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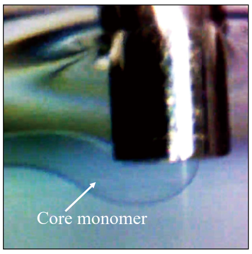


# Formation of 3D Polymer Optical Waveguides

Sho YAKABE*, Ken MANABE, Dai SASAKI, and Takaaki ISHIGURE

The Mosquito method, a polymer optical waveguide fabrication method invented by Professor Ishigure at Keio University, enables the three-dimensional (3D) formation of core patterns in cladding using a commercially available micro dispenser and a multi-axis syringe-scanning robot. This fabrication method is expected to be used to realize devices required for 3D waveguides such as Fan-in/Fan-out (FIFO) devices, which are essential for the introduction of multicore fibers (MCF). On the other hand, prior studies have mainly examined multimode waveguides, and several issues need to be solved for making single-mode devices. In particular, the core shape tends to deteriorate from circular due to monomer flow caused by needle scanning in the cladding, which is a factor that increases the connection loss with the optical fiber. This paper presents a theoretical and experimental study on the fabrication of single-mode waveguides by the Mosquito method and the formation of circular cores using the method to reduce connection loss with single-mode optical fibers.

Keywords: polymer optical waveguide, the Mosquito method, low loss, single mode

## 1. Introduction

Following the rapid development of Cloud services in recent years, the construction of hyper-scale data centers is increasing, especially in North America. In such large-scale data centers, it is extremely important both to increase the processing speed of their servers and switches and to reduce power consumption. One of the key technologies that support the growth of data center networks is the optical interconnect that uses optical fiber as the signal transmission line. Currently, fiber cables with multi-fiber push-on (MPO*1) connector, which enables batch connection of several optical fibers are used for the connection between the optical transceiver on the front panel and optical fibers. In recent years, the number of optical fibers attached to an MPO connector tends to increase to achieve higher bandwidth density.[1] Moreover, MCF, which arranges several cores that function as a signal line within one optical fiber, is a promising type of optical fiber that is capable of significantly increasing the number of optical channels per cross-sectional area. A type of optical connector that enables a multifold increase in the number of optical channels per cross-sectional area by replacing the existing single core fiber (SCF) with MCF has also been reported.[2] However, there are issues to be addressed for deploying MCF in data center networks. For instance, FIFO is required when MCF is connected to a transmitter-receiver, where it is necessary to convert the channel arrangement from a one-dimensional array to a two-dimensional circular array. This is because, in an optical transceiver, semiconductor lasers are commonly one-dimensional arrays. For this issue, various optical connection methods using FIFO have been proposed.[3],[4] In particular, glass and polymer optical waveguides with 3D core patterns are expected to realize compact FIFO devices with low connection loss.[5] One of the fabrication methods of this 3D waveguide that is drawing attention is the polymer optical waveguide fabrication method using a micro dispenser and multi-axis syringe scanning robot invented by Professor Ishigure at Keio University, known as "the Mosquito method."[6]-[8] This paper discusses the basic research on the 3D polymer waveguide fabricated through the Mosquito method, which was conducted jointly with Professor Ishigure.

## 2. Mosquito Method

The common fabrication methods thus far reported include photolithography which uses photomask,[9],[10] UV imprinting,[11] and laser drawing.[12],[13] With the above-mentioned methods using photomasks, it is possible to easily achieve inter-core pitch conversion within one plane (horizontal to the substrate surface).[14] However, the freedom of core patterns is limited to the area inside this single plane. Moreover, as the cores are rectangular, an increase in connection loss is a concern when it is used for connections with single-mode fiber (SMF) due to the mismatch in their mode field. Meanwhile, the Mosquito method fabricates an optical waveguide by using a dispenser and a multi-axis robot. Figure 1 shows the waveguide fabrication process of the Mosquito method. The needle with a syringe tip is

