Polymer waveguide with 4-channel graded-index circular cores for parallel optical interconnects

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Abstract: A polymer waveguide with 4-channel graded-index circular cores is fabricated by the preform method. Very low loss (0.028 dB/cm at a wavelength of 850 nm) and high bandwidth (83 Gbps for 1 m, estimated) properties are experimentally demonstrated by the new waveguide for the first time. By densely aligning the cores during the preform fabrication, a waveguide with a pitch size of 56 μm and a core diameter of 50 μm is obtained, which is expected to be utilized in high-speed and high-density parallel optical interconnections.

OCIS codes: (230.7370) Waveguides; (200.4650) Optical interconnect

References and links

1. P. Pepeljugoski, M. J. Hackert, J. S. Abbott, S. E. Swanson, S. E. Golowich, A. J. Ritger, P. Kolesar, Y. C. Chen, and P. Pleunis, "Development of system specification for laser-optimized 50-μm multimode fiber for multigigabit short-wavelength LANs," J. Lightwave Technol. **21**, 1256-1275 (2003).
2. A. F. Benner, M. Ignatowski, J. Lash, D. M. Kuchta, and M. Ritter, "Exploitation of optical interconnects in future server architectures," IBM J. Res. & Dev. **49**, 755-776 (2005).
3. D. M. Kuchta, Y. H. Kwark, C. Schuster, C. Baks, C. Haymes, J. Schaub, P. Pepeljugoski, L. Shan, R. John, D. Kucharski, D. Rogers, M. Ritter, J. Jewell, L. A. Graham, K. Schrödinger, A. Schild, and H.-M. Rein, "120-Gb/s VCSEL-based parallel-optical interconnect and custom 120-Gb/s Testing Station," J. Lightwave Technol. **22**, 2200-2212 (2004).
4. L. Schares, J. A. Kash, F. E. Doany, C. L. Schow, C. Schuster,D. M. Kuchta, P. K. Pepeljugoski, J. M. Trewhella, C. W. Baks, R. A. John, L. Shan, L.Y. H. Kwark, R. A. Budd, P. Chiniwalla,F. R. Libsch, J. Rosner, C. K.Tsang, C. S. Patel, J. D. Schaub, R. Dangel, F. Horst,B. J. Offrein, D. Kucharski, D. Guckenberger, S. Hegde, H. Nyikal,C.-K. Lin, A. Tandon, G. R. Trott, M. Nystrom, D. P Bour, M. R. T. Tan, and D. W. Dolfi, "Terabus: Terabit/second-class card-level optical interconnect technologies," J. Sel. Top. Quantum Electron. **12**, 1032-1044 (2006).
5. K. Suzuki, Y. Wakazono, A. Suzuki, S. Suzuki, T. Yamaguchi, K. Kikuchi, H. Nakagawa, O. Ibaragi, and M. Aoyagi, "40Gb/s parallel optical interconnection module for optical backplane application," *in Proceedings of Electronic Packaging Technology Conference*, (Institute of Electrical and Electronics and Engineering Components, Packaging and Manufacturing Technology Society, Singapore, 2005), Vol. 1, pp. 367- 370.
6. J. A. Kash, F. Doany, D. Kuchta, P. Pepeljugoski, L. Schares, J. Schaub, C. Schow, J. Trewhella, C. Baks, Y. Kwark, C. Schuster, L. Shan, C. Patel, C. Tsang, J. Rosner, F. Libsch, R. Budd, P. Chiniwalla, D. Guckenberger, D. Kucharski, R. Dangel, B. Offrein, M. Tan, G. Trott, D. Lin, A. Tandon, and M. Nystrom, "Terabus: a chip-to-chip parallel optical interconnect," *in Proceedings of IEEE-LEOS Annual Meeting* (Institute of Electrical and Electronics and Engineering – Lasers and Electro-Optics Society, Sydney, 2005), pp. 363-364.
7. F. E. Doany, P. K. Pepeljugoski, A. C. Lehman, J. A. Kash, and R. Dangel, "Measurement of optical dispersion in multimode polymer waveguide," *in Proceedings of IEEE-LEOS Summer Topical Meeting Optical Interconnects & VLSI Photonics*, (Institute of Electrical and Electronics and Engineering – Lasers and Electro-Optics Society, San Diego, 2004), pp. 31-32.
8. T. Ishigure, E. Nihei, and Y. Koike, "Graded-index polymer optical fiber for high speed data communication," Appl. Opt. **33**, 4261-4266 (1994).
9. T. Ishigure, S. Tanaka, E. Kobayashi and Y. Koike, "Accurate refractive index profiling in a graded-Index plastic optical fiber exceeding gigabit transmission rates," J. Lightw. Technol. **20**, 1449-1456 (2002).

