High-density channel alignment of graded index core polymer optical waveguide and its crosstalk analysis with ray tracing method

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Abstract: We fabricate graded index (GI) multi-channel polymer optical waveguides comprised of poly methyl methacrylate (PMMA)-poly benzyl methacrylate copolymer for the purpose of achieving high thermal stability in the GI profiles. The waveguides obtained show slightly higher propagation loss (0.033 dB/cm at 850 nm) than doped PMMA based GI-core polymer waveguides we have reported, due to the excess scattering loss inherent to the mixture of copolymer and homo-polymer in the core area. In this paper, we focus on the influence of the excess scattering loss on mode conversion and inter-channel crosstalk. We simulate the behavior of light propagating inside the core with and without the scattering effect. Using the simulation, the excess loss experimentally observed in the copolymer-core waveguide is successfully reproduced, and then, we find that the excess scattering loss of 0.008 dB/cm could increase the inter-channel crosstalk from −30 dB to −23 dB which agrees with the experimentally observed value. Although the simulation of the inter-channel crosstalk was performed only on our GI-core polymer optical waveguides, it is capable of modeling the conventional SI rectangular-core waveguides. Some amount of excess scattering is generally observed in the conventional SI-core waveguides, and thus, the application of this simulation to SI-core waveguides allows a feasible design for high-density alignment of the waveguides.

OCIS codes: (250.5460) Polymer waveguides; (200.4650) Optical interconnects; (080.5692) Ray trajectories in inhomogeneous media.

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1. Introduction

Multimode and multi-channel polymer optical waveguides have been expected to be high performance data communication devices for short range interconnections, ranging from on-board to board-to-board [1,2]. Specifically, polymer optical waveguides embedded on a printed circuit board (PCB) have already been developed for on-board interconnection applications [2,3].

For the polymer optical waveguides on PCBs, thermal stability is required to endure the normal lamination and solder reflow processes. Hence, polymer materials that have high thermal stability have been chosen for comprising the polymer waveguides. However, there have been few polymer materials that satisfy the requirement of not only low optical loss but high thermal stability and low cost. Therefore, in most cases, polymer materials that show higher intrinsic scattering loss have been utilized, since thermal stability would be the first priority. Furthermore, since photolithography or imprinting processes have been widely utilized for fabricating the polymer waveguides directly on-board, the conventional design of these polymer waveguides have had step-index (SI) rectangular cores which utilizes total internal reflection to propagate the light inside the cores . Thus, much attention has been focused on the waveguide fabrication process to obtain a smooth surface at the core-cladding boundary in order to reduce the propagation loss. However, the propagation loss would be 0.1 dB/cm or higher except for some state-of-the-art ones [1,2], due to the excess scattering and absorption losses inherent to the polymer material. Even for such on-board polymer optical waveguides, much higher channel data rates and density are required in the past few years [1], and thus current trends of polymer waveguide design are in smaller core size (~35 μm) and narrower inter-core pitch (~65 μm). Because of the high excess scattering loss, inter-channel crosstalk in those polymer optical waveguides is of great concern when much narrower pitch design is required for higher-density channel alignment [4,5].

In order to address these problems, we have proposed to apply graded-index (GI) core polymer optical waveguides to such an on-board interconnection application [6,7]. According to the previous studies, we experimentally verified the advantage of the GI-core polymer optical waveguide: the ability to reduce the propagation loss due to structural imperfections, transmitting a data rate of 12.5 Gbps through each channel, and decreasing the crosstalk value to less than −30 dB [6,7]. However, since the previous GI-core waveguides we reported were composed of low-loss poly methyl methacrylate (PMMA), the thermal stability of the waveguides was not high enough. In particular, we already confirmed that the GI profile formed by the concentration distribution of dopant was not stable at a temperature higher than 85 °C [8]. In order to increase the thermal stability of the GI-core polymer optical waveguides, we need to substitute the PMMA for other polymer materials with a high glass transition temperature, while it could have higher excess scattering loss.

Therefore, in this paper, we show how the scattering loss affects the inter-channel crosstalk in GI-core polymer optical waveguides both theoretically and experimentally. In the experimental part, we demonstrate that excess scattering loss causes higher crosstalk, by

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using a copolymer of PMMA and poly benzyl methacrylate (BzMA). Here, the copolymer core material provides high thermal stability in the GI profile. Meanwhile, the copolymer based optical waveguide shows an excess scattering loss of approximately 0.01 dB/cm at 850-nm wavelength, according to our previous studies [9].

