f] Shanghai Aerospace Electronic Technology Institute Shanghai, 201109 China

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ABSTRACT

Non-mechanical laser beam steering has been reported previously in liquid crystal array devices. To be one of the most promising candidates to be practical non-mechanical laser deflector, its laser induced effect still has few theoretical model. In this paper, we propose a theoretical model to analyze this laser induced effect of LC-OPA to evaluate the deterioration on phased beam steering. The model has three parts: laser induced thermal distribution; temperature dependence of material parameters and beam steering deterioration. After these three steps, the far field of laser beam is obtained to demonstrate the steering performance with the respect to the incident laser beam power and beam waist.

1. Introduction

Liquid crystal (LC) devices have already been one of hot research interests, because of its wide applications, such as: panel display [1], beam control [2], laser communication [3], and so on. Generally, LC devices being applied on these areas are divided into four categories: amplitude modulation, phase modulation, tunable and nonlinear. Amplitude modulation devices using twist nematic (TN) liquid crystal such as liquid crystal display has less sensitivity on its working condition including working temperature, thickness, and so on. However, phase modulation and tunable devices are sensitively dependent on its thickness, dielectric tensor, refractive index, elastic coefficient and so on. Meanwhile, when phase shift device is an array panel, it is called spatial light modulator, it has already demonstrated very attractive properties on a couple of applications such as: non-mechanical laser beam steering on Lidar [4,5], Lasercom [6,7], ROADM [8,9], OAM multiplexed [10] and so on.

All of the above applications are working on the condition that laser beam is propagating through the layer of liquid crystal. The questions we researched more previously are almost based on that the wave-front of incident beam is modulated by the liquid crystal layer. the laser induced effect on device has usually been neglected. Although iKhoo and other researchers have established some interesting works on the laser induced nonlinear effect including Gaussian rings [11,12] and so on. And also some initial experiments on damage threshold have been done and demonstrated high compatibility for high power density up to 100 W/cm^2 [13]. If the input laser beam is on the high repeated pulse laser, such as Q-switch, the working situation and damage experiments are finished on a couple of different conditions that the energy density of which is higher than 20 J/cm^2 to illustrate liquid crystal optical phased steering can also been applied on the field of Q-switch laser [14].

But very less discussion was reported on laser induced deterioration of phased beam steering.

According to the ordinary structure of liquid crystal device, ITO and PI layer are indispensable but absorbing laser so as to form temperature increase and thermal distribution. LC refractive index is mainly determined by the molecular structure, wavelength, and temperature. Several models [15] have been developed to describe the wavelength-dependent LC refractive indices. As the temperature increases, refractive index of e-beam behaves differently from one of

* Corresponding author at: School of Optoelectronic information, University of Electronic Science and Technology of China, Chengdu 610054, China.
E-mail address: xiangruwang@uestc.edu.cn (X. Wang).

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o-beam. The derivative of refractive index of e-beam is always negative. However, that of o-beam changes from negative to positive as the temperature exceeds the crossover temperature. Some semi-empirical models have been developed for describing the temperature effect on the LC refractive indices. And ST Wu proposed another efficient four parameters model [15] based on Vuks equation [16] to illustrate the temperature independence of LC materials.

To be one of the most promising candidates to be non-mechanical laser deflector, liquid crystal optical phased array (LC-OPA) has already researched much and been deployed somewhere. However, its laser induced effect still has to be studied because of few theoretical model and experimental verification. In this paper, we propose a theoretical model to analyze this laser induced effect of LC-OPA to evaluate the deterioration on phased beam steering. The model has three parts: laser induced thermal distribution; temperature dependence of material parameters and beam steering deterioration. After these three steps, the far field of laser beam is obtained. i.e. all of information of steering beam could be analyzed according their own definition.

2. Laser induced thermal distribution

When LC-OPA is working on transmission mode, laser beam propagates through the aperture of this device, as shown in Fig. 1. The upper conductive layer is lithographically prepared with isolated, transparent, and conductive striped ITO electrodes as grating electrodes, where the width of electrode is a, the gap between electrode is b. The lower conductive glass-based surface is the ITO common electrode (COM). Nematic liquid crystal is filled in the space between these two ITO layers as the medium of phase modulation. Meanwhile, in order to have a good boundary anchor, rubbing alignment should be accomplished on two PI layers.

To analyze the laser induced effect on laser beam steering, the heat transfer model has to be discussed first. On the steady model of heat transfer, temperature T is governed by

$$k\nabla^2 T + q = 0 \tag{1}$$

where q is the heat source density in the unit of W/m^3, k is the heat transfer coefficient. according to the theory of laser absorption, heat source is determined by the intensity of incident laser beam I and absorption coefficient α, i.e.$q = I{\cdot}\alpha$.

