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Liquid crystal based non-mechanical beam tracking technology

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ABSTRACT

The simulation and experimental testing of a non-mechanical beam tracking technology was investigated, in which a liquid crystal spatial light modulator (LCSLM) was used as a beam steering control device. The LCSLM was capable of steering the beam from −2.8947 to 2.8947° with a resolution of approximately 0.0226°. The LCSLM-based tracking system was simulated by MATLAB, and the Bode diagram indicated that the tracking performance was better than −17 dB when the disturbance frequency was 1 Hz. The tracking experiment was also executed to test the actual performance. The experimental data revealed that the tracking error (1σ) ranged from $0.024\theta_{max}$ to $0.225\theta_{max}$ when the disturbance frequency ranged from 0.2 to 2.0 Hz with an amplitude of θ_{max}=2.4873°. Simulation and experimental testing demonstrated the feasibility of the non-mechanical beam tracking technology that employs liquid crystals.

1. Introduction

Free-space laser communication has become a hot topic in the field of wireless communications technology, because it offers high transfer rate, small size and light weight. Furthermore, it is highly immune to electromagnetic interference and interception, making itself a secure communication technology for military applications. Since the 1980s, significant progress in spaceborne, airborne and shipborne laser communications has been achieved [1–3], which has laid a solid foundation for the effort to establish a global laser communication network.

The small divergence of the laser beam requires precise positioning, which is extremely critical to the high-data-rate transmission. Therefore, beam tracking technology is vital to building laser links between moving communication transceivers. In order to achieve this goal, traditional methods have generally employed mechanical turntables or actuated mirrors. However, in recent years, there have been great improvements in the micro-mechanical [4] and non-mechanical beam steering technologies, such as the acousto-optic modulator [5] and the liquid crystal device [6,7], so that these technologies can now be used in laser communication systems. By generating optical phased arrays, the liquid crystal spatial light modulator (LCSLM) steers the laser beam without using any moving parts, which means there is no rotational inertia and that consequently, the LCSLM can suppress beam disturbances more efficiently. Moreover, use of the LCSLM allows the size, weight and power consumption of the transceiver system to be greatly reduced. Due to its unique optical properties, liquid crystal material offers broad possibilities in the application of non-mechanical beam steering technology. The liquid crystal polarization grating can allow beam steering at an angle > ±40° [8]. Also, the liquid crystal optical phased array has a fine control accuracy of approximately 0.02° [9,10]. Using two-dimensional phase patterns [11] or cascaded one-dimensional liquid crystal devices [12], two-dimensional beam steering can be achieved.

However, the application of liquid crystal beam steering technology in laser communications is still in its experimental demonstration stage. Refs. [6] and [7] have reported high speed laser communication demonstration experiments that used the LCSLM as the beam steering device, but these studies do not refer to the details of the beam tracking content. Therefore, in this paper, laser beam tracking based on the LCSLM will be thoroughly discussed. In the first section of this article, the beam steering performance of the LCSLM is analyzed. Next, the LCSLM-based tracking system is modeled by the MATLAB. Finally, the system's tracking performance is simulated and verified experimentally.

2. Theory

Using the electrically controlled birefringence of the liquid crystal, the LCSLM modulates the incident light phase by changing the optical path difference between the ordinary light and the extraordinary light. It acts as a blazed grating when driven by a saw-tooth phase pattern,

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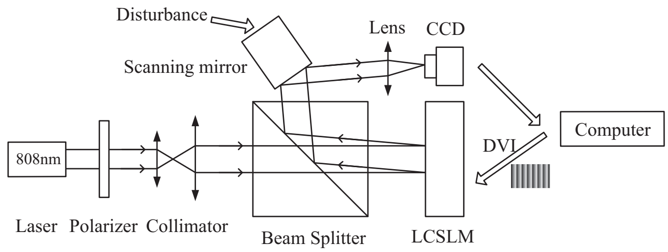

Fig. 1. Diagram of the beam tracking experiment.

and then most of the light energy is concentrated in the first-order diffraction. Therefore, the incident light is steered to the selected angle. Assuming that the phase shift of the adjacent liquid crystal pixels is α, the steering angle θ of the first-order diffraction light under the condition of vertical incidence satisfies the equation:

$$\alpha = \frac{2\pi d}{\lambda}\sin\theta, \tag{1}$$

where λ is the wavelength of the incident light, and d is the liquid crystal pixel size.

The LCSLM modulates the light phase by applying different driving voltages, which correspond to various gray scales in the hologram. In general, the gray scale is n-bit quantized, so the values of $0\sim2^n$ correspond to the phase modulation of $0\sim2\pi$. The gray variation of the adjacent liquid crystal pixels can be expressed as $\Delta G=\alpha(2^n/2\pi)$. Then the relationship between the steering angle and the gray variation can be written as

$$\theta = \arcsin\left(\frac{\lambda}{2^n d}\Delta G\right). \tag{2}$$

By substituting ΔG into the diffraction efficiency formula [13], the first blazed order diffraction efficiency can be given as

$$\eta = \left[\frac{\sin(\Delta G\pi/2^n)}{\Delta G\pi/2^n}\right]^2. \tag{3}$$

3. Beam steering performance

The Pluto-NIR-2, which is a commercial phase-only LCSLM made by HOLOEYE Photonics, was used as a beam steering control device in the experimental tracking system, as shown in Fig. 1. The LCSLM comprises 1920×1080 pixels with the maximum frame rate of 60 Hz.

