Multichannel Parallel Polymer Waveguide With Circular W-Shaped Index Profile Cores

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***Abstract*—We fabricate a parallel optical waveguide whose cores are composed of perdeuterated acrylate polymer. We experimentally demonstrate that this waveguide has lower loss by one order of magnitude compared to an acrylate-based waveguide at 850-nm wavelength. The eye diagram measured after a 12.5-Gb/s 15-m transmission shows that this waveguide has sufficiently high bandwidth. In addition, we verify a strong crosstalk reduction due to the specific (W-shaped) refractive index profile in the waveguide.**

***Index Terms*—Interchannel optical crosstalk, parallel optical waveguide, perdeuterated acrylate polymer, W-shaped index profile.**

I. Introduction

THE RAPID increase of Internet traffic and development of large-scale-integration technology are requiring high-performance core routers and switches in backbone networks. For realizing a low bit-error-ratio (BER) transmission at a data rate of 10 Gb/s and beyond, electrical interconnections in such equipment can be difficult because of electromagnetic noise and crosstalk [1].

Therefore, polymer optical waveguides are drawing much attention recently as an alternative to copper wires [2], because they are fabricated and implemented cost-effectively. For ultrashort-reach applications (several centimeters), polymer waveguides fabricated by lithographic or imprinting processes can be utilized, while interconnections on printed circuit boards (PCBs) require a length of 1 m or longer. In those applications, the optical properties of current polymer waveguides such as propagation loss and dispersion are not necessarily suitable. To address these demands, we proposed polymer parallel optical waveguides with circular graded-index (GI) cores fabricated by the preform method for the first time [3], [4]. The novel waveguide composed of acrylate polymer exhibited very low attenuation (under 0.03 dB/cm) and high bandwidth (83 Gb/s $\cdot$ m) at a wavelength of 850 nm. Those superior properties enabled a 12.5-Gb/s transmission over a length of 3.0 m [3], [4]. Additionally, we demonstrated that interchannel crosstalk of the waveguide was relatively small (~ -30 dB), because GI profile tightly confines the electric field of propagation modes within the center of the core [5].

However, the propagation loss of 0.03 dB/cm corresponds to 3-dB (half) power attenuation after a 1-m transmission, which is not necessarily low enough.

We also need to restrict the interchannel crosstalk as low as possible for the high-end backplane interconnections requiring high-speed and high-density signal transmission with very low BER. Therefore, in this letter, we fabricate parallel optical waveguides whose cores are composed of perdeuterated acrylate polymer with much lower propagation loss than conventional hydrogenated acrylate-based waveguides. In addition to the extremely low propagation loss, the refractive index valley at the boundary of GI core and cladding is another advantage of this novel waveguide. This specific index profile is called W-shaped index profile.

In this letter, we show the experimental data for the refractive index profile, the propagation loss, and a 12.5-Gb/s signal transmission over the perdeuterated acrylate-based waveguide. Finally, the interchannel crosstalk reduction achieved by the W-shaped index profile is discussed.

II. Experiment

A. Refractive Index Profile

We succeeded in fabricating novel waveguides with four-channel circular cores in the same way as in [3]. Only the cores of this waveguide are composed of perdeuterated acrylate polymer (strictly speaking, the region surrounding the core periphery also contains the perdeuterated polymer), and the outermost layer of the cores are made of general hydrogenated acrylate polymer. Because the perdeuterated acrylate has refractive index slightly lower than that of general acrylate ($\delta n = 0.004$ at 589 nm), a valley of refractive index is formed at the core–cladding boundary. Parabolic refractive index distributions are formed inside the cores and thus, the GI profile with the index valley in the novel waveguide can be called a W-shaped index profile, as shown in [6].

