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Polymeric optical waveguide devices exploiting special properties of polymer materials

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ABSTRACT

Optical polymer materials have many unique features that are unavailable in other inorganic optical materials. These include large thermo-optic effect with low thermal conductivity, index tunability by solution blending, structural diversity, freestanding flexibility, and controllable birefringence. Various functional integrated optic devices have been investigated by our group based on the specialties of fluorinated polymer material, which include extremely low crosstalk integrated optics, strain-controlled flexible waveguide tunable lasers, and birefringence-tuned polarization controllers. They have been demonstrated to have good performance, large fabrication tolerance, and high reliability, and they will be important building blocks for extending the application territory of polymeric optical waveguide devices.

1. Introduction

Polymers have a molecular structure comprising long chains of one-dimensional covalent bonds and secondary bonding networks between the long chains. The structural peculiarity of polymers contributes to unique properties such as structural flexibility, large temperature dependence, and low thermal conductivity; however, it also involves weak thermal stability and chemical instability such as photo-oxidation.

Fluorinated polymers have been investigated for the purpose of overcoming the problem of optical loss of polymers near optical communication windows due to vibrational overtone absorption [1]. With the contribution of organic chemistry, the propagation loss of fluorinated polymer has been reduced below 0.1 dB/cm [2,3]. The stronger C–F bond compared to the C–H bond also improves thermal and chemical stability owing to the effect of a decreased electron energy level [4,5]. Therefore, fluorinated polymer can exhibit much improved thermal stability at temperatures greater than 350 °C, and no photo-oxidation has been observed in the devices operating under strong optical power in WDM optical communications [6,7].

Polymer materials for optical devices have many unique features such as large thermo-optic (TO) effect, refractive index tunability by solution blending, structural diversity, freestanding flexibility, and controllable material birefringence, as illustrated in Fig. 1. These special features of polymers have been utilized for the demonstration of polymeric integrated optic devices such as novel TO devices relying on the large index tunability, single-mode waveguides with significantly different core diameters, flexible functional waveguide devices, and birefringence-modulated polarization-controlling devices. The fluorinated polymer developed by ChemOptics Co., ZPU, has excellent processibility for fabricating integrated optic waveguide devices comprising multilayers of thin film polymers. ZPU polymers are suitable for producing polymer layers of various thicknesses (1–50 μm) by using spin coating and UV curing processes without any sophisticated chemical treatment or thermal sequence. Many novel optical waveguide devices made of the fluorinated polymers have been demonstrated, and they will be summarized in this review. In each section, the devices are categorized according to the features of the polymer material that has been utilized for creating the novel polymer devices.

2. Large TO effect and low thermal conductivity

The optical refractive index of a polymer is dominantly determined by the packing density of the polymer material rather than other dipole effects. When a polymer is expanded by applying heat, its molecular density drops, which leads to a decrease in the optical refractive index, resulting in a negative TO coefficient. Owing to the weak bonding force of secondary bonding, the polymer's efficiency in terms of volume expansion is superior to

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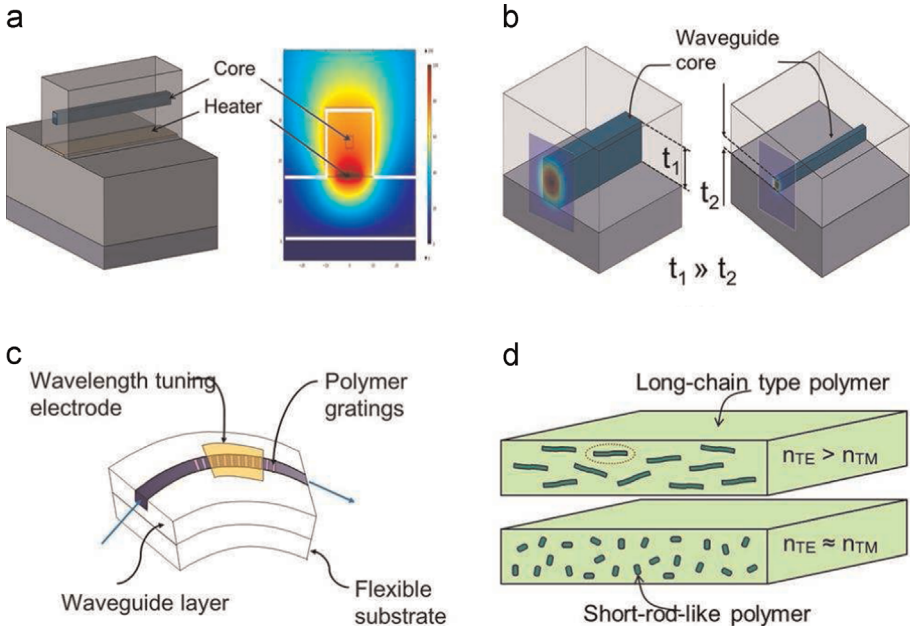

