

# Multifunctional Optical Waveguide Chips

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(Invited paper)

## ABSTRACT

Based on polymeric materials, the possibilities of monolithic integration of various optical waveguide components are discussed and, especially, the efforts to realize the functions of optical modulation and amplification on a single optical chip are made. Exploration of more capabilities of optical waveguides is also emphasized. The work on exploring functions of optical waveguides for the applications in WDM components and photonic phased-array radar systems are presented and multifunctional optical waveguide chips with the explored functions are fabricated.

**Keywords:** integrated optics, optical waveguide, polymer

## 1. INTRODUCTION

Since the concept of integrated optical circuits was introduced in 1969<sup>1</sup>, it has been expected that all optical devices with various functions, including light sources, optical guiding and processing devices, and photodetectors, can be fabricated on a single substrate, like integrated electronic circuits. With the development of optical fiber communications and related technologies of optical components, a lot of efforts to monolithically integrate optical components have been made based on waveguide optics, microelectromechanical systems (MEMS), micro-optics, multichip module (MCM), and other technologies. Because the requirements of materials, device structures, and processing techniques for fabricating different optical components are rather different, the technology of integrated optical circuits is still in its initiation stage at present and there is a long way to go to finally realize the expected fully-integrated optical circuits.

Optical polymer is one of the potential materials that have been applied in the area of optical components and photonic circuits<sup>2</sup>. A lot of works on polymeric optical components, including low-loss waveguides<sup>3,2</sup>, high-speed electro-optic (EO) modulators<sup>4,5</sup>, thermo-optic (TO) switches<sup>6,7</sup>, and even optical amplifiers<sup>8,9</sup> and light sources<sup>10</sup>, have been reported and demonstrated the advantages of polymeric materials. In this paper, our efforts on the monolithic integration of polymeric optical waveguide devices are presented.

In fact, exploration of extra capabilities of optical waveguides is a practical way to expand the application fields of optical waveguides and its related components. In this paper, the functions of optical waveguides are developed for the application on optical fiber communications and photonic phased-array antennas (PAA). These functions are then integrated into optical waveguide chips with other optical waveguide components.

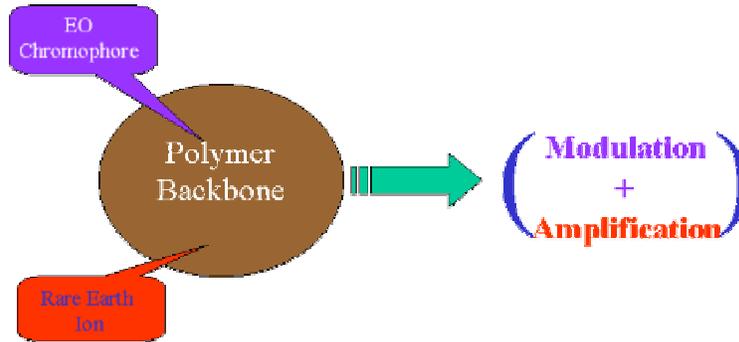
## 2. MONOLITHIC INTEGRATION OF VARIOUS OPTICAL COMPONENTS

A fully integrated optical circuits are expected to be able to perform functions such as guiding, splitting/combining, switching, wavelength multiplexing/demultiplexing, modulating, light amplifying, and even lasing and photo-detecting. To realize the monolithic integration of optical components, first of all, low-loss and highly stable polymeric materials are needed as the backbone of optical waveguide chips. By now this problem has been solved to a certain extent<sup>2</sup>. With the same processing techniques, it is not difficult to do the integration of polymeric optical waveguides, polymeric waveguide splitters/combiners, polymeric wavelength multiplexers/demultiplexers (such as AWG), and other polymeric passive waveguide components. Meanwhile, polymeric materials have strong TO effect and polymer-based TO switches and VOA are generally low-power driven and polarization-independent. It is also convenient to integrate TO polymeric components with the other passive components. In part 3, TO polymeric VOA and switches are integrated into two dual-functional polymeric waveguide chips, respectively, which are designed for the applications in WDM and photonic PAA.

