[Technical Paper]

Self-Written Waveguide Technology with Light-Curable Resin for Easy Optical Interconnection

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Abstract

The success of smart optical interconnects for practical use strongly depends on the development of sophisticated coupling technologies that can achieve both high coupling efficiency and easy alignment. One promising technology for solving these problems is the fiber self-written waveguide (SWW) method, which uses light-curable resin. We fabricated a micro-scale 90° light-path converter on the top of mechanically transferable connector that enables smart connection between fibers and an optical wiring board. Then, building upon this fiber SWW technology, we devised a new technology called the mask-transfer SWW method. By applying this technology, we developed a new polymer V-groove fabrication method, which enables V-grooves to be formed at designated positions to facilitate coupling between fibers and devices.

Keywords: Optical Interconnect, UV-curable Resin, Self-written Waveguide, Polymer V-groove, Mask-transfer Method

1. Introduction

Optical interconnects have attracted much attention as a solution to the metallic wiring bottleneck. Recently, equipment for signal processing and information transmission has become faster. As a consequence, metallic wiring is approaching the limit of its capabilities, and optical interconnects are needed in board-to-board interconnection in order to overcome this bottleneck.[1–3] However, optical wiring has some limitations. For example, high optical coupling efficiency requires extremely precise alignment. To develop practical optical interconnects, sophisticated packaging and coupling technologies are needed that can achieve both high coupling efficiency and easy alignment.

The fiber self-written waveguide (SWW) method is a promising approach to solving these problems.[4, 5] The fiber SWW method uses a light-curable resin and a fiber. An optical channel waveguide can be fabricated by irradiating a UV-light and/or a blue laser beam into the resin from the fiber facet. This optical waveguide is formed in the shape of an icicle from the end face of the optical fiber. Inherent to this technology is the very high coupling efficiency achieved between the fiber and the fabricated wave-

guide core. Building upon the fiber SWW technology, we devised a new technology called the mask-transfer SWW method.[6–8] This method involves contact exposure of UV-curable resin through a photomask. A unique aspect of this method is that SWWs having two-dimensional array patterns can be fabricated by a single shot of a UV beam.

We used these methods to fabricate and test several new optical interconnect devices. First, we introduce a micro-scale 90° light-path conversion device attached to a mechanically transferable (MT) connector. We fabricated this new device by the fiber SWW method.[9] Second, we propose a new V-groove fabrication method that applies the mask-transfer SWW method.[10] The use of V-grooves is a well-known technique for aligning optical fibers. The mask-transfer SWW method enables V-groove formation at designated positions to facilitate coupling between fibers and devices.

2. Fabricating a 90° Light-path Conversion Device by the Self-written Waveguide Method

2.1 Proposed device configuration

Transmitting an optical signal into an optical fiber from a

Fig. 1 Proposed 90° light-path conversion device (MMF = multimode optical fiber).

vertical-cavity surface-emitting laser (VCSEL) mounted on an optoelectronic printed wiring board (PWB) requires 90° light-path conversion. Figure 1 shows a schematic drawing of the proposed device, which has 4-channel SWWs.[9] These SWWs are fabricated using conventional fiber SWW technology,[4, 5] and fabricated SWWs are covered with low-index cladding resin by the mask-transfer SWW method.[6–8] Optical devices can be passively aligned by using the alignment pins of the MT connector.

2.2 Fabrication and evaluation

We fabricated a prototype of the 90° light-path conversion device. Figure 2 shows a schematic illustration of the fabrication process, the details of which are as follows.

- Set a 45° mirror-end glass substrate and a MT connector; fill the space with light-curable core resin.
- Cover with a glass stopper; irradiate a blue laser beam with the optical fiber of the MT connector. Repeat four times.
- Wash off uncured resin after forming the 4-channel SWWs.
- Refill the space with light-curable resin; irradiate with UV light from a mercury-xenon lamp.
- Wash off uncured resin, and remove the mirror and glass stopper.

We used a 405 nm wavelength laser beam to cure the core resin, which has a refractive index of 1.588 at a wavelength of 850 nm. Figure 3 shows the dimensions and appearance of the fabricated SWWs, as observed under an optical microscope. The core of the 90° light-path conversion device was fabricated as designed, although the device had a slightly undulating pattern. The lengths of the fabricated core's arms are 628 and 405 μm . The diameter of the connector-side core is 43 μm , which is 7 μm smaller than that of the optical fiber. Figure 4 shows photographs of a prototype SWW device after formation of the

Fig. 2 Fabrication process.