Fig. 1. Unique features of polymer materials crucial for the investigation of novel polymeric optical waveguide devices: (a) superior thermo-optic effect; (b) structural diversity; (c) flexible waveguide devices; and (d) controllable optical birefringence through molecular shape design.

that of any other material. The TO coefficient of polymer is approximately -1×10^{-4} to -3×10^{-4} °C for most optical polymers, and the index change could be as low as –0.03 for a temperature change of 100 °C.

Another factor affecting the efficiency of TO devices is the thermal conductivity of the materials. Thermal conductivity is dependent on the material bonding structure, and the weak bonding of polymer chains results in a slow propagation of heat energy through the polymer. The thermal conductivity of polymer is one-tenth that of silica material. As a result, TO polymer devices have a TO index tuning capability almost 100 times higher than that of silica devices [8].

By virtue of the significant TO effect of polymer materials, novel digital optical switches (DOS) have been demonstrated during the early stage of polymer device research [9,10]. As illustrated in Fig. 2, DOSs operate based on the mode evolution of the guided mode, and they have an advantage of easy switching control owing to their digital-like switching response. However, DOS devices require significant refractive index change, Δn, of approximately 10^{-2} for the switching. This is why the DOS configuration is effective only in polymer waveguide devices.

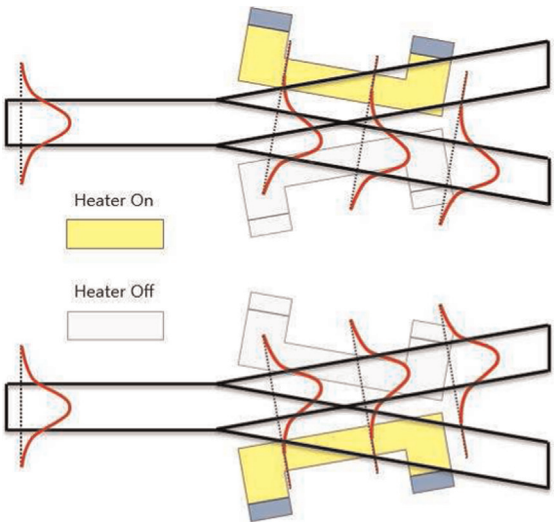

Fig. 2. Digital optical switches based on the large refractive index change due to the TO effect of polymer material.

One of the critical problems of waveguide-type optical switches is the poor crosstalk between adjacent output waveguides. In waveguide devices, compared to fiber-optic devices, it has been difficult to reduce the optical crosstalk below –40 dB, which is an important specification for switching devices in many communication applications. In DOS devices, mode evolution efficiency determines the crosstalk, and the remaining light due to odd mode coupling induces crosstalk of approximately –30 dB. Hence, to reduce crosstalk below –40 dB, an attenuator device was integrated with the DOS in a cascade form to attenuate the remaining crosstalk light [11,12]. The attenuator device was completely merged with the DOS by locating the attenuator device at the curved output waveguide of the DOS device as shown in Fig. 3; then the crosstalk was reduced to –70 dB, which was the record for waveguide-type switch devices [13]. The insertion loss of the VOA integrated DOS device was about 1.5 dB for both polarizations. Polymer DOS devices have been deployed for optical networks to connect the sub-stations of wireless communications. The operating speed of the TO switching device is limited by the slow heat flow through the polymer material. In general polymeric TO devices without special device structure modification, the response time is usually on the order of a few milliseconds.

The large TO effect of polymer material is attractive for designing novel polymeric variable optical attenuators (VOAs). In the waveguide device, if one imposes a significant refractive index perturbation on the waveguide core, the waveguide turns into the cut-off condition. An optical attenuator based on a cut-off modulator was demonstrated with a simple device structure consisting of a straight heating electrode placed on top of a straight polymer waveguide [14]. In this case, a temperature change greater than 100 °C was required to achieve signal attenuation greater than 30 dB, and thermal stability of fluorinated polymer became crucial. Compared to the phase modulator-type VOA [15,16], the cut-off VOA had an advantage in its transfer function, which was linearly proportional to the heating power and had no periodic response [6,17].

To reduce the required refractive index change for the signal

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