Direct photofabrication of refractive-index-modulated multimode optical waveguide using photosensitive sol-gel hybrid materials

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Photosensitive sol-gel hybrid materials (hybrimers) exhibited a thick film property, an efficient refractive index tunability through the control of their compositions, and a high photosensitivity upon UV exposure. The materials were used for the direct photofabrication of the multimode optical waveguide (MOW) with a large core structure. Due to the outstanding optical properties of these materials, problems and complexities associated with the fabrication of MOW could be overcome, and a MOW with good propagation performance could be easily fabricated. Importantly, a propagation loss of as low as 0.13 dB cm^{-1} at 850 nm could be obtained. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2138368]

An optical waveguide (OW) device is an important component for use in optical interconnection, optical signal processing, and optical connection in optical communication systems.[1–3] Currently, the rapidly increasing demand for communication is causing a rapid increase in the use of an OW device and the ability to easily arrange optical fibers is particularly needed in order rapidly and efficiently to transfer an optical signal. To satisfy this requirement, the fabrication of a multimode optical waveguide (MOW) device with a large core structure is considered very important and has been actively studied recently.[4–6] In general, the OW device is produced using a semiconductor production technology that includes lithographic or etching techniques. The clad layer or the core layer is typically formed through a spin coating process and a deposition process, and is made of silica or polymers with different refractive indices. However, these methods are rather complex and need several steps, which increases the cost of the OW device and reduces its reliability. Moreover, silica exhibit the limitations in obtaining a large refractive index change between the core and clad layers and in fabricating a large core structure and a polymeric OW has a low thermal stability due to the low thermal stability of polymer materials. Accordingly, the use of silica and polymer materials is problematic because it is difficult to produce a high performance MOW for optical communication. For these reasons, many studies have concentrated on simplifying the fabrication process as well as studying the optimum materials for a MOW.

In recent years, the sol-gel hybrid materials (hybrimers) were found to produce a thick film of over 10 microns or more through simple single spin-coating, which is a crucial factor for a MOW with a large core structure and which could reduce the steps in the fabrication of a MOW. Moreover, these hybrimers exhibited the high photosensitivity, meaning a larger refractive index and volume changes upon UV exposure. The photosensitivity of these materials could be increased with the simple addition of photoactive molecules, which would produce the high performance of a MOW. These materials also have the potential to be used in simple single-step photopatterning due to the simultaneous changes in both their refractive index and volume without any etching step.[7–9] Thus, these photosensitive hybrimers have been widely used for the photofabrication of highly efficient optical devices.[10,11] Therefore, photosensitive hybrimers are good candidates for producing a high-efficiency MOW with a large core structure of 10 microns or more.

In this study, we thus sought to fabricate a high-efficiency MOW with crack-free large core structures on a clad layer using photosensitive hybrimers with outstanding optical properties through a photo mask. Finally, we simply

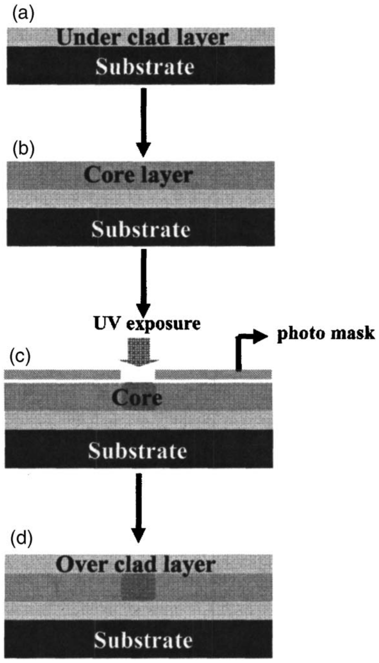

FIG. 1. Schematic diagram of the direct photofabrication of a MOW using photosensitive hybrimers. (a) Formation of the underclad layer through UV and thermal curing; (b) Spin coating of the core layer on the underclad layer; (c) Direct photofabrication of the large core structure in the core layer with a photo mask; and (d) Final formation of the overclad layer through UV and thermal curing.