Fig. 1 shows the cross-sectional interference fringe patterns of the waveguide (A) with GI profiles and of the aforementioned waveguide (B) with W-shaped index profiles. These two photographs are observed by an interferometric slab method. Fig. 2 shows the refractive index profiles of the waveguides (A) and (B) calculated from the interference fringe patterns. As shown in Fig. 1(b), a GI profile is formed in the core regions, and the index valley exists around the cores, which is shown by the dark fringes in the photograph. Since this index valley has slightly lower refractive index than the outer surrounding region by up to 0.002, the W-shaped index profile is obtained, as shown in Fig. 2.

B. Propagation Loss at 850 nm

In the current trends of optical interconnections, vertical-cavity surface-emitting lasers (VCSELs) at a wavelength of 850 nm are to be utilized. Therefore, we measure the

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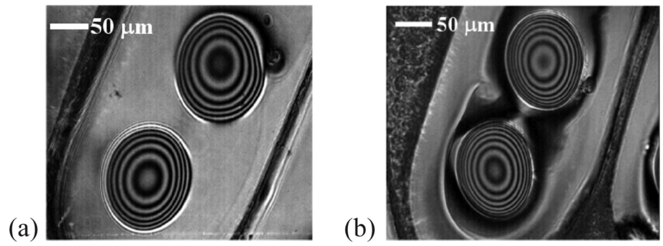

Fig. 1. (a) Interference fringe pattern of 100-μm core waveguide with GI profile. (b) Interference fringe pattern of 100-μm core waveguide with W-shaped profile.

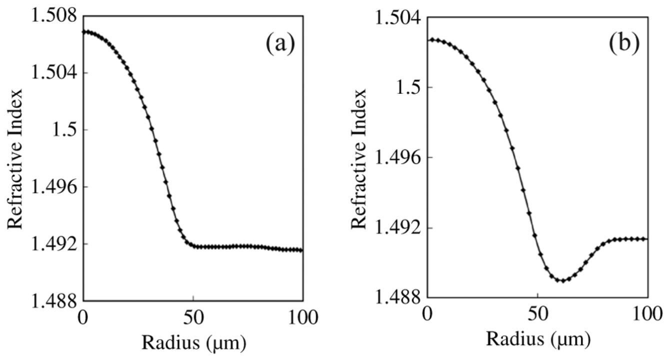

Fig. 2. Refractive index profile of a core of the waveguide with (a) GI profile and (b) W-shaped index profile.

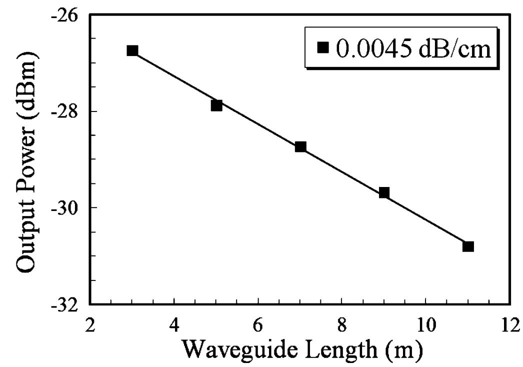

Fig. 3. Cutback plot of one channel of the waveguide (B).

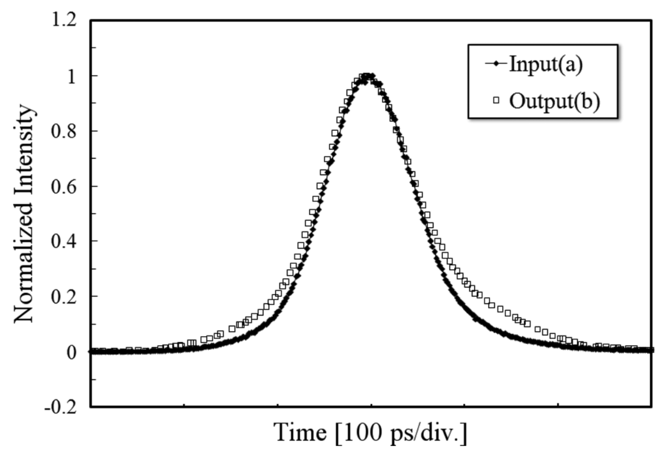

Fig. 4. Waveforms of input pulse (●) and output pulse (□) after a 5.0-m waveguide transmission at a wavelength of 850 nm.

propagation loss at 850 nm. Since the core region is composed of a perdeuterated acrylate with low intrinsic absorption loss [7], it is expected that the propagation loss of the waveguide at 850 nm could be much lower than the normal acrylate-based waveguide (0.029 dB/cm [3], [4]).