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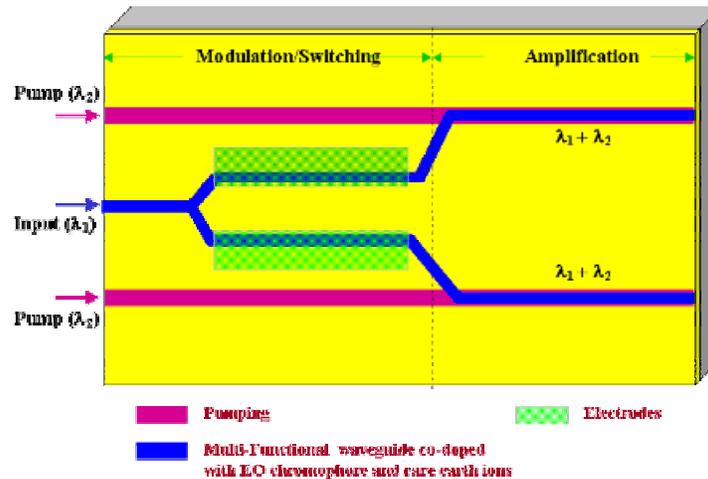
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To realize the optical amplification in polymeric waveguides, rare-earth ions are commonly doped into the polymeric materials<sup>8</sup>. When lightwave at a certain wavelength is pumped into the rare-earth-ion-doped waveguides, the amplification of the transported optical signal can be acquired. To enable the modulation function in polymeric waveguides, it is a better way to disperse EO chromophores into backbone polymers<sup>11</sup>. After the polymer doped with EO chromophores is electrically poled, the EO effect is generated and can be employed to design high-speed optical modulators and other related optical components. Therefore, it is possible to complete the integration of amplifiers and modulators with other optical waveguide components if the rare-earth ions and EO chromophores can successfully be doped into the identical backbone polymeric materials, as shown in Figure 1.



**Fig. 1** The way to enable the functions of modulation and amplification in optical waveguide chips

Figure 2 illustrates a cascaded dual-functional module having a 1x2 optical modulator and two post-modulation gain controllers. The optical modulator is an EO-polymer-based Y-fed directional coupler<sup>12</sup>. The two gain controllers are two optical polymeric amplifiers with the pump-light wavelength of  $\lambda_1$ . This chip had been made by using photolime gel as the backbone polymer and its modulation and amplification capabilities had been observed by co-doping EO chromophores (Chlorophenol red) and rare-earth ions ( $\text{Nd}^{+3}$ ) into the backbone. The contact poling technique is applied to generate the EO effect<sup>12</sup>.



**Fig. 2** A dual-functional optical waveguide chip consisting of an optical modulator and two optical amplifiers

The backbone polymeric material photolime gel is not a stable system for practical applications. So polyimides Ultradel 9000 series were used to replace photolime gel<sup>9</sup>. To meet the requirement of high stability at various environments and low loss at the communication windows of 1550nm or 1310 nm, we are trying other better polymer systems, for example, OPI N3000 series, the polyimide products from Hitachi Chemical.

In above experiments, the EO coefficient  $r_{33}$  of the poled polymer has the maximum value of 22pm/V at 633nm and is very small at 1064nm while  $\text{Nd}^{+3}$  ion is commonly used for the amplification at the wavelength of 1064nm. The

operation wavelength is not identical. So the EO chromophore FTC was selected in our succeeding experiments<sup>13</sup>. Now great progress has been made on EO polymeric materials and high-speed polymeric modulators since EO chromophores CLD series and FTC were synthesized<sup>11</sup>. All these EO chromophores have showed large EO coefficients at the wavelengths of 1064, 1310, and 1550nm.

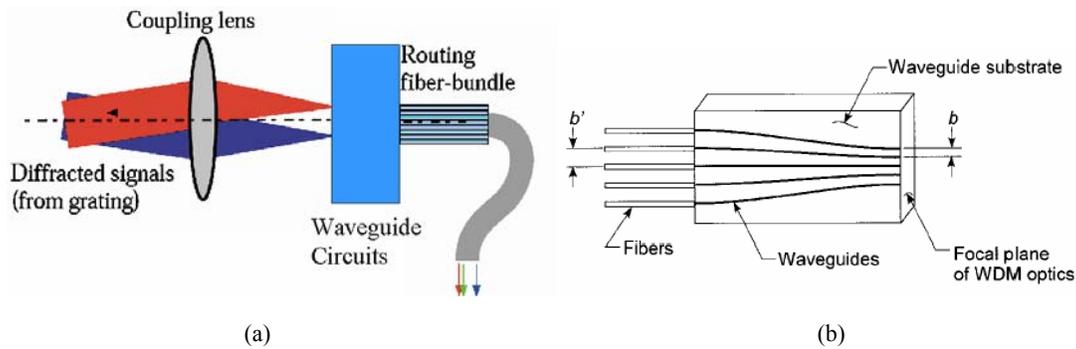
To operate at 1550nm, Erbium ions are commonly used for optical amplifiers. In [14], Er-doped polyimide amplification was studied. As pointed by A. Polman<sup>8</sup>, the generally used erbium salts are insoluble in the polymer precursors. A. Polman et al designed two ways to solve this problem: a) rare earth ions are first encapsulated in an organic cage complex and then doped into polymer waveguides; and b) the Er ions are first embedded in SiO<sub>2</sub> colloids and then dispersed in the backbone polymer<sup>8</sup>.