On the other hand, for the theoretical analysis, we utilize a ray tracing simulation in which the influence of the light scattering within the core area is involved. Finally we calculate the output intensity profile after a certain propagation distance with respect to the combination of several key parameters. The simulation results show a similar trend to the experiment results. This allows us to find the relationship among the light scattering, mode conversion and inter-channel crosstalk quantitatively.

2. Waveguide Fabrication and Characterization

We fabricate copolymer based multi-channel polymer optical waveguides by means of the preform method we have reported in [6]. In this paper, we use a monomer mixture composed of 20-wt.% BzMA in MMA monomer instead of diphenyl sulfide (DPS) doped PMMA for the core material. Our target is to form a graded refractive index distribution approximated by the power-law form shown by Eq. (1) in each circular-shaped core (channel) area. Here, the refractive index profile $n(r)$ as a function of the distance r from the core center is written with a parameter of index exponent g as [10]

$$n(r) = n_1[1-2\Delta(r/a)^g]^{1/2} \tag{1}$$

where, Δ is the relative refractive index difference, n_1 is the highest refractive index value in the core region (normally at the core center), and a is the core radius.

When we apply the GI-core polymer optical waveguides to board-level optical interconnections, the thermal stability of the dopant added polymer has been of a great concern. Actually, we confirmed that the refractive index profile formed in a GI polymer optical fiber (POF) comprised of dopant added to PMMA degraded after aging at 85 °C due to the diffusion of dopant in the PMMA matrix [5]. On the other hand, the refractive index profile formed with copolymer is stable enough because the copolymer molecules do not diffuse easily. On the other hand, we also reported that [11] a copolymer of MMA and BzMA in the GI POF showed higher scattering loss due to its long chain structure, compared to DPS doped PMMA, particularly when the GI preforms were fabricated by means of the interfacial-gel polymerization technique.

Therefore, we focus on the "excess scattering loss," of the MMA-BzMA copolymer based GI-core polymer optical waveguides in this paper. The processes of the preform fabrication and refractive index profile control are described in [6,12], and basically, we use the same processes in this paper. First, a mold composed of two glass plates and a Teflon flame was filled with MMA monomer, in which several round brass rods were aligned in parallel. The mold was placed in an autoclave under 60 °C and 0.3-MPa N_2 gas atmosphere for four hours in order to polymerize the monomer. After the polymerization reaction completed, the rods were removed to form holes for the cores, and then a plate-like PMMA based cladding was fabricated. For the core area, a mixture of 20-wt.% BzMA in MMA monomer was used. Secondly, the core area was polymerized in an autoclave at 120 °C for 48 hours to obtain a preform. During the core polymerization reaction, a concentration distribution of BzMA-MMA copolymer is formed in each core area, which makes a near-parabolic refractive index distribution. We have called this process as the interfacial-gel polymerization technique [10]. Finally, the preform was heat-drawn to a multi-channel polymer optical waveguide with several hundreds of meters long. The diameter of each core is controlled around 100 μm during the heat-drawing process, while the refractive indices of the core (n_1) and cladding (n_2) are 1.5005 and 1.492, respectively, as shown in Fig. 1. The fitted g values correspond to Eq. (1) are 2.461, 2.476, and 2.460 for the left, middle, and right channel, respectively.

Here, the excess scattering loss is caused from the copolymer core as follows: during the core polymerization process, the homo-polymer of PMMA comprising the cladding is

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dissolved into the monomer mixture inside the core, while the newly polymerized copolymer of MMA and BzMA also exists in the core region. Thus, the GI-cores formed by the interfacial-gel co-polymerization process are composed of a PMMA homo-polymer and a copolymer of MMA and BzMA. This mixture of two kinds of polymers with different refractive indices leads to large heterogeneous structures that enhance the scattering loss [13].