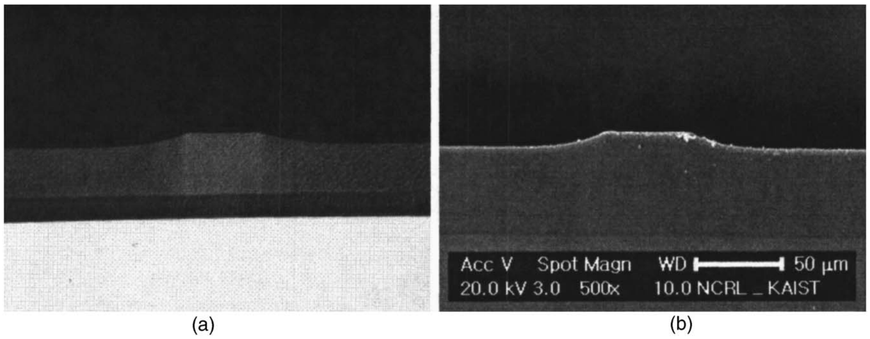

FIG. 2. (a) Optical micrograph and (b) scanning electron micrograph of a MOW including large core structure and under clad layer directly photofabricated using a photo mask.

manufactured a MOW with an efficient refractive index modulation between its core and clad layers and a low propagation loss through the direct photofabrication.

In our experiments, the hybrimers were prepared using methacryloxypropyl-trimethoxysilane (MPTMS, Aldrich), perfluoroalkylsilane (PFAS, Toshiba), and diphenylsilanediol (DPSD, TCI) as precursors and barium hydroxide monohydrate ($Ba(OH)_2 \cdot H_2O$, Aldrich) as a catalyst to promote the polycondensation reaction among theses precursors. The DPSD content was fixed at 50 mol % and the content ratio of PFAS with the role of decreasing the refractive index due to the perfluoroalkyl group of PFAS was changed from 10% to 12.5% to produce an efficient refractive index difference between the core and the clad layers, and maintain 50 mol % in the total proportion of MPTMS and PFAS, and barium hydroxide monohydrate (about 0.1 mol % of the precursors) was added as a catalyst, as described in previous reports on fabricating a MOW.[12] The obtained hybrimers were mixed with a photoinitiator, benzyldimethylketal (BDK, Aldrich), which facilitates various photoinduced reactions as well as increases the photosensitivity via UV light exposure. In particular, the different contents of BDK were added in the hybrimer with the composition for the UV curing of a clad layer and the photofabrication of a large core structure with a considerable refractive index modulation in a core layer. The photosensitive hybrimers with BDK were filtered using a 0.45-μm-sized filter to remove the remaining $Ba(OH)_2 \cdot H_2O$ and dust. These photosensitive hybrimers were used for the direct photofabrication of a MOW.

The direct photofabrication process of a MOW is schematically illustrated in Fig. 1, which shows a typical experiment to fabricate a MOW. First, the photosensitive hybrimers with PFAS content ratio of 12.5% and a BDK of 2 wt. % are spin-coated on *p*-type Si (100) wafers for the formation of an underclad layer with a 1000-rpm spinning speed for 30 s. Then, UV curing is carried out for 30 s with an Hg UV lamp (Oriel97435, $\lambda = 350 \sim 390$ nm, optical power density $= 100$ mW cm^{-2}) and consolidated by baking it at 150 °C for 4 h. Second, photosensitive hybrimers with a PFAS content ratio of 10% and a BDK of 10 wt. % are spin-coated on a clad layer for the formation of a core layer with a 500-rpm spinning speed for 30 s. After this, direct photofabrication of the large core structure in the core layer is carried out for 30 min with an Hg UV lamp using a photo mask, after which the patterned MOW is heat-treated at 150 C for 4 h to produce an efficient refractive index difference between the large core structure and the areas around the core areas, including the clad layer. Finally, for the passivation of the photofabricated MOW, photosensitive hybrimers with the same composition as the underclad layer are spin-coated on the core layer with a 1000-rpm spinning speed for 30 s. Then, UV curing is carried out for 30 s with an Hg UV lamp and then consolidated by baking at 150 °C for 4 h for a chemically and mechanically stable MOW.

