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Electro-optic phase modulation with a symmetrical metal-cladding waveguide

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A bulk electro-optic (EO) modulator based on the ultrahigh-order guided modes, which are excited in a symmetrical metal-cladding waveguide (SMCW), has been exploited. This kind of mode in a SMCW has high sensitivity to phase shift by changing the refractive index of the guiding layer. Compared with phase modulation via the bulk EO modulator without a waveguide, the applied half-wave voltage is reduced for one magnitude. This work may have practical applications in optical information processes.

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1. INTRODUCTION

The phase modulator is a kind of device that can modulate the phase of light through some specific physical mechanisms like the voltage-dependent birefringence effect of liquid crystals and the electro-optic (EO) effect. It is of great importance in a wide variety of fields, such as *Q*-switches [1], coherent combining of laser beams [2], and holography [3]. The liquid crystal spatial light modulator (LC-SLM) is the most mature application nowadays using phase modulation [4], in which many advantages have been put forward, such as no moving parts, mature manufacturing process, and low power consumption, but it has a long respond time [5]. Microelectromechanical systems (MEMS)-based movable micromirrors have also been achieved. They can offer a fast phase modulation speed typically at about 10 kHz [6]. However, only a binary amplitude mode is accessible owing to their complex device structures, and a complicated fabrication process also makes them less attractive. EO phase modulators have a fast response compared with MEMS and LC-SLMs [7]. For EO applications, lithium niobate is a popular material owing to its large EO coefficient, and many EO modulations based on lithium niobate have been demonstrated [8]. However, longitudinal EO modulation, which is commonly used in SLM, needs a large driving voltage for a 2π phase modulation, and as a result, the application may be restricted.

In this paper, we demonstrate a longitudinal EO phase modulator with a symmetrical metal-cladding waveguide (SMCW) to realize a nearly 2π phase modulation. This phase modulator relies on the EO effect of lithium niobate and is assisted by ultrahigh-order guided modes (UOMs) in the SMCW. The SMCW structure is constructed to substantially reduce the required voltage owing to the fact that the resonance in the waveguide could extend the interaction length.

2. THEORY AND EXPERIMENT

The structure of the SMCW is illustrated in Figs. 1(a) and 1(b). A Z-cut lithium niobate is sandwiched by two Ag layers with different thicknesses. The upper Ag layer acts as a coupling layer [9]. It is used to couple the incident light into the waveguide, while another Ag layer is a substrate layer. The lithium niobate wafer performs as the guided layer. Two Cu strips are used as electrodes.

The SMCW is distinguished with traditional coupling technology. SMCWs do not need prism or grating couplers to confine incident light [10,11]. Light can be directly coupled from free space due to the effective index of the UOMs being smaller than that of air [12,13]. The coupling modes in the SMCW can form UOMs which have a narrow full width at half-maximum (FWHM) [14]. UOMs have high sensitivity to the change of the refractive index of the guiding layer. In addition, UOMs also have some attractive characteristics, such as small propagation constant, strong modes density, and large Goos–Hänchen shift [12], which make the SMCW attractive.

This kind of SMCW structure can greatly reduce the applied voltages compared with the method that only relies on the EO effect in bulk lithium niobate without the SMCW structure. If a Z-cut lithium niobate wafer does not have a SMCW structure, the phase delay suffered by the light waves through the lithium niobate wafer when a Z-direction voltage is applied is

$$\Delta\varphi = \varphi_0 - \pi\frac{n^3 r_{13} U}{\lambda}, \qquad (1)$$

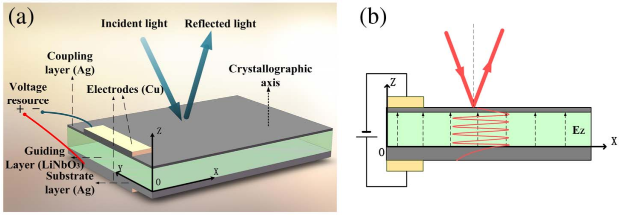

Fig. 1. (a) 3D schematic diagram of the SMCW. (b) Cross-section diagram of the SMCW.

where n is the ordinary refractive index of lithium niobate when no voltage is applied on the waveguide and l is the propagation distance of incident light. r_{13} is the EO coefficient, U is the applied voltage, and λ is the wavelength of the incident light.

