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High-speed electro-optic switch based on nonlinear polymer-clad waveguide incorporated with quasi-in-plane coplanar waveguide electrodes

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ABSTRACT

Nonlinear optical (NLO) polymer is a promising material for active waveguide devices that can provide large bandwidth and high-speed response time. However, the performance of the active devices is not only related to the waveguide materials, but also related to the waveguide and electrode structures. In this paper, a high-speed Mach–Zehnder interferometer (MZI) type of electro-optic (EO) switch based on NLO polymer-clad waveguide was fabricated. The quasi-in-plane coplanar waveguide electrodes were also introduced to enhance the poling and modulating efficiency. The characteristic parameters of the waveguide and electrode were carefully designed and simulated. The switches were fabricated by the conventional micro-fabrication process. Under 1550-nm operating wavelength, a typical fabricated switch showed a low insertion loss of 10.2 dB, and the switching rise time and fall time were 55.58 and 57.98 ns, respectively. The proposed waveguide and electrode structures could be developed into other active EO devices and also used as the component in the polymer-based large-scale photonic integrated circuit.

1. Introduction

With the rapid development of high bit and high-capacity optical telecommunication system, integrated optical waveguide devices, such as optical switches, optical amplifiers, optical modulators and optical attenuators, have drawn more and more attention [1–10]. Among these devices, optical switches based on electro-optic (EO) effect play a key role in the optical telecommunication network, and have been widely used in optical cross connect (OXC), optical add-drop multiplexing (OADM) and other high-speed signal processing systems [11–13]. The desired specifications for EO switches are low driving voltage, high modulation efficiency and fast switching response [14,15]. Especially, for high-speed optical communication systems, the modulation bandwidth should be as wide as possible. However, the most developed inorganic materials have an intrinsic limitation for bandwidth and response speed for switches due to the high dispersion of dielectric function between microwave and optical wave frequency, and the EO coefficients of the inorganic materials are also limited.

The EO devices based on nonlinear optical (NLO) polymers have become a research hotspot for their higher response speed, lower half wave voltage (V_π) and higher bandwidth [16,17]. The EO activity of NLO polymers are contributed from the movement of the π electrons, and the NLO polymers present great potential in the preparation of high-speed EO switches [18]. Besides that, the modulation speed of the material is mainly limited by the bandwidth of the device. Fortunately, the NLO polymers have the distinct advantage that their dielectric constant shows little dispersion over a wide range of frequencies and therefore the electrical and optical refractive indices are closely matched. Therefore, in NLO polymer EO devices the higher bandwidth and

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response speed could be obtained which is mainly benefited from the smaller difference value of the effective refractive index between microwave and optical wave. And the lower V_π is profit from the higher EO coefficients of the NLO polymers [19]. Furthermore, NLO polymer materials still have the advantages of simple fabricating process, moderate cost and easy integration. Therefore, the relative EO devices based on NLO polymers have been extensively studied. Research is continuing to improve the performance of NLO polymers and EO devices by means of designing the new chromophores and novel device structures [20–23]. In the past two decades, various NLO polymers have been studied for the application of EO waveguide devices, which could be divided into two categories: the guest–host EO materials and the main/side-chain bonding EO materials [24,25]. Compared to the main/side-chain system, the guest-host EO materials have the advantages of simple synthesis process and low cost. The waveguides and electrodes were also optimized by introducing some novel structures. However, there are still some problems need to be solved. One of the main challenges is to reduce the insertion loss of the NLO polymer-based EO switch, especially for loss of the large-scale integrated active devices with EO switch or modulator [26]. In conventional EO switches, NLO polymer was usually used as the core layer of the waveguides, surrounding with the passive polymer claddings [27,28]. And the propagation loss of the device was usually high, which was mainly resulted from the intrinsic optical absorption of the NLO polymer doped with chromophores. The surface morphology of the waveguide core, which was usually fabricated by dry etching method, also had an important influence on the insertion loss of the device. Moreover, to obtain EO effect and modulation function, the NLO core layer must be poled effectively with an enough high DC voltage at or near its glass transmission temperature. Therefore, it is required that the resistivity of NLO core layer should be higher than that of claddings to drop sufficient poling voltage on the core layer. However, the resistivity of the latest NLO polymer with high EO coefficient was usually lower due to the use of highly conjugated π-electron chromophores with the maximum doping concentration in polymer host, and it is difficult to select the cladding materials whose resistivities are lower than that of the core layers [29]. To enhance the poling and modulating efficiency, the in-plane coplanar waveguide structure has been studied, however, the fabrication process was complicated [30].