10. J. B. Schlager, M. J. Hackert, P. Pepeljugoski, and J. Gwinn, “Measurements for enhanced bandwidth performance over 62.5-μm multimode fiber in short-wavelength local area networks,” J. Lightwave Technol. **21**, 1276-1285 (2003).
11. T. Ishigure, K. Ohdoko, Y. Ishiyama, and Y. Koike, "Mode coupling control and new index profile of GI POF for restricted launch condition in very short-reach networks," J. Lightwave Technol. **23**, 2443-2448 (2005).
12. R. Dangel, U. Bapst, C. Berger, R. Beyeler, L. Dellmann, F. Horst, B. Offrein, and G.-L. Bona, “Development of a low-cost low-loss polymer waveguide technology for parallel optical interconnect applications,” *in Proceedings of IEEE-LEOS Summer Topical Meeting Optical Interconnects & VLSI Photonics*, (Institute of Electrical and Electronics and Engineering – Lasers and Electro-Optics Society, San Diego, 2004), pp. 29-30.
13. T. Ishigure, Y. Koike, and J. W. Fleming, “Optimum index profile of the perfluorinated polymer based GI polymer optical fiber and its dispersion properties,” J. Lightwave Technol. **18,** 178-184 (2000).

1. Introduction

Increasing data rates of very-short-reach networks such as local area networks (LANs) by serial optical links [1, 2] are creating processing-power limitation of servers, routers switches and computers which have been utilized by copper interconnects on printed circuit boards (PCBs). Particularly, when the data rate increases beyond 10 Gbps, it is predicted that the effects of reflections and crosstalk on electrical interconnections would be another serious problems.

For the bottleneck of electrical interconnections, a parallel optical interconnection has been proposed [3], and already adopted in some high-performance servers for rack-to-rack interconnections. In addition to the “inter-rack” applications, the intra-board and backplane interconnections will utilize the optical solution [4, 5]. For realizing these transitions to optical interconnect, a large number of proposals are reported particularly on the integration of optical waveguides in PCBs. In those approaches, polymers are acknowledged as a key material for making optical waveguides, since polymer materials have a great potential in terms of optical properties, simplicity of processing, and cost effectiveness. Particularly, current trends are in multimode polymer waveguides for parallel optical interconnections [6, 7]. Therefore, a wide variety of polymer materials have been proposed for waveguides, and in general, polymer waveguides have been prepared by photolithographic or imprinting techniques, in which almost all of the polymer waveguides have a square or rectangular core shape, and the refractive index of the core is uniform. Since optical signals in those waveguides propagate by total internal reflection, the smoothness of the core-cladding boundary has been a key parameter to reduce the propagation loss. Although several outstanding propagation loss properties have been reported [7], the average loss of polymer waveguides is still as high as 0.1 dB/cm at a wavelength of 850 nm.

In this paper, we succeeded in fabricating a polymer waveguide with 4-channel circular graded-index (GI) cores for the first time by the preform method. The parabolic refractive index profiles formed in the cores confine the optical signal at the core center well, and thus, the waveguides exhibit very low loss (0.028 dB/cm) and very high bandwidth (estimated to be higher than 83 Gbps•m), which are superior to conventional waveguides with square or rectangular cores with step-index (SI) profiles [7]. Transmission experiments at a data rate of 12.5 Gbps over 3-m-long waveguide show good eye openings. In addition to the technological advancement, this new waveguide is suited for mass production and has a freedom in structural design such as core diameter and pitch. Fabrication process and characteristics of the waveguides newly fabricated are described in detail in the following sections.

2. Fabrication of polymer waveguide

A large number of fabrication processes for polymer waveguides have been proposed, and most of them utilize lithographic processes or imprinting methods. Therefore, the shapes of

#80842 - $15.00 USD Received 8 Mar 2007; revised 20 Apr 2007; accepted 26 Apr 2007; published 27 Apr 2007

the cross-section of core in polymer waveguides are generally designed to be square or rectangular, and the refractive index of the core region is uniform.