The propagation loss of the obtained copolymer-based core waveguide is evaluated by utilizing the cut-back method [6]. In this measurement, incoherent light from a Halogen-Tungsten lump is coupled to a core of the waveguide via a 50-μm core multimode fiber (MMF) probe (1-m length), and the output light from the core is coupled to another 50-μm core MMF probe to guide to the optical spectrum analyzer (ANDO AQ-6315B). From the slope of the output power variation at a wavelength of 850 nm, the propagation loss is obtained as 0.033 dB/cm, which is higher than that (0.028 dB/cm) of a DPS doped core waveguide [6,7]. As expected, an excess scattering loss of 0.005 dB/cm from the copolymer based core increases the total propagation loss. Although the excess loss of 0.005 dB/cm seems very low, the loss measurement using the cut-back method was carried out for the waveguides with several-meters long, which is long enough for evaluating the loss with good accuracy.

When we previously fabricated a P(MMA-BzMA) core GI polymer optical fiber (POF) using the interfacial-gel polymerization technique, the loss of the POF was as high as 0.002 to 0.0025 dB/cm at 650-nm wavelength, while a dopant-based GI POF showed 0.0015 dB/cm at the same wavelength. Therefore, an excess scattering loss of approximately 0.001 dB/cm was caused in the copolymer-based core GI POF. For optical links that need to connect a distance of hundreds of meters, the "excess scattering loss" of even 0.001 dB/cm is seriously high. Meanwhile, an excess loss of 0.005 dB/cm observed in our waveguide looks very low for a link with a few tens of centimeters [13]. We will discuss the influence of the excess scattering loss on the performance of the waveguides.

One of the important characteristics of the GI-core waveguides is the optical field confinement near the core center [7]. However, the optical confinement might be deteriorated in the newly obtained copolymer based waveguide, due to the mode conversion caused by the excess scattering. Therefore, we evaluate the optical confinement in the copolymer based waveguide by observing the output near-field pattern (NFP) under a restricted mode launch (RML) condition. For the NFP measurement, output light from a VCSEL at 850 nm wavelength is coupled to a core of the waveguide via a single mode fiber (SMF) with 10-μm diameter. Figure 2 shows the NFP after a 1-m waveguide transmission when a horizontal offset is added at the launching position. Even in the case of high-loss copolymer-core waveguide, the NFP is almost axially symmetric and strongly confined near the core center when launched at the core center (0 μm). From this result, we confirm the existence of near parabolic refractive index profile in the core. Under the offset launch condition, the higher-order modes are selectively launched, and thus, typical NFPs with two separated peaks like a dumbbell shape are clearly observed, particularly under an offset of 20 μm and beyond.

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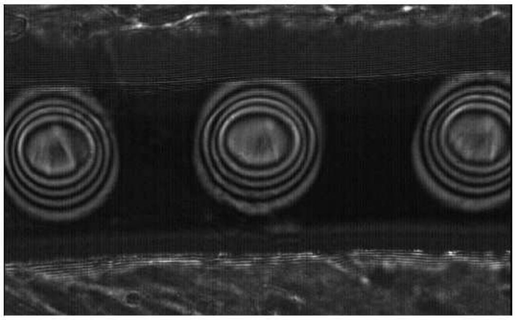

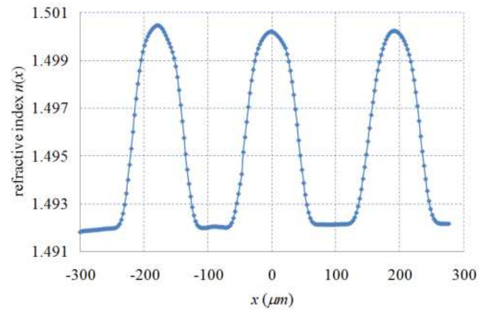

(a) (b)

Fig. 1. (a) The refractive index profile measured using an interference microscope. The concentric interference fringes show the graded index variation within the core area. (b) Refractive index profile measured on the horizontal line connecting the core centers. The core radius of each core is approximately 50 μm and pitch (from the center to center) is approximately 200 μm.

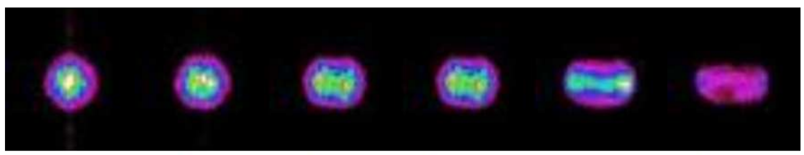

Fig. 2. NFP after a 1-m waveguide transmission of a copolymer based optical waveguide under restricted launch condition and offset launch (move horizontally). The offset distance is shown beneath each profile.

