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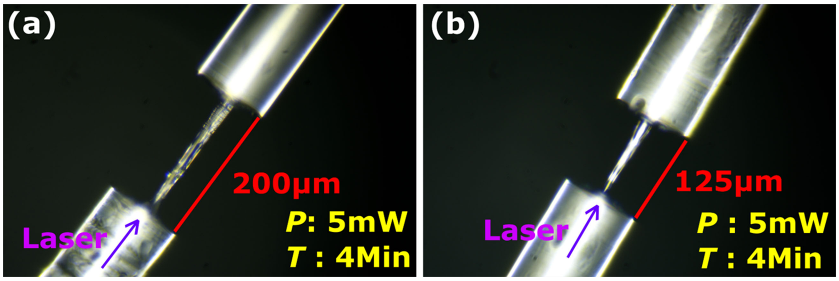

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Light-Induced Waveguide With Directional Transmission

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Abstract: Herein, we propose and demonstrate that the light-induced optical polymeric waveguides can function as the fully online optical connectors with directional transmission characteristics. The light-induced optical waveguides, which can be used for the optical couplings between single-mode fibers, are fabricated by using a photopolymerizable resin system formed by a 405-nm laser. Subsequently, the transmission characteristics of the light-induced waveguides with different parameters are investigated, and the experimental results reveal that the (directional) transmission characteristics can be modified by controlling the structure of the light-induced waveguides by controlling the illumination time (single-side) or the ratio of the illumination intensity (dual-side). Additionally, the preliminary experimental results reveal that the light-induced optical waveguides can function as the optical connectors. The light-induced waveguide build-up process, which is simple and effective, can be applied to the fabrication of polymer-based optical waveguide modules and for optical interconnections. Simultaneously, this present technique could be a feasible method of incorporating devices such as filters, isolators, and polarizers into fibers, which can potentially contribute to further expansion of integrated optoelectronic system.

Index Terms: Fiber optics, light-induced waveguide, directional transmission, photopolymer.

1. Introduction

Miniaturization of photonic devices is being intensively focused because they drive great scientific and technological developments in the fields of optical communications, bio-photonics, photonic integrations, and microwave photonics [1]–[4]. That is, the dimension mismatch between the traditional optical devices and the photonics system will be a dominant factor limiting the future micromation and integration of photonics system. Therefore, in order to meet the requirements of the development of optical communication and optical information processing technology, the performance and integration of the integrated photonic systems or devices should be further developed and improved. Currently, among all the photonic integration technologies, polymer-based integration technology offers many distinctive advantages, such as ease of processability, high flexibility, and ease of synthesis of various materials with various optical properties. Meanwhile, the polymeric optical waveguides [5] and components, such as arrayed waveguide grating [6]–[8], splitter [9], optical switch [10], and filter [11], [12], also have attracted much attention for use in optical interconnects and in integrated devices for optical communications in the access network and the home network areas

To date, the polymeric optical waveguides can be fabricated by multistep processes using lithography [13]–[15], laser-writing [16], and ion etching [17]–[19]. Since these processes require time and patience, many types of simple and low-cost polymer optical waveguide fabrication methods were reported which included a laser lithography method [20], a light-induced polymerization method [21], and a hot-embossing method [22]. In contrast, the light-induced polymerization is a mask-less and on-demand process, and thus the various forms of optical waveguides can be fabricated by this method. Especially, the production of light-induced polymeric waveguides can enable automation of the optical interconnection between waveguides (such as optical fibers) during the waveguide formation process, and it does not require any additional alignment process [23]. Recently, light-induced optical waveguide formation is a recognized technology whereby we can form a solid waveguide from a liquid photopolymer to interconnect different waveguides (such as optical fibers) [24]–[28]. In previous reports, the light-induced optical waveguides can only function as the optical connectors [22], [25], however, in some special applications, the light-induced optical waveguides should contain other special functions, such as isolation, attenuation and so on.

In this letter, light-induced optical waveguides with directional propagation are fabricated by using a photopolymerizable resin system formed by a 405 nm laser. We demonstrate that optical couplings between single-mode fibers can be quickly and easily implemented by using the light-induced optical waveguides. Additionally, we investigate the effects of structure of the light-induced waveguides on the transmission characteristics. The experimental results reveal that the (directional) transmission characteristics can be modified by changing the structure of the light-induced waveguides by controlling the illumination time (single-side) or the ratio of the illumination intensity (dual-side). The light-induced waveguide build-up process, which is simple and effective, can be applied to the fabrication of polymer-based optical waveguide modules and for optical interconnections.

