GI-core polymer parallel optical waveguide with high-loss, carbon-black-doped cladding for extra low inter-channel crosstalk

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Abstract: Graded-index (GI) polymer parallel optical waveguides with high-absorption, carbon-black-doped cladding are fabricated using the preform method in order to reduce the inter-channel crosstalk. The waveguides exhibit a lower inter-channel crosstalk (<-69.3dB) than optically-transparent-clad waveguides (~-33.7 dB) and maintain low propagation loss (0.029dB/cm). We characterize the waveguides with different concentration of carbon black in order to confirm the required concentration (required absorption loss) for keeping the inter-channel crosstalk low enough. In addition, carbon-black-doped waveguides are fabricated directly on a substrate by means of a soft-lithography method. Crosstalk is sufficiently decreased despite the high scattering loss of the core material, while insertion loss is not increased. Furthermore, we fabricate a waveguide with a high-scattering-loss cladding to confirm the origin of low crosstalk in carbon-black-doped waveguides. We confirm that high scattering loss of cladding is not necessarily as effective for crosstalk reduction as high absorption loss of cladding.

OCIS codes: (060.2280) Fiber design and fabrication; (200.4650) Optical interconnects; (230.7370) Waveguides; (250.5460) Polymer waveguides.

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1. Introduction

Accompanied by the increase of the signal transmission rate in core routers in metro and core communication networks, the required data throughput for their backplanes is approaching the performance limit [1,2]. To overcome this limitation in data throughput, optical interconnections have been expected to be introduced to backplane, board-to-board, and even chip-to-chip interconnections in place of electrical interconnections. In particular, for board-level optical interconnections with high-density channel alignment, we have reported polymer parallel optical waveguides with graded-index (GI) cores [3], and have confirmed that the GI-core waveguides show a low propagation loss, low inter-channel crosstalk, and ease of on-board implementation.

However, when considering the much higher density alignment of waveguide arrays with very short pitch, inter-channel crosstalk is of concern even in GI-core waveguides as schematically shown in Fig. 1(a). Actually, it was already reported [4] that the crosstalk in conventional step-index (SI) core waveguides increased when the pitch size was reduced from 250 μm to less than its half value (100 μm). Therefore, in this paper, we realize much lower inter-channel crosstalk in GI-core polymer waveguides with “high-loss” carbon-black-doped cladding. The structure of the waveguides is schematically shown in Fig. 1(b). In the new waveguide, the light that is scattered and leaked out from one core is absorbed by the carbon black doped in the cladding and thus hardly reaches to the adjacent cores. Since the GI profile confines the propagating mode fields tightly near the core center [5], the optical power of propagating modes is less affected by the high-loss cladding than conventional SI core waveguides in which all the modes are reflected at the core-cladding boundary. Consequently, we expect that the low propagation loss of GI core waveguides is maintained.

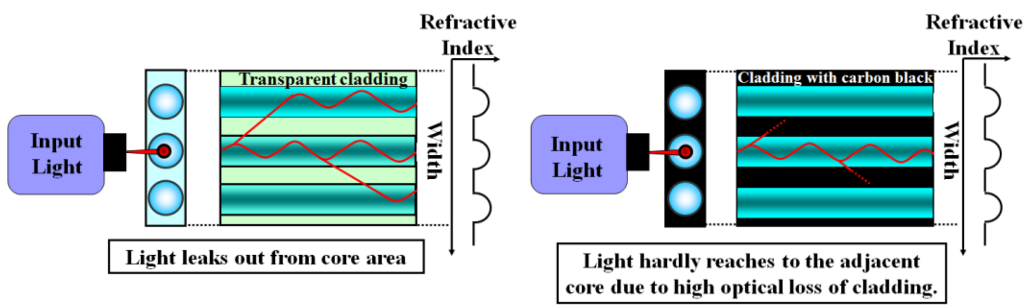

Fig. 1. Schematics of crosstalk reduction in waveguides with carbon-black-doped cladding.

2. Fabrication method of carbon-black-doped waveguide

In this paper, we adopt the preform method for fabricating waveguides. Utilizing the preform method, waveguides with GI profile cores have been successfully fabricated, and we showed many superior characteristics to conventional waveguides in our previous report [3], [5]. In addition, the preform method has been utilized as a fabrication method for GI polymer optical fibers (GI-POFs), which is described in more detail in references [6–8].

