Polymeric optical waveguides

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This paper reviews singlemode polymeric waveguides with a low propagation loss in the infrared region which we fabricated using deuterated (d-) fluoromethacrylate polymer (PFMA) and d-polysiloxane. We applied the waveguides made with d-PFMA to various kinds of devices, and have summarized their characteristics. In addition, we fabricated and characterized thermally and environmentally stable waveguides using newly synthesized d-polysiloxane.

1. INTRODUCTION

Polymeric optical waveguides are divided into three categories in terms of their core sizes, which are 5-10 μm square for singlemode systems, 40-60 μm square for multimode glass fiber systems, and 500-1000 μm square for multimode plastic fiber systems. Singlemode waveguide devices have been mainly studied with a view to applications in optical fiber telecommunication systems [1]. By contrast, multimode waveguide devices have been extensively developed for local area use in large data computer communication systems [2]. However, the recently developed multimedia systems have been constructed using both telecommunication and local data communication systems which are connected and which interact with each other in a complex fashion.

This paper presents our work on singlemode polymeric waveguides with a low loss in the infrared region. First we review waveguide devices using deuterated (d-) fluoromethacrylate polymer (PFMA), and discuss the merits and demerits of d-PFMA waveguides. Next we introduce a newly synthesized d-polysiloxane which is heat-resistant and highly transparent in the infrared region.

2. D-PFMA DEVICES

Imamura, Yoshimura and Izawa reported the successful fabrication of highly transparent waveguides with a propagation loss of less than 0.1 dB/cm at 1.3 μm using d-PFMA which have highly controllable refractive indices [3], [4]. Subsequently these polymer waveguides were applied in directional couplers [5], Mach-Zehnder (MZ) interferometers [6], ring resonators [7], MZ interferometer type thermooptic (TO) switches [8], and arrayed-waveguide grating multiplexers [9]. These phase sensitive devices require that both the refractive indices and shapes of waveguides are well-controlled. They have been fabricated by photolithography and reactive ion etching (RIE) using d-PFMA with highly controlled refractive indices. These waveguide devices were previously realized by using silica glass waveguides [10].

Furthermore, flexible devices, which are difficult to realize using silica glass waveguides, have also been fabricated using d-PFMA. These are waveguides whose output intensity is controlled by bending [6], and free-standing flexible waveguides [11]. The output intensity control waveguides consist of a directional coupler or an MZ interferometer, which are shown schematically in Fig.1. By applying mechanical force, the coupling ratio can be controlled from 99 % to 1% with high precision (< 1%)[6]. Figure 2 shows a free-standing flexible singlemode waveguide which has low bending loss of less than 0.1 dB for a bending radius R = 10 mm [11].

The optical characteristics of d-PFMA are shown in Table 1. As the thermooptic coefficient of d- PFMA is much larger than that of silica glass, it has the advantage of being applicable to TO switches. Hida, Onose and Imamura [8] demonstrated MZ type TO switches which operated at 4.8 mW. This operation power is two orders of magnitude lower than that of silica-based TO switches. Recently, the digital Y-branching type TO switch, which is different from the MZ type, has been developed of by W.Horsthuis et al. [12] and R. Moosburger et al. [13]. The switching power of the Y-branching type TO switches was one order of magnitude larger than that of MZ type TO switches. Another distinctive characteristic of d-PFMA is its low birefringence. The low birefringence in waveguides generally acts good performance