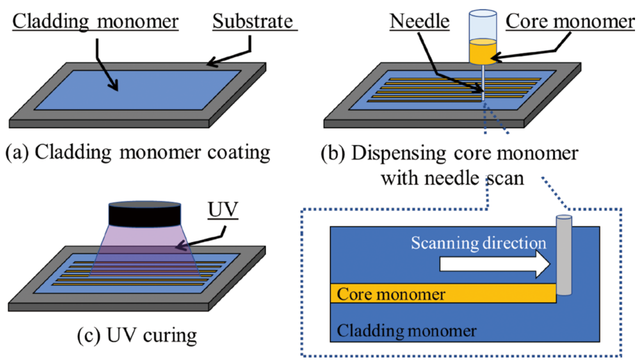


Fig. 1. Waveguide fabrication process of the Mosquito method

inserted into the UV curing resin for cladding that has not yet hardened, and the syringe (needle tip) is moved to the desired direction by the multi-axis robot while dispensing UV curable resin monomer for cores with a high refractive index from the needle tip using the dispenser. Following this, the both monomers are hardened by being exposed to UV light, resulting in a core arrangement that matches the pre-programmed trajectory.

Thus, the Mosquito method is capable of three-dimensionally changing core arrangements by altering the scanning direction of the robot. Therefore, it is expected to achieve fabrication and size reduction of optical communication devices such as FIFO.

## 3. Low-loss Single-mode Polymer Optical Waveguide

### 3-1 Fabrication conditions

To fabricate a single-mode waveguide using the Mosquito method, we examined the fabrication conditions. As the shape of the core of the waveguide fabricated through the Mosquito method is circular, it is inferred that the single-mode conditions can be calculated using the same method as the one used for optical fibers. The number of modes transmitted in optical fibers can be predicted through Eq. (1).

$$V = \frac{2\pi a}{\lambda} NA \quad \cdots\cdots (1)$$

Here, $V$ is the normalized frequency, $a$ is the core radius of the waveguide, $\lambda$ is the free-space wavelength, and $NA$ is the numerical aperture of the waveguide. Moreover, the numerical aperture is calculated from the refractive indices of the core and the cladding of the waveguide. In this paper, the organic-inorganic hybrid resin was used as the material for the polymer optical waveguide. The refractive indices of the core polymer and the cladding polymer at a wavelength of 1.31 μm are 1.577 and 1.568 respectively, and the numerical aperture was calculated to be 0.168.

The normalized frequency that satisfies a single mode is defined to be less than 2.405. As the numerical aperture is obtained from the refractive indices of the core and the cladding, the normalized frequency in this examination can be obtained only from the core radius. Thus, from the calculated value of the normalized frequency, the UV curable resin used in this examination satisfies the single-mode conditions when the core radius is less than 3 μm.

Next, the conditions of dispensing UV curable resin from the dispenser were examined to fabricate a waveguide with a core diameter that satisfies the single-mode conditions. The flow amount ($Q$) of UV curable resin dispensed from the needle tip is determined by Eq. (2) based on the Navier Stokes Equation. Moreover, the initial core diameter $2a$ of the dispensed UV curable resin is obtained from Eq. (3), thus enabling the prediction of core diameter.

$$Q = \frac{\pi d^4 p}{128 \eta L} \quad \cdots\cdots (2)$$

$$2a = 2\sqrt{\frac{Q}{\pi U}} = \sqrt{\frac{p d^4}{32 L \eta U}} \quad \cdots\cdots (3)$$

Here, $p$ is the dispensing pressure, $L$ is the needle length, $d$ is the needle internal diameter, $\eta$ is the viscosity of the resin, and $U$ is the scanning velocity of the needle. To fabricate a waveguide that satisfies the single-mode conditions calculated from the normalized frequency, the fabrication of the waveguide was performed using the fabrication conditions listed in Table 1, which resulted in the core diameter that is less than 6 μm (the single-mode condition is that the core radius is less than 3 μm).

Table 1. Fabrication conditions of polymer optical waveguide

| Parameters | Values |
|---|---|
| Dispensing pressure : $p$ | 500 kPa |
| Needle length : $L$ | 15 mm |
| Needle I.D : $d$ | 100 μm |
| Viscosity of core : $\eta$ | 71000 cP |
| Scan Velocity : $U$ | 80 mm/sec |
| Core diameter : $2a$ | 4.1 μm |

Photo 1 shows the cross-section of the fabricated polymer optical waveguide, Photo 2 shows the enlargement of each core, and Fig. 2 shows their Near Field Patterns (NFP*2). Note that the cores were fabricated in the order of Ch.1 to Ch.12.