For fabricating a waveguide with GI cores, at first, several acrylic-polymer-based rods which have a GI core are prepared using the interfacial-gel polymerization technique [6], as shown in Fig. 2(a). Then, the rods with GI core are inserted into a mold composed of a Π-shaped Teflon frame and two glass plates as shown Fig. 2(b). Next, methyl methacrylate (MMA) monomer doped with a specified amount of carbon black powder is poured into the mold in order to fill the gap between the rods and mold. After the polymerization reaction of

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the MMA monomer completes, a preform plate is obtained, and finally, the preform is heat-drawn to a waveguide, like optical fibers, as shown in Fig. 2(c).

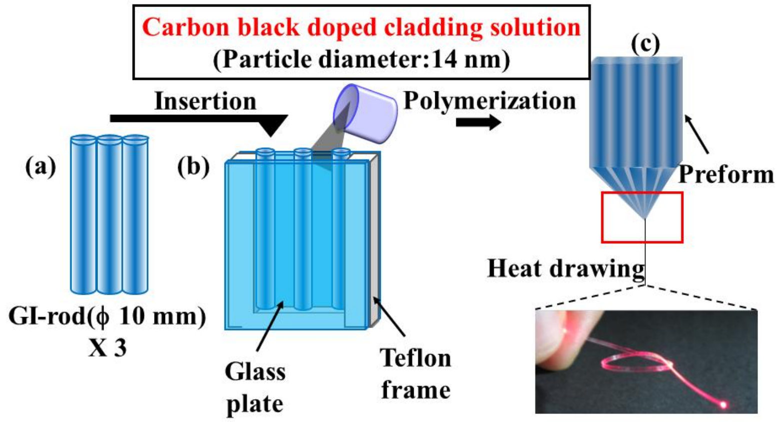

Fig. 2. Fabrication process of a waveguide with high attenuation cladding.

3. Experimental results and discussion of carbon black doped waveguides

3.1 Refractive index and propagation loss

The cores in the obtained waveguides are composed of a PMMA doped with diphenyl sulfide (DPS), while PMMA doped with carbon black is the cladding material. A cross-section of actual fabricated waveguides is shown in Fig. 3.

Although various kinds of waveguides with desired core size and pitch can be obtained by adjusting the preform design and heat-drawing conditions, the core diameters in this paper are fixed to approximately 80 ~100 μm and pitches between the cores to 230 μm.

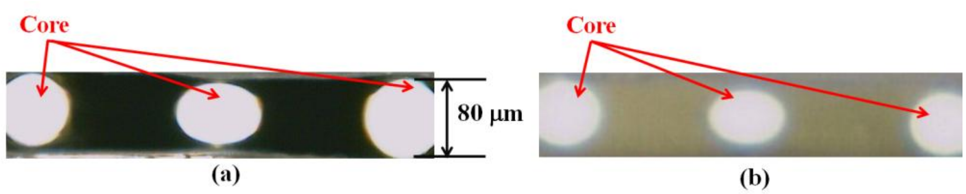

Fig. 3. Cross-sections of waveguides with high attenuation cladding (a):waveguide with carbon in cladding (b):waveguide with no carbon in cladding.

We confirm from Fig. 3 that the novel waveguide with carbon in the cladding shows a high contrast in the output optical power between the core and cladding compared with that of the waveguide with no carbon included in the cladding (Fig. 3(b)). The concentration of carbon black in the cladding shown in Fig. 3 (a) is 25 ppm. This result indicates that the carbon-black-doped cladding effectively reduces the light power in the cladding, which is leaked from the cores, while the core regions maintain low loss.

Figure 4(a) shows an interference fringe pattern observed from the carbon-doped waveguide. For this measurement, the waveguide is sliced to obtain a thin plate sample (less than 200-μm thickness). The concentric interference fringes in the core regions shown in Fig. 4 (a) indicate that parabolic refractive index profiles (GI profiles) are successfully formed in each core region. Figure 4(b) is the refractive index calculated from the fringe pattern shown in Fig. 4 (a). Near parabolic index profiles are actually formed in all the cores.

