POLYMERIC WAVEGUIDES AND DEVICES FOR INTEGRATED OPTICS APPLICATIONS

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ABSTRACT

Polymers have many desirable properties, such as low-cost, ease of fabrication, high flexibility, and tailored made properties. Indeed, they are attractive for integrated optics applications. In this paper, polymeric materials and various fabrication techniques used currently are discussed and compared, and optical waveguides and devices are reviewed.

INTRODUCTION

Cost-effective and functional optical devices are required for expanding the optical communication networks, and integrated optics or planar waveguide technology is expected to play a major role. Polymeric waveguide devices are expected to meet the requirement because they can be fabricated using a low-cost process with high manufacturing output. The low temperature fabrication process also gives the designer a large degree of freedom. Also, most polymer materials have a thermo-optic coefficient (about ten times larger than that of silica), hence devices can be temperature tuned over a wider spectral range. Polymeric materials offer many distinct properties compared to other materials such as silica and III-V compound semiconductors. It is widely known that silica glass has high thermal stability as well as low optical loss. On the other hand, polymers are attractive to be used due to their ease of fabrication, low production cost, and compatibility with Si and GaAs fabrication technologies. Such properties are important factors for the practical implementation of complex, high-density interconnects and optical circuits. Polymers can be deposited directly on any kind of substrates, and this is advantageous over other optical waveguide materials such as SiO_2, $LiNbO_3$, and III-V materials. Tailored made polymer materials offer high structural flexibility by different combination of the monomers, and an accurate control of the refractive indices and properties can be achieved. The thermo-optic coefficient of polymers is an order of magnitude larger than that of silica glasses, and efficient thermo-optic devices have been fabricated. These polymers exhibit low thermal conductivities and large thermal index changes [1]. Active polymeric waveguide devices have also been demonstrated. Electro-optic modulator with bandwidth up to 110 GHz has been reported [2], showing that fast electronic response is possible in polymer materials as well as low operating voltage [3].

POLYMERIC MATERIALS AND DEVICES FABRICATOIN

Most of the polymeric waveguides reported so far were fabricated using reactive ion beam etching [4,5], photo-bleaching [6,7], and ion-implantation [8] processes. These methods involve many processing steps, and can lead to a long fabrication time and low yield. Photolithography followed by reactive ion beam etching (RIE) is the most common fabrication method, because the polymeric materials are not required to be UV or electron beam sensitive. However, RIE generates relatively rough surface that in turn increases the scattering loss. Laser [9] and electron beam direct writings [10,11] are advantageous over others techniques because fewer steps are involved. The direct write technique has the advantage of being mask-less, allowing rapid and inexpensive prototyping, in contrast to conventional mask-based photolithographic approach, in which a mask must be produced before the fabrication of the device. Nanometer patterns with flexibility in writing complex structures using electron beam direct writing are also possible. Table 1 summarizes the materials used and the waveguide properties.

To achieve low cost and high throughput, single UV lithography and molding techniques have also been developed. Single UV lithography involves only one exposure step, and patterns with feature sizes well into the submicron range over large areas can be produced routinely. However, only material is UV sensitive, and the process cannot be applied to curved surfaces. Molding is another attractive alternative method, and includes either soft or nanoimprint lithography depending on the mold materials. Three-dimensional microstructures with sub-nanoscale features have been demonstrated using both methods. Optical devices illustrated including waveguide coupler [12], nanowire polarizers [13], T-gate or air-bridge [14], organic solid-state lasers [15], as well as distributed feedback and Bragg reflector resonators for plastic laser [16,17].

Different kinds of polymeric materials have been used, and each has its own advantages and disadvantages, depending on the device structures and applications. Recent polymeric waveguide devices demonstrated include TM-pass polarizer [18], tunable optical add/drop filter/multiplexer (OADM) using cascaded Mach-Zehnders [19], thermo-optic switch [20], athermal arrayed-waveguide grating (AWG) multiplexer [21], and filters using electron beam direct writing [22]. Figs. 1 and 3 show the polymeric waveguide and Bragg gratings generated using electron beam direct writing technique. The atomic force microscope (AFM) image shows very smooth surface and vertical sidewall for the waveguide, indicating that surface scattering loss is minimized. For the Bragg gratings fabricated, a -27dB transmission peak (~99% reflection) was obtained at 1550nm wavelength. Dispersion study was also performed on planar Bragg gratings for WDM systems [23], and the dispersion is lower than that of fiber Bragg gratings. Table 2 summarizes the polymeric waveguide devices demonstrated.