For the crosstalk measurement, the middle of the three cores was launched via an SMF probe, and the output power from the specified points on the cross-section of the output end was measured. The photo of the output cross-section when the crosstalk was measured is shown in Fig. 3. Note that the rims of the adjacent cores are brighter than their inner area, as shown in Fig. 3. This means even if the light is well confined near the launched core center, a little power leaks out and then re-couples to the adjacent channels (mode conversion). This phenomenon is a result of the crosstalk in our waveguide and will be discussed later. The copolymer based waveguide fabricated in this paper exhibits higher crosstalk (−23.47 dB for the left channel and −23.71 dB for the right) than the DPS doped waveguide which showed a crosstalk of −30 dB and less [6]. Due to the higher excess scattering loss from the copolymer based waveguide, higher power light is leaked from the core and would increase the crosstalk value. Table 1 shows the measurement results of both DPS doped and copolymer based waveguides.

Fig. 3. The middle core of 1-m long copolymer based waveguide was launched for crosstalk measurement. We can observe the ring like pattern in adjacent channels. In this sample, the core radius of each core is approximately 50 μm and pitch (from the center to center) is approximately 200 μm.

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Table 1. Measurement results of the waveguides

	DPS dopant	Copolymer based
Loss (dB/cm)	0.028	0.033
Crosstalk at 1 m (dB)	< 30	~-23.6

3. Theoretical Analysis of Inter-channel Crosstalk

As mentioned in the previous section, the copolymer based optical waveguides exhibited higher scattering loss than dopant based ones. It is believed that loss caused by light scattering is one of the factors enhancing mode conversion. Therefore, there is a concern that the higher scattering loss broadens the optical field in the whole core and even into the cladding region. Subsequently, when the light signal is no longer confined in the core due to the mode conversion caused by multiple scatterings, it leaks out and could re-couple to the adjacent channels. It is not easy to find an appropriate way to simulate the light scattering phenomena by randomly distributed polymer chain structures based on wave-optics theory. Thus, in this paper, we apply the ray tracing method for the simulation. Although the zero-wavelength ($\lambda = 0$) condition is assumed, we can still apply the local plane wave theory near the core-cladding boundary, where the refractive index is nearly constant within the range of wavelength scale distance [14]. It is well known that ray trace simulation is applicable when the waveguides support large number of propagating mode, while wave optics theory should be applied with decreasing the propagating mode number. Thus, the 50-μm core which is a typical core size of multimode fiber was very important for analyzing the waveguides with ray trace simulation. However, in this case, the signal wavelength would be 1.3 μm. On the other hand, in this paper, since a shorter wavelength (850 nm) is utilized, the number of propagation modes would be large enough even for 35-μm core waveguide to apply this ray-trace model. Here, it is very important that we suppose only mode conversion is the dominant factor for the inter-channel crosstalk here. We are also applying a wave optics theory for smaller pitch waveguide design where mode coupling should be considered. This issue will be published elsewhere.

3.1 Ray tracing method for GI circular core waveguides

For graded index media, the route of rays is obtained by solving the eikonal equation and position vector within the circular core area. The general cylindrical form of the ray equations with respect to radial, azimuthal and longitudinal directions in (r, ϕ, z) are written as follows

$$\begin{cases} \dfrac{d}{ds}\left[n(r)\dfrac{dr}{ds}\right] - rn(r)\left(\dfrac{d\varphi}{ds}\right)^2 = \dfrac{dn(r)}{dr} \\ \dfrac{d}{ds}\left[n(r)\dfrac{d\varphi}{ds}\right] + \dfrac{2n(r)}{r}\dfrac{d\varphi}{ds}\dfrac{dr}{ds} = 0 \\ \dfrac{d}{ds}\left[n(r)\dfrac{dz}{ds}\right] = 0 \end{cases} \tag{2}$$

where, s is the distance along the ray path. The trajectory along with the z direction is written as

$$z = \beta \int \frac{dr}{[n^2(r) - \beta^2 - l^2 a^2 / r^2]^{1/2}} \tag{3}$$

where, β and l are the ray invariants, and a is the radius of the core. Equation (3) describes the behavior of bound rays which carries the total intensity. For the leaky, refracting and tunneling rays, their trajectories are similar to the bound rays, and we calculate the

