Laminated polymer waveguide fan-out device for uncoupled multi-core fibers

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Abstract: A compact waveguide-type fan-out device for uncoupled multi-core fibers was demonstrated using a laminated polymer waveguide (LPW). The core spacing in the vertical direction was precisely controlled by the spin-coating of epoxy resin cladding with accurate viscosity control, while that in the lateral direction was determined precisely by using a photomask. The simultaneous coupling from the fan-out device to a seven-core MCF was successfully demonstrated. Next, we measured the offset loss characteristics of the cores of the LPW and calculated the spot size of the respective cores. The theoretical coupling losses evaluated from the spot size and the offset were as low as 0.2 – 7.5 dB.

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References and links


1. Introduction

One of the authors previously proposed a new type of optical fiber called a heterogeneous uncoupled multi-core fiber (MCF) that drastically increases the transmission capacity by a space-division multiplexing technique [1,2]. To realize a transmission system using the multi-core fiber, a compact integrated fan-out device is required for the massive connection. Thus far, three-dimensional fan-out devices fabricated by ultrashort-pulse laser inscription, using a tapered MCF connector, and using a bulky individual manipulation apparatus have been reported [3–5]. However, no waveguide-type fan-out devices with the possibility of
integration with other waveguide devices such as WDM filters using film deposition and photolithography technique have yet been reported.

In this study, a compact integrated connection (fan-out) device from an uncoupled seven-core fiber to an array of single-core fibers was fabricated using Laminated Polymer Waveguide (LPW) structure [6]. The core spacing in the vertical direction was precisely controlled by spin-coating with accurate viscosity control of the epoxy resin cladding, while the core spacing in the lateral direction was determined precisely using an EB-written photomask. A low coupling loss connection from the fan-out device to the seven-core MCF was demonstrated.

![Fig. 1. Schematic view of LPW fan-out device.](image)

2. Fabrication

2.1 Design of LPW

Figure 1 shows a schematic view of the LPW fan-out device. The input end is butt-coupled to the MCF, whereas the output end is connected to an array of single-core fibers. The lateral core spacing at the input end of the LPW was designed to be 45 μm, which was identical to that of the MCF.

![Fig. 2. Dispersion curve of rectangular waveguide.](image)

First, the dispersion characteristic of the rectangular waveguide was calculated to design the refractive index contrast and the core size of the LPW. Figure 2 illustrates the dispersion curve of the rectangular waveguide, which was analyzed using numerical analysis solver.
FemSIM\textsuperscript{3} (Rsoft). The parameters of the waveguide that can satisfy the single-mode condition were determined from this curve. A core width of 7.9x7.9 \( \mu m \) and a refractive index contrast of 0.4\% were adopted. In this case, the spot size (half of the mode field diameter) of the waveguide was 4.8 \( \mu m \), which matched that of MCF.

The size of fabricated device is 22 mm \( \times \) 12 mm. The chip size of V groove holder of fiber array is 3 mm width \( \times \) 2 mm height (1mm thick V-grooved chip covered by 1 mm thick glass chip). The fiber spacing of fiber array is 250 \( \mu m \), and so the channel waveguides in the fan-out device involve S curve bends consisting of circular arc of 20 degrees. Thus the difference of channel length is only several hundred microns. The bend radius was designed to be 21 mm which corresponds to the theoretical bending loss of \( 10^{-6} \) dB/bend. Since the theoretical bending loss is much smaller than the propagation loss as discussed later, the bend radius can be reduced to several millimeters and the propagation loss due to the absorption loss can reduced by shortening the device length.

