Densely Aligned Multichannel Polymer Waveguide With Low Inter-Channel Crosstalk

Yusuke Takeyoshi, *Student Member, IEEE*, and Takaaki Ishigure, *Member, IEEE*

***Abstract*—We succeeded in fabricating an acrylate-polymer based four-channel parallel optical waveguide with densely aligned graded-index (GI) circular cores (58-μm pitch) by the preform method. Although inter-channel optical crosstalk is concerned in such highly integrated channels, we verify a strong confinement effect of electric field at the core center achieved by parabolic refractive index profile (GI). Low inter-channel crosstalk is demonstrated by the polymer waveguides with densely aligned GI cores.**

***Index Terms*—Graded-index (GI) profile, low inter-channel crosstalk, optical interconnection, parallel optical waveguide.**

I. Introduction

In recent years, the rapid increase of Internet traffic and of large-scale integrated clock frequency has boosted the demands of high-performance core routers, switches, and servers. The interconnections within the equipment are expected to require highly integrated transmission of a data rate of 10 Gb/s per channel and beyond with extremely low bit-error rate (BER), under 10^{-18} [1]. For such a high signal integrity at such a high data rate, conventional electrical interconnects would have several problems such as large attenuation of high-frequency components, crosstalk, and skew for parallel signal transmission. With this background, multimode polymer optical waveguides are drawing much attention [2] as an alternative to copper wire, because they are fabricated and implemented cost effectively. As a solution to this demand, we succeeded in fabricating polymer parallel optical waveguides with circular graded-index (GI) cores by the preform method [3] for the first time. The novel waveguide composed of acrylate polymer exhibited very low attenuation (under 0.03 dB/cm) and high bandwidth (83 Gb/s·m) at a wavelength of 850 nm. The low loss and high bandwidth properties of the waveguide enabled a 12.5-Gb/s transmission over a length of 3.0 m [3], [4]. The relatively large cores (50–100 μm) of the waveguide are suitable with the alignment accuracy of a vertical-cavity surface-emitting laser (VCSEL) array and detector array. However, the pitch was designed to be as small as 50–120 μm in order to realize high density integration. It is of a general concern that input signal to a certain channel transfers to other channels during transmission, which is called inter-channel crosstalk, degrading the signal integrity. In this letter, we demonstrate that the GI cores in the novel waveguides confine the electric field of propagation modes within the center of the core more tightly than step refractive index (SI) cores. We also examine the low inter-channel crosstalk achieved by the strong confinement, followed by the effect of offset-launch on the inter-channel crosstalk.

Manuscript received April 11, 2007; revised June 18, 2007.

The authors are with the Faculty of Science and Technology, Keio University, Yokohama, Japan (e-mail: takeyoshi@a5.keio.jp; ishigure@appi.keio.ac.jp).

Digital Object Identifier 10.1109/LPT.2007.903529

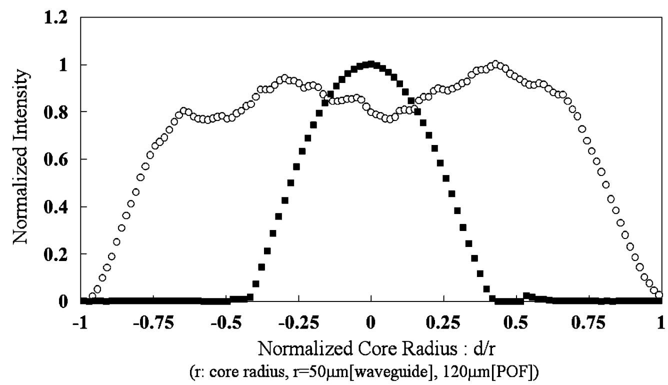

Fig. 1. Intensity profile after 1-m transmission of waveguide and SI POF launched via SMF. Plot (■) represents NFP of a single core of parallel waveguide. Plot (○) represents NFP of SI-POF. Abbreviation "d" is distance from peak position of NFP.

II. Experiment, Results, and Discussion

A. Electric Field Confinement Effect

We fabricate acrylate-based four-channel optical waveguides with GI circular cores in the same way as in the [3] and [4]. In this letter, we focus on the two waveguides with different structures. The measured waveguide: (a) has a core diameter and a pitch of 100 μm and 120 μm, respectively, while more highly integrated waveguide (b) has 50-μm cores with 58 μm pitch.

Fig. 1 shows the near-field-pattern (NFP) of the cross section of waveguide (a) indicated by closed squares. The center of a core is launched by a laser diode (LD) at 850 nm.