On the other hand, the waveguide we propose in this paper is composed of cores with a circular shape, and each of them has a parabolic refractive index profile. In order to fabricate such a polymer waveguide with 4-chnnel circular cores formed by parabolic refractive index profiles, we utilize the preform process. We have already reported the interfacial-gel polymerization technique that is a fabrication process of preforms for high-bandwidth graded-index polymer optical fibers (GI POF) [8, 9]. In the interfacial-gel polymerization process, a parabolic refractive index profile in the core region is formed during the polymerization procedure of the preform. In this paper, this preform preparation process is applied to form 4-channel parallel cores in the preforms for the novel waveguides.

At first, test-tube like polymer tubes with outer and inner diameters of 8 mm and 4 mm, respectively, and a length of 30 cm are prepared by acrylate polymer. Next, four polymer tubes obtained are inserted into a polymer container that is also made of the same acrylate polymer, and the tubes are aligned in the container. It is preferable that the polymer container has a rectangular cross-section and be slightly shorter than the aligned tubes.

In this paper, as an example, a large diameter polymer tube with ellipsoidal cross-section is used for the container as shown in Fig. 1 because of the ease of preparation. The inner space of the tube with ellipsoidal cross-section is designed to have a major axis of 40 mm, and a minor axis of 9 mm, so that the four polymer tubes mentioned above can be fit into the inner space and well aligned.

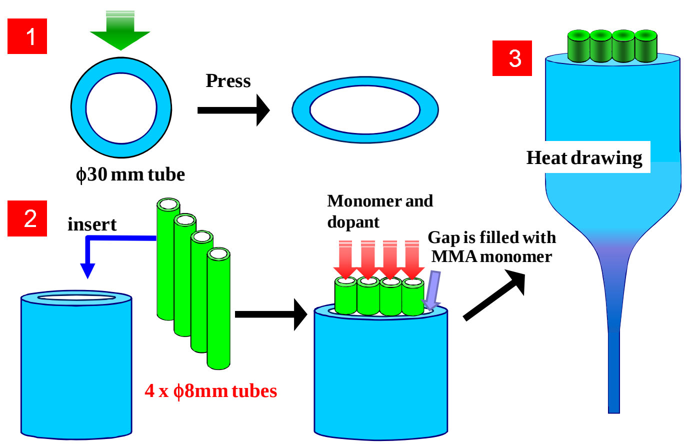

Fig. 1. Schematic representation of waveguide fabrication process by the preform method.

The gap between the aligned polymer tubes and ellipsoidal inner space is filled with the same acrylate monomer, while inside of the aligned polymer tubes is filled with a mixture of acrylate monomer and dopant in order to form parabolic refractive index profiles [9]. Subsequently, the monomer is polymerized in an oil bath to fabricate the preform.

After the polymerization finishes, the preform with ellipsoidal cross-section for waveguide is obtained. The polymer waveguide with 4-channel circular graded-index cores is fabricated by heat-drawing the preform, similar to drawing GI POF [8, 9]. The cross-sections of the obtained waveguides are shown in Figs. 2(a) and 2(b). It is found in Fig. 2 that the four cores are aligned, and the circular shape is maintained even after the heat-drawing; the core diameter of the waveguide A is approximately 100 μm, whereas waveguide B is 50 μm. It is noted that the pitch (distance between the adjacent cores, 116 μm in waveguide A and 58 μm in waveguide B) can easily be varied, by adjusting the diameters of the aligned polymer tubes, and heat-drawing condition. For high-density interconnection, small pitch size is preferred, and thus this preform process has a freedom in designing the waveguide structure.

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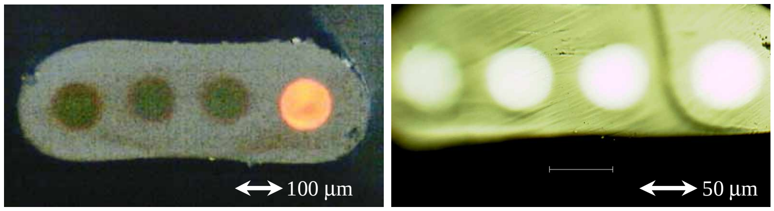

Fig. 2. Photographs of cross-section of waveguides (a)Waveguide A: 100 µm-diameter cores with 116-µm pitch (light beam from a 650-nm LD is coupled to the far-right core) (b)Waveguide B: 50 µm-diameter cores with 58-µm pitch