2. Experiment and Discussion

2.1 Single-Side Experiments and Discussion

The light-induced optical waveguide fabrication process is illustrated in Fig. 1. As shown in Fig. 1(a), the single-mode fibers (Core diameter: 8 μm, Cladding diameter: 125 μm, S1310-P, Nufern) with clean and flat end face are placed in front of each other, and they can be moved by motorized XYZ positioners. For the optimal alignment between fibers, the transmitted intensity of laser light serves as a reference for alignment, and the positioning is optimized by maximizing the transmission of laser light using the high precision stages. Besides that, a microscope with a CCD camera is used to facilitate alignment between fibers. After the alignment, the fibers are separated by using the positioning stages, and the gap between fibers sets from tens to hundreds of micrometers. Subsequently, the UV curable polymer is applied, a small drop of the UV curable polymer (NOA 81, Thorlabs Inc.) is put between two fibers to make a liquid bridge between them. Then, by irradiating with 405-nm laser light (405 nm FP single-mode coaxial laser diode, Lightsensing Technologies Ltd.) through fiber, photo-polymerization and light-induced optical waveguide fabrication start, as shown in Fig. 1(b). From Fig. 1(c), an initial light-induced optical waveguide caused by photocuring formed very rapidly between the two fibers. Finally, the remaining uncured polymer is rinsed off using ethanol, and leaving an exposed polymer light-induced waveguide rigidly attached between the fiber ends as an extension of the fiber core, as shown in Fig. 1(d). Fig. 1(e) shows the transmission measurement scheme. In this setup, in order to investigate the transmission characteristics of the polymer light-induced waveguide between two conventional single-mode fibers, a laser diode sends light to a single-mode fiber, and the light couples to another single-mode fiber through this polymer light-induced waveguide, then the transmitted light is detected by a spectrometer (Ocean Optics, HR4000).

In order to verify the feasibility and controllability of the light-induced waveguide, the different parameters are selected to fabricate the light-induced waveguide with different geometrical

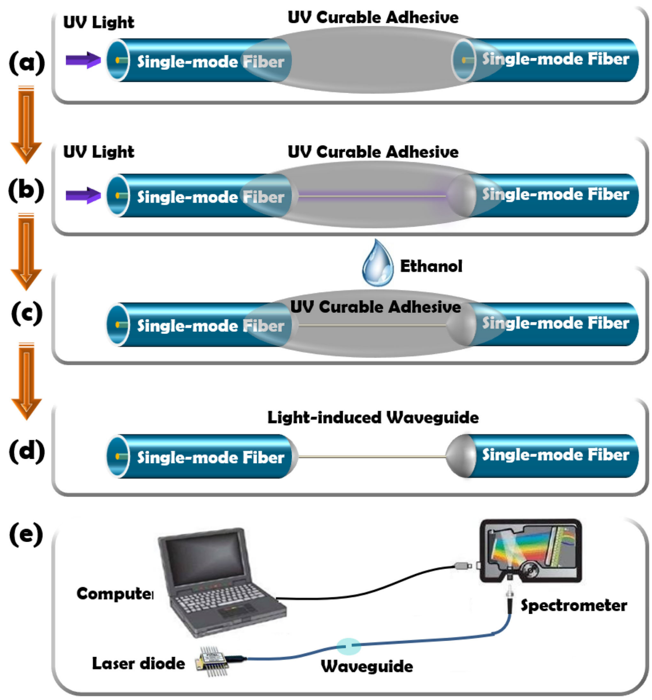

Fig. 1. (a)–(d) Schematics of the fabrication sequence of the light-induced waveguide, (e) Measurement scheme.