Propagation loss of the waveguides is measured by the cutback method on the waveguide (B) with 100-μm-diameter cores at 120-μm pitch from a length of 11 m to 3 m. A 50-μm core multimode fiber (MMF) with a length of 1 m is utilized for launching a channel of the waveguide, and a 100-μm core MMF probe (1 m) is used to guide the output light from the launched core to an optical power meter. It should be noted that such a long waveguide is required for cut-back measurement because the loss is extremely low.

Fig. 3 shows the results of the cut-back process. From the slope of the plots in Fig. 3, the propagation loss of each channel is obtained, and the average loss of four channels is 0.0049 dB/cm, which is much lower than that of the waveguide with circular GI cores we previously fabricated [3] with general acrylate (0.029 dB/cm). This low-loss value means that the optical power attenuation is reduced to 0.5 dB even after transmitting 1.0 m, and which is low enough for optical interconnection on PCBs.

C. Bandwidth Performance and 12.5-Gb/s Transmission

Optical interconnects for high-performance computing requires that each channel is capable of transmitting signals at 10 Gb/s and beyond with very low BER. Therefore, in addition to the propagation loss, modal dispersion is an important issue. We investigate the bandwidth of the novel waveguide and demonstrate a 12.5-Gb/s signal transmission at 850 nm.

1) Bandwidth Measurement at 850 nm: Since the measured waveguide has W-shaped index profile in the core region, as shown in Fig. 2(b), modal dispersion is lower than just a parabolic refractive index profile [6]. The bandwidth measurement was performed as follows: First, one channel is launched in a 5-m-long waveguide (B) with 100-μm cores via a 9-μm-core single-mode-fiber probe, and the output pulse waveform from the waveguide [Fig. 4(b)] is measured by a sampling head (Hamamatsu, C8188), where a 100-μm core GI-MMF is used as a probe for detection. In the next step, we measure the output pulse from the two direct-connected probes (for launch and detection) as an input pulse [Fig. 4(a)], then compare the root-mean-square (rms) widths of the pulses (a) and (b).

The rms width broadening of the output pulse is 24.4 ps for a 5-m transmission, which corresponds to 4.9 ps/m when the pulse broadening is assumed to be linear with respect to the waveguide length. The estimated data rate from the rms pulse broadening is up to 50 Gb/s for 1 m, and this high bandwidth sufficiently satisfies the requirement for optical interconnections on PCBs.

2) 12.5-Gb/s Transmission at 850 nm: A 12.5-Gb/s pseudorandom bit sequences signal from a commercial VCSEL at 850 nm is sent through a 15-m-long waveguide (B) (100-μm core diameter) via a 50-μm core MMF probe, and optical output from the core of the waveguide is collected by a 100-μm-core MMF probe to guide to a high-speed photoreceiver. Fig. 5 shows the eye diagram after propagation through the 15-m-long waveguide.

It is obvious in Fig. 5 that no degradation in the eye diagram is observed even after a 15-m-long transmission owing to

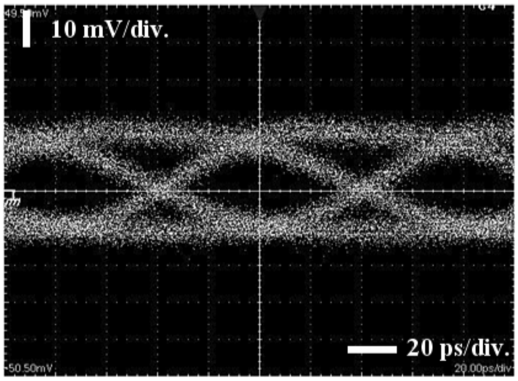

Fig. 5. Eye diagram at 12.5 Gb/s after propagation through a 15-m waveguide (100-μm diameter core) at 850-nm wavelength.