When the input laser is Q-switch pulse laser, with a repeat rate of f and a pulse width of τ_0, and pulse energy is E_0, when the

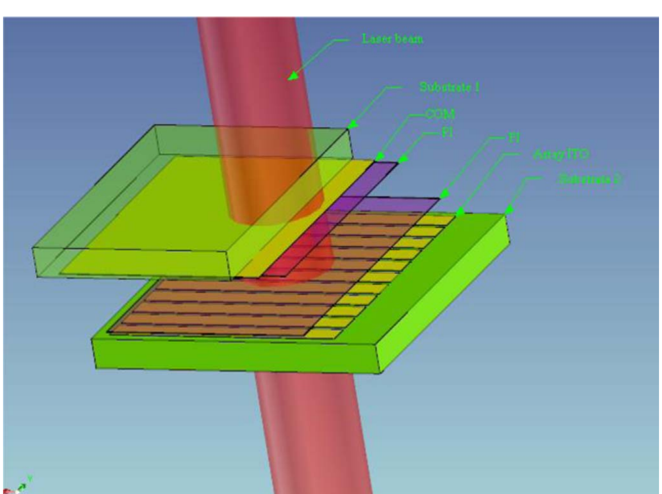

Fig. 1. Sketch of laser normally incident into LC-OPA with silica substrate, ITO com and array electrodes, PI anchoring layer.

repeat rate is quite low, i.e., the transient process of heat transfer is governed by

$$k\nabla^2 T + q = \rho C_p \frac{\partial T}{\partial t} \tag{2}$$

where ρ is the density on the unit of kg/m^3, C_p is the heat capacity in the unit of $J/kg{\cdot}K$. Usually, when it is used on high pulse repeat rate such as Lidar system, f is usually on the order of kHz, so that laser induce effect would tend to be steady very fast on some seconds, where the heat source density can be assumed to be averaged, i.e.,$q = E_0 f\alpha/S$, and S is the area of cross section.

On the case of low repeat frequency, pulse energy is usually quite high so that nonlinear effect must be considered, i.e., the proposed model here may be invalid.

With the purpose of reducing laser absorption, fused silica and diluent PI are selected. However, there is few alternative candidate materials as conductive film. Although graphene is a promising 2-D conductive transparent material, it is until now not easy to realize multi micro size panel electrodes. Therefore, ITO is the mainly heat source layer because of its relatively high laser absorption coefficient. In the other word, the absorption coefficient α mentioned above is α_0 on the position of ITO, but approximate zero elsewhere.

According to geometric properties of all of these layers as shown in Fig. 1(a) the thickness of ITO layer is on the order of tens of nanometers that is much less than the thickness of liquid crystal layer on the order of a few of microns; (b) the width of single ITO grating electrode and the gap between each on the order of micron is much less that the size of this LC-OPA device on the order of millimeter. A heat transfer module is established on Multiphysics Comsol. which is a powerful simulation tool using the method of finite element (FEM). After a couple of standard procedures such as setting up subdomain and boundary condition and some material parameters being listed on Table 1.

After solving this module, temperature distribution is shown in Fig. 2(a), and its cross section plot in the center of liquid crystal layer is shown in Fig. 2(b). Generally, from Fig. 1(a), temperature has a typically understandable gradient distribution, the layer of heat source has a maximum temperature in the center. and the same constant temperature on the boundary because of the constant temperature condition configuration $T_0 = 300K$.

Meanwhile, from Fig. 2(b), we have to attention that: owing to the periodic heat distribution, the temperature has some saw tooth fluctuation. Therein, the amplitude of fluctuation is 0.01 K. Comparing the average temperature, it is relatively small so as to be neglected.

Heat transfer is a physical problem based heat flux. When the size of heat source is much smaller than the domain we concern, heat sources are considered as singular points. Meanwhile, when the gap between these singular points, contributions from these heart sources can be averaged. Therefore, on the following theoretical analysis, heat density on the upper grating electrode, heat source density q_{up} can assumed as slow varying distribution which is only dependent on incident laser intensity I but not fast varying as defined before.

Table 1
some material parameters related with thermal model.

Parameters	Value	Unit
Heat transfer coefficient of LC [17]	0.2	W/(m K)
Heat transfer coefficient of silica [18]	1.3	W/(m K)
Heat transfer coefficient of ITO [19]	11	W/(m K)
Thickness of ITO	100	nm
Absorption of ITO layer	0.05	