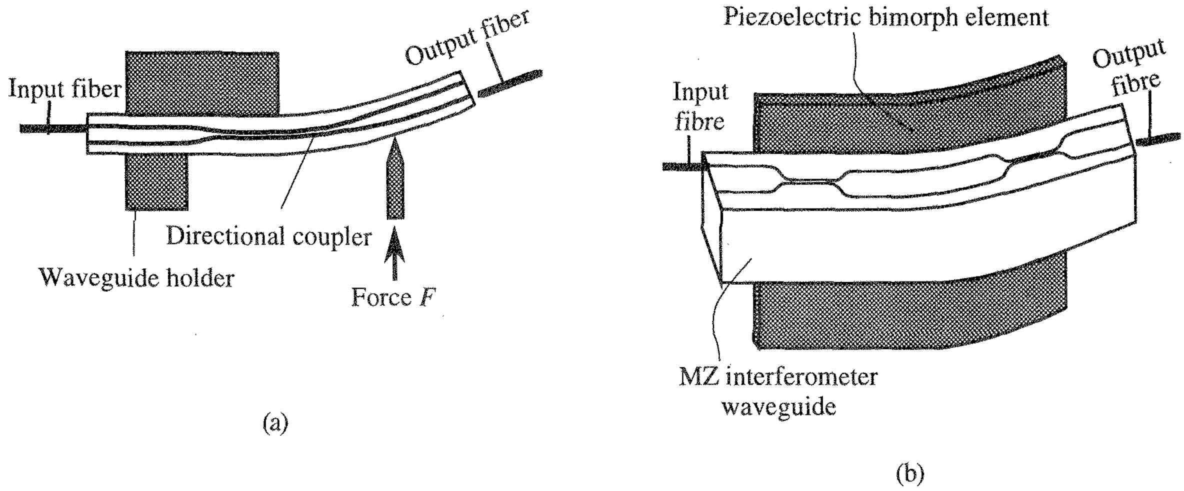

Figure 1. Bending-type output intensity controller. (a) directional coupler type (b) MZ interferometer type

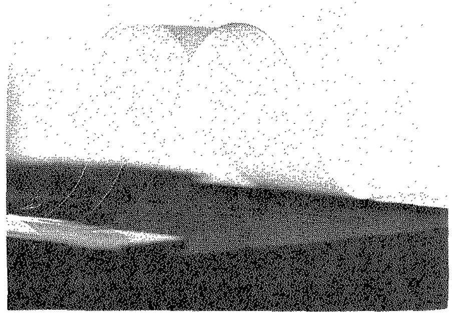

Figure 2. Free-standing flexible waveguide

Table 1. Optical characteristics of d--PFMA

Propagation loss	0.1 dB/cm(1.3μm) 1.5 dB/cm(1.55μm)
Birefringence	6×10^{-6}
Thermooptic Coefficient	$1 \times 10^{-4} K^{-1}$
Humidity-Optic Coefficient*	10^{-5} % RH^{-1}

* refractive index dependence of humidity

Table 2. Waveguide devices using d-PFMA fabricated by authors

Devices	Characteristics	Ref.
Directional coupler	Coupling ratio: 0-100 %, Total excess loss: 0.4 dB	[5]
MZ interferometer	Well controlled 3 dB coupler	[6]
Ring resonator	Finesse: 14.8, Extinction ratio: 0.83	[7]
MZ interferometer type TO switch	Switching power: 5 mW	[8]
Arrayed-waveguide grating multiplexer	Total loss: 8-11 dB, Crosstalk: <-20dB Channel spacing: 0.65 nm, Polarization shift: 0.03 nm	[9]
Bending-type output intensity controller	Coupling ratio: 1% to 99 % with precision :< 1%	[6]
Free-standing flexible waveguide	Loss: < 0.1 dB at bending radius of 10mm	[11]

in terms of passive devices operation. On the other hand, its large humidity-optic coefficient sometimes results in poor quality operation.[14,15]

The characteristics of the abovementioned devices are summarized in Table 2.

The stability of devices with pigtailed fibers is very important in terms of system applications. Recently Ooba et al. [16] studied the stability of d-PFMA waveguides where pigtailed fibers were attached to the waveguide chips with low connection loss and thermal stability up to 75 °C.

3. ENVIRONMENTAL STABILITY OF D-POLYSILOXANE WAVEGUIDES

D-PFMA is disadvantageous both in terms of its thermal stability which is limited to less than around 100 °C [17] and its propagation loss of 1.5 dB/cm at 1.55 μm. We therefore focused on the following three important requirements when synthesizing our new waveguide polymer.

(1) high transparency at both 1.3 μm and 1.55 μm.
(2) high thermal and environmental stability.
(3) high refractive index controllability

In order to satisfy all three of these requirements, d-polysiloxane, which was used for the waveguide core polymer, was synthesized by using d- phenylsilyl chloride monomers as the starting materials. This section describes a newly synthesized d-polysiloxane waveguide which satisfies the requirements of low loss in the infrared region, long storage stability in a humid environment, and short-term heat resistance under soldering process conditions [18,19].