Figure 2 shows an optical micrograph (a) and a scanning electron micrograph (b) of a MOW including its core structure and underclad layer, directly photofabricated using a photo mask. As shown in the figure, a thick film of close to 40 μm for the core layer with a large core structure could be formed evenly on the underclad layer with a 15-μm thickness through single spin-coating, and no cracks appeared after UV and thermal curing using the photosensitive hybrimers. Moreover, the MOW exhibited a well-shaped large core structure with a 40-μm width through the negative-type sensitivity of photosensitive hybrimers upon UV exposure, which related to the photoinduced reactions such as photopolymerization, photolocking, and photomigration between the hybrimer matrix and the BDK within the exposed core.[7–11,13] Thus, photosensitive hybrimers with a thick film property and a good photopatternability are potential materials for the direct photofabrication of a MOW. This series of photoinduced reactions in photosensitive hybrimers also cause a considerable refractive index increase in the large core structure of a MOW, as well as the volume change. The BDK in the exposed core was fixed within the hybrimer matrix by various photoinduced reactions, after which it was

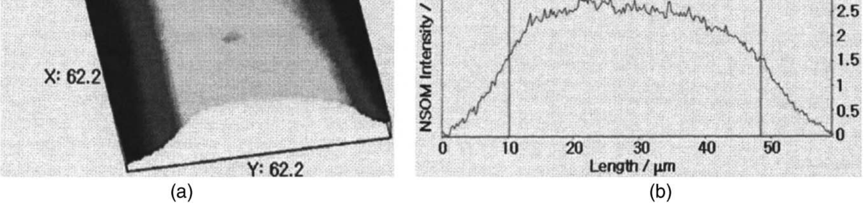

FIG. 3. (a) 3D NSOM image and (b) 2D NSOM line profile of the optical intensity representing the refractive index profile of the core area of a MOW.

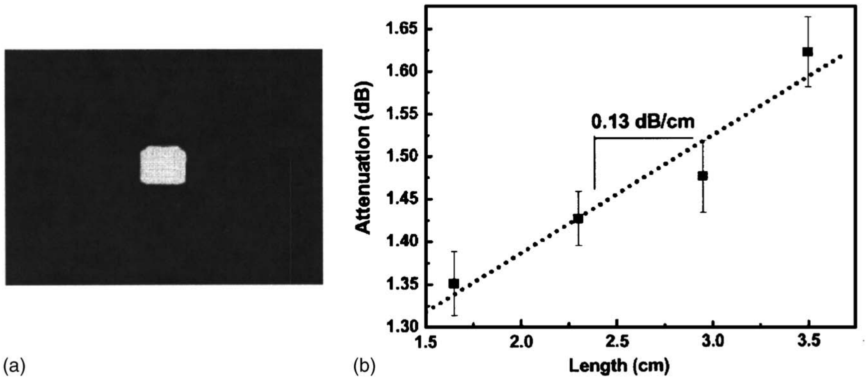

FIG. 4. (a) Light propagation near-field image and (b) propagation loss of the directly photofabricated MOW.

not removed by heating and drying. On the other hand, the BDK in the unexposed area was volatile and was easily removed by baking, after which the different characteristics of the BDK in the UV exposed core area and in the unexposed areas around the core areas in a MOW produced large refractive index changes. As shown in Fig. 2(b), the different contrast due to the refractive index difference between the UV-exposed core structure and the unexposed areas around the core areas including the underclad layer could be detected, which supports the refractive index increase in the core structure from various photoinduced reactions of the photosensitive hybrimers upon UV exposure. The respective refractive indices of the clad layer and the core layer in the photofabricated MOW were 1.486 and 1.501, respectively, at 1550 nm and the refractive index of the photofabricated core structure was much higher than that of other areas in a fabricated MOW due to the strong photoinduced reactions within the core structure upon UV exposure through a photo mask.