From Eq. (1) we can know that the voltage needed to produce a phase shift of 2π is very large; when $\lambda = 632.8$ nm, the required voltage is 11036 V. However, if a SMCW structure is constructed, due to resonance of the waveguide, the applied voltage will be reduced dramatically.

For the SMCW, the reflectivity with different incident angles is shown in Fig. 2(a). We only calculate the TM mode for simplification due to the little difference between the TM mode and TE mode of light in the SMCW, especially at small incident angles. When the waveguide can maintain the guide mode, it should satisfy

$$2\kappa d - 2\phi_{12} - 2\phi_{10} = 2m\pi, \tag{2}$$

where

$$\kappa = 2\pi n \cos\theta/\lambda, \tag{3}$$

λ is the wavelength of incident light, d is the thickness of lithium niobate, φ_{12} and φ_{10} are the total internal reflection phase shifts of the interface between the upper Ag layer and lithium niobate, and the interface between lithium niobate and the substrate Ag, which are both determined by the incident angle θ. m in Eq. (2) is the mode order. Equation (2) is also known as the dispersion equation of the waveguide. The waveguide can only accept the light with the several θ s, which satisfy Eq. (2).

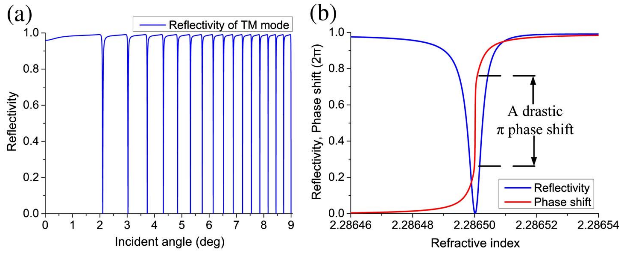

Fig. 2. (a) Calculated reflectivity of the TM mode in the SMCW with different incident angles. (b) Simulated reflectivity and phase shift of the TM mode in the SMCW with different refractive indices. The phase has a drastic π shift and the experiment is also carried out in this range.

The reflectivity of the SMCW for the TM mode of the light beam that can be calculated from the boundary condition is

$$R = \left| \frac{\gamma_{23} + \gamma_{012}\ \exp(-2\alpha d_1)}{1 + \gamma_{23}\gamma_{012}\ \exp(-2\alpha d_1)} \right|^2. \tag{4}$$

γ_{23} and γ_{012} in Eq. (4) are given by

$$\gamma_{23} = -\frac{i\varepsilon_2 k_3 + \varepsilon_3 \alpha}{-i\varepsilon_2 k_3 + \varepsilon_3 \alpha}, \tag{5}$$

$$\gamma_{012} = -\frac{\gamma_{12} + \gamma_{01}\ \exp(2ik_1 d)}{1 + \gamma_{12}\gamma_{01}\ \exp(2ik_1 d)}, \tag{6}$$

where γ_{12} and γ_{01} in Eq. (6) are

$$\gamma_{12} = \frac{\varepsilon_1 \alpha + i\varepsilon_2 k_1}{\varepsilon_1 \alpha - i\varepsilon_2 k_1}, \tag{7}$$

$$\gamma_{01} = \frac{\varepsilon_1 \alpha + i\varepsilon_0 k_1}{-\varepsilon_1 \alpha + i\varepsilon_0 k_1}. \tag{8}$$

