Serial branching mode multi/demultiplexer for homogeneous multi-core fibers

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Abstract: Mode-evolutional serial branching mode multi/demultiplexer (SBMM) for homogeneous coupled multi-core fiber was demonstrated. This multi/multiplexer has some advantages such as the high fabrication tolerance and small wavelength and polarization dependences owing to the principle of adiabatic mode-evolutional phenomenon. The SBMM was fabricated using polymer materials. The selective four mode excitation with the low crosstalk of less than −10 dB and small wavelength dependence were realized within the CL-band.

Keywords: mode multi/demultiplexer, mode division multiplexing, coupled multi-core fiber

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

References

1 Introduction

Mode division multiplexing (MDM) transmission technique [1] has been proposed to overcome the capacity crunch in the optical fiber communication. The orthogonal eigenmodes in a fiber are utilized as independent transmission channels in the MDM scheme. Thus far, to realize the MDM transmission, several novel optical fibers have been proposed such as the few-mode fiber (FMF) [2, 3, 4] which supports several modes by expanding the core diameter and strongly coupled multicore fiber (MCF) [5, 6] which utilizes coupled modes supported in coupled single mode cores as independent transmission channels. On the other hand, weakly coupled MCFs have been proposed and demonstrated [7, 8] to reduce the difference of group delay between coupled modes. As the strongly coupled MCF [5, 6], we have proposed and demonstrated a novel coupled MCF, named homogeneous coupled MCF, which supports strongly coupled modes by arranging several identical single mode cores close to each other.

In the FMF, since the transverse coordinate axes of the guided modes are rotated along with the propagation, it is difficult to demultiplex the degenerated higher order modes such as LP_{11}^{even} and LP_{11}^{odd} modes at the output end of the FMF. Although the mixed modes including degenerated modes can be resolved by MIMO, the load of the MIMO processing is increased with the increase of the number of modes. In contrast, the transverse coordinate axes of the mode are fixed depending on the core arrangement in the homogeneous coupled MCF, so that the mode demultiplexing is possible without the MIMO processing.

In this study, we propose a serial branching mode multiplexer (SBMM) [9] for the homogeneous coupled MCFs and successfully demonstrate a selective four mode excitation. This multiplexer has some advantages such as the large fabrication tolerance and small wavelength and polarization dependences, since this device is based on the adiabatic mode evolution [10, 11].

2 Design of serial branching mode multi/demultiplexer

Here, let us consider the case that the SBMM is used as a demultiplexer for the convenience of analysis. In a rectangular waveguide, the propagation constant of the guided mode becomes large when the core width is increased, and vice versa. In addition, the propagation constant of the higher order mode is smaller than that of the fundamental mode. In the SBMM, the width of the bus line that is a multimode
waveguide is tapered off along with the propagation direction, and the width of the drop line which is a single mode waveguide is increased toward the output end as shown in Fig. 1. Owing to the double tapered structure, the magnitude relation of the propagation constants between the higher order mode guided in the bus line and the fundamental mode in the drop line is inverted along with the propagation. As a result, the power of the higher order mode in the bus line is adiabatically transformed to the fundamental mode in the drop line. Fig. 1 illustrates the 3rd order mode branching region. In the case of four modes branching, three adiabatic taper branching elements are cascaded and the modes are successively branched from the higher order mode.

![Diagram of mode demultiplexer](image)

**Fig. 1.** The schematic view of 3rd order mode branching region of serial branching mode demultiplexer.

At the beginning, to design the bus line width at each branching region, the relation of the propagation constant of each mode and the waveguide width was calculated using a numerical mode solver (FemSIM by Rsoft) as shown in Fig. 2.