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transmission coefficients and sum the total intensity outside the launched core. In the case of a GI circular core fiber, the corresponding transmission coefficients for refracting and tunneling rays are written as

$$T_{ref} = 1 - \left(\frac{\lambda}{16\pi n_2^3 \sin^3 \theta_t} \frac{dn^2(r)}{dr} \bigg|_{r=a^-} \right)^2 \tag{4}$$

and

$$T_{tun} = \exp\left[-\frac{4\pi}{\lambda} \int_{r_{tp}}^{r_{rad}} \{\beta^2 + (la/r)^2 - n^2(r)\}^{1/2} dr \right] \tag{5}$$

where, r_{rad} is the radiation radius, r_{tp} is the radius of turning point, λ is the wavelength and θ_t is the angle between refracted ray and the core-cladding boundary. In our waveguide, n_2 = 1.492 and a = 50 µm, the calculated transmission coefficient of the refracting ray is almost zero. This indicates that the light propagating near the area of the core-cladding boundary could easily leak out by unexpected refractive index fluctuations due to the unclear boundary. Besides, for the parabolic refractive index profile, i.e. $g = 2$ in Eq. (1), the trajectory of the ray projected to the cross section of core area is a closed ellipse, except for the meridional rays. In our waveguide, g is approximated to be 2.46 from the measured index profile in Fig. 1(b) and this approximated g value is applied to the following calculations. Meanwhile, we neglect the slight deviation from a perfect ellipse for approximation.

3.2 Influence of light scattering

For evaluating the influence of light scattering in the core regions by the simulation, some assumptions are made. First, no back scattering is considered. The rays propagate only from the input end to the output end in a certain length with a helical trajectory determined by Eq. (3). The propagation length is randomly determined and generally is in a range of several hundred micrometers in our simulation algorithm. When a ray propagates this one unit of length, three parameters are incorporated to include the influence of light scattering: probability of scattering (p), maximum number of scattered ray (N_s) and maximum angle difference to the original ray direction (θ_m). The probability of scattering ranges from 0 to 100%, which corresponds to no scattering and absolute scattering, respectively. Here, a random number which ranges from 0 to 1 is generated by the simulation program. When the random number is smaller than p value, the ray splits to N_s rays at this node, otherwise, the ray passes through this node without split. The maximum value of N_s which is set to be 5 in this model, determines how many rays are generated at this node, i.e. the number of scattered ray could be 0 to N_s. The maximum angle difference to the original ray direction (θ_m) is determined by the numerical aperture of the channel. Once a ray is scattered, it splits to several rays with individually specified directions with the angle θ_m to the original ray direction. Here, we suppose that the angle θ_m satisfies a Gaussian distribution. Each of the scattered rays carries different intensity that depends on the angle θ_m. Namely, the scattering angle ($\Delta\theta_k$) and k^{th} intensity (I_k) for the scattered ray is written as follows:

$$\Delta\theta_k = \pm\theta_m \sqrt{-\log(R)} \tag{6}$$

and

$$I_k = \frac{|\Delta\theta_k|^{-1}}{\sum_{k=1}^{n} |\Delta\theta_k|^{-1}} I_0 (1 - T_k) \tag{7}$$

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where, R is random number (from 0 to 1), I_0 is the intensity of the original ray, and T_k is the transmission coefficient of k^{th} tunneling rays calculated from Eq. (5). Then, each ray proceeds to the next node.

This process continues until all the rays propagate over the preset distance. With these parameters, we can quantify the influence of the light scattering even in the higher scattering loss materials such as the copolymer of MMA and BzMA. Figure 4 shows one ray propagates within the core with and without the scattering described above. Here, we launch a ray at the point (30, 0, 0), when the radius of the core is 50 μm. The values of n_1 and n_2 are set to be 1.5005 and 1.492, respectively, which are identical to the measured values. In the channel with scattering, if a ray leaks out from the core and hits the cladding-air boundary, the ray would leave away from the waveguide or reflect back depending on the incident angle to the cladding-air interface. If it reflects back, it can propagate inside the cladding with a zigzag route, as shown in Fig. 4(b) or re-couple to the other channels if we suppose a multichannel case.