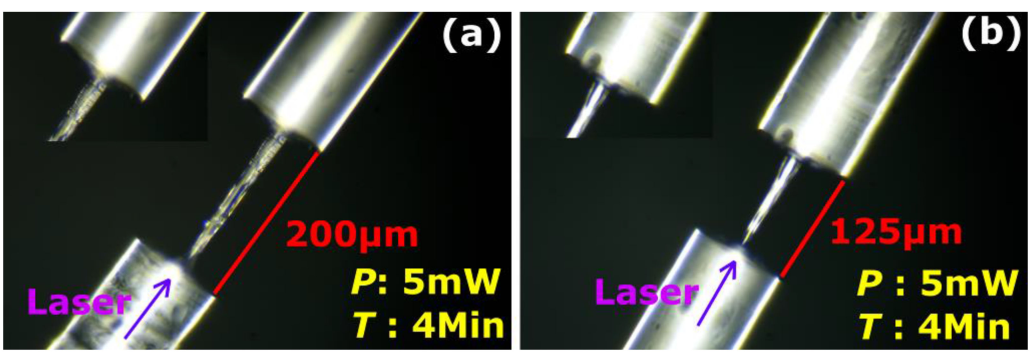

Fig. 2. Photograph showing a light-induced waveguide grown between two single-mode fibers (a) L = 200 μm, P = 5 mW, T = 4 Min, and (b) L = 125 μm, P = 5 mW, T = 4 Min. Insets: larger magnifications.

morphology. Fig. 2 shows the light-induced waveguide with different geometry while we select technological parameters. Fig. 2(a) shows the light-induced waveguide with 200 μm length. Fig. 2(b) presents the light-induced waveguide with 125 μm length. The larger magnifications are shown in the insets of Fig. 2, from the insets, it can be observed that the end diameter is 22.5 and 18 μm for the 200 and 125 μm light-induced waveguide, respectively.

By using the above process, while the gap between fibers sets as 200 μm, the UV-curable polymer-based light-induced optical waveguide with different morphologies can be prepared by change the illumination time, and the typical microscope images of the light-induced optical waveguides with different illumination time are shown in Fig. 3, and the larger magnifications are shown in the insets of Fig. 3. Fig. 3(a), 3(b) and 3(c) presents the microscope images of the light-induced optical waveguides with 3 Min, 4 Min and 5 Min illumination time, respectively. Typically, the shape and size of the light-induced waveguide constructed between two fibers is determined by the

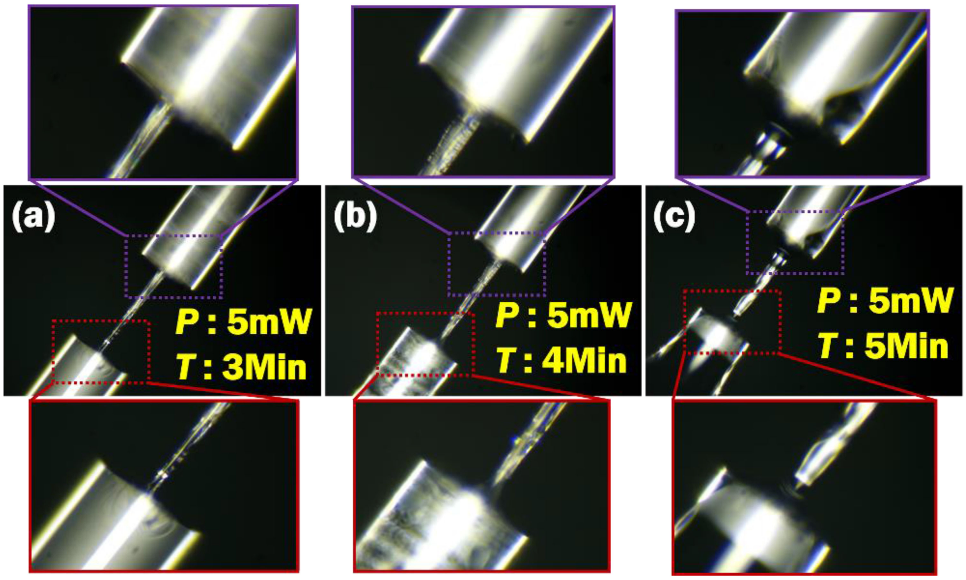

Fig. 3. Photograph showing a light-induced waveguide grown between two single-mode fibers with different illumination time (a) T = 3 Min, (b) T = 4 Min and (c) T = 5 Min. Insets: larger magnifications.

TABLE 1
Simulation Parameters

Core radius	4 μm
Cladding radius	62.5 μm
Initial radius	4 μm
Terminal radius	11.5 μm
Waveguide RI	1.51

laser beam emerging from the fiber core, and the subsequent polymeric light-induced optical waveguide only form near the core region. From Fig. 3, while the laser power sets 5 mW, the geometries and features of the light-induced waveguide are significantly dependent on the illumination time. Additionally, we observe that the light-induced optical waveguide generally possesses a terminal bulge, and the longer illumination time results in a light-induced optical waveguide with a thicker terminal radius. Hereby, we demonstrate the feasibility of the preparation of the light-induced optical waveguide to realize the physical attachment between single-mode fibers by this process.