Photo 1. Sectional image of the optical waveguide fabricated through the Mosquito method

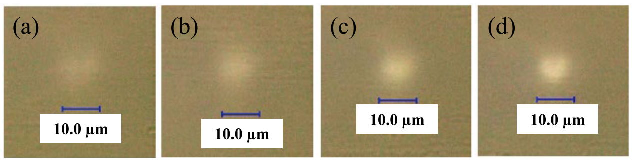


Photo 2. Enlargement of the section of each core
(a) Ch.2 (b) Ch.5 (c) Ch.8 (d) Ch.12

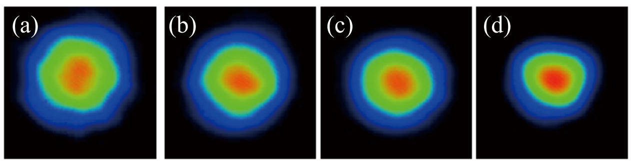


Fig. 2. Light intensity distribution of each core (NFP)
(a) Ch.2 (b) Ch.5 (c) Ch.8 (d) Ch.12

From the core section shown in Photo 2, it is verified that circular cores whose diameters are 10 μm or less were formed. However, it was also observed that, especially in the smaller channel numbers, the boundary between the core and the cladding was not clear. Therefore, it is not always possible to accurately measure core diameters from the observation of cross-sectional images. Next, through the NFP measurement in 1.31 µm wavelength shown in Fig. 2, it was verified that every core satisfied the single-mode conditions.

Meanwhile, there are several issues to be solved before applying this single-mode waveguide to optical components with functions such as pitch conversion or connection with SMF array (for instance FIFO device for MCF). One such issue is the circularity of the mode field. Figure 3 shows the relationship between the mode field diameter (MFD*3) of both the horizontal direction (X-axis, (MFD(X)) and the vertical direction (Z-axis, MFD(Z)) and the interim time (channel number). Moreover, Fig. 3 also shows the vertical to horizontal ratio (VHR), which is the MFD ratio between the horizontal direction and the vertical direction, as the index for circularity. The fact that the MFD measured at two directions orthogonal to each other is different indicates that the mode field has an elliptical profile. Another issue is the discrepancies in the MFD among several cores arranged within one cladding. With the Mosquito method, each core is dispensed one after the other, and the monomer of both the cores and the cladding is exposed to UV light at once after all the cores were dispensed. Therefore, the "interim time," which is the time between the dispensing of one core monomer and the start of UV curing is different for each channel. During this time, the liquid core monomer and cladding monomer mutually diffuse and expand MFD. Furthermore, it shows that when the interim time is shorter (i.e. with a larger channel number), the mode field has an elliptic shape that is longer in the horizontal direction. However, when the interim time is made longer (i.e. the channel number is made smaller), VHR approximates 1 and begins to display perfect circularity. This fluctuation in MFD is caused by the difference in interim times among the cores.

These issues cause an increase in the connection loss of optical fibers and prevent the practical application of the polymer optical waveguide.

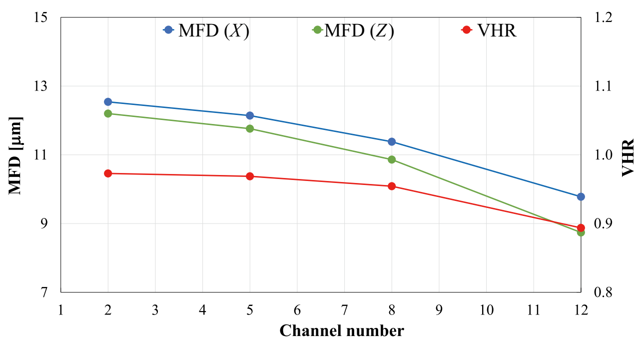


Fig. 3. MFD and VHR of each core

### 3-2 Stabilization of MFD among cores

First, the method to limit the discrepancy among the cores in the waveguide was examined. From the observation of the image of the core end surface, it was inferred that the discrepancy is caused by the mutual diffusion of the core monomer and cladding monomer. Thus, temperature control of the monomer was conducted as the method to limit the mutual diffusion. To verify the impact of mutual diffusion when the monomer temperature is controlled, cores were fabricated after the monomer temperature stabilized under the setting value based on the fabrication conditions listed in Table 1. The MFD at 1.31 µm wavelength was measured by launching each core of the waveguides using an SMF. Figure 4 shows the relationship between the interim time and MFD at each temperature. Here, interim time indicates the time between the dispensing of UV-cured resin that becomes a core and its curing through exposure to UV.