Table 1 List of polymeric materials and waveguide properties

Method of Fabrication	**Materials**	**Waveguide loss and other properties**
Molding	Photolime gel-based polymer	633nm 0.5-2dB/cm
	EGDMA	1300nm 0.3dB/cm
Spin coating (planar)	PBZT	834nm 4.81dB/cm
UV lithography	PMMA Dye-doped	632.8nm 0.08dB/cm
UV lithography/RIE	PPSQ	632.8nm 0.16dB/cm Δn=0.003 0.19% birefringence at 632.8nm
	PFCB	1330nm 0.25dB/cm 1550nm 0.2dB/cm Tg ~400ºC
	BCB	1330nm 0.5dB/cm 1550nm <1.5dB/cm Tg>350ºC
	d-PMMA	830nm 0.02dB/cm
	Polysiloxane	1330nm 0.17dB/cm 1550nm 0.43dB/cm
UV lithography/ Inductively Coupled Plasma (ICP)	Chloro-fluorinated polyimides	1550nm <0.4dB/cm Δn=0.01-0.12 at 1550nm
RIE/photobleaching	PMMA-DR1	1330nm 0.4dB/cm Tg ~250oC/131oC
UV lithography/Laser direct writing	AlliedSignal optical polymers (acrylate monomers)	1550nm 0.24dB/cm $\Delta n<2x10^{-5}$ at 1550nm PDL=0.01dB/cm
Electron beam direct writing	ENR	1550nm 0.48 dB/cm (TM mode) 1330nm 0.22 dB/cm (TM mode)

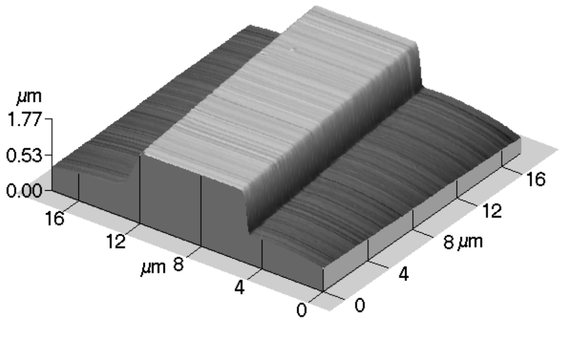

Fig. 1 Atomic force microscope image of a 6 µm single mode channel waveguide without upper cladding.

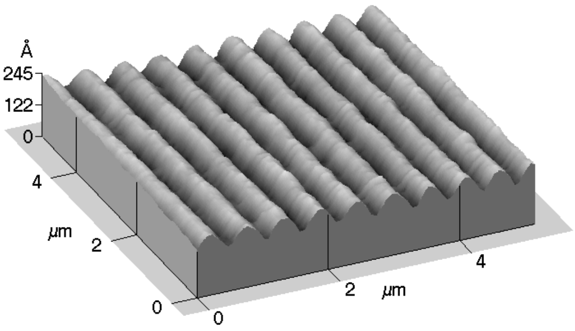

Fig. 2 Bragg gratings generated using electron beam direct writing

Table 2 List of polymeric devices demonstrated

Fabrication method	Device demonstrated
Molding	Organic solid-state lasers - BCB with Alq:DCM dye
UV lithography/Laser direct write with photochemical process	Tunable optical add/drop filter/multiplexer (OADM) using cascaded Mach-Zehnders - AlliedSignal optical polymer
UV lithography/ RIE	Athermal arrayed-waveguide grating (AWG) multiplexer - Fluoroacrylate type polymers Electro-optic modulators - PUR-DR19 Thermo-optic switch (with metal evaporated electrode) - FPAE - Fluorinated polyimide TM-pass polarizer (with photobleaching) - PMMA-DR1
Electron beam direct write	Waveguide wavelength filter - ENR

CONCLUSIONS

In conclusion, polymers are attractive materials to be used for integrated optics device applications. Polymeric optical waveguide devices start appearing on the commercial market, and these devices will find applications in many areas, such as telecommunications, LAN, CATV, and in sensors.

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