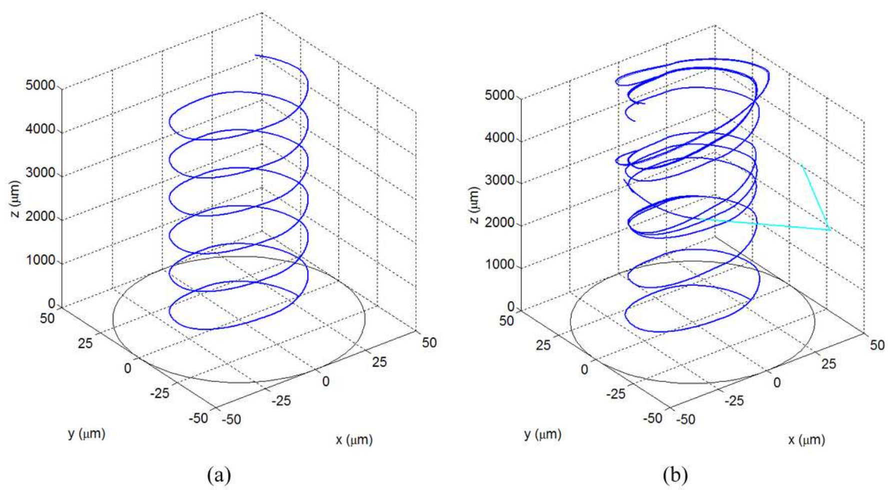

Fig. 4. One ray injects to the channel from (x, y, z) = (30, 0, 0) with 3° of angle to the z axis: (a) without and (b) with scattering effect. The rays penetrate the core-cladding boundary are those refracted rays.

3.3 NFP from single channel waveguide

From Eq. (3) to (7), the intensity profile at the output end can be calculated. We simulate the NFPs under the offset launching condition used in Fig. 2. For more realistic case, we consider multiple rays launched with the Monte-Carlo method. The rays are injected into a restricted area in the core by a bundle of divergent rays, while the input intensity profile of this area is assumed to have a Gaussian distribution. Figure 5 shows how light scattering influences the calculated NFPs after a 3-cm propagation distance by varying the offset distance from 10 to 40 μm. When all the rays propagate with no scattering, as shown in Fig. 5(a), an ellipsoidal ring-like pattern is observed and higher output power is accumulated as two peaks near the launching and its conjugating positions. We find that the output power is still mostly confined in the core. On the other hand, when we take the influence of light scattering into account, as shown in Fig. 5(b), the results clearly show similar trends to the experimental results in Fig. 2. When the offset is 10 μm, the NFP still looks similar to that with no scattering in Fig. 5(a). However, the number of the output rays near the rim area increases, with increasing the offset distance, and under 40-μm offset launch, the output rays are observed from whole core area even for such a short distance as 3 cm. Thus, we confirm high scattering loss of the waveguide broadens the output NFP to the area near the core-cladding boundary, and the rays could be easily leaked out from the core; this is one of the causes of inter-channel crosstalk.

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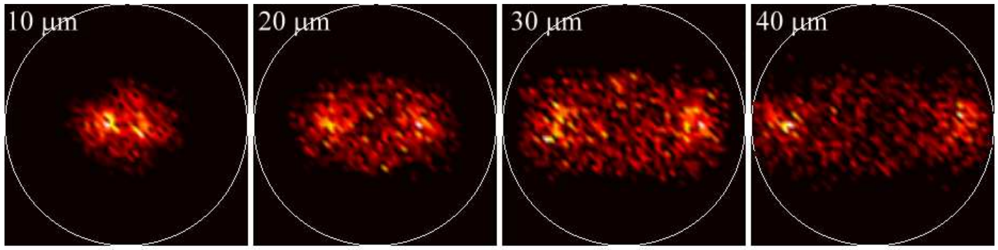
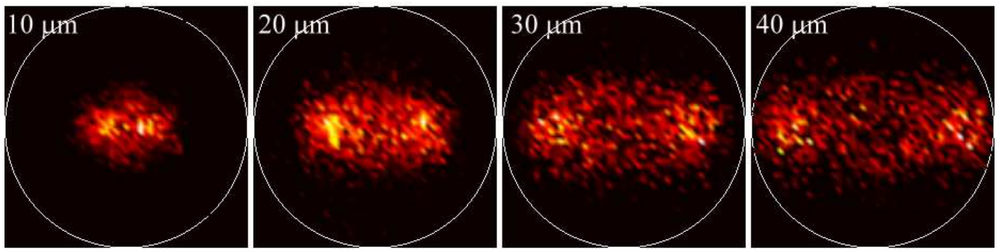