For Eqs. (4)–(8), ε_j is the relative permittivity ($j = 1, 2, 3$ denotes the bottom Ag layer, lithium niobate, the upper Ag layer, and the air), and $\alpha = \sqrt{\beta^2 - k^2\varepsilon_0}$ is the attenuation coefficient of both the upper and bottom Ag layers (due to $\varepsilon_0 = \varepsilon_2$). $k = 2\pi/\lambda$ is the wavenumber in vacuum, $k_i = \sqrt{k^2\varepsilon_0 - \beta^2}$ is the propagation constant in the z direction in the air ($i = 3$) and in lithium niobate ($i = 1$). $\beta = k\sqrt{\varepsilon_3}\ \sin\theta$. d and d_1 are the thicknesses of lithium niobate and the upper Ag layer.

The vacuum evaporation method was used to fabricate the two layers of the Ag film in the SMCW. The upper Ag layer is about 40 nm thick, while the substrate is 300 nm. The 40 nm thickness for the coupling layer is optimal, which can be simulated from Eq. (4) and the simulated reflectivity under the 40 nm thick of coupling layer is shown in Fig. 2(a). The guiding layer is a 1 mm thick Z-cut lithium niobate crystal for the reason that a thinner crystal plate is difficult for fabrication and also reduces the mode density, while in thicker ones, the lower-order modes may be inseparable [15]. A 1 mm thick lithium niobate is suitable for our experiment. The waveguide is then sandwiched between two conductors, which function as electrodes, as shown in Fig. 1.

Figure 2(b) shows the reflectivity and phase shift with different refractive indices of lithium niobate simulated from Eq. (4) under our experimental condition. In one resonance dip, the phase has a drastic π shift, and the simulated half-wave voltage can be easily obtained, which is about 25 V. A 2π phase modulation can be realized by modulating the phase in this drastic phase changing area using different directions of electric field on the SMCW. When a forward voltage is applied, which means a forward electric field, a fast phase change of π could be received, and when the electric field was reversed by changing the direction of the applied voltage, we got a drastic phase shift of $-\pi$. According to the calculation result, the required voltage for 2π phase modulation is 50 V. Compared with phase modulation without the SMCW structure, the simulated required voltage in the SMCW could be drastically reduced for over 10,000 V.

The experimental setup is depicted in Fig. 3. In the experiment, a He–Ne laser (632.8 nm, 17 mW, 0.82 mrad beam divergence) was used. Two apertures with diameters of 1 mm were used for collimation. The light beam then passed through a 50/50 non-polarizing beam splitter (NPBS) and was split into

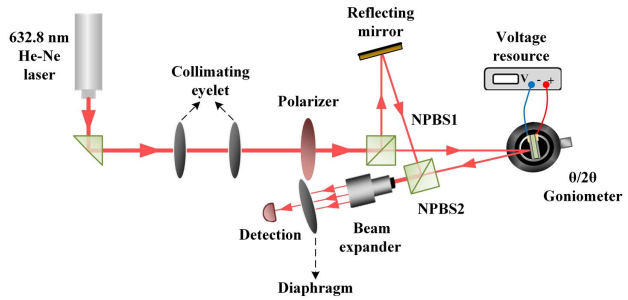

Fig. 3. Experimental setup.

two beams. One beam of light was reflected by a reflecting mirror, the other was incident on the waveguide. The waveguide was vertically put on a computer-controlled $\theta/2\theta$ goniometer, which could modulate the incident angle with great precision. The refractive index of lithium niobate changes with the applied voltage of the SMCW due to the EO effect. Both of the two light beams were combined by another 50/50 NPBS. A beam expander was used and then interference fringes could be observed on the screen. An adjustable aperture was used to select a small area in the interference fringes and we only detected the light that passed through the aperture. Finally, the phase shift at different voltages with the change of the light intensity was received by the detector. The reflecting light of the SMCW at different applied voltages when scanning around the incident angle (8.4 deg) was first detected; the scanning started from the lowest point of the resonance dip when the applied voltage was 0 V, which is illustrated in Fig. 4. The resonance dip shifts to the right with the increase of applied voltages. Figure 5 shows the experimental result of the 2π phase modulation. For a drastic 2π phase shift, we just need to add voltage from −800 V to 800 V. Compared with the required voltage in EO modulators without the SMCW, the applied voltage in our experiment using the SMCW can be reduced for nearly 10,000 V.