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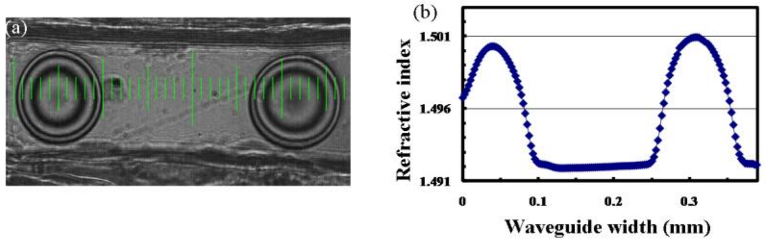

Fig. 4. (a) Interference fringe pattern observed from a carbon-black-doped clad polymer waveguide (b) Refractive index profile formed in the waveguide shown in Fig. 4(a).

The propagation loss of the GI-core waveguide with carbon-black-doped cladding is measured using the cut-back method. Because the waveguides are heat-drawn from a preform, a waveguide several tens of meters long or longer can be obtained from one preform. Therefore, we can begin the cut-back test from a several meter-long waveguide, which leads to accurate propagation loss results. For coupling the light from a white light source (ANDO, AQ-4303 halogen-tungsten lump) to a core of the waveguide, we use a GI multimode fiber probe with a 50 μm core diameter. The output light from the core of waveguide is coupled to another GI-MMF probe to guide the light to an optical spectrum analyzer (ANDO, AQ-6328B). Then, the optical power at a wavelength of 850 nm is extracted from the spectrum data in order to calculate the propagation loss. The result is shown in Fig. 5. Despite the existence of high-loss cladding, the propagation loss is as low as 0.029 dB/cm, as shown in Fig. 5. This value is exactly the same as that of GI-core waveguides whose cladding does not involve carbon black [3].

In the case of conventional SI-core waveguides, it would be difficult to maintain low propagation loss when the cladding is composed of highly absorptive materials, because all the propagating modes in SI-cores propagate by total internal reflection, and thus, the propagating modes suffer from high-loss cladding when they are reflected. Therefore, the low propagation loss shown in Fig. 5 is a specific characteristic in GI-core waveguides.

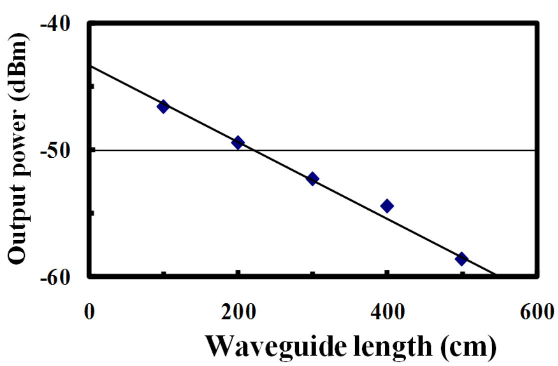

Fig. 5. Propagation loss of a carbon-black doped waveguide.

3.2 Inter-channel crosstalk

Inter-channel crosstalk is caused by optical power coupling among multiple channels in the parallel-core waveguides. As mentioned before, GI-core waveguides can decrease the inter-channel crosstalk due to the optical confinement effect of GI core. However, for satisfying the requirement of high-density channel alignment, inter-core pitch would be reduced to several micrometers. Therefore, even in GI-core waveguides, we should pay attention to the inter-channel crosstalk.

We evaluate the inter-channel crosstalk in several GI-core polymer waveguides, and investigate the effect of carbon black in the cladding on the crosstalk. We measure the

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crosstalk at a wavelength of 850 nm. The measurement setup is schematically shown in Fig. 6. Though vertical cavity surface emitting lasers (VCSELs) with an emitting area diameter of approximately 10 μm is common for optical interconnections, we use a launching MMF probe with a 50-μm core diameter, supposing the worst case for the inter-channel crosstalk. By scanning the MMF detection probe over the cross-section of the output end of 1-m waveguides, output power distribution is measured, and then, the crosstalk is calculated.

For the actual on-board interconnection applications, we should also evaluate the crosstalk by directly butt-coupling the VCSELs to waveguides. However, the spot diameter and the divergence angle of output beam from VCSEL chips currently available are strongly dependent on each VCSEL structure and even on the bias current. Hence, it is difficult to realize a reproducible launching condition when a specific VCSEL chip is butt-coupled to waveguides.