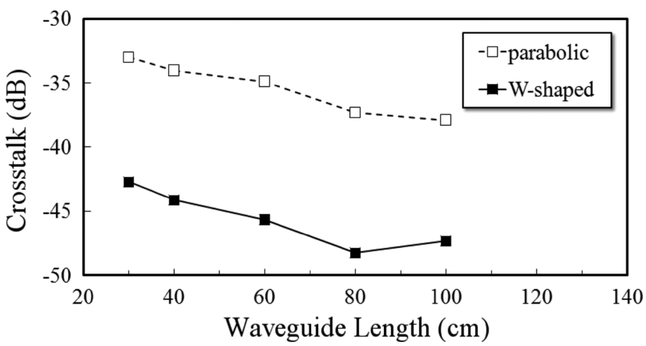

Fig. 6. Crosstalk at various lengths of two waveguides. The plot (□) represents acrylate-based GI waveguide, and the plot (■) represents perdeuterated acrylate-based W-shaped waveguide.

small modal dispersion achieved by the W-shaped index profile and extremely low loss of perdeuterated acrylate. As far as we know, a 12.5-Gb/s transmission for 15-m distance is the highest bit-rate-distance product achieved by polymer parallel optical waveguides ever reported. Although the length of 15 m is not necessarily required even in optical interconnects on PCBs, this low loss and high bandwidth enables a large link margin.

D. Interchannel Crosstalk

We compare the interchannel crosstalk between the acrylate-based waveguide (A) with GI profile [5] and the perdeuterated waveguide (B) with W-shaped index profile. The signal wavelength is 850 nm, and 50-μm- and 100-μm-diameter core GI-MMFs are utilized as the launch and detection probes, respectively. Both waveguides have 100-μm cores with 120-μm pitch. The dependence of the crosstalk on propagation length when one edge core is launched is shown in Fig. 6. The open squares and the closed squares in Fig. 6 are the crosstalk (ratio of the coupled power to emitting power from the launched core) of the GI waveguide and the W-shaped, respectively. Because of the electrical field confinement effect by refractive index profile, crosstalk decreases with increasing the waveguide length in both waveguides. Furthermore, the result in Fig. 6 shows that the crosstalk of the waveguide with W-shaped index profile is restricted to ~ -45 dB, while that with GI profile is ~ -30 dB.

This dramatic crosstalk reduction (15 dB down) is achieved by the W-shaped index profile. The optical signal leaked from the launched core is partially reflected at the index valley (low refractive index) before coupling to the adjacent cores, which consequently restricts interchannel crosstalk. This very low interchannel crosstalk will maintain a low BER of each channel, and thus, further highly integrated (smaller pitch) and high-speed parallel optical interconnection can be achieved by the waveguides with W-shaped profiles.

III. Conclusion

We succeeded in fabricating multimode parallel optical waveguides whose circular cores are composed of perdeuterated acrylate. These new waveguides exhibit ~0.0049 dB/cm at a wavelength of 850 nm because of the small absorption loss of perdeuterated acrylate, which is the lowest propagation loss ever reported for a polymer waveguide. At the same wavelength, data rate up to 50 Gb/s can be transmitted by a single channel in the waveguide owing to small modal dispersion of W-shaped index profile. A 12.5-Gb/s signal transmission is demonstrated over the waveguide length of 15 m. In addition, the index valley formed at the core–cladding boundary allows interchannel crosstalk to be dramatically reduced (-45 dB for 1-m waveguide).

We conclude that the novel polymer waveguide with W-shaped index profile are ideal for high-speed and highly integrated parallel optical interconnection.

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