The NFP indicated by open circles in Fig. 1 is obtained by a 240-μm core SI plastic optical fiber (POF: Mitsubishi, SK-10) launched under the same condition. The horizontal axis represents the normalized core radius. Fig. 1 shows that the GI waveguide confines electric field of propagation modes at the core center very tightly even after a 1-m transmission, which is a suitable length for intra-board and backplane optical interconnections. In this measurement, the waveguide is launched via a 9-μm core single-mode fiber (SMF), which is a model of a launch condition with conventional VCSEL. Since the spot diameter of the output beam from VCSELs is known to be as small as 15 μm [5], which is only slightly larger than the core size of the SMF probe, the light from VCSEL array could be tightly confined at the center of cores as well.

1041-1135/$25.00 © 2007 IEEE

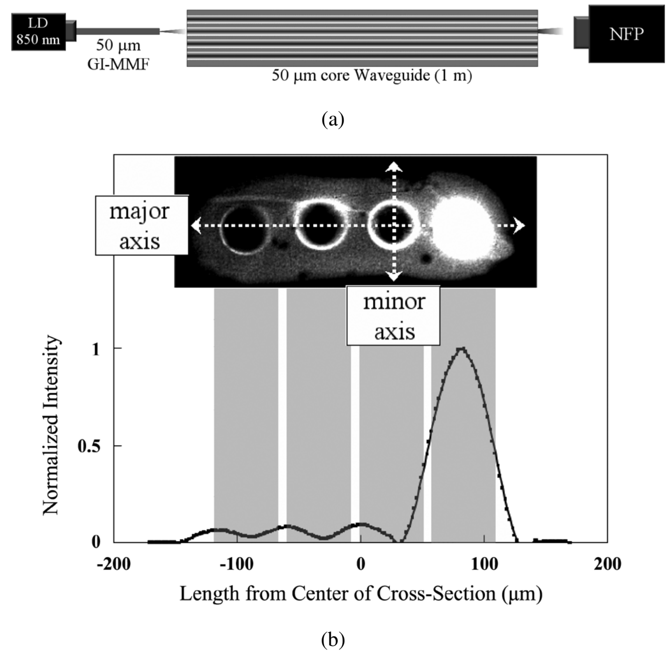

Fig. 2 (a) Schematic representation of crosstalk measurement system. NFP after 1-m transmission of waveguide (b) when the center of one edge core is launched. Inset is a photograph of cross section. Highlighted areas by gray color correspond to core region.

In the case of a 240-μm core SI-POF, electric field of light spreads over the entire core region after a 1-m transmission. This phenomenon is also observed in conventional polymer parallel optical waveguides with rectangular SI cores [6]. However, such rectangular SI-core waveguides cannot be evaluated experimentally because they are not commercially available. From these results, we verify the strong effect of electric field confinement by GI profile, and this effect improves the coupling efficiency with detector and restricts inter-channel crosstalk.

B. Inter-Channel Crosstalk Evaluation

Power coupling of the propagation modes from the launched channel to other channels (i.e., inter-channel crosstalk) is relevant for backplane parallel interconnection applications that require very low BER transmission. Therefore, we examine the crosstalk property of the fabricated waveguides.

1) Coupled Optical Power Profile: Crosstalk measurements are performed on the two samples: waveguides (a) and (b), mentioned previously. The NA of each core is approximately 0.2. First, we measure the NFP after a 1-m transmission through waveguide (b) in which the center of an edge core is launched via a 50-μm diameter GI-MMF probe as shown in Fig. 2(a). Fig. 2(b) shows the intensity profile along the major axis of the cross section indicated by the dotted line in the inset of Fig. 2(b) (the photo of the cross section).

Since almost all the modes of the core are launched, which is different from Fig. 1, output power profile from the launched core [at the far-right edge in Fig. 2(b)] is entirely distributed in the core area. Furthermore, optical power is coupled to the unlaunched cores (i.e., crosstalk) as shown in Fig. 2. However, it is noteworthy that the coupled power profile shows a ring pattern. This result indicates that crosstalk signal is dominantly coupled

