Optica Applicata, Vol. XXXIX, No. 3, 2009

Design and fabrication of an organic/inorganic hybrid co-planar waveguide electro-optic modulator

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We have successfully designed and demonstrated a co-planar waveguide (CPW) Mach–Zehnder (MZ) electro-optic (EO) modulator using a strip-loaded waveguide structure. The hybrid material, easily synthesized by sol–gel process, with a large EO coefficient of r_{33} = 50 pm/V and a long-term stability at 80 °C for 200 hours is selected as the active layer. A simple and easily fabricated strip-loaded waveguide structure is designed for utilizing the EO material and reducing the coupling loss with optical fiber. The optimized design principles of the efficient transmission for such a modulator are discussed. The measured half-wave voltage V_π of 8.5 V for the MZ modulator is gained at 1550 nm and shows a good agreement with the simulating result.

Keywords: organic/inorganic, electro-optic modulator, strip-loaded, Mach–Zehnder.

1. Introduction

The development of nonlinear polymers has attracted the advanced organic optical devices with practicability and compactness [1–3]. The organic polymer doped with chromophores has attracted more and more attention because of their greater electro-optic (EO) coefficients, low processing cost, fast electronic response and wideband operation [4]. EO modulators, as the key devices for optical communication networks, are attractive and make a great progress in recent years. EO modulators up to 100 GHz and low half-wave voltage by Mach–Zehnder (MZ) intensity modulation have been demonstrated using an all polymer method [5–7]. However, there are two major concerns for polymer modulators: the unstable poling stability caused by the relaxation of chromophore alignment and the high optical loss in communication band window [8].

The hybrid organic/inorganic materials prepared by the sol–gel process attract more interest for their processing flexibility, low loss, and low cost [9]. They have both the merits of inorganic glass and organic polymer. The hybrid materials have a low dielectric constant because of the doped host material and the good thermal stability due to rigid and stable inorganic network [10]. In this letter, we report the research of the organic/inorganic hybrid EO materials with good characteristics prepared by sol–gel process. A strip-loaded waveguide is designed based on this hybrid material for fabricating the co-planar waveguide (CPW) modulator. A good EO response of this modulator is successfully gained in testing the sample.

2. Design principle

Figure 1 illustrates the cross-sectional views of the CPW modulator, which consists of a strip-loaded waveguide and a co-planar electrode. This structure eliminates damage to the EO material by the dry etching process and also avoids the cracks for EO material caused by the mismatch of the thermal expansion constant. Furthermore, the induced guiding core reduces the coupling loss with optical fiber due to the EO film being 0.7 μm in thickness.

For optimization of the parameters and efficient transmission, the software for simulation is used, as shown in Fig. 2, where the optimum width of the waveguide is 4 μm, the distance between the two MZ waveguides is 30 μm in the interaction region

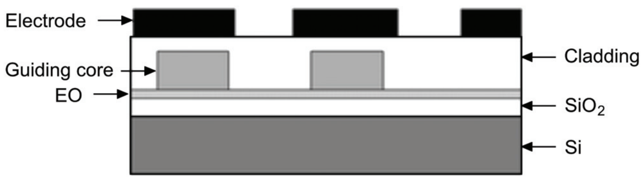

Fig. 1. Cross-sectional view of CPW modulator.