From the result, the tendency for the MFD variation due to the interim time to be larger when the temperature of the UV curing resin is higher was verified. Especially when the temperature of the cladding monomer was 13°C, the MFD variation became approx. 0.02 µm/s and the maximum interim time to fabricate all 12 cores became approx. 40 seconds. Thus, it is possible to limit the maximum difference in MFD to within 1 µm.

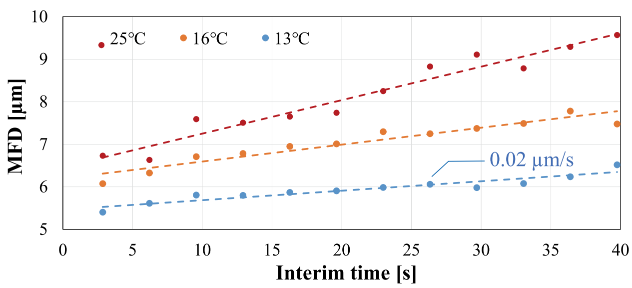


Fig. 4. Relationship between interim time and MFD at each monomer temperature

### 3-3 Making core shape circular

The shapes of the common SMF core and mode field are circular. Therefore, if the mode field of the fabricated polymer waveguide is elliptical, there is a concern that there will be an increase in connection loss due to the mismatch between mode fields when it is connected to SMF. Thus, the flow of the core monomer dispensed from the needle tip into the cladding monomer was theoretically analyzed using flow analysis software to form circular cores. Here, a general thermal fluid analysis software ANSYS Fluent was used for the analysis. Figure 5 shows the fluid analysis model of the Mosquito method. This model consists of two layers of fluid, namely the cladding monomer and air, in addition to the dispensed core monomer. Three parameters, namely, the viscosities of two monomers, surface tension, and density, are considered for the flow calculation of monomer.

One example of the analysis results is presented here. The result shown in Fig. 6 contains the side view cross-section of the core monomer being dispensed and the cross sections at three points that are perpendicular to the scanning direction. The positions of the cross-section of Figs. 6

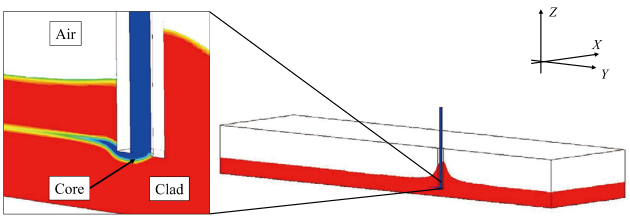


Fig. 5. Flow analysis model for waveguide fabrication through the Mosquito method

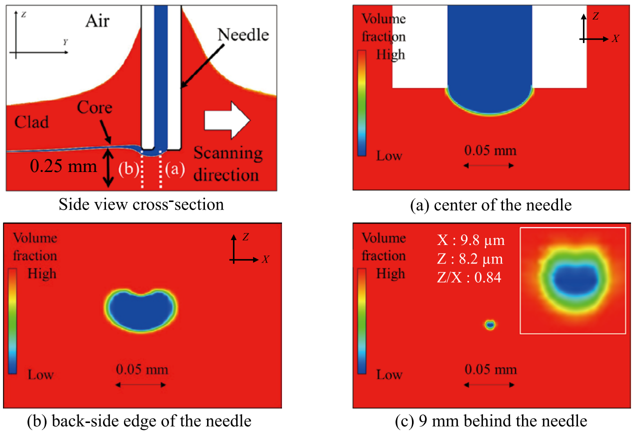


Fig. 6. Cross section perpendicular to the needle scanning direction
(a) Center of the needle (Y = 0 mm)
(b) Back-side edge of the needle (Y = 0.115 mm)
(c) 9 mm behind the needle (Y = 9.115 mm)[15]

(a) to (c) are the center of the needle (Y = 0 mm), the back-side edge of the needle (Y = 0.115 mm), and 9 mm behind the back-side edge of the needle (Y = 9.115 mm) respectively. In this flow analysis model, the thickness of the cladding monomer was set at 0.5 mm and the height of the needle tip from the substrate surface was set at 0.25 mm.