In this paper, we presented an easy-to-fabricate approach to accomplishing a high-speed EO switch based on MZI waveguide structure with NLO polymer cladding. To enhance the poling and modulating efficiency, the quasi-in-plane coplanar waveguide electrodes were introduced and patterned on the surface of the upper-cladding. The applied electrical field could modulate the optical signal by means of modulating the evanescent field leaked into the NLO cladding. Moreover, the guest-host EO material MS-TCF/P(MMA-GMA) was synthesized, and the optical and thermal properties were also characterized. The switch was fabricated on SiO_2 substrate by all-wet etching method with a simple process. Design procedures, simulation, as well as performances of the EO switch were also described.

2. Waveguide materials

In this paper, the chromophores MS-TCF were synthesized and employed into our EO switches as guest material of the NLO polymer cladding, and the chemical formula is shown in Fig. 1(a). The cross-linkable polymer P(MMA-GMA) with chemical and physical stability was selected as the host material, which was copolymerized by methylmethacrylate (MMA) and glycidyl methacrylate (GMA), and Fig. 1(b) shows the chemical formula. The physical doping process of the 15 wt% MS-TCF/P(MMA-GMA) is as

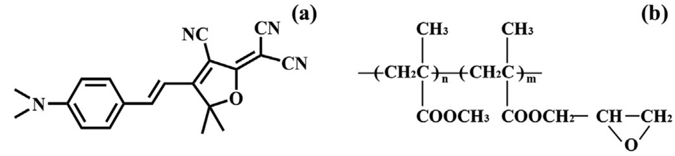

Fig. 1. Chemical formula of (a) MS-TCF and (b) P(MMA-GMA).

follows. Firstly, MS-TCF was fully dissolved in cyclopentanone and stirred for 5 h. Then the solution was filtered by a disposable filter with a 0.22 μm and incorporated with P(MMA-GMA) host material, then stirred for 24 h.

The films were prepared to measure the thermal and optical characteristics. Thermal behavior of the NLO cladding material MS-TCF/P(MMA-GMA) was firstly investigated by differential scanning calorimeter (DSC) and thermo-gravimetric analysis (TGA). From the results in Fig. 2, when the temperature increased from the room temperature to 120 °C, a tiny weight loss could be seen, at the same time some tiny endothermic peaks appeared. With the increase of the temperature, a greatly intensity of weight loss was observed in the range from 120 to 270 °C. And there are two minor endothermic peaks around 120 and 219 °C which were related to the melt and release of the organic molecules. As the temperature further increased to the range of 270–450 °C, there was a large weight loss could be observed, at the same time the largest exothermic peak appeared which was attributed to the decomposition and combustions of most of the organic materials. It could be revealed from the measured results that the glass transition temperature of MS-TCF/P(MMA-GMA) was about 120 °C, and no decomposition was observed at around 270 °C. Then the NLO film MS-TCF/P(MMA-GMA) with 15 wt% dye concentration was prepared on ITO substrate, and baked at 110 °C for 2.5 h. After contact poling, the EO coefficient γ_{33} of the film was measured by the reflection method and was about 25.8 pm/V. The refractive index of the film was also measured by an M-2000 UI variable angle incidence spectroscopic ellipsometer, which is about 1.518 at 1550 nm wavelength.

On the other hand, SU-8 2005 negative photoresist (from MicroChem Corporation) was selected as the core layer, which has a low absorption at 1550 nm wavelength communication window. Moreover, this material could be easily processed by photolithography and wet etching methods. Based on this fabricating method, the waveguide had a smooth surface, which could result in a low transmission loss.

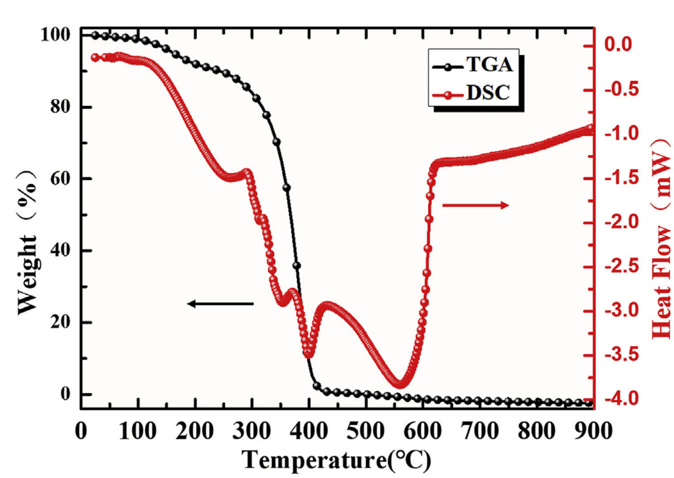

Fig. 2. DSC and TGA of the NLO cladding material.