2.2 Precise control of polymer thickness

The core is made of poly-methyl-methacrylate (PMMA, molecular weight: 100,000), which is one of the many optically transparent polymer materials. The core layers were fabricated by spin-coating and air-drying. A solution of PMMA dissolved in chlorobenzene (C\(_6\)H\(_5\)Cl) was used to form the cores. The solution was made from 32.6 g of PMMA and 100 ml of C\(_6\)H\(_5\)Cl, and the viscosity measured by a viscometer (VM-100A-M by CBC Co., Ltd) was 260 cP at a density of 1.0 g/cm\(^3\). The dependence of the PMMA thickness on the rotation speed during the spin-coating of PMMA solution was measured and is illustrated in Fig. 3. Here, the thickness was measured using a Metricon prism coupler PC-2010. The first rotation was for 5 sec at a speed of 400 rpm and the main rotation speed was varied to control the thickness. The time of the main rotation was 45 sec. From Fig. 3, the rotation speed required for a thickness of 7.9 \( \mu m \) was determined to be 1500 rpm.

![Fig. 3. Rotation speed dependence of thickness of PMMA.](image)

Since we put a high priority on the ease of fabrication process in this study, we adopted PMMA as the core material. However, more reliable polymer will be used as the core material. The most important point of this waveguide is the use of UV-cured epoxy resin, because the flat surface can be obtained after the curing process as describe below. Owing to this property of UV-cured epoxy resin, the stacking of waveguide is possible.
The cladding layers were fabricated by the spin-coating and UV curing of epoxy resin. The epoxy resin was a solvent-free oligomer supplied by NTT-AT. In the spin coating process, even if the substrate surface involves ridge structure, the flat surface is obtained when the thickness of spin-coated film is thicker than the ridge height. After spin-coating process, the curing process usually follows. If the film does not shrink after the curing process, perfectly flat surface is obtained [7]. Therefore, the core spacing in the vertical direction can be precisely controlled by the rotation speed during spin-coating and the viscosity of the resin. According to Ref [7], the dependence of the thickness on the rotation speed, rotation time, and other factors is expressed by

$$h(t) = \frac{1}{4\pi f} \sqrt{\frac{3\eta}{\rho t}}$$  

(1)

where $h(t)$ is the thickness as a function of the rotation time $t$, $f$ is the rotation speed, $\eta$ is the viscosity, and $\rho$ is the density. The thickness of the cladding was designed to be 39 $\mu$m to obtain a core spacing of 45 $\mu$m for the triangular arrangement of cores. However, the viscosity of the UV-cured epoxy resin was easily changed during the fabrication process owing to small fluctuations in the ambient temperature. Therefore, the rotation speed was regulated to adjust the cladding thickness to 39 $\mu$m. Thus, the viscosity dependence of the rotation speed for $h = 39$ $\mu$m was calculated from Eq. (1) and is illustrated in Fig. 4. Here the rotation time was 60 sec. Then the rotation speed was adjusted to the optimum value by referring to the measured value of viscosity and Fig. 4 at each spin-coating of the UV-cured epoxy resin.

*Fig. 4. Viscosity dependence of rotation speed of UV-cured epoxy resin for thickness of 39 $\mu$m.*

### 2.3 Fabrication process

Figure 5 illustrates the fabrication process of the LPW. In this work, a 1 mm-thick Si substrate was used to avoid the distortion caused by the tension induced by the curing of the resin. First, a thin SiO$_2$ layer was formed on the Si substrate by thermal oxidation in order to increase the adhesion between the bottom cladding polymer layer and the substrate. Next, the bottom cladding layer was fabricated by the spin-coating and UV-curing of the epoxy resin. Then, the core layer was fabricated by the spin-coating of PMMA solution. Here, a polyvinyl alcohol (PVA) layer was spin-coated to avoid the intermixing of the PMMA with the photo-
resist, formed in the next step. Since the PMMA and photoresist were both organic-soluble, the water-soluble polymer PVA was adopted. Then another resin (OMR85) layer was fabricated by spin-coating and UV curing to prevent the PVA layer from dissolving when it was immersed in the water in the patterning step. Next, the waveguide pattern was formed by photolithography using a silicone-based photoresist (Nano hybrid silicone, by ADEKA Co.) and RIE using O₂ gas. Finally, the mask layer was removed by the lift-off process using water. Then, these steps were repeated to form a multilayer waveguide.

