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Sub-aperture coherence method to realize ultra-high resolution laser beam deflection

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ABSTRACT

A new phase controlled method is proposed to realize ultra-high resolution laser beam deflection on the physics of coherence between sub-apertures on one device of liquid crystal optical phased array (LC-OPA). Sub-apertures are electronically switchable and divided from a uniform device of LC-OPA. In the approach of sub-aperture coherence (SAC), numerical simulation results show the characteristics of far field including SAC steering step and angular width. Meanwhile, the method of SAC has also been verified by experiments showing a good agreement with the simulation results of ultra-high resolution beam deflection.

1. Introduction

Since the first invention of 1-D optical phased array (OPA) by Dr. Meyer using a multichannel lithium tantalite crystal in 1971 [1], the technique of OPA has attracted significant attentions in the area of Lidar and laser communication. Subsequently, several novel methods were promoted to achieve the requirement on the non-mechanical laser steering such as Lenslet array [2], micro-electromechanical systems [3], electrowetting [4] and liquid crystal [5], etc.

The technique of OPA plays a crucial role in the laser scanner in free space laser communication system because of its merits on high precision and agile scan. It could be used to detect and range the distance and azimuth information of target on the specific domain. Therefore, it can speed up the acquisition, tracking and pointing (ATP) progress before data communication. Meanwhile, it also has some applications in Lidar, laser display, information storage and processing, etc. [6–9]. Comparing with the classic mechanical beam scanner that has some complex plane sets and rotary gimbal, liquid crystal optical phased array (LC-OPA) is a real-time programmable and low voltage driven optoelectronic device, using the material of nematic liquid crystal as the working medium of phase modulation [11–13]. It has some obvious advantages such as inertial less, high precision, agile scan and low size weight and power assumption (SWaP). Meanwhile, its previous short leg in deflective efficiency has also been overcome on some level by predecessors [7,10]. Even more, its application has been extended into the domain of mid-infrared [14] and fast response devices [15]. On the point of high resolution using LC-OPA, it has not been discussed too much. For decades, LC-OPA has been controlled by the approach of blazing grating, steering step of which is not constant to generate a serial of non-uniform wave positions [7]. After invention of the method of uniform steering called variable period grating, the resolution can be realized in the order of 20 μrad [16]. Meanwhile, liquid crystal optical wedge is also another method to achieve high resolution in the order of few μrad [17], but its steering range is too narrow. A cascade system with wide range LC-OPA and fine resolution wedge is a good choice but it increases the total insert loss.

In this paper, we propose a new phase control method to achieve high angular resolution by the approach of sub-aperture coherence (SAC), the overlapped far field of which is from two subdomains being divided from the same aperture.

2. Theory

The general configuration of LC-OPA deflector is shown in Fig. 1. The upper conductive layer is lithographically prepared with transparent and conductive indium-tin-oxide (ITO) stripe electrodes as an array of grating electrodes, the width of each electrode is *a* and the gap

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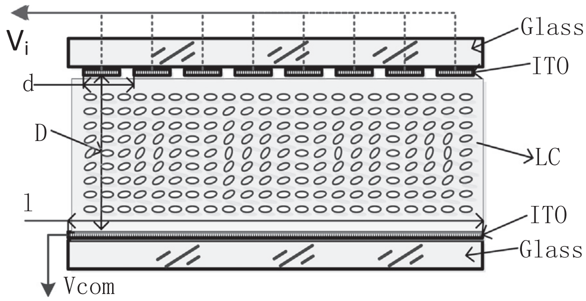

Fig. 1. The conceptual sketch of liquid crystal optical phase array.

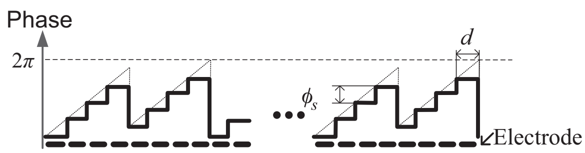

Fig. 2. Schematic diagram of equivalent phase grating formed by non-periodic voltage.

is b, so that a period of $d=a+b$. The lower conductive glass-based surface is the ITO common electrode. Nematic liquid crystal is filled in the space between these two glass substrates as the medium of phase modulation. Meanwhile, the thickness of LC cell is maintained by a few spherical plastic spacers with a diameter of l. The device of LC-OPA is driven by a chip on glass (COG) driver that has 8-bit input and hundreds of output channels. According to the physics of electrically controlled birefringence liquid crystal, the refractive index of the liquid crystal and the driving voltage satisfy a nonlinear monotone function relationship in the AC electric field.

When the device of LC-OPA is working on the mode of variable period grating (VPG) [10], the ideal phase modulation is an ideal multi-steps function, shown in Fig. 2 and defined as

$$\phi(x)=\left[\sum_{n=1}^{N}\delta(x-nd)\exp(j\,\mathrm{rem}(n\,\phi_s,2\pi))\right]\otimes\mathrm{rect}(x/d) \quad (1)$$

where n is the number of electrodes within one period, $\mathrm{rem}(x,2\pi)$ stands for the remainder operation of x divided by 2π. ϕ_s is the phase increment between two adjacent electrodes, $\otimes$ stands for convolution operation, and $\mathrm{rect}(x/d)$ is a window function with a width parameter of d.