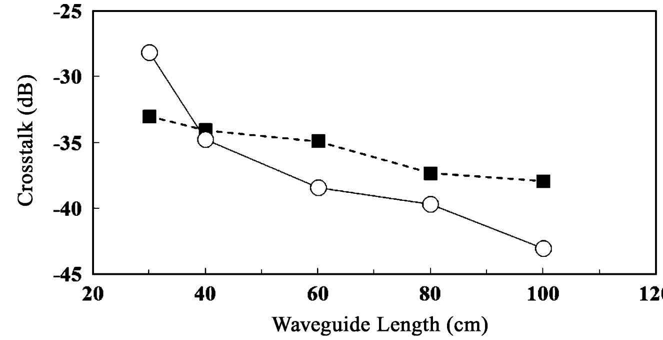

Fig. 3. Crosstalk at various lengths of waveguides. Plot (■) represents waveguide (a), which has 100-μm cores at 120-μm pitch, and plot (○) represents waveguide (b), which has 50-μm cores at 58-μm pitch.

to the high-order modes of unlaunched cores, because the ring pattern of NFP is the same profile as that of high-order modes in conventional GI-POFs [7]. On the other hand, in the case of SI-POF, the NFP of all the modes equally distributes over the core, which is independent of the launch condition [8]. Therefore, the ring-like crosstalk power profile shown in Fig. 2(b) is specific to the waveguides with GI profile. If photo detectors with an effective area smaller than the core size of waveguides are used, this crosstalk is spatially filtered, and by combining with the electric field confinement effect shown in Fig. 1, very low crosstalk is expected in these new waveguides. In this case, it is important to design optimal core and detector sizes for minimizing the coupling loss between the waveguide and detector.

2) Crosstalk Measurement: We quantitatively measure the dependence of the crosstalk on propagation length when one edge core of the waveguide (a) and waveguide (b) is launched. The launch condition is the same as that in Fig. 2. Here, the crosstalk is obtained by measuring the output signal power from the launched core and the coupled power from the adjacent core by utilizing a 1-m length GI-MMF as a detection probe. The core diameter of the detection probe is matched to the core size of the measured waveguides. The result is shown in Fig. 3.

Crosstalk of waveguide (a) and highly integrated waveguide (b) increases as the waveguide length decreases, but it is maintained as low as -30 dB (0.1% of signal power) or smaller. Optical confinement within the core center restricts the leakage of the electric field and results in the small crosstalk. It is noted that with increasing the propagation length, the crosstalk decreases, although the long propagation length is supposed to increase the crosstalk. This result is attributed to high propagation loss (0.03 dB/cm [3]) of the waveguides at a wavelength of 850 nm. Compared to conventional polymer waveguides composed of acrylate polymer, the loss of 0.03 dB/cm is very low. However, at 850 nm, intrinsic absorption loss due to carbon–hydrogen bonding in polymer waveguides is as high as 0.025 dB/cm. Therefore, during the propagation in the polymer waveguides for several tens of centimeters, leaked optical power from the launched core is strongly attenuated; thus, crosstalk also decreases. Furthermore, the reason for higher crosstalk of the waveguide (b) after 30-cm propagation is considered as follows. Since the core size of the launch probe (50 μm) is the same in both measurements, optical power coupled to the higher order modes in the 50-μm core waveguide is higher than that of

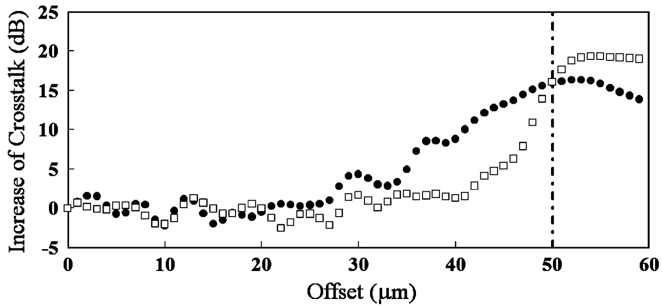

Fig. 4. Crosstalk increment caused by offset launch. Plot (●) represents major-axis-direction offset, and plot (□) represents minor-axis-direction offset. Broken line indicates core-cladding boundary.

100-μm cores. Higher order modes are generally leaked easily and then coupled to the adjacent cores. Some amount of optical power from the probe may be coupled even to the adjacent core at the input end, because of the small pitch. The power coupling results in higher crosstalk in the 50-μm core waveguide at the shorter length (less than 40 cm) compared to the 100-μm core waveguide. In waveguide (a) with 100-μm diameter cores, if the detection probe diameter is decreased from 100 to 50 μm, we observe drastic crosstalk reduction, which is achieved by the spatial filtering effect of the coupled crosstalk power mentioned previously. Actually, the crosstalk is reduced from -38 dB to -42 dB by small-sized detector for the 1-m waveguide.