In order to confirm the refractive index modulation between the UV-exposed core structure and the unexposed areas around the core areas in the MOW, the effect of a refractive index increase in the core structure from the photoinduced reactions in photosensitive hybrimers was measured in a reflection mode using a Near-field Scanning Optical Microscope (NSOM, Nanonics-NSOM/SPM-100) with an AR laser ($\lambda = 488$ nm) as the probing source. Figure 3 shows 3D NSOM image (a) and the 2D NSOM line profile of the optical intensity of the reflection that represents the refractive index difference between the core and the areas around the core of a MOW (b). The optical intensity profile that represents the refractive index difference between the core and the areas around the core is remarkably different, and the optical intensity of the core structure of the MOW is much higher than that of the areas around the core, as shown in Fig. 3. The UV-exposed core structure has a higher refractive index than the unexposed areas around the core, which relates directly to the various photoinduced reactions between the hybrimer matrix and the BDK within the UV-exposed core through a photo mask. The direct photofabricated MOW that exhibits a strong refractive index difference between the large core structure and the areas around the core is thus a very good candidate for a high-efficiency MOW.

In order to evaluate the propagation performance of the directly photofabricated MOW, its light propagation property and propagation loss were checked. Figure 4(a) exhibits the light propagation near-field image of the directly photofabricated MOW, and Fig. 4(b) shows its propagation loss. The directly photofabricated MOW showed a strong light propagation performance, and its propagation loss, which was measured using the cutback method, was as low as approximately 0.13 dB cm^{-1} at an 850 nm wavelength. This good light propagation performance and low propagation loss are due to the low optical absorption of hybrimers in addition to the efficient refractive index difference between their core structure and the areas around their core by their high photosensitivity due to various photoinduced reactions of photosensitive hybrimers. Therefore, the MOW that was directly photofabricated using the photosensitive hybrimers with outstanding optical properties can have a high efficiency such as the capability to rapidly and efficiently transfer optical signals due to its large core structure and low propagation loss, and is suitable for various optical applications, including optical signal processing and optical connection in optical communication systems.

In conclusion, the photosensitive hybrimers, which can form thick films, exhibited an efficient refractive index tunability and a high photosensitivity. The MOW with a large core structure was directly fabricated on the photomasked thick photosensitive hybrimer film through simple UV exposure. The photofabricated MOW exhibited an efficient refractive index modulation between its large core structure and its clad area. Finally, the photofabricated MOW showed good propagation performance and a propagation loss of as low as 0.13 dB cm^{-1} at 850 nm.

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[1] A. Yariv, IEEE Photon. Technol. Lett. **14**, 483 (2002).
[2] S. Mookherjea, Appl. Phys. Lett. **84**, 3265 (2004).
[3] J. Valenta, T. Ostatnicky, I. Pelant, R. G. Elliman, J. Linnors, and B. Honerlage, J. Appl. Phys. **96**, 5222 (2004).
[4] M. J. Zwanenburg, J. F. Peters, J. H. H. Bongaerts, S. A. de Vries, D. L. Abernathy, and J. F. van der Veen, Phys. Rev. Lett. **82**, 1696 (1999).
[5] X. J. Lu, C. H. Jang, D. C. An, Q. J. Zhou, L. Sun, X. P. Zhang, R. T. Chen, and D. Dawson, Appl. Phys. Lett. **81**, 795 (2002).
[6] X. Y. Ao and S. L. He, Opt. Lett. **29**, 2864 (2004).
[7] O. H. Park, J. I. Jung, and B. S. Bae, J. Mater. Res. **16**, 2143 (2001).
[8] B. S. Bae, O. H. Park, R. Charters, B. Luther-Davies, and G. R. Atkins, J. Mater. Res. **16**, 3184 (2001).
[9] O. H. Park, S. J. Kim, and B. S. Bae, J. Mater. Chem. **14**, 1749 (2004).
[10] D. J. Kang, J. K. Kim, and B. S. Bae, Opt. Express **12**, 3947 (2004).
[11] D. J. Kang, P. V. Phong, and B. S. Bae, Appl. Phys. Lett. **85**, 4289 (2004).
[12] W. S. Kim, K. S. Kim, Y. J. Eo, Y. Yoon, and B. S. Bae, J. Mater. Chem. **15**, 465 (2005).
[13] A. H. O. Kärkkäinen, J. M. Tamkin, J. D. Rogers, D. R. Neal, O. E. Hormi, G. E. Jabbour, J. T. Rantala, and M. R. Descour, Appl. Opt. **41**, 3988 (2002).