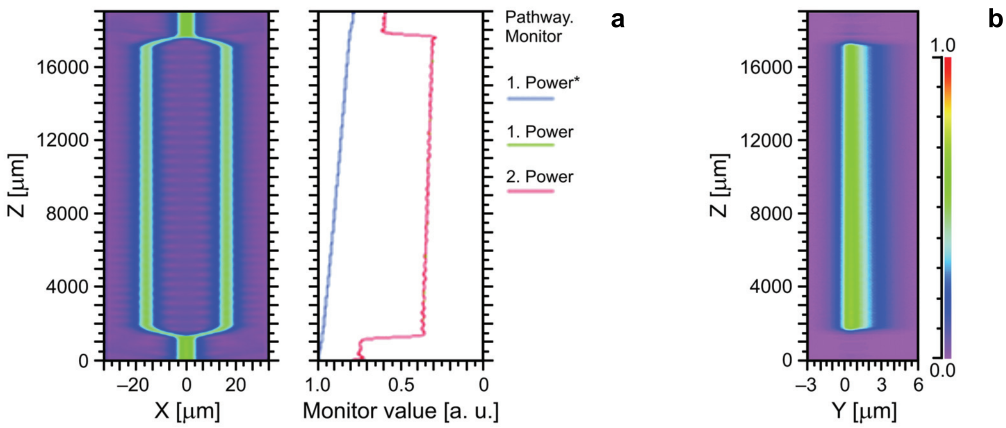

Fig. 2. Optical power distribution for mode propagation. Top view and the integrated mode power for total waveguide (blue), the EO material layer (red) and the guiding core layer (green); *X* and *Z* axes correspond to transverse and propagating directions (**a**). Side view at the center of each EO MZ waveguide arm; *Y* axe corresponds to vertical direction (**b**).

and the active region length is 1.5 cm. The refractive index of the EO material, guiding core and top cladding are 1.55, 1.496 and 1.483 at the wavelength of 1550 nm, respectively. The guiding waveguide consists of the polymer core and the top cladding with a refractive index difference of 0.87%; a ⟨100⟩ silicon wafer with 3 μm of thermally grown oxides is used as substrate. Figure 2**a** shows the optical power distribution in one of the two MZ arms. It reveals a good mode confinement in the EO layer during the propagation. Figure 2**b** shows a side view of the power distribution in EO layer and enables the suitable thickness of the guiding core for less than 3 μm. These calculation results clearly show a good confinement of the optical intensity in the EO layer for the 1550 nm wavelength.

The voltage V_π of the CPW MZ modulator can be defined as

$$V_\pi = \frac{\lambda}{2 n_0^3 r_{33}} \frac{G}{\Gamma L} \tag{1}$$

where G is the gap spacing, L is the length of the interaction region, r_{33} is the EO coefficient, λ is the central wavelength, n_0 is the refraction index, Γ is the overlap integral factor, which can be expressed as

$$\Gamma = \frac{G}{U} \frac{\iint\limits_{x,y} E_e(x, y)\, E_0^2(x, y)\, \mathrm{d}x\, \mathrm{d}y}{\iint\limits_{x,y} E_0^2(x, y)\, \mathrm{d}x\, \mathrm{d}y} \tag{2}$$

while $E_e(x, y)$ is the electric field distributive function of the electrode, $E_0(x, y)$ is the normalized optical distributive function in the waveguide [11]. For reducing the value of voltage V_π we confine the value of G to 9 μm. And then, the V_π value of 8 V is calculated by the simulation with Matlab.

3. Experiment and testing

The Disperse Red 1 (DR1) doped inorganic films are successfully synthesized by an easy and low-cost sol–gel processing. We choose the tetraethyl orthosilicate (TEOS) and the tetrabutyl-titanate ($Ti(OC_4H_9)_4$) as the stable and rigid three--dimensional inorganic framework. The DR1 chromophores are aligned and fixed into the framework during the period of corona poling. The compositions of the starting solution are as follows: DR1, TEOS, and $Ti(OC_4H_9)_4$, with the molar ratio 0.04:1.0:0.6, respectively. $Ti(OC_4H_9)_4$ is used to adjust the refraction index of EO materials. Hydrochloric acid (35 wt.% HCL) is mixed with the sol-solution and then stirred for 45 min. The EO hybrid with the thickness of 0.7 μm is spin coated on the ITO glass and then corona poled (30 min at 80 °C, 1 h at 120 °C with a high voltage) in N_2 protection. A simple reflection method is used to measure the r_{33} value [12, 13].

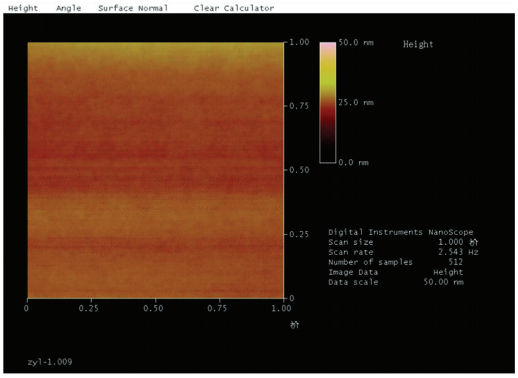

Fig. 3. AFM 3D micrograph image of hybrid EO material.