3) Effect of Offset Launch on Crosstalk: In actual link applications, VCSEL arrays do not always launch the center of each core in the waveguides. Increasing the number of channels makes it difficult to perfectly align all the VCSELs with the cores of the waveguide.

The NA of GI cores varies depending on the distance from the core center, and then this local NA of GI cores can also vary the optical confinement effect depending on the launch position. Therefore, the influence on crosstalk is a great concern if misalignment is caused between the light source and the cores of waveguide.

In this paper, we investigate how much crosstalk is increased by such an offset launching as follows: we measure the output power from the adjacent channel when the center of one core is launched via a SMF probe. Then, output power variation is evaluated by displacing the probe position from the center to periphery by 1-μm step. The offset displacement is performed in two orthogonal directions: one is the direction along the major axis and the other is the minor axis as shown in Fig. 2. Waveguide (a) with 100-μm cores is used for the measurement.

Fig. 4 shows the result. In Fig. 4, crosstalk to the adjacent channel shows little change over the range of offset from 0 to 25 μm, regardless of the offset directions, which implies little power leakage from the launched core due to the offset launch.

On the contrary, in the offset range from 25 to 40 μm, a small increase in the crosstalk is observed under the offset along the minor-axis direction, while as high as a 10-dB increase under the major-axis offset is also observed. It is obvious that the launching position by the SMF probe comes close to the adjacent core when the offset is along the major axis. Thus, crosstalk is strongly dependent on the offset direction, particularly in the offset range of 25 to 40 μm. These results indicate that, in the case of a 100-μm diameter core, offset should be less than 25 μm (half of the core radius) in the major-axis direction in order to minimize crosstalk, even if cores have a graded-index profile. We can conclude that the tolerance in misalignment between the center of the light beam and cores of waveguide is almost half size of the core radius, which would be large enough for the current integration technique in printed circuit boards.

III. Conclusion

We experimentally verify the electric-field confinement effect of graded-index circular cores in the novel polymer waveguides we developed. We also demonstrate low inter-channel crosstalk property achieved by the confinement effect. We observe that the crosstalk is mainly coupled to the higher order modes whose electric field is localized at the core periphery. Therefore, even if a slight amount of optical power is coupled to the adjacent cores, the inter-channel crosstalk can be reduced by a photo detector with an effective area slightly smaller than the core diameter of waveguides. In this case, the optimum design of both core diameter and effective area of photo detector is a very important issue to decrease the coupling loss between them as well. Finally, we confirm that 25 μm of offset launch is tolerated in a 100-μm core 120-μm pitch polymer waveguides maintaining the inter-channel crosstalk increase of less than a few decibels. Therefore, the polymer waveguides with circular graded-index core would be a key device in high-density and high-speed optical interconnections.

References

[1] 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.*, vol. 49, no. 4/5, pp. 755–776, Sep. 2005.

[2] 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. Lightw. Technol.*, vol. 22, no. 9, pp. 2200–2212, Sep. 2004.

[3] T. Ishigure and Y. Takeyoshi, “Polymer waveguide with 4-channel GI cores toward high-speed optical interconnects,” presented at the Conf. Lasers Electro-Optics (CLEO ’07), Baltimore, MD, 2007, Paper JTuA32.

[4] T. Ishigure and Y. Takeyoshi, “Polymer waveguide with 4-channel graded-index circular cores for parallel optical interconnects,” *Opt. Exp.*, vol. 15, no. 9, pp. 5843–5850, Apr. 2007.

[5] C. Berger, B. J. Offrein, and M. Schmatz, “Challenges for the introduction of board-level optical interconnect technology into product development roadmaps,” *Proc. SPIE*, vol. 6124, p. 61240J, 2006.

[6] F. E. Donay, P. K. Pepeljugoski, A. C. Lehman, J. A. Kash, and R. Dangel, “Measurement of optical dispersion in multimode polymer waveguides,” in *Proc. IEEE-LEOS Topical Meeting*, San Diego, CA, 2004, pp. 31–32.

[7] T. Ishigure, K. Ohdoko, and Y. Koike, “Mode coupling control and new index profile of GI POF for restricted launch condition in very short-reach networks,” *J. Lightw. Technol.*, vol. 23, no. 12, pp. 2443–2448, Dec. 2005.

[8] T. Ishigure, M. Kano, and Y. Koike, “Which is a more serious factor to the bandwidth of GI POF: Differential mode attenuation or mode coupling?,” *J. Lightw. Technol.*, vol. 18, no. 7, pp. 959–966, Jul. 2002.