The scheme of VPG is introduced from classic microwave phased array radar beam controlling scheme. The peak angular position on the far field θ_s is determined by

$$\sin\,\theta_s=\phi_s/(k_0d) \quad (2)$$

where k_0 is the vacuum wavenumber of incident laser beam. And the beam profile is determined by Fraunhofer's law,

$$E_{far}(\theta_x)=c\int_{-\infty}^{\infty}E_{near}(x)exp(-jk_0\theta_x x)dx \quad (3)$$

In the ideal case shown in Fig. 2, the analytical equation of phase modulation (1) is derived into the discrete form, phase modulation of the i-th electrode

$$\phi_i=\mathrm{rem}((i-1)k_0d\,\sin\,\theta_s,2\pi) \quad (4)$$

On the steady state, angular position of coherent far field is determined by Eqs. (2) and (3), so that, the minimum steering step $\Delta\theta_s=\Delta\phi_s/(k_0d)$ is governed by the minimum of phase shift $\Delta\phi_s$ for a given device and wavelength. In the practical system, the minimum of phase shift $\Delta\phi_s$ is determined by input data bit of IC driver, LC material, and other device parameters. Usually, it can be of the order of $\pi/1000$ rad, so that a steering step of 50 μrad is in the given wavelength of 1 μm. In fact, in the practical laser communication system, this steering step of 50 μrad is not precise enough to track the random vibrational satellite platform.

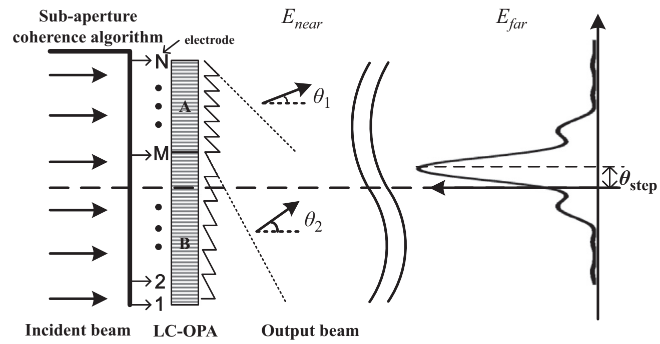

Fig. 3. The sketch of SAC scan using LCOPA.

Here, the algorithm we propose can make the steering step smaller by the given device without changing any hardware so as to track the communication terminal synchronously. The dynamic process of this phase controlled by the SAC method is sketched in Fig. 3. Different from classic one, LC-OPA here is electronically divided into two subdomains A and B; meanwhile, the width of each is defined by A and B, respectively. According to the illustration in Fig. 3 the required phase modulation at each electrode on subdomains A and B is determined by two adjacent angles θ_2 and θ_1, respectively. Therein, the boundary between subdomains A and B is electronically switchable to change the occupation of each subdomain. After long distance propagation, the far field profile could be generated according to the principle of diffraction.

According to Eq. (4), the corresponding phase shifts of the i-th electrode on subdomains A and B are ϕ_{i2} and ϕ_{i1} respectively. Generally, the phase shift

$$\phi_i=\begin{cases}\phi_{i2} & 0\le i\le N\\ \phi_{i1} & N<i\le N_{max}\end{cases} \quad (5)$$

where N is the index of electrode on the boundary between A and B, so $0\le N\le N_{max}$, where N_{max} is the total number of electrodes.

In the classic LC-OPA, N is N_{max} or 0 and the phase distribution of phase shifter is shown in Fig. 4(a) and (c). The far field beam centers of these two cases should be in the angular position of θ_1 or θ_2. Importantly, this gap between θ_1 and θ_2 is the limitation in the resolution of beam deflection.

Here, in the case of SAC LC-OPA, value of N can be changed from 0 to N_{max}, the occupation rate of subdomain A, η is defined as $\eta=N/N_{max}$, the phase distribution of phase shifter is shown in Fig. 4(b). Its far field is the coherent overlap of two parts $E_{A,far}$ and $E_{B,far}$ that are generated by subdomains A and B, respectively.

$$E_{far}=E_{Afar}+E_{B,far} \quad (6)$$

Therein, the far field profile of each is determined by (3). If we assume a uniform incident beam in the device $|E(x)|=E_0$, the corresponding near field out of optical aperture $E_{A,near}$ and $E_{B,near}$ is $E(x)=E_0\exp[j\phi(x)]$, and phase $\phi(x)$ is

$$\phi(x)=\begin{cases}\mathrm{rem}((i-1)k_0d\,\sin\,\theta_1,2\pi) & x\le Nd\\ \mathrm{rem}((i-1)k_0d\,\sin\,\theta_2,2\pi) & x>Nd\end{cases} \quad (7)$$

Optical fields from subdomains A and B are from the same laser source having the same wavelength and polarization. They can have a coherent beam overlap in the far field. It would generate a new beam peak θ_{cs} that is between θ_1 and θ_2. It is easy to conclude that when the boundary between subdomains A and B moves from left to right, i.e. the value of η goes from 0 to 1, the coherent new peak center moves from θ_1 to θ_2. And the detailed