(a)



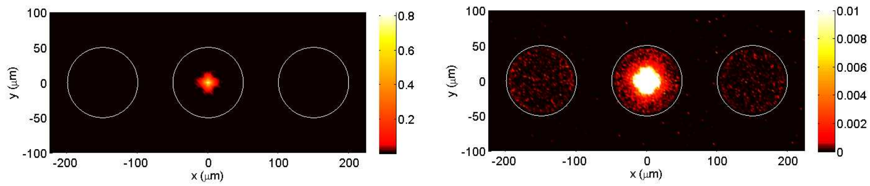
(b)

Fig. 5. The calculated NFP under offset launching conditions (a) without and (b) with scattering effect. The offset distance from left to right is 10, 20, 30 and 40 μm. In this simulation p = 10%, N_s = 5 and θ_m = 20 is applied. The white circle surround the calculated NFP is the assumed core-cladding boundary.

3.4 NFP from multi-channel waveguide

For the GI multi-channel waveguide simulation, three channels (left, middle, and right) cases are considered. The middle core is launched as is the case of Fig. 3. For more a realistic condition, the unclear core-cladding boundary shown in Fig. 1(b) is also taken into account. We assume the refracted rays project into the other channels with a skin depth of 5 μm. If the ray path grazes under the simulated core-cladding boundary with a distance smaller than the skin depth, it would directly penetrate that area and keep its intensity unchanged. Besides, three channels with the same characteristics are considered. Those re-coupled rays follow the same algorithm mentioned above and they also propagate with scattering.

Figure 6 shows the calculated NFPs without and with light scattering for the multi-channel waveguide, where the colored-bar beside each graph shows the intensity normalized by the intensity of all the injected rays. The parameters describing the light scattering are the same as those of previous single channel condition. In the calculated NFP without scattering case shown in Fig. 6(a), we hardly observe any output rays from the adjacent channels. On the other hand, in the case with scattering-included condition, some amount of output power from the adjacent channels is clearly observed, and they form a circular pattern near to the core-cladding boundary. This is due to the leaked rays that are trapped by the GI profile in the adjacent core. Moreover, this simulation also confirms the superior performance of GI profile compared to the conventional waveguide with step index medium.



(a) (b)

Fig. 6. The calculated NFP (a) without and (b) with scattering effect included for a GI multi-channel waveguide. In this simulation, the parameters are identical as single channel case.

3.5 Loss and crosstalk analysis for multi-channel condition

We analyze the relationship between the scattering loss and inter-channel crosstalk using the similar algorithm to the multi-channel case mentioned above. In the MMA-BzMA copolymer based GI-core waveguides, excess scattering loss is experimentally observed; it is well known that the propagation loss at 850-nm wavelength includes the inherent absorption loss of approximately 0.025 dB/cm due to the carbon-hydrogen stretching vibration [13]. Therefore, the experimentally measured propagation loss of 0.033 dB/cm (as shown in Table. 1) includes the scattering loss of 0.008 dB/cm. Meanwhile, in the simulation, the center of the middle core in a three-channel waveguide is launched. Here, we vary the scattering probability from 0.5% to 50% and then calculate the propagation loss in dB/cm in order to find the reasonable initial values of the parameters realizing the excess scattering loss of 0.008 dB/cm.