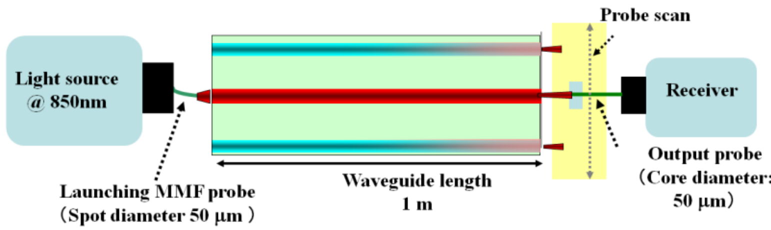

Fig. 6. Schematics of measurement system of inter-channel crosstalk.

Figure 7 shows the power distribution at the output end of 1-m waveguides with and without carbon black in the cladding, when only the middle core (Ch. 2) is launched. In the case of the carbon-doped waveguide (blue curve), double peaks are observed in Ch. 1 and Ch.3, which means a ring like output is observed. The ring-shaped output is a typical power profile in the high-order modes of GI cores [8]. Thus, some amount of crosstalk is observed particularly to the high-order modes, but the crosstalk measured at the core center of Ch. 1 and Ch. 3 is completely suppressed. The flat power profile around −80 dBm in blue carve indicates the detection limit of the receiver. As shown in Fig. 7, the crosstalk of −33.7 dB in the undoped-clad waveguide is quite low, but less than −68 dB of crosstalk observed in the carbon-black-doped-clad waveguide.

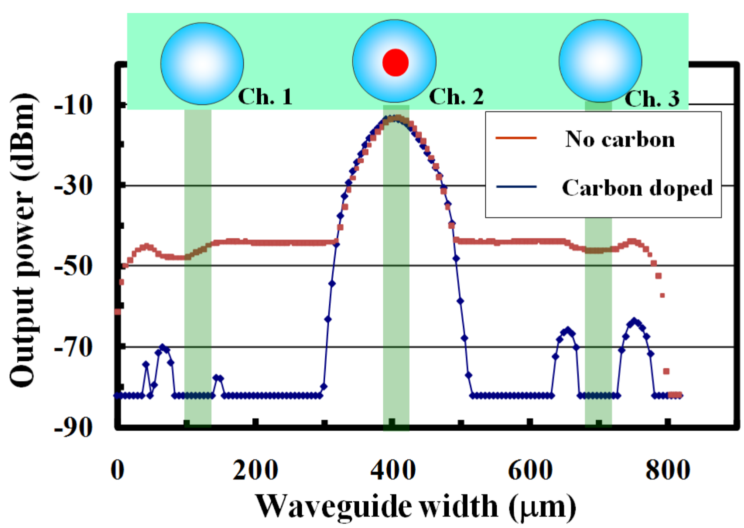

Fig. 7. Power distribution at the output end of waveguides with and without carbon black in cladding.

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The difference of 34 dB indicates that the crosstalk in the undoped-clad waveguide is about 2000 times larger than that of the carbon doped waveguide. Table 1 summarizes the crosstalk results with a wide variety of carbon-black-doping concentrations. From this result, we confirm that the inter-channel crosstalk is sufficiently decreased by doping the cladding with carbon black.

Table 1. Comparison of Waveguides with Different Concentration of Carbon Black in Cladding

Concentration value of carbon black (ppm)	10	25	100	500
Core diameter / pitch (μm/ μm)	98/270	90/230	85/248	110/320
Propagation loss (dB/cm)	0.023	0.029	0.027	0.030
Numerical aperture (NA)	0.170	0.180	0.155	0.173
Index exponent value (g value)	2.8	2.5	2.7	2.7
Transmittance value of a 10-μm thick plate @850 nm(%)	80.1	48.3	9.9	2.1
Crosstalk after 5 cm propagation (dB)	–36.8	–51.0	–44.6	>-68.8
Crosstalk after 1m propagation (dB)	–45.3	>-69.3	>-69.1	>-68.6