### 3. EXPLORATION OF FUNCTIONS OF OPTICAL WAVEGUIDES

Besides its common capabilities, optical waveguide may be designed with special functions and used in more application fields.

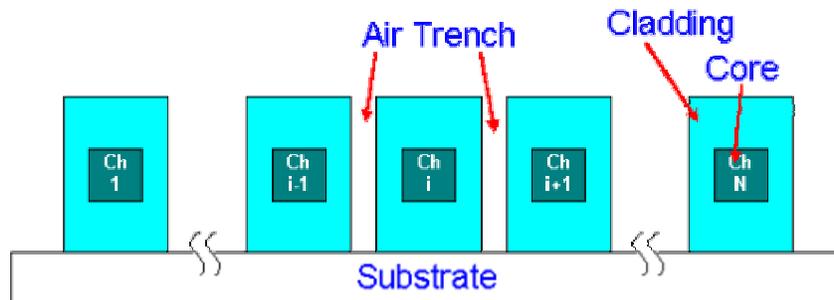
#### 3.1 Optical Waveguide Chips of Waveguide Concentrators and VOA Arrays

For grating-based WDM multiplexers/demultiplexers, its performance with large passband, low crosstalk, and low insertion loss is always expected. As mentioned in [15], adding a waveguide concentrator structure into the interface of the input/output fiber arrays, as shown in Figure 3 (a), is a way to reduce the ratio  $b/d$  of fiber spacing to the core of the input/output fiber at the interface and thus to enlarge the channel passband.



**Fig. 3** (a) Schematic illustration of a hybrid MUX based on free-space optics and diffraction gratings. (b) A waveguide concentrator between the fiber bundle and the free-space focal plane. (Adapted from Fig. 2 in [16])

Figure 3 (b) shows the structure of the waveguide concentrator we designed. The ratio of the waveguide spacing  $b$  to the mode size of the waveguide at the concentrated end for the focal plane of WDM optics is designed to meet the requirements of the channel passband<sup>15</sup>. At the other end of the waveguide concentrator, the waveguide spacing  $b'$  and size are designed to match the fiber-array V-groove and the optical fibers, respectively. To decrease the crosstalk caused by the reduced spacing of the adjacent waveguides at the concentrated end, air trenches are set between waveguides, as shown in Figure 4. The analytical results show the crosstalk can be lowered down to below  $-35$ dB.



**Fig. 4** The Cross-section of the waveguide concentrator at the end for the focal plane of WDM optics

The air trenches are set in the middle of every two adjacent waveguides. They made the horizontal mode size narrower at the concentrated end while at the fiber-coupling end they have little influence on the field distribution of the waveguide mode. Because the whole chip is long enough, the mode-transforming loss from one end to the other end and the related waveguide bending loss can all be ignored.

Just because the polymeric waveguide concentrator is employed in the design of grating-based WDM multiplexers/demultiplexers, polymeric VOA can be very easily integrated into the whole WDM components by monolithically designing and fabricating the VOA with the waveguide concentrator in a optical waveguide chip, as shown in Figure 5. Polyimides Ultradel 9000 series are used in our experiments. The air trenches are etched by RIE. The VOA is based on the thermo-optic effect of polymeric materials. The experiment results show the flatness of the insertion loss of the 16-consecuting channels is within 1dB, the dynamic range of VOA is larger than 25dB, and the response speed of VOA is in the order of ms.