Next, the relationship between the needle tip height and the ratio between the vertical direction (*Z*) and the horizontal direction (*X*) of the core diameter (VHR) was calculated and summarized in Fig. 7. When the needle is just a cylindrical tube (straight needle), it is difficult to form circular cores even when the height of the needle tip is adjusted. Meanwhile, when the needle tip shape has a 10° tapered angle, the VHR of the core diameter maintains a value close to 1.0 when the needle tip height is higher than 0.2 mm. Therefore, while it becomes possible to fabricate a circular core by using a tapered needle, it also requires a certain cladding thickness. Figure 7 also shows the VHR of core diameter when the tapering angle of the needle is 20°. When the tapering angle is 20°, VHR close to 1.0 could be obtained even when the needle height is less than 0.2 mm. Thus, it shows that the flow of the cladding monomer determined by the needle tip shape influences the core shape, and the usage of the tapered needle is an effective method of forming the circular shape.

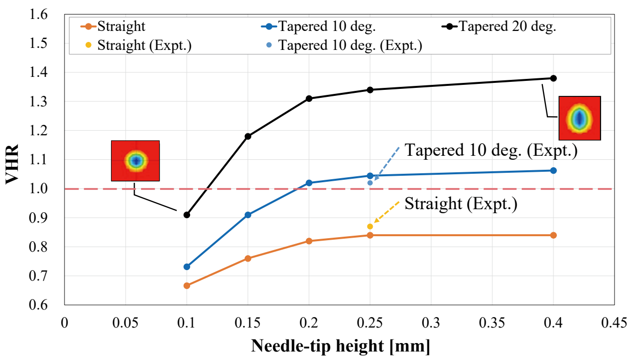


Fig. 7. Relationship between needle tip height and VHR[16]

## 4. Low-loss Polymer Optical Waveguide with a Circular Core

The result of the monomer flow analysis in the previous section showed that it is possible to form circular cores with the tapered needle by appropriately adjusting the needle tip height. A polymer waveguide was fabricated using a tapered needle to compare the results of experimental and theoretical calculations. The fabrication conditions follow those in Table 1 (except for the needle measurement). Photo 3 shows a cross-section image of the fabricated polymer waveguide. Photo 4 is an enlargement of some of the cores. Compared to the cores formed by a straight needle as shown in Photo 2, these sections show that every core is circular with an even diameter.

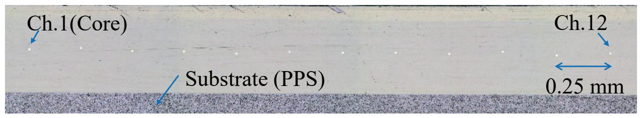


Photo 3. Sectional image of an optical waveguide fabricated through the Mosquito method

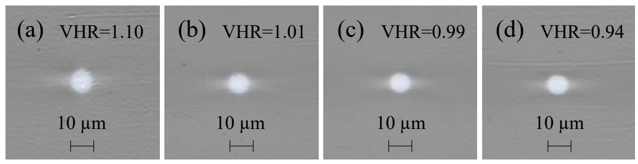


Photo 4. Enlargement of the section of each core
(a) Ch.1 (b) Ch.4 (c) Ch.8 (d) Ch.12

Figure 8 shows the result of measuring the NFP of every core of the waveguide shown in Photo 3 and Photo 4 at 1.31 µm wavelength. This result demonstrated that every core satisfied the single-mode conditions. Figure 8 (a) shows that the MFD of the two orthogonally intersecting directions (*X*-axis and *Z*-axis) match well. Next, the VHR of core diameter is estimated from the NFP of every core. As shown in Fig. 8 (b), the average of the measurements of VHR of core diameter is 1.02, displaying a slight discrepancy between the measurement value and analysis value, and it shows that the actual core shape is better than that of the analysis value. One of the reasons why the observed core shape improved is that the core monomer dispensed into the cladding monomer becomes closer to the circle as time passes due to its surface tension. Figure 8 (a) shows that the fluctuation of MFD in relation to the channel number vibrates a little, especially in the Z direction. In the process of core monomer dispensing shown in Fig. 1 (b), the needle scans in a zigzagging trajectory, and it scans in the +*Y* direction at the channels with odd numbers, and in the -*Y* direction for the channels with even numbers. This difference in the scanning directions can potentially cause discrepancies in MFD, especially in the *Z* direction.