3.3 Characteristics depending on concentration of carbon black

In order to verify the contribution of carbon black to the extremely low crosstalk, several waveguides with different carbon-black concentrations in the cladding are characterized in more detail. The results are also summarized in Table 1. First, no significant differences in the core diameters and pitches are observed for the waveguides with the concentration of 10, 25, and 100 ppm. Second, the parameters that could influence the light confinement at the core center, like the propagation loss, the numerical aperture, and the index exponent values, are almost the same. (The index exponent values are calculated from the measured refractive index profiles of the waveguides.). Although the index exponent values have slight differences, such a small difference has less effect on the light confinement around the core center. Meanwhile, the transmittance values of the carbon-doped PMMA plate is evaluated by independently fabricated plate samples. It is clearly observed that the transmittance value decreases as the concentration of carbon-black increases. Hence, the absorption loss is varied widely by changing the concentration of carbon black.

The crosstalk shows a remarkable difference between the waveguides with concentrations of 10 ppm and 25 ppm. On the other hand, it is noteworthy that the waveguides with a concentration higher than 25 ppm show almost the same inter-channel crosstalk, which is completely suppressed. This result indicates that a concentration of carbon black higher than 10 ppm is needed to reduce the inter-channel crosstalk for GI-core waveguides with 90-μm core diameter and 250-μm pitch.

In addition, we fabricate a waveguide with 500 ppm carbon-black-doped cladding, and measure its characteristics in the same manner as the waveguides with other concentrations. Although the core sizes and inter-channel pitches are larger than other waveguides, it is notable that the waveguide shows as low inter-channel crosstalk as the other waveguides. In the case of GI-core waveguides, the inter-channel crosstalk generally increases with decreasing the waveguide length [9], but in the case of the waveguide with 500-ppm carbon-black-doped cladding, the low crosstalk of less than –69 dB is maintained even under a waveguide length of 5 cm.

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4. Carbon-black-doped clad waveguide by soft-lithography method

For a simple and easy implementation on printed circuit boards, polymer waveguides should be fabricated on a substrate directly. For direct waveguide fabrication on a substrate, UV curable resins are commonly used, but some UV curable resins have much higher scattering loss than PMMA. We already succeeded in fabricating GI-core polymer waveguides utilizing a UV-curable resin and then found that the high-scattering loss inherent to the core material substantially increased the crosstalk even in the case of GI-core waveguides [10]. The main cause of the high crosstalk in the waveguide with high-scattering loss is the mode conversion to the guiding modes in the adjacent cores from the cladding modes that are scattered and leaked out from the core. Therefore, it is expected that carbon black doping contributes to reducing the crosstalk in such high scattering loss waveguides. The waveguides with carbon-black-doped cladding are fabricated by means of the same soft lithography method that we used in [10] as follows: First, a silicone resin (poly dimethyl siloxane: PDMS) stamp for imprinting is fabricated. The core-cladding structure (grooves) is formed by projecting the convex patterns on the PDMS stamp against the under-cladding monomer layer. A UV-curable acrylate monomer (TPIR-202 from Tokyo Ohka Kogyo Co. Ltd.) doped with carbon black is used for the cladding, and DPS is also used as the dopant in the core region.

In the next step, the grooves on the under-cladding layer are filled with the core monomer (TPIR-202 with DPS), followed by the core polymerization under UV exposure. After the core polymerization, the over-cladding layer (carbon black is doped) is coated again, and finally, after UV exposure for curing, the core-cladding waveguide structure is obtained. In the curing process of the under-cladding layer and cores, we do not complete the polymerization reaction by adjusting the UV exposure. Therefore, the monomer (and dopant) filled in the grooves are allowed to diffuse into the gel-state cladding layer during the curing process of the cores. Thus, a concentration distribution of the dopant is formed in the core area, which corresponds to a near-parabolic refractive index distribution.

Figure 8 shows cross sections of fabricated waveguides with and without carbon particles in the cladding. The core size and the pitch of the two waveguides are approximately 80x50 μm, and 250 μm, respectively.

(a)

(b)

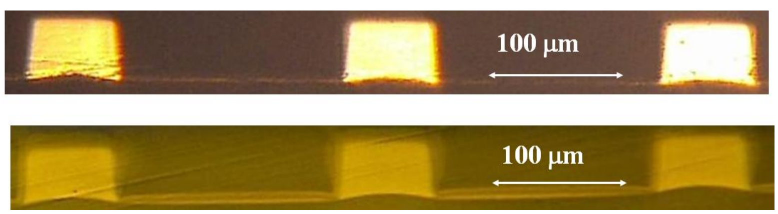

Fig. 8. Cross-sections of waveguides (a) with carbon-black in cladding (b) without carbon black in cladding fabricated using a soft lithography process.