3. Experimental Results and Discussion

3.1 Refractive index profile, propagation loss, and impulse response function measurements

Refractive index profiles formed in the cores are measured by an interferometric slab method, in which a thin slab sample is cut out of the waveguide. From the observed image by an interference microscope (Mizojiri Optics, TD series), the circular core shape is also confirmed. Figure 3 shows an image of the cross-section of the waveguide B (sliced sample) observed by the interferometric microscope. Contour patterns of concentric interference fringes are observed in the circular core regions, which indicates that a parabolic refractive index profile is formed in each core region. The refractive index profile obtained from the fringe patterns in Fig. 3 is shown in Fig. 4. The index profiles are calculated along the broken line shown in Fig. 3, which connects the centers of three cores. The fringe pattern of the far left core is slightly deformed. This deformation could be caused by an excess stress during the slice sample preparation.

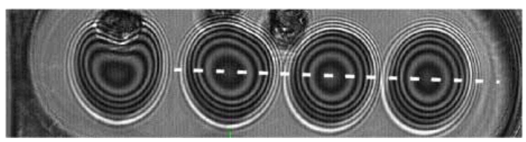

Fig. 3. Interference fringe pattern on the cross-section of polymer waveguide (Waveguide B).

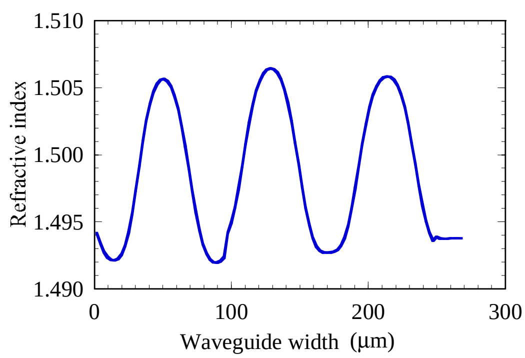

Fig. 4. Refractive index profile obtained from the fringe pattern shown in Fig. 3.

However, in the other three cores, almost the same index profile is formed, and it is found that the core diameter and pitch of this waveguide are approximately 50 µm and 70 µm, respectively. The pitch size obtained from the index profile is slightly larger than the pitch size obtained from the near-field pattern profile (58 µm).

Propagation loss of the waveguides is measured by the cut-back method at a wavelength of 850 nm. It is well known that optical characteristics of multimode waveguides such as loss and bandwidth are strongly affected by launch condition [10, 11] and thus, the launching condition in the loss measurement could be an important issue. However, we expect that the

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circular graded-index core of the waveguide allows for high coupling efficiency with multimode fiber (MMF) with circular core, which would be one of the advantages of this new waveguide. Therefore, in this paper, a 50-µm core MMF with a length of 2 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 a detector for the loss measurements. Figure 5 shows the results of the cut-back process for waveguide C (130-µm core and 154-µm pitch). It is noted that the unit of the horizontal axis is not "cm" but "m," which means that the waveguide sample is long enough and the loss is low enough to detect the output optical power even after a 5-m transmission. From the slope of the plot in Fig. 5, the propagation loss of each channel is obtained, and they are summarized in Table 1 compared to the loss values of the other two waveguides (waveguide A and B). The average loss of the waveguide C is 0.029 dB/cm, which is lower than those of existing waveguides with rectangular SI cores [12]. As shown in Table 1, low-loss properties are observed regardless of the core diameter. Since the loss of conventional GI-POFs composed of the same acrylate polymer at 850 nm is 0.025 dB/cm [13], the loss could be decreased to 0.025 dB/cm by reducing the structural irregularity, which is almost achieved in the waveguide A (0.026 dB/cm).

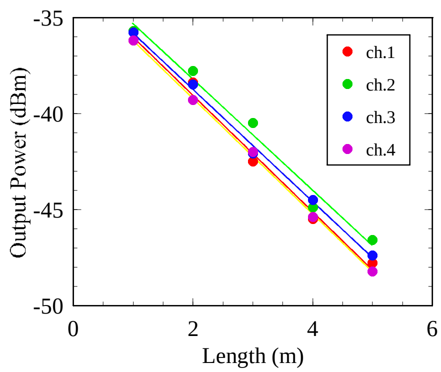

Fig. 5. Results of the loss measurement by the cut-back process for Waveguide C.

Table 1. Propagation Loss of Each Channel in Polymer Waveguide with Circular Graded-Index Cores.