Subsequently, the transmission characteristics of the light-induced optical waveguides will be investigated, however, before experimental investigation, the simulation should be implemented to theoretically verify the transmission characteristics. In this simulation, the parameters are as shown in Table 1, which corresponding to the experimental geometry parameters of the light-induced waveguide with 3 Min illumination time (as shown in Fig. 3), and the refractive index (RI) of the light-induced optical waveguides provided by the supplier is 1.51. The transmission is simulated by using the beam propagation method. While the transmission direction is corresponding to the growth direction of the light-induced waveguide, the simulated transmission result is illuminated in Fig. 4(a). However, the transmission direction is contrary to the growth direction of the light-induced waveguide, the simulated transmission result is illuminated in Fig. 4(b). From Fig. 4, the simulated results reveal that the directional transmission characteristic is significant, and we

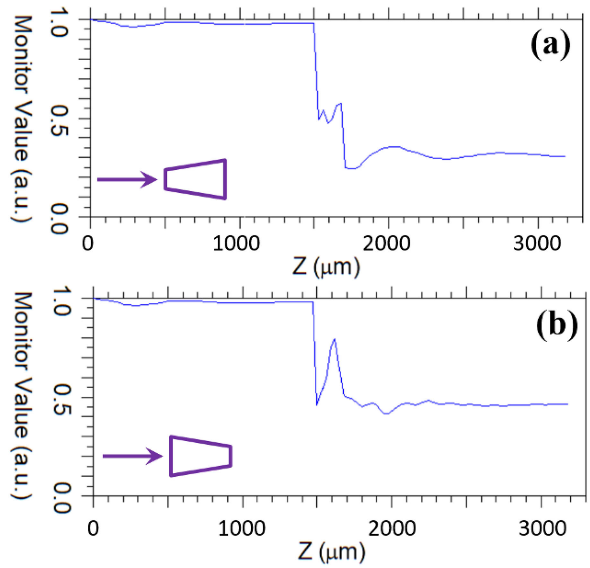

Fig. 4. Simulation of the directional propagation of the light-induced waveguide (a) Transmission direction: corresponding to the growth direction of the light-induced waveguide (b) Transmission direction: contrary to the growth direction of the light-induced waveguide.

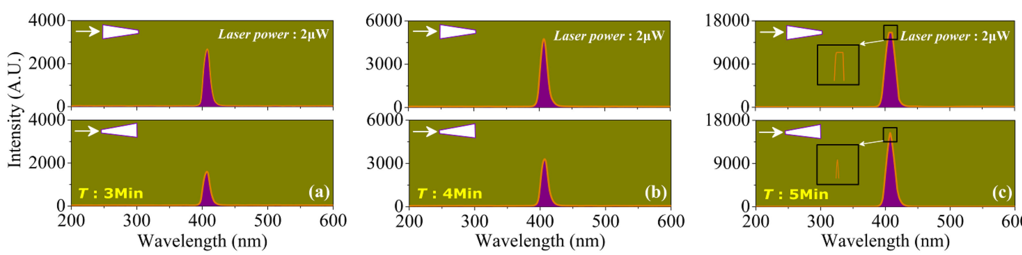

Fig. 5. Directional propagation of the light-induced waveguide with different illumination time (a) T = 3 Min, (b) T = 4 Min and (c) T = 5 Min. Insets: larger magnifications. Upper: Transmission direction is contrary to the growth direction of the light-induced waveguide, Lower: Transmission direction is corresponding to the growth direction of the light-induced waveguide.

define the bidirectional difference value (D-value) as: D-value = $(P_{contrary} - P_{corresponding})/P_{contrary}$. $P_{contrary}$ and $P_{corresponding}$ are the transmission power while the transmission direction is contrary and corresponding to the growth direction of the light-induced waveguide, respectively. For this simulated model, the D-value is about 41.9%.