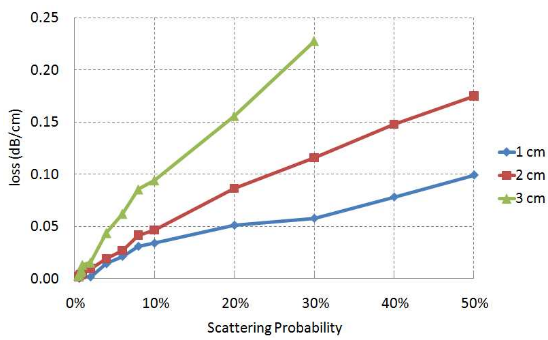


Fig. 7. The scattering probability p dominates the scattering loss and shows the unexpected propagation length dependence.

The calculated propagation loss is shown in Fig. 7. Here, we find that the scattering probability p dominates the loss value. Even a scattering probability of 10% is still too high for obtaining the scattering loss of 0.008 dB/cm. When p increases, propagation length dependence of the scattering loss also increases, as shown in Fig. 7. Although this length dependence can be observed in multimode core under a restricted launch condition, other two parameters, N_s and θ_m, are slightly adjusted in order to obtain reliable results. Then we theoretically verify that an excess scattering increases the inter-channel crosstalk as follows.

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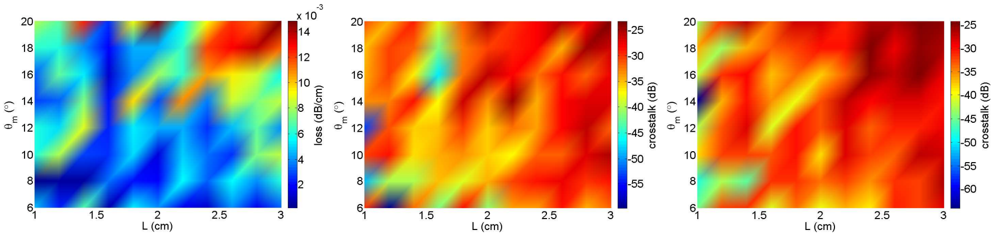

(a) (b) (c)

Fig. 8. (a) The loss value (in dB/cm) for the center channel. (b) The crosstalk value (in dB) for the right channel and (c) left channel.

After some calculations, we can conclude the maximum number of scattered rays plays a minor role in this simulation. Here, $N_s = 5$ is fixed and the scattering probability is determined to be 1%. We try to find the relationship among the propagation distance L, the maximum scattered angle θ_m, and propagation loss. Figure 8 (a) shows when θ_m is smaller than 14 degrees, the propagation loss is as low as 0.01 dB/cm, and is almost independent on the waveguide length. Thus, we succeeded in modeling the copolymer based GI core waveguide shown in Fig. 3. Using these parameters, inter-channel crosstalk is calculated, and the results are shown in Fig. 8(b) and Fig. 8(c). As we expected, the crosstalk values are a little lower than −30 dB in the area where θ_m is smaller than 14 degrees. Meanwhile, with increasing the value of θ_m, the crosstalk increases to −25 dB. Thus, it is obvious that the excess scattering loss of the waveguide significantly increases the crosstalk, and we find a good coincidence with the experimental result shown in Table. 1. Further theoretical analysis on the crosstalk, such as inter-core pitch, refractive index profile, or fiber NA dependences will be carried out utilizing this modeling tool, and then will be published elsewhere.

4. Conclusion

We fabricated a polymer optical waveguide with GI-circular cores using P(MMA-BzMA) copolymer for the core. Although the copolymer core possesses higher thermal stability in the refractive index profile than doped PMMA core waveguides, an excess scattering loss as high as 0.008 dB/cm is observed. Hence, we evaluated the influence of the excess scattering loss on the mode conversion and inter-channel crosstalk in the multi-channel GI-core polymer optical waveguide. The ray tracing method is utilized for the simulation. In the single channel condition, the calculated output NFP showed the optical confinement effect of the GI profile when no scattering was taken into account, while a significant NFP degradation was observed due to the mode conversion caused by the light scattering. For the multi-channel condition, the loss and crosstalk value can be clearly quantified by the similar way. The results encourage us toward further optimization processes and add more practical considerations.

Although the simulation of the inter-channel crosstalk was performed only on our GI-core polymer optical waveguides, it is capable of modeling the conventional SI rectangular-core waveguides. As we mentioned above, some amount of excess scattering is generally observed in the conventional SI-core waveguides, and thus, the application of this simulation to SI-core waveguides helps find a feasible design for high-density alignment of the waveguides.

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