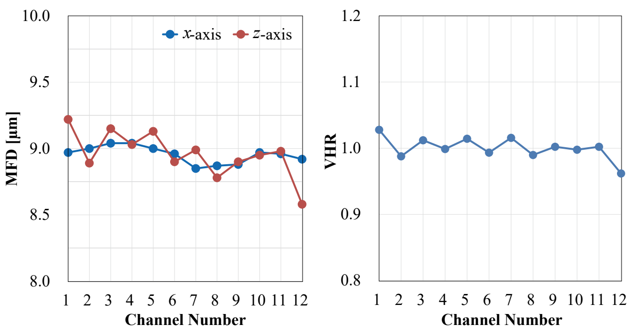


Fig. 8. NFP measurement result at 1.31μm wavelength
(a) MFD in the X and Z direction (b) VHR of each core

Next, the fabricated polymer waveguide was inserted between two SMFs, and its insertion loss was measured with the same 1.31 μm wavelength as that of the NFP measurement. This insertion loss includes the two connection losses between the polymer waveguide and SMFs, and the propagation loss within the waveguide (3 cm in length). The cores of the waveguide and the SMFs were aligned on the automatic stage for the insertion loss measurement. Here, a refractive index matching material was applied between them to reduce the Fresnel loss. Figure 9 shows the insertion loss of the fabricated waveguide with 12 cores. From the existing study,[17] the propagation loss unique to this polymer material at 1.31 μm was estimated to be 0.30 dB/cm. As the waveguide length is 3 cm, the propagation loss in the entire waveguide was estimated to be 0.90 dB. Moreover, the average connection loss between

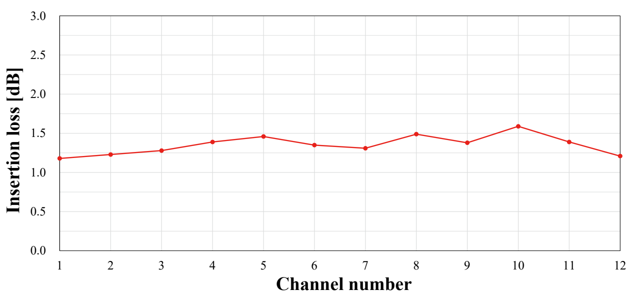


Fig. 9. Insertion loss of the polymer waveguide at its connection with SMF

the SMF and the polymer optical waveguide calculated from the mode field was 0.15 dB. Thus, it was verified to be sufficiently small.

## 5. Conclusion

A polymer optical waveguide with circular cores fabricated through the Mosquito method that satisfies the single-mode conditions was designed to apply to optical connection components such as the FIFO device for MCF. Following this, the method to reduce variation in optical properties among several cores was examined both theoretically and experimentally.

First, it was verified that when monomer diffusion between the core and the cladding is controlled by keeping the monomer temperature low, it is possible to limit the variation in MFD among the cores.

Next, it was elucidated through a theoretical flow analysis that for the fabrication of cores in a perfect circle, the flow of the core monomer immediately after dispensing near the needle tip is important as it influences the core shape. It was discovered that it is possible to form circular cores by optimizing the needle tip height from the substrate surface as well as the shape of the needle tip, thereby solving this issue.

A challenge we had was how to fabricate a single-mode waveguide through the Mosquito method while maintaining the uniformity of optical properties among several cores, which is required for optical connection components of a single-mode core. In our examination, this issue was solved by optimizing the fabrication conditions both theoretically and experimentally.

In the future, it is expected that optical waveguide type connection devices using the single-mode waveguide fabricated through the Mosquito method will be created.

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### Technical Terms

*1 Multi-fiber Push-on (MPO) connector: An optical fiber connector connects optical fibers through PC connection technology.

*2 Near field pattern (NFP): It indicates the distribution of light strength on a light-emitting surface (in this paper, the end surface of a polymer optical waveguide).

*3 Mode field diameter (MFD): An index represents the spread of electric field distribution that is propagated through the single-mode optical fiber of the optical waveguide.

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## Contributors

The lead author is indicated by an asterisk (*).


### S. YAKABE*

• Doctor of Engineering
Assistant Manager, Optical Communications Laboratory

### K. MANABE

• Assistant General Manager, Analysis Technology Research Center

### D. SASAKI

• Group Manager, Optical Communications Laboratory

### T. ISHIGURE

• Professor, Keio University