The theoretical analysis demonstrates that the light-induced waveguide possesses the directional transmission characteristics. To verify that, the transmission properties of the light-induced waveguides are investigated experimentally. The transmission characteristics are measured between single-mode fibers connected by the light-induced waveguides with different illumination time, and the measurement scheme is illustrated in Fig. 1(e). The probe beam wavelength is 405 nm (neglecting the absorption attenuation). As Fig. 5 shows, the transmission power increases with the increasing illumination time, and the transmission power can be changed by controlling the illumination time. For clarity, Fig. 6(a) presents the transmission power of the light-induced waveguides with the illumination time, while the transmission direction is corresponding to the growth direction of the light-induced waveguide. From Fig. 5, the bidirectional difference value of the transmission is also very significant. And Fig. 6(b) illustrates the relationship between bidirectional D-value and the illumination time. In Fig. 6(b), the bidirectional D-value of the transmission decreases with the

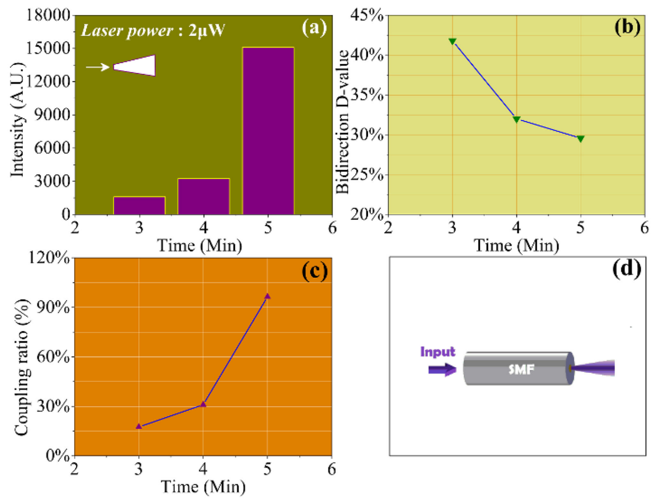

Fig. 6. (a) Transmission of the light-induced waveguide, (b) Relationship between bidirectional D-value and the illuminated time, (c) Relationship between coupling ratio and the illuminated time, (d) Light divergence.

increasing illumination time. The bidirectional D-values of the transmission are 41.8%, 32% and 29.6% for the light-induced waveguide with 3 Min, 4 Min and 5 Min illumination time, respectively. Meanwhile, as shown as Fig. 6(c), unlike the D-values of the transmission, the coupling ratio of the transmission increases with the increasing illumination time.

The bidirectional D-value of the transmission is suggested to be associated with laser light divergence during waveguide preparation. As indicates in Fig. 6(d), at the fiber end, the light diffracts and spreads with an increasingly radius which is related to propagated distance, near the fiber end face, light has the least divergence and the distribution of light field is relatively uniform [29]. Thus, while the light emits from a fiber into a photorefractive material, the structure and refractive index distribution of the front-end light-induced waveguide is approximately uniform along radius. However, since light diffracts, at the far-end, a light-induced waveguide forms in the photorefractive material, tapering to a larger diameter, meanwhile, the refractive index of the waveguide reduces gradually along the radius. After photocuring, the remaining uncured material is rinsed off using ethanol, leaving an exposed polymer waveguide bridge rigidly attached between the fiber ends. The front-end light-induced waveguide can be regarded as the multi-mode waveguide with air cladding, while the far-end light-induced waveguide is analogous to the waveguide with low refractive index polymeric cladding. Thereby, the propagation from the front-end light-induced waveguide to far-end (which is corresponding to the growth direction of the light-induced waveguide) can be considered as the coupling process from multimode to single-mode optical waveguide, the attenuation along the growth direction of the light-induced waveguide is greater than that along the opposite direction.

2.2 Dual-Side Experiments and Discussion

To verify the controllability of bidirectional D-values of the transmission, the dual-side illumination should be implemented, as shown as Fig. 7. In this experiment, we demonstrate that the bidirectional D-values of the transmission can be adjusted by using different ratio of the illumination intensity. Fig. 8 illustrates the characteristics of the dual-side light-induced waveguide with different ratio of the illumination intensity. Fig. 8(a) and 8(b) respectively presents the morphology and the transmission characteristic, while the dual-side laser intensity and illumination time are identical (laser power sets as 5 mW, illumination time is 3 Min). From Fig. 8(a), at both ends, the light-induced waveguide has the approximately equal radius. And in Fig. 8(b), the bidirectional D-values of the transmission is close to 1%. The relatively low bidirectional D-values is mainly attributed that the dual-side

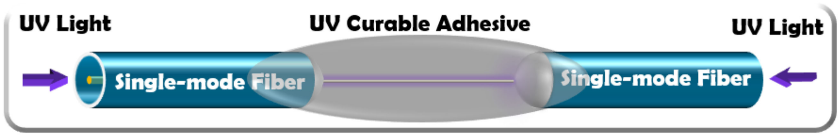

Fig. 7. Schematics of the dual-side fabrication of the light-induced waveguide.