The concentration of carbon black in the cladding is 250 ppm. We confirm from Fig. 8 that the novel waveguide with carbon in the cladding shows a high contrast of the output optical power between the core and cladding. These images suggest the carbon-black-doped cladding exhibits very high optical loss, while the core regions maintain the same loss as those with no carbon doping.

The crosstalk difference between the waveguides with and without carbon particles in their claddings is evaluated in the same way as shown in Fig. 6. Figure 9 shows the output power distribution at the end of 3.2-cm waveguides, when the middle of five cores is launched (shown schematically in Fig. 9). The crosstalk calculated from Fig. 9 is −7.1 dB in the waveguide without carbon black, while it is dramatically decreased to −23 dB in the carbon-black-doped waveguide. The difference is 16 dB. The crosstalk reduction effect of carbon black in the waveguide fabricated using soft-lithography is smaller than that in PMMA waveguides fabricated by the preform method shown in Table 1, because of the high scattering loss of TPIR-202 (originally higher crosstalk). However, it is observed from Fig. 9

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that the output power from the launched core (middle core) is hardly attenuated by carbon black, and maintains a value of −20 dBm.

From the results in the waveguides composed of TPIR-202 polymers, we find that high-scattering loss of "core polymer" and irregularities in the core-cladding structure increase the inter-channel crosstalk as high as −7.1 dB. Hence, high-loss waveguides possibly show high crosstalk that is mainly due to mode conversion, even if they have sufficiently wide pitch. In addition, we also confirm that absorptive cladding can effectively reduce the optical power of cladding modes, and consequently, low inter-channel crosstalk is achieved even in such a high-scattering-loss waveguide, if it has GI cores. When we focus on the optical power loss of cladding modes, not only absorptive cladding but also a hazy, high-scattering loss cladding (not core) would be another solution to reduce the crosstalk. In the next section, we show absorptive claddings are more effective for crosstalk reduction.

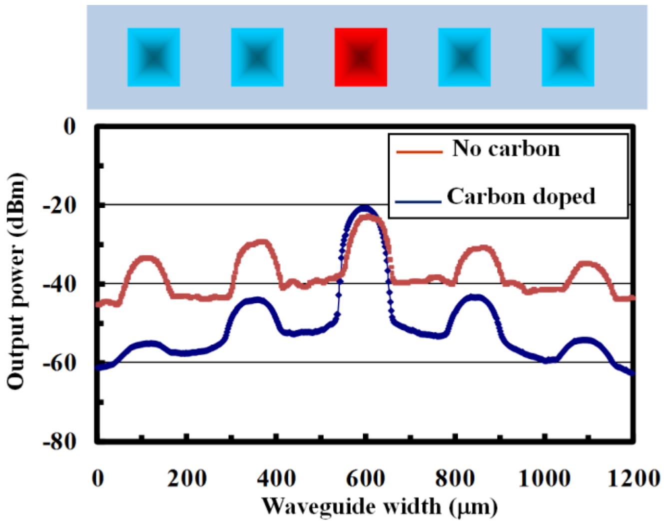

Fig. 9. Power distribution at the output end of waveguides with and without carbon black in the cladding fabricated using a soft lithography process.

5. Waveguide with high scattering cladding

From the above discussions, we verify that a "high-loss" cladding is a key to decrease the inter-channel crosstalk. However, there are two factors for optical loss in the cladding: absorption and scattering. By doping carbon black, the absorption mainly increases, although aggregated carbon black particles may slightly increase the scattering loss. Meanwhile, scattering losses can also attenuate the crosstalk. Therefore, we compare two waveguides with high-scattering-loss and high-absorption-loss claddings in order to confirm that the high absorption loss mainly contributes to the crosstalk reduction.