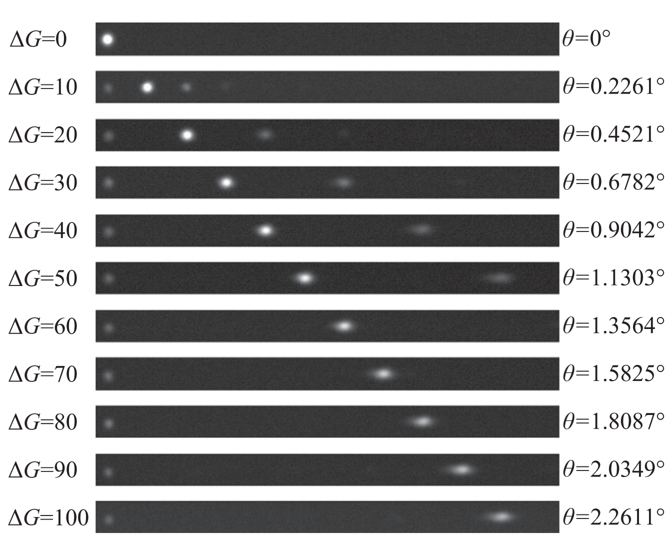

Fig. 2. Diffraction patterns for different steering angles.

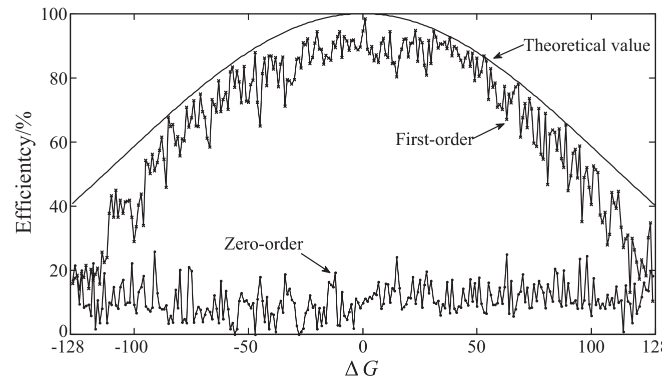

Fig. 3. Diffraction efficiency.

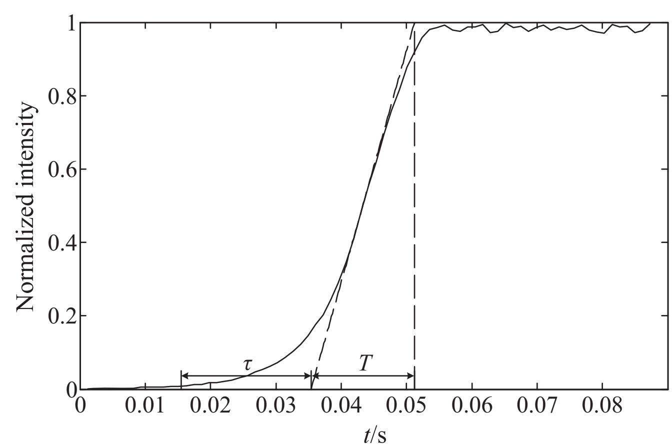

Fig. 4. Step response curve.

Each pixel is 8.0 μm with 256(8-bit) gray levels. It requires an advance compensation to ensure the linear phase modulation. In the experiment, the laser wavelength was 808 nm. After passing through the polarizer, the laser beam was incident to the LCSLM, which allowed its first-order diffraction light to be steered to the desired position. The beam speckle pattern was recorded by a CCD camera. The focal length of the imaging lens was 50 mm. A scanning mirror was used to simulate beam disturbances to test the performance of the LCSLM-based tracking system.

The beam steering performance of the proposed system was initially examined. The LCSLM was controlled by entering a series of holograms using a digital visual interface (DVI). According to Eq. (2), if ΔG was set from 0 to 128, the first-order diffraction angle could be distributed from 0 to 2.8947° with the resolution of approximately 0.0226°. Fig. 2 shows ten diffraction patterns as examples, which indicate that the steering angle θ was approximately linear to the gray variation ΔG. In the same way, setting the ΔG values from 0 to −128 allows for another 128 diffraction angles from 0 to −2.8947°. As shown in Fig. 2, the CCD camera recorded another two spurious diffraction order speckles (the zero-order and the second-order) in addition to those of the first-order that were recorded. The reason for this is that the grating phase range cannot be optimized to exactly 2π.

Fig. 3 displays the first-order diffraction efficiencies, which decreased with the increase of the steering angles. Although spurious diffraction orders could be observed, the first-order was still considered as the tracking light for its higher efficiency. Owing to the limitations of the field of view (FOV), only a few second-order speckles with small steering angles could be seen by the CCD camera, thus they affected the first-order slightly, as shown in Fig. 2. However, the zero-order speckles had great influence, because they remained still and con-

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