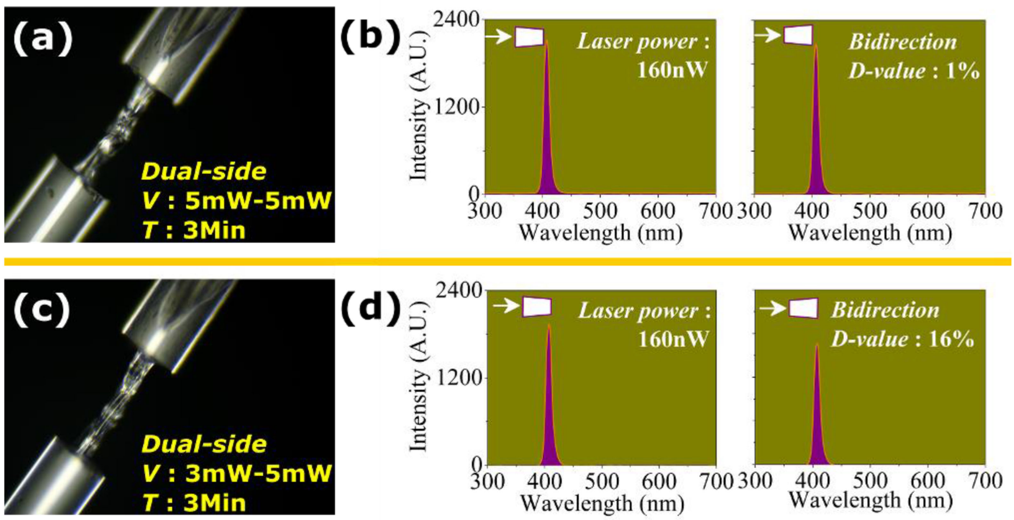

Fig. 8. Characteristics of the dual-side light-induced waveguide with different ratio of the illumination intensity (a) The morphology and (b) The transmission characteristic, while the dual-side laser intensity and illumination time are identical, (c) The morphology and (d) The transmission characteristic, while the dual-side laser intensity and illumination time are unidentical.

illumination will result in a uniform dimension or refractive index distribution at both ends of the light-induced waveguide. However, while the dual-side laser intensity is unidentical (laser power respectively sets as 5 mW and 3 mW, the illumination time is both 3 Min), the morphology and the transmission characteristic are shown in Fig. 8(c) and 8(d), respectively. From Fig. 8(c), at both ends, the radiuses of the light-induced waveguide are significantly different. And in Fig. 8(d), while the dual-side laser intensity is unidentical, the bidirectional D-values of the transmission reaches up to 16%. The preliminary results indicate that the morphology and the transmission characteristic of the light-induced waveguide can be effectively adjusted by controlling the dual-side ratio of the illumination intensity or time. Additionally, these experimental results indicate that light-induced waveguides have potential to realize the functions of polymer-based optical waveguide modules and optical interconnections, in principle, this present technique also can potentially contribute to future expansion of incorporating devices and integrated optoelectronic system.

3. Conclusion

To summarize, we propose and demonstrate that the light-induced optical polymeric waveguides can function as the fully online optical connectors with a directional propagation characteristic. The light-induced optical waveguides, which can be used for the optical couplings between single-mode fibers, are fabricated by using a photopolymerizable resin system formed by a 405 nm laser. We demonstrate that optical couplings between single-mode fibers can be quickly and easily implemented by using the light-induced optical waveguides. Additionally, the transmission characteristics of the light-induced waveguides with different preparation parameters are investigated.

The preliminary experimental results reveal that the (directional) transmission characteristics can be modified by changing the structure of the light-induced waveguides by controlling the illumination time (single-side) or the ratio of the illumination intensity (dual-side). The light-induced waveguide build-up process, which is simple and effective, can be applied to the fabrication of polymer-based optical waveguide modules and for optical interconnections. Simultaneously, this present technique could be a feasible method of incorporating devices such as filters, isolators and polarizers into fibers, which can potentially contribute to future expansion of integrated optoelectronic system.

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