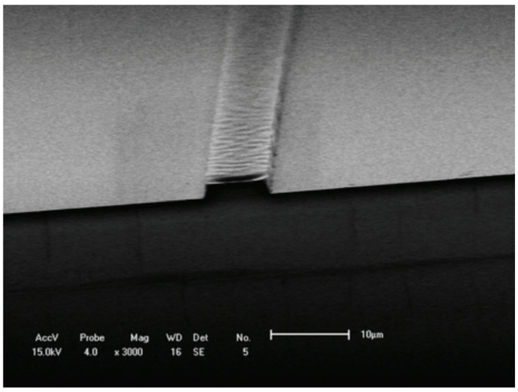

Fig. 4. SEM of a channel waveguide after RIE.

Figure 3 shows the atomic force microscope (AFM) image of the EO material film after the poling. In the 3D micrograph, a smooth surface is obtained and the root mean square (rms) of the EO material surface is only 2.108 nm. The value of 50 pm/V is gained and the well poled stability at a temperature of 80 °C is measured (unvaried for 200 hours).

For the waveguide fabrication, a silica wafer with 3 μm thermally grown oxides is used because of its match with EO material in the thermal expansion constant. First, a 0.7-μm-thick EO material is spin coated on the substrate. The material of polymethyl methacylate glyciclyl methacrylate (PMMA-GMA) with bis-A-epoxy is fabricated as the core layer, followed by thermal annealing at 120 °C for 3 h. The photoresist is spin coated and baked at 80 °C for 20 min, exposed for 40 sec using UV light at a 365 nm wavelength under a photomask to wet etching, then reactive ion etched (RIE) in O_2 for 30 min. Scanning electron microscope (SEM) micrograph of the cross-sections of the waveguide is shown in Fig. 4. A 3 μm thick PMMA-GMA is coated as the top cladding.

Finally, the top electrode is deposited on the top cladding of about 100-nm-thick aluminum for testing. Figure 5 shows a setup of the EO testing system. Low frequency modulation with a sine AC voltage of 1 kHz and the DC bias voltages are

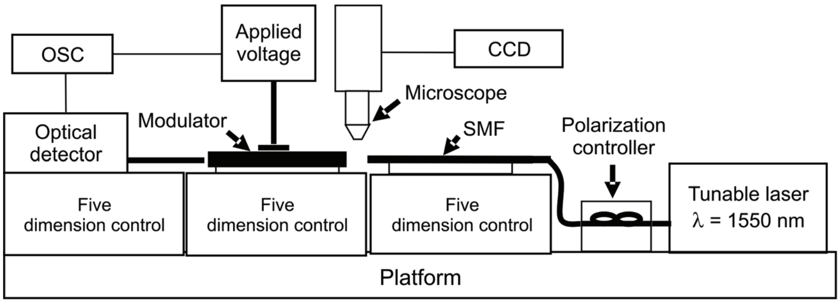

Fig. 5. Schematic setup for EO modulation.

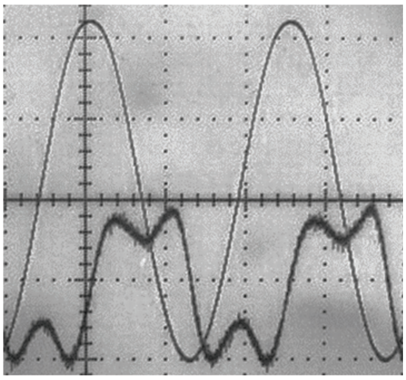

Fig. 6. Trace of modulated voltage and optical signal. Upper: applied voltage, lower: optical output signal.

added to the sample. Light with TM polarization is coupled into the waveguide through a single mode fiber. The detected optical response is simultaneously observed by an oscilloscope, as illustrated in Fig. 6. The measured voltage V_π of the modulator is about 8.5 V with a 1.5-cm-long CPW electrode in a 3.5-cm-long device. It is in a good agreement with the calculated value.

4. Conclusions

In conclusion, we have successfully designed and demonstrated a CPW MZ modulator using a strip-loaded waveguide structure based on the hybrid EO material with low cost and good poling stability. The CPW modulator is successfully fabricated and the voltage V_π of 8.5 V is obtained. We get the approximate V_π value as the calculation result. Considering the excellent thermal stability of the hybrid film and the simple processes for the device fabrication, this type of device has great potential for electro--optic devices applications.

Acknowledgment – The authors would like to acknowledge the support from the Major State Basic Research Development Program of China (973) (No: 2006CB302803).

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Received December 11, 2008