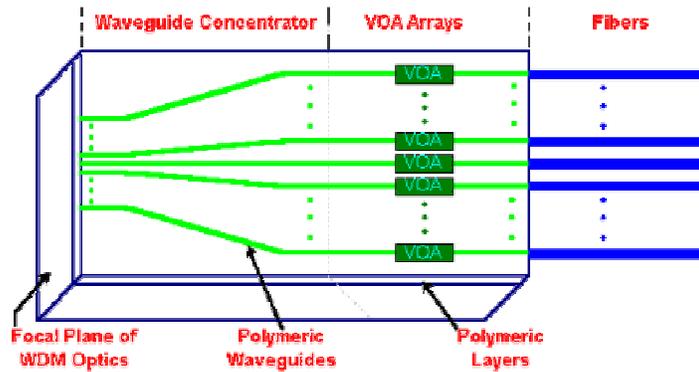


Fig. 5 The dual-functional optical waveguide chips consisting of a waveguide concentrator and a VOA arrays for WDM

### 3.2 Optical Waveguide Chips of True-Time-Delay Modules

In a phased-array radar system, using delay lines rather than phase shifters can eliminate the beam-squint phenomena<sup>17</sup>. Therefore, true-time-delay (TTD) lines are important modules for wideband phased-array antennas. Recent years there has been a growing interest in applying the photonic technology to phased array systems, especially to optical beam forming and steering. The photonic technology gives better measures to form TTD networks than the traditional electronic technology.

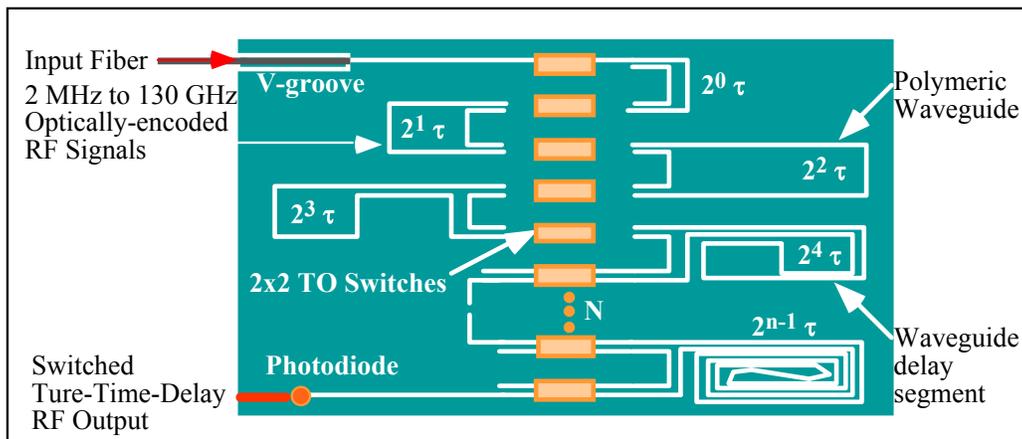


Fig. 6 A multifunctional optical waveguide chip for photonic phased-array antennas: a programmable optical TTD module using monolithically integrated polymer-based waveguides and 2x2 switches.

Figure 6 shows a schematic diagram of an optical TTD network using switched optical waveguide circuits<sup>18</sup>. In this configuration, optical waveguides with various lengths are designed as the delay lines and 2x2 optical switches are used

to control the light route. Thus the optical RF signal is optionally routed through waveguide delay lines whose lengths increase successively by a power of 2. Since each switch allows the signal to either connect or bypass a delay line, a delay  $T$  may be inserted which can take any value, in increments of  $\Delta\tau$ , up to the maximum value  $T_{\max}=(2^N-1)(\Delta\tau)$  if  $N$  waveguide delay lines are designed. Using polyimides, this TTD network can be monolithically integrated on an optical waveguide chip. As a result, it eliminates the most difficult optical packaging problem associated with the delicate interfaces between optical PM fibers and 2x2 switches. Meanwhile, such a monolithic approach offers more precision for the RF phase than the fiber-delay-lines because the waveguide length is photolithography-defined with an accuracy of sub-micrometer.

To design and fabricate this chip, how to structure the long delay-line waveguides is one of the key issues. Figure 7 shows a ten-meter long polyimide waveguide circuit fabricated by using photolithography<sup>19</sup>. If needed and possible, polymeric optical amplifiers can be added along the delay-line waveguides to balance the long-waveguide optical loss.