3. Experimental results

3.1 Cross section of LPW and core offset

Cross-sectional microscopic images of the fan-out device and the multi-core fiber (Sumitomo Electric Industries Ltd.), used in this measurement are shown in Figs. 6(a) and 6(b), respectively. Cores labeled with the same number were butt-coupled. The core spacing of the multi-core fiber was 45.0 μm and the mode field diameter 2wₘ (wₘ: spot size) ranged from 9.72 to 9.85 μm. The symbol of δ in Fig. 6(a) denotes the amount of offset of cores from the center of the corresponding cores of the MCF, which was measured from the microscope image. Table 1 shows the measured values of the lateral offset δₓ and the vertical offset δᵧ, and the resulting absolute value of offset \( \delta = \sqrt{\delta_x^2 + \delta_y^2} \).
Fig. 6. Cross-sectional microscopic images. Figure 6(a) and 6(b) correspond to LPW and MCF.

Table 1. Measured offset in x and y directions.

<table>
<thead>
<tr>
<th>Core No.</th>
<th>$\delta_x [\mu m]$</th>
<th>$\delta_y [\mu m]$</th>
<th>$\delta [\mu m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.1</td>
<td>5.5</td>
<td>6.9</td>
</tr>
<tr>
<td>2</td>
<td>4.1</td>
<td>4.9</td>
<td>6.4</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>3.7</td>
<td>3.3</td>
<td>5.0</td>
</tr>
<tr>
<td>7</td>
<td>3.7</td>
<td>2.9</td>
<td>4.7</td>
</tr>
</tbody>
</table>

3.2 Mode field diameter measurement of cores

The measured offset loss was used to evaluate the spot sizes of the cores. The coupling loss $\alpha$ is given by

$$\alpha = 10 \log_{10} \left( \frac{2w_1w_2}{w_1^2 + w_2^2} \right) - 4.34 \left( \frac{2\delta^2}{w_1^2 + w_2^2} \right) \text{ [dB]} \quad (2)$$

where $w_1$ and $w_2$ are the spot sizes of connected cores and $\delta$ is the offset. Using this relation, an unknown spot size $w_1$ can be obtained from the measured coupling loss characteristics and the values of $w_2$ and $\delta$.

The measurement setup which was used to evaluate the spot sizes of the LPW is illustrated in Fig. 7. The laser light from a tunable laser emitting light at a 1550 nm wavelength was launched into a small spot single-mode fiber (SMF), with a mode field diameter (MFD) of 4.45 $\mu$m. The small spot SMF was used to minimize the effect of the measurement error of coupling loss on the spot size.

Fig. 7. Setup for measuring spot size (SMF).
First, the output power was measured from the corresponding cores of the LPW and SMFs by connecting the small-spot SMF to the input ends of the LPW. The insertion losses of the seven cores of the fan-out device were measured using the measurement setup shown in Fig. 7. Next, the output power was measured when the center axis of the SMF was shifted by $\delta_x \mu m$ in the $x$ direction from the center of core of the LPW. Here, $x$ is the horizontal direction in Fig. 6(a) which is parallel to the surface of the substrate. Next, the offset value $\delta_x$ was varied in the range from 2 to 7 $\mu m$. In the same way, the output loss was measured in the $y$ direction.

The measured results are shown in Figs. 8(a)-8(g). In these figures, the dots show the measured results, and the solid and dashed curves show the least-squares fits of the measured results to $\alpha = a\delta^2$ in the $x$ and $y$ directions, respectively.

\[
2a^2 \left( \frac{2\delta^2}{w_{SMF}^2 + w_{LPW}^2} \right) = ax^2
\]  

Fig. 8. Measured results of offset loss and least-squares fitting. Figure 8(a)-8(g) correspond to core number #1-#7.

Since these curves correspond to Eq. (2), the following equation is obtained
where \( w_{\text{SMF}} \) is the spot size of the SMF, \( w_{\text{LPW}} \) is the spot size of the LPW and \( \delta \) corresponds to \( x \) on the right-hand side and \( a \) is the fitting parameter. Since \( w_{\text{SMF}} \) and \( a \) are given, \( w_{\text{LPW}} \) can be obtained. Substituting these values of \( w_{\text{SMF}} \) and \( \delta \) given in Table 1 into Eq. (3), theoretical values for the offset loss and spot size mismatch loss of individual cores were obtained and are summarized in Table 2.