Fig. 3 Dimensions and of fabricated SWW arms.

Fig. 4 Photograph of prototype.

cladding.

We measured optical coupling loss with an 850 nm laser diode beam by setting a multimode fiber at the end face of the prototype. The losses were approximately 3.2 and 3.4 dB for the transmitter and receiver, respectively. The receiver is coupled into the micro prism from the MT connector side, as shown by the arrow in Fig. 3.

2.3 Optical loss and tolerance width

We analyzed the optical loss and positional tolerance of

the optical fiber for the proposed device through a ray-tracing simulation. The simulation results are summarized in Fig. 5. A model was constructed from SWW models with a 45° mirror. We set the model dimensions to be equal to those of the fabricated device.

Optical losses of 2.28 and 1.65 dB were obtained at $0\ \mu\text{m}$ off-axis for the transmitter and receiver, respectively. In addition, the 1 dB down-tolerance widths of the transmitter and receiver were 15 and $25\ \mu\text{m}$, respectively, when the input/output fiber was moved along the x-axis.

The simulated loss was less than the measured loss of the prototype. The optical loss of the prototype can likely be attributed to the following factors.

- (1) Scattering of the irradiation beam at mirror surfaces.
- (2) Non-uniform SWW shapes, for example, the undulating pattern.

Our experimental study on SWW fabrication conditions suggests that fabricating SWWs of uniform shape requires a lower-mode irradiation beam and higher optical power. Therefore, we expect that the optical coupling loss can be improved by adjusting the fabrication condition.

A major advantage of the proposed device is that a built-in alignment scheme for optical devices on the board can be incorporated into the prism. A possible scheme is shown in Fig. 6. By placing holes for the metallic pins of

Fig. 5 Results of optical loss and positional tolerance simulation.

Fig. 6 Built-in alignment scheme.

MT connector, alignment pins can be formed using SWW technology, and holes for the alignment pins are prepared on the VCSEL module on the PWB. By inserting alignment pins into the holes on the VCSEL module, optical coupling can be easily accomplished. In addition, the light-path conversion angle is not limited to 90° ; any angle is possible by changing the mirror angle. Our study of SWW fabrication conditions suggests that SWW fabrication using a lower-mode irradiation beam and higher optical power could improve the optical coupling loss.

3. Polymer V-grooves Prepared by the Mask-transfer SWW Method

3.1 Mask-transfer self-written waveguide method

The mask-transfer SWW method is developed from the fiber SWW method,[6–8] and allows easy and rapid fabrication of various waveguide patterns at the same time. The basic experimental setup is shown in Fig. 7. UV-curable resin is injected between the photomask and substrate, and the thickness of the device is governed by the size of the air gap between them. The SWWs are formed at room temperature by shining UV light through the photomask. The SWW cross-section is precisely controlled by the aperture of the photomask pattern. For instance, $M \times N$ SWWs can be fabricated by using an $M \times N$ array pattern and a single shot of UV light.

3.2 Proposed method for polymer V-grooves

We propose a new method for preparing polymer V-grooves by the mask-transfer SWW method.[10] The fabrication process is schematically shown in Fig. 8. We first prepared a photomask that has periodic black and

Fig. 7 Experimental setup for the basic mask-transfer SWW method.

Fig. 8 Fabrication of polymer V-grooves.

white stripes, the width of which controls the width of the V-grooves formed. When we irradiated the UV-curable resin with two UV beams at an offset angle through the mask aperture, the regions underneath the black stripes were not irradiated and remained uncured. This forms V-grooves that have a slope angle θ after removing the uncured resin.

3.3 Mask-transfer self-written waveguide V-groove fabrication using a prism

In the basic setup described above, the mask-transfer SWW fabrication method requires two UV beams. However, the process can be made very simple and efficient by using an isosceles prism, as shown in Fig. 9. In this way, V-grooves can be fabricated using a single UV beam. We assumed that the refractive indices of the resin, prism, and mask are the same. The slope angle θ is given by

$$\theta = \theta_i - \arcsin\left\{\frac{\sin(\theta_t)}{n}\right\}$$

where

$$\theta_i = 90 - \frac{\theta_t}{2}$$

Here, θ_i is the incident angle of the beam and θ_t is the top angle of the prism.