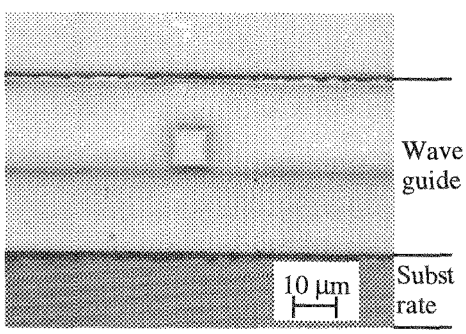

Figure 3. Cross-section photograph of d-polysiloxane wavegide.

We used the polymer to fabricate singlemode channel waveguides by conventional photolithography and RIE, as shown in Fig.3. The propagation loss of the channel waveguides was measured and found to be 0.17 dB/cm at 1.31 μm and 0.43 dB/cm at 1.55 μm, where the refractive index of the core polymer was 1.5365, and the refractive index difference, Δn, between the core and the cladding polymers was 0.3 % at both 1.3 μm and 1.55 μm.

In order to estimate the thermal and environmental stability of these polysiloxane waveguides, we carried out three tests under different conditions on straight waveguides. The propagation losses at 1.31 and 1.55 μm remained unchanged after heating at 200 °C for 30 minutes as shown in Fig. 4, at 120 °C for 1000 hours, and at 90 % RH and

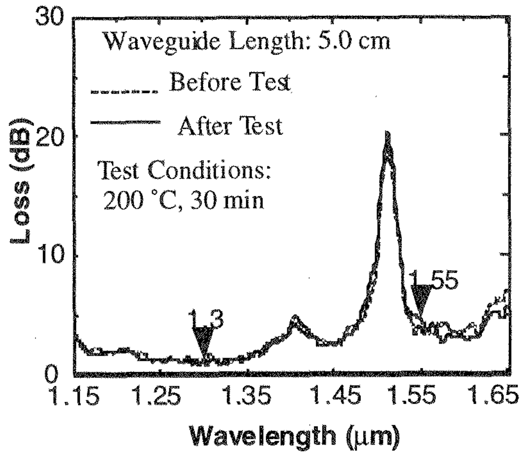

Figure 4. Heating tests before and after at 200 °C for 30 minutes.

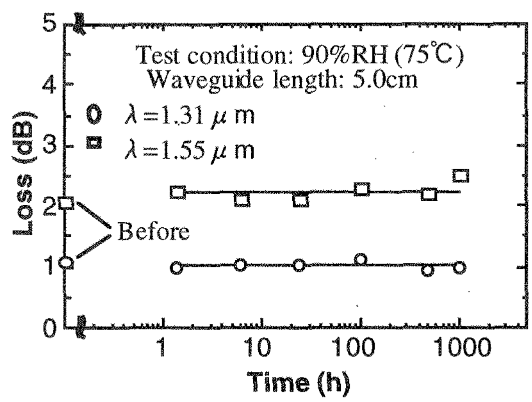

Figure 5. Environmentally stable tests under humid conditions at 90 % RH and 75 °C for 1000 hours.

75 °C for 1000 hours as shown in Fig. 5. High heat-resistance singlemode waveguides fabricated using f-polyimides have been also studied by Matsuura et al.[20]

4. CONCLUSIONS

This paper describes singlemode polymeric waveguides with a low propagation loss in the infrared region for use in optical fiber communication systems. D-PFMA were applied to directional couplers, MZ interferometers, ring resonators, MZ interferometer type TO switches, and arrayed-waveguide grating multiplexers. The devices show good levels of performance. The flexible characteristic of polymer was also exploited in free-standing flexible waveguides and bending-type output intensity controller. In addition, we fabricated and characterized thermally and environmentally stable waveguides using newly synthesized d-polysiloxane.

The recent development of interconnections has had a strong effect on polymeric optical waveguide devices, irrespective of whether they are employed in singlemode or multimode systems.

ACKNOWLEDGMENTS

The authors wish to thank T.Izawa, K.Sugii, H.Hiratsuka and H.Kozawaguchi for their encouragement. They also thank R.Yoshimura, Y.Hida, H.Nakagome, M.Usui, T.Watanabe, M.Amano, S.Sugawara, S.Hayashida, S.Tomaru, T.Kurihara, A.Kaneko, H.Sato, K.Onose, Y.Hibino, K.Manabe, and A.Sakuma for help and discussions.

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