In order to focus only on the loss factor in the cladding, we fabricate waveguides with a high-scattering-loss cladding by means of the preform method. Here, by blending a small amount of benzyl methacrylate (BzMA) homopolymer into the PMMA, a hazy (high scattering loss) cladding is obtained due to a phase separation effect. Actually, a PMMA bulk (c) including 0.5 wt. % of BzMA polymer appears hazy, as shown in Fig. 10. The characteristics of the carbon-black-doped clad waveguide and the BzMA-powder-doped clad waveguide are compared in Table 2. As Table 2 shows, the two waveguides have similar structures in terms of the core diameter and inter-channel pitches. Furthermore, the parameters that influence the light confinement effect, like propagation loss, numerical aperture, and index exponent values are almost the same. Even the light transmittance value at 850 nm is almost identical in the cases of 25-ppm carbon-black-doped one and BzMA doped counterpart. Here, the transmittance of *undoped* PMMA plate with a 10 mm thickness is

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defined to be 100%, and thus, the transmittance values in Table 2 are just the ratio of transmitted optical power between doped polymer and undoped polymer. Meanwhile, the crosstalk is remarkably different between the carbon-black-doped and BzMA-powder-doped clad waveguides. In Table 2, the results of 10-ppm carbon-black-doped waveguide are also shown for a comparison. In the case of the 10-ppm carbon-black-doped polymer, the light transmittance at 850-nm wavelength is 80. 1%, which is higher than that of 0.5-wt.% BzMA-doped polymer. However, the crosstalk in the waveguide with 10-ppm carbon-black-doped clad (–45.3 dB) is lower than that (–36.0 dB) in the BzMA doped counterpart. Therefore, it is verified that the low crosstalk values in the waveguides with carbon-black-doped cladding is attributed to the high “absorption” loss, while high scattering loss would not necessarily contribute to the crosstalk reduction effectively.

From the results in Section 5, it is of another concern that high-scattering loss in cladding can increase the crosstalk (due to a multiple scattering effect.) However, it is noteworthy that the crosstalk of –36.0 dB is comparable to the crosstalk in the waveguides with undoped PMMA cladding shown in Fig. 7. In order to carefully investigate the contribution of scattering loss, we should vary the haze of the cladding and evaluate the crosstalk. This result will be described elsewhere.

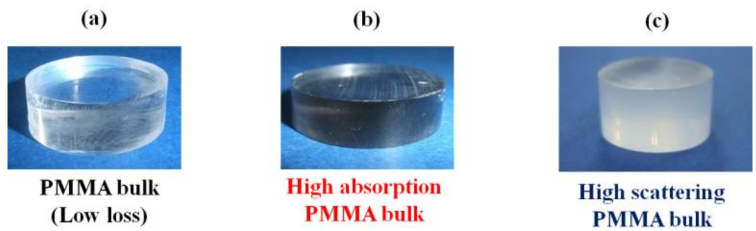

Fig. 10. Appearance of PMMA bulks with (a) no attenuation material (b) high absorption material (c) high scattering material.

Table 2. Characteristics of Waveguides with Carbon Black or BzMA Powder in Claddings

	Carbon black waveguide (10 ppm)	Carbon black waveguide (25 ppm)	BzMA doped waveguide (0.5 wt.%)
Core diameter /pitch (μm/μm)	98/270	90/230	95/250
Propagation loss (dB/cm)	0.029	0.029	0.030
Numerical aperture (NA)	0.170	0.180	0.176
Index exponent value (g value)	2.8	2.5	2.2
Transmittance value of 10 mm bulk @850 nm(%)	80.1	48.4	55.4
Crosstalk after 1m propagation (dB)	–45.3	<-69.3	- 36.0

6. Conclusions

We fabricated novel GI-core polymer parallel optical waveguides with carbon-black-doped cladding to add a high-absorption-loss to the cladding. We demonstrated that the waveguides with high-absorption-cladding could reduce the inter-channel crosstalk dramatically, maintaining the low propagation loss of the cores. At the same time, it was suggested that a concentration higher than 10 ppm of carbon black doping into the cladding is preferable for the crosstalk reduction. In addition, the crosstalk of the waveguides fabricated by means of the lithography method was decreased by carbon-black doping in the cladding despite the high scattering loss of the waveguide (core) material.

We also confirmed that other waveguides with high scattering loss in the cladding were not as effective as high absorption loss did for reducing the crosstalk.

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