Channel	Loss
Waveguide A	0.026 dB/cm
Waveguide B	0.028 dB/cm
Waveguide C	
ch. 1	0.030 dB/cm
ch. 2	0.029 dB/cm
ch. 3	0.028 dB/cm
ch. 4	0.030 dB/cm

The remarkably low loss of the new waveguides can be attributed to the graded-index circular core. As mentioned above, conventional polymer waveguides have square or rectangular SI cores. Therefore, by improving the smoothness of the core-cladding boundary, the propagation loss has been reduced [12]. On the other hand, as the electric field of the modes in graded-index core is confined within the center region [11], the irregular structure at the core-cladding boundary in the GI-core waveguides has less effect on the propagation loss. Figure 6 shows the near-field patterns (NFP) from a single channel of the waveguide with circular graded-index core (waveguide A, 100-µm diameter) obtained in this paper. Although the core diameter estimated from the refractive index profile is 100 µm, the beam-spot diameter in the NFP in Fig. 6(a) is approximately 60 µm when the core diameter of the launching MMF probe is 100 µm. If the probe fiber is a single-mode fiber with smaller core diameter, the beam-spot diameter in NFP is much smaller than 100 µm as shown in Fig. 6(c).

We already confirmed that the launch condition dependence, i.e. mode-order dependence, on NFP is typical of the GI-core waveguide structure [11], while the output NFP form SI core is independent of the mode order [10]. From the results of the NFP, it is found that the core-cladding boundary has less of an effect on the light transmission.

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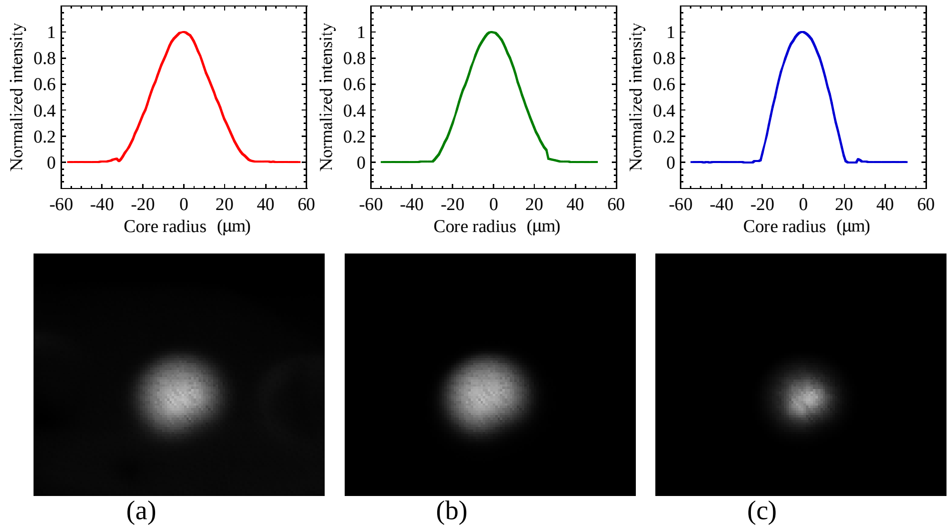

Fig. 6. Observed NFP image (Bottom) and intensity profile on radial direction (Top) from a channel of 100-µm core waveguide (Waveguide A). (a) launched via 100-µm core MMF probe (b) launched via 50-µm core MMF probe (c) launched via 9-µm core SMF probe

3.2 Bandwidth performance and 12.5 Gbps transmission

We expect that the parabolic refractive index profiles in the waveguides play an important role in reducing modal dispersion rather than reducing propagation loss. We investigate the performance of the new waveguides by measuring the pulse broadening due to modal dispersion as follows: An 80-ps wide pulse from a VCSEL at a wavelength of 850 nm is launched into one channel of the waveguide (waveguide B) with a core and pitch of 50 µm and 58 µm, respectively, via a MMF probe (50-µm core). The length of the tested waveguide is 5 m. The output from the waveguide is coupled to a short 50-µm core MMF probe. The light output from the probe is coupled to either optical power-meter to evaluate the alignment loss or an optical sampling oscilloscope (Hamamatsu, C8188) for evaluating the output pulse width. Figure 7(a) shows the comparison of the input (red curve) and output (blue curve) waveforms from the waveguide. After 5 m of transmission, little pulse broadening is observed. The pulse broadening in root mean square (r.m.s) width is calculated to be 15 ps for the 5-m transmission, from which we can estimate the -3dB bandwidth to be 63 GHz by the Fourier Transform of the input and output pulses. Therefore, the modal dispersion in the new waveguide is not a problem for data rates up to 83 Gbps for 1 m length. In Table 2, the results of output pulse broadening and -3dB bandwidth of all the waveguides used in this paper (waveguide A, B and C) are summarized. A large difference in the -3dB bandwidth is observed among the three waveguides, which could be attributed to perturbation of the refractive index profiles. Since the fabrication process of the preform for the waveguides is not matured, the refractive index profiles formed in the waveguides can be deviated from the optimum profile. However, for a 1-m transmission, higher than 10 Gbps transmission is capable in all the waveguides, and we confirm in this paper that if the index profile is optimized, such a high bandwidth as 63 GHz (waveguide B) can be obtained.