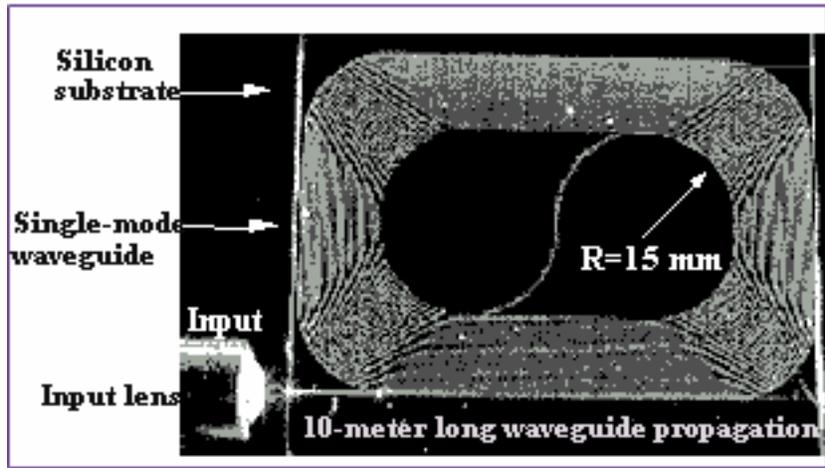


Fig.7 A ten-meter long polymeric waveguide delay line

Another key issue is the design of the optical switch. Because the TO effect of polymeric materials is polarization-independent and sufficiently strong, TO polymeric switches are the potential candidates for the integrated optical TTD module. In [7], we designed a 2x2 total-internal-reflection (TIR) polymeric switch with a X-junction, as shown in Figure 8(a), for this integrated module. Using the same processing techniques as the waveguide delay lines, this TO optical switch was fabricated. Figure 8(b) gives the characteristics of the 2x2 polymeric switch. The crosstalk measured is less than -28dB. The switching power is about 132mW, which can be lowered to 50mW by improving the driving efficiency.

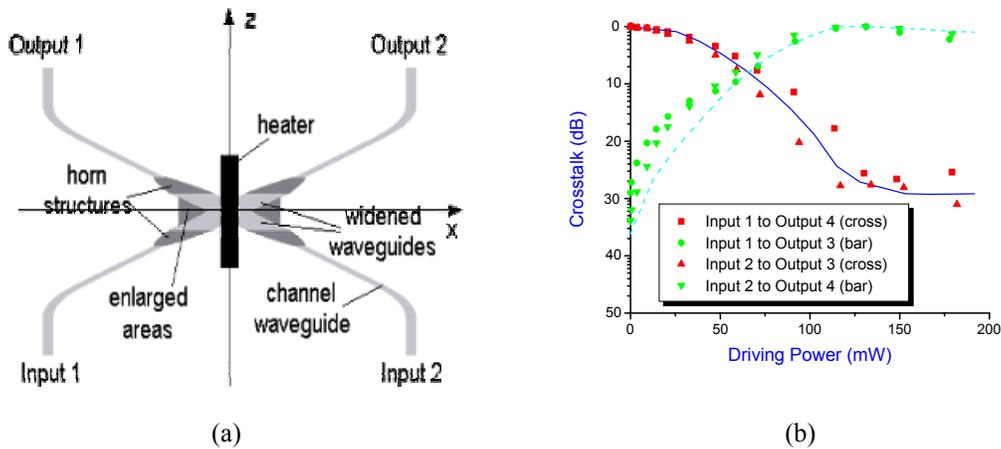


Fig.8 (a) The structure of the 2x2 TO TIR polymeric switch; (b) The analytical and measured switching characteristics.

#### 4. SUMMARY

Monolithic integration of various optical waveguide components is a goal of photonics development. Based on polymeric materials, we discussed the possibilities to monolithically fabricate various optical waveguide components. Especially, the efforts to integrate the functions of optical modulation and amplification into an optical waveguide chip are made.

Exploration of more functions of optical waveguides is also an emphasized issue in this paper. Optical waveguide may show interesting capabilities. To integrate these capabilities with other functions of optical waveguides is a practical way to expand its applications to wider fields, such as optical communication, photonic phased arrays, optical signal processing, and optical sensors (e.g. optical fiber gyroscopes). We explored capabilities of optical waveguides for the applications on WDM devices and TTD modules and made dual-functional optical waveguide chips with the explored capabilities.

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