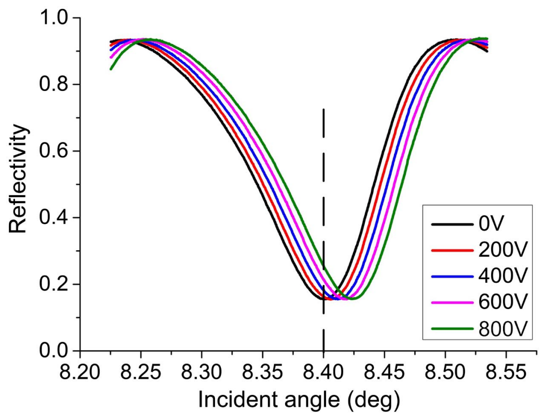

Fig. 4. Experimental reflectivity of the SMCW when scanning around the incident angle under different applied voltages. The scanning started from the lowest point of the resonance dip when the applied voltage is 0 V.

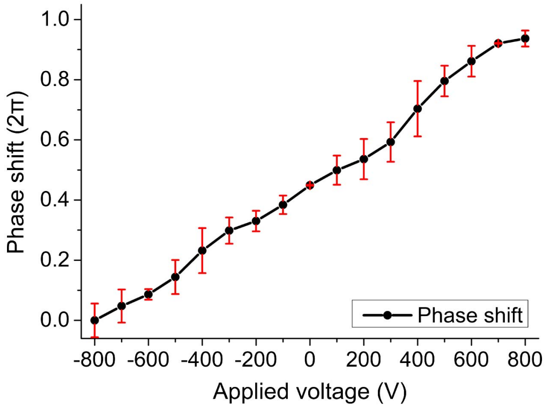

Fig. 5. Experimental phase shift of 2π; the applied voltage is from −800 V to 800V.

3. DISCUSSION AND CONCLUSION

The applied voltage is larger than the theoretical result in the experiment. From Figs. 2(a) and 4, we can know that the FWHM of UOMs in the experiment, which is about 1.75 mrad, is wider than the simulation result. The simulated FWHM is 0.08 mrad. One of the main reasons for this deviation is that the laser has a divergence angle, which is 0.82 mrad. Due to the fact that the laser has such a divergence angle, light could be coupled to the SMCW within a small range of incident angles when modulating the applied voltage. As a result, the sensitivity of the SMCW will be decreased, and the FWHM could be enlarged. This would result in the large required voltage for a 2π phase modulation. The light scattering on the surface of the SMCW may also account for the deviation. The cladding-metal film of the waveguide structure is rough in the nanoscale. The 40 mm thickness of the upper cladding layer is suitable for the best resonance from simulation [9], which can be observed in Fig. 2(a). Little roughness or unevenness of the cladding layer may cause the decrease of the sensitivity of the SMCW owing to the fact that the FWHM of UOMs is narrow. In addition, the metal absorption would also be an unavoidable problem. To further reduce the required voltage, methods that can reduce the divergence of the laser can be considered, and ways that can achieve an Ag layer with great flatness and smoothness may also attribute to a better result.

In summary, we demonstrate a phase modulator using a SMCW which is based on the EO effect of lithium niobate. When the incident angle meets with the resonance angle, light can be directly coupled to the SMCW from free space. In the resonance dip, a drastic π phase shift can be received. A $-\pi$ to π phase shift can be obtained by applying a backward and forward voltage. This method can reduce the required voltage for one magnitude compared with EO phase modulation without a SMCW.

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