As a comparison, the pulse broadening from an SI type waveguide for such a short distance as 1 m is also shown in Fig. 7(b). Here, instead of a waveguide with SI core, a 240-µm core SI POF (Mitsubishi; SK-10) with a length of 1 m is used for the measurement. It is difficult to compare the pulse broadening of the SI POF to those of conventional waveguide with SI core, because the numerical aperture (NA) of the SI POF is higher than those of conventional waveguides. Due to the high NA, even after a 1-m transmission, 70 ps of r.m.s

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width broadening is observed as shown in Fig. 7(b). Although modal dispersion in such a short distance is generally not a problem in the case of conventional waveguides [6], the reduction of modal dispersion by engineering the refractive index profile would become more important for data rates higher than 10 Gbps/ch. Furthermore, the waveguide with circular graded-index cores can be utilized from very short (~1m) to short reach (~ several tens of meters) because of low modal dispersion. Thus, the specification of waveguides for optical interconnection from intra- and inter-board to inter-rack could be consolidated, possibly reducing the cost of interconnection devices.

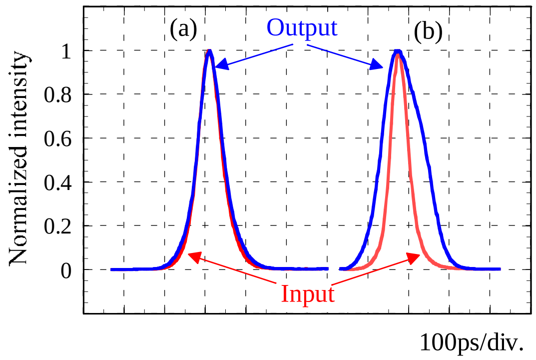

Fig. 7. Output pulse and reference pulse waveforms of (a) 5-m long waveguide with graded-index core (Waveguide B) and (b) 1-m long SI POF for 850 nm.

Table 2.Output Pulse Broadening and -3dB Bandwidth of a channel in Polymer Waveguide with Circular Graded-Index Cores.

	Pulse Broadening (ps/m)	-3dB Bandwidth
Waveguide A	10	19 GHz
Waveguide B	3	63 GHz
Waveguide C	7	27 GHz

With this new waveguide with graded-index cores, we are able to demonstrate 12.5 Gbps signal transmission for a length of 3 m. A 12.5 Gbps signal that is provided by a commercial VCSEL at 850 nm (California Scientific Inc., V-126), is sent through a 3-m-long waveguide (130-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 commercial high-speed photo-receiver (California Scientific Inc., P-101). Figures 8(a) and 8(b) show the eye diagrams of back-to-back and measured after the waveguide transmission. When the back-to-back eye diagram is taken, the output power is adjusted to be the same (-11.5 dBm) as that after the waveguide transmission by a variable optical attenuator. No degradation in the eye diagram is observed even after a 3-m transmission, due to small modal dispersion as indicated in Fig. 7. A 12.5 Gbps transmission for 3-m distance would be the highest bit rate-distance product achieved by polymer waveguides ever reported as far as we know. Figure 9(a) shows an eye diagram of 10 Gbps transmission through the same waveguide used in Fig. 8. In this case, the waveguide length is 1 m. In Fig. 9(b), an eye diagram of 10 Gbps transmission through SI POF (SK-10) with a length of 1m is also shown for a comparison. In the cases of Fig. 9(a) and 9(b), the optical power coupled to the photo-receiver is controlled to be -12.5 dBm and -12.42 dBm, respectively by a variable optical attenuator. Although the output power from the waveguide with graded index core is almost the same as or even slightly lower than that from the SI POF, wider eye opening is observed in the waveguide in Fig. 9(a). This result indicates that larger modal dispersion in the SI POF deteriorates the eye diagram. Therefore, although it is known that modal dispersion in conventional polymer waveguides with SI-core is not a serious issue even for such a data rate as high as 10 Gbps in very short distance transmission, small modal dispersion provided by graded-index cores can reduce the power penalty, enabling longer distance transmission or allows for large power margin in total interconnection systems.