Figure 10 shows the relationship between θ and θ_t . The shape of the polymer V-groove can be adjusted by changing θ_t , meaning that this fabrication process is extremely flexible.

Fig. 9 Irradiation with an isosceles triangular prism.

Fig. 10 Relationship between slope angle θ and angle θ_t at the top of the prism.

3.4 Fabrication and evaluation

V-groove fabrication was conducted using the setup shown in Fig. 9. The height of a V-groove depends on the size of the air gap between the photomask and glass slide substrate. A UV-curable resin (DVD-003, Nippon Kayaku Co., Ltd.) was exposed to a 365 nm UV beam with a power density of 12.5 mW/cm² for 5 s. In separate fabrication trials to prepare V-grooves with different shapes, two isosceles triangular prisms were used, which had θ_t of 60° and 90°. Both prisms had a refractive index of 1.47. We prepared a photomask that has alternating 50-μm-wide white stripes and 200-μm-wide black stripes, as shown in Fig. 11. Figure 12 shows photographs of the V-grooves fabricated on glass slides by using these prisms. The results demonstrate that V-groove shape is controlled by θ_t . Some differences were found between the theoretical values of θ and the values measured in the V-grooves. The top and bottom of the V-groove sides had maximum errors of 5–10 μm, and the maximum difference in the slope angle was 6.8°.

Figure 13 shows a photograph of an optical fiber in a V-groove fabricated with the 60° prism. The position of the fiber core placed on the V-groove is shifted, which would reduce optical coupling efficiency, thus demonstrating that accurate height, width, and slope angle are required for

Fig. 11 Photomask with black and white stripes.

Fig. 12 Fabricated V-grooves.

Fig. 13 Optical fiber placed on a fabricated V-groove.

Table 1 Comparison of V-groove materials and fabrication methods.

Substrate	Silicon wafer	Glass plate	Polymer
Fabrication method	Wet etching	Cutting	MTSW
Precision	High	Medium	Medium
Cost	High	High	Low
Utility	Practical	Practical	Research
Productivity	Low	Low	High
Bend	Not possible	Difficult	Possible
Thermal stability	High	High	Medium
Adjustment of V angle	Difficult	Possible	Easy
Package order	V-groove first	V-groove first	Device first

V-groove fabrication. The fabrication errors seem large at present; nevertheless, the polymer V-grooves fabricated by this method could be used in multimode fiber systems. It is important to reduce the fabrication errors in the shape of the V-grooves for future optical systems and other applications. The cause of the fabrication errors has not yet been identified, although it is probably due to poor UV collimation and error in the angle of beam incidence on the prism. We expect that the reproducibility of V-groove shape can be substantially improved by optimizing the fabrication conditions. Our ultimate goal is that this method can be used for single-mode fiber systems.

3.5 Advantages of mask-transfer self-written waveguide V-groove fabrication

Table 1 compares fabrication methods for V-grooves. Conventional fabrication methods require sophisticated technology, thus resulting in high costs. In contrast, the mask-transfer SWW method uses a simple room-temperature process and an inexpensive resin. Of particular note is that V-grooves can be fabricated anywhere on the substrate, even after the device is assembled.

4. Conclusion

We have proposed and demonstrated two optical interconnect devices fabricated using fiber SWW and mask-transfer SWW technologies with a light-curable resin. First, we proposed a microscale 90° light-path conversion device fabricated by the fiber SWW method. Although further improvements in optical coupling efficiency are necessary, we confirmed that the device is feasible by ray-tracing simulation analysis. Our device enables easy optical coupling between optical fibers and VCSEL modules on PWBs. Next, we fabricated polymer V-grooves by applying the mask-transfer SWW method. We demon-

strated that a prism can make this process simpler and more efficient: Two offset beams can be formed from a single UV beam. The shape of the V-groove can be controlled by adjusting the top angle of the prism. The optical interconnect devices fabricated using self-written waveguide technologies are promising and will lead to substantial advances in future optical interconnect devices.

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Osamu Mikami received his B.S., M.S., and Ph.D. in applied physics from Osaka University in 1969, 1971, and 1978, respectively. In 1971, he joined the Nippon Telegraph and Telephone Public Corporation (now NTT), where he was engaged in research on reversible holographic storage,

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He first proposed the new concept of an “optical pin” for connecting between an optical fiber and optical wiring, and later proposed a new technology called mask-transfer self-written waveguides, which enables mass production of polymer optical pins in two-dimensional array structures.

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