The expansion of spot size from the designed value in the \( x \) direction seems to be attributed to the broadening of core width in the \( x \) direction. This broadening of core width in the \( x \) direction seems to be caused by the insufficient UV-curing of resin layer (OMR85) between PVA layer and silicone-based photoresist layer. This resin (OMR85) layer with insufficient UV-curing might be partially patterned in the waveguide patterning process using silicone-based photoresist and the width was broadened after the etching process using RIE. On the other hand, the reduction of spot size from the designed value in the \( y \) direction seems to be attributed to the difference of the refractive index of epoxy resin from the designed one. The refractive index of UV-cured epoxy resin was controlled in the synthesis process of organic material. However, the refractive index may be deviated from the value which was used in the waveguide design. The deviation of refractive index from the value used in the waveguide design was evaluated to be 0.002-0.006.

### Table 2. Spot size, spot size mismatch loss, and offset loss of individual cores.

<table>
<thead>
<tr>
<th>Core No.</th>
<th>( w_x ) [( \mu \text{m} )]</th>
<th>( w_y ) [( \mu \text{m} )]</th>
<th>( \alpha_{\text{Core}} ) [dB]</th>
<th>( \alpha_{\text{Offset}} ) [dB]</th>
</tr>
</thead>
<tbody>
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<td>5.5</td>
<td>5.8</td>
<td>0.09</td>
<td>6.4</td>
</tr>
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<td>0.19</td>
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</tr>
<tr>
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<td>5.8</td>
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<td>0.0</td>
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<td>7.2</td>
<td>5.3</td>
<td>0.33</td>
<td>3.0</td>
</tr>
</tbody>
</table>

#### 3.3 Coupling to 7-core MCF

The insertion losses of the seven cores of the LPW fan-out device were measured using the measurement setup shown in Fig. 9.

![Setup for measuring insertion loss](image)

The MCF was butt-coupled to the fan-out device, and the insertion loss was measured by launching each core of the MCF using the single core fiber. In this measurement, cores #3, #4, and #5 were aligned so that the insertion loss was minimized.
The measured and theoretical losses given in section 3.2 are illustrated in Fig. 10. In this figure, the vertical axis on the left hand side indicates the offset loss and measured insertion loss, while the vertical axis on the right-hand side indicates the spot size mismatch loss. Note that the scales on the left and right sides are different. Since the bending radius is 21mm and the theoretical bending loss was evaluated to be less than $10^{-6}$ dB as discussed section 2.1, the bending loss can be ignored. Therefore the residual loss, which is the difference between the measured insertion loss and the sum of offset loss and spot size mismatch loss, is about 2.2-5.4 dB. Since the absorption loss of PMMA was reported to be 0.8-1.0 dB/cm, this residual loss is mostly attributed to the absorption loss of polymer materials [8]. In addition, bubbles were observed in some waveguides and may cause the extra loss. This absorption loss will be reduced by the proper choice of core and cladding materials.

4. Conclusions

Technique of the fabricating on LPW fan-out device was established. The mode field diameters of individual cores of the LPW were evaluated using a small spot single mode fiber and by offset loss measurement. Then, the simultaneous coupling from the fan-out device to a seven-core MCF was demonstrated.

The centers of cores #3-#5 were accurately adjusted by the precise fabrication of the photomask pattern, and the coupling losses were as low as 0.2 dB. The core centers in the upper and lower layers (#1, #2, #6, and #7) were shifted from those of the MCF owing to the fabrication error of the cladding thickness and the lateral misalignment of the photomask. Precise control of the cladding thickness will be possible by temperature control during the spin coating of UV resin.

Acknowledgment

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Fig. 10. Theoretical offset loss, theoretical spot size mismatch loss, and measured insertion loss.