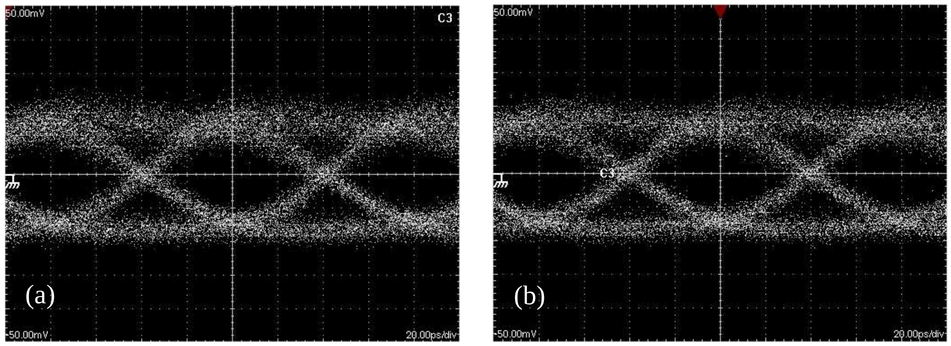

Fig. 8. Eye diagrams at 12.5 Gbps (a) back-to-back and (b) after propagation through 3-m waveguide (130-µm core).

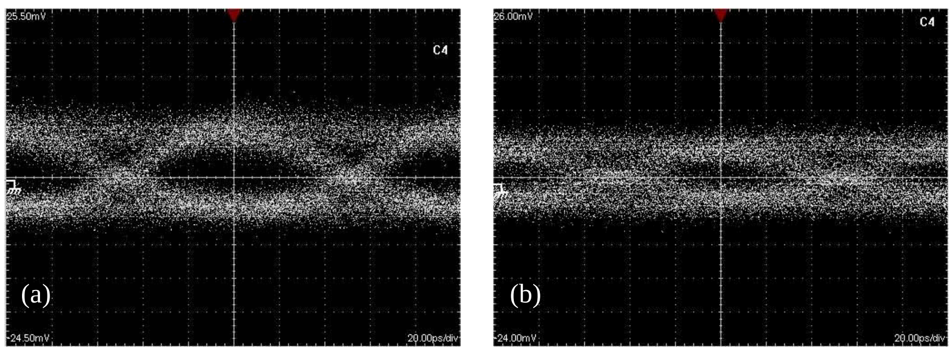

Fig. 9. Eye diagrams at 10 Gbps for 850 nm (a): after propagation through 1-m waveguide (130-µm core) when optical output power is -12.5 dBm, and (b): after propagation through 1-m SI POF when optical output power is -12.42 dBm.

4. Conclusion

We propose a low-loss and high-bandwidth multimode polymer waveguide with multi-channel circular graded-index cores for the first time, and demonstrate a parallel optical interconnection using the polymer waveguides. The graded-index circular cores offer a high-coupling efficiency with multimode fibers with circular core commonly used in short-distance optical links, because of which we expect the novel waveguides can be utilized widely in backplane and rack-to-rack interconnections. Compared with conventional polymer waveguides with step-index square or rectangular cores, the electric field of the propagating modes is confined within the core center in graded-index cores. Therefore, very low loss (0.028 dB/cm for 850-nm) is obtained, which is less influenced by the roughness of the core-cladding boundary. In addition to the effect of propagation-loss reduction, small modal dispersion due to the graded-index cores is also demonstrated experimentally. Although modal dispersion in conventional waveguides with step-index cores is not a significant problem for such a very-short-reach regime, we confirm that small modal dispersion due to graded-index profiles allows for a large freedom in link design, since the power penalty due to modal dispersion can be reduced, particularly at data rates higher than 10 Gbps. Furthermore, the polymer waveguides with circular graded-index cores can be utilized not only in intra-board or backplane interconnections but also in other relatively long-reach interconnections such as inter-board.

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