![Graph of propagation constant vs. waveguide width](image)

**Fig. 2.** Waveguide width dependence of the propagation constant of each mode.

Here, the core thickness $t$ and the refractive index contrast $\Delta$ were designed to be 2.75 $\mu$m and 1.0%, respectively, so that the vertical spot size is matched to that of
the homogeneous coupled MCF [6]. The width of the end of bus line was 20 \( \mu m \) to couple the light efficiently to the homogeneous coupled MCF with the core width of 20 \( \mu m \) [6]. The bus line width of the \( n \)-th order mode branching region was determined to be smaller than that of the cutoff waveguide width of the \((n + 1)\)-th order mode. Then, the width of the drop line of \( n \)-th order mode at the starting point of the bus line was determined to satisfy the following condition,

\[
\beta_{n}^{\text{drop}} < \beta_{n+1}^{\text{bus}}
\]  

where, \( \beta_{n}^{\text{drop}} \) and \( \beta_{n+1}^{\text{bus}} \) are the propagation constants of the fundamental mode of the drop line and the \((n - 1)\)-th order mode of the bus line, respectively.

Subsequently, the mode excitation ratio, i.e. the ratio of the power of the mode which is branched to the drop line to that of the mode which remains in the bus line, was calculated to design the optimum structural parameters of SBMM using the beam propagation tool (BeamPROP by Rsoft). The analytical model is shown in Fig. 3. Here, the waveguide widths of both input and output ends of the bus line and drop line (\( W_{B_{\text{max}}}, W_{B_{\text{min}}}, W_{\text{max}}, W_{\text{min}} \)) have been already determined in accordance with the aforementioned condition Eq. (1). The waveguide length of each branching region, \( L \), was 1000 \( \mu m \). The side walls of the bus and drop line waveguides at around the position where these waveguides reach their minimum spacing were designed to be parallel to buffer the fabrication error, and the length of this parallel waveguide region, \( L_{p} \), was designed to be 50 \( \mu m \). The length from the input end to the starting point of the parallel waveguide region, \( L_{1} \), was 250 \( \mu m \). To determine the waveguide structure, the mode excitation ratio was calculated varying other waveguide parameters, i.e. \( W_{\text{mid}}, d_{e}, d_{m}, \) and \( d_{s} \), so that the mode excitation ratio is smaller than \(-25\) dB. As a result, it was found that the drop line width, \( W_{\text{mid}} \), is most influential to the demultiplexing property when the drop line and the bus line reach their minimum spacing. From the calculated results, the waveguide parameters were designed as summarized in Table I. The results of mode propagation analysis using these parameters are shown in Fig. 4. The mode excitation ratios at the wavelength of 1550 nm were \(-25.7\) dB, \(-32.1\) dB, and \(-34.0\) dB for 3rd order, 2nd order, and 1st order mode branching regions, respectively.

Fig. 3. Structural parameters in the beam propagation analysis of SBMM as a demultiplexer
The mode crosstalk for each branching region was calculated using the same analytical model as described above. The calculated results are shown in Fig. 5. It can be seen from Fig. 5 that the crosstalk was less than $-25$ dB for each branching region. The crosstalk from the higher order mode to the lower order mode in the bus line can be negligible since the higher order mode would be cutoff at the lower order mode branching region due to the tapering structure of the bus line.

Lastly, the wavelength dependence of the crosstalk and the fabrication tolerance of the SBMM were evaluated. Here, let us consider the asymmetric coupler type mode multiplexer for TE$_{00}$ and TE$_{10}$ modes for the comparison [12]. In the asymmetric coupler, it is indispensable to strictly determine the waveguide parameters such as the waveguide width $W$, gap between waveguides $g$, and the coupler interaction length $l$, so that the propagation constants of two modes are equal. In contrast, what is needed in the SBMM is that the magnitude of the propagation constants of two modes are adiabatically inverted in the interaction region. Fig. 6 shows the calculated result of the wavelength dependence of the crosstalk against

### Table 1. Structural parameters of designed SBMM *[$\mu$m]*

<table>
<thead>
<tr>
<th></th>
<th>3rd order mode branching region</th>
<th>2nd order mode branching region</th>
<th>1st order mode branching region</th>
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<tbody>
<tr>
<td>$W_{min}$</td>
<td>2.1</td>
<td>2.5</td>
<td>3.2</td>
</tr>
<tr>
<td>$W_{mid}$</td>
<td>2.4</td>
<td>2.9</td>
<td>3.6</td>
</tr>
<tr>
<td>$W_{max}$</td>
<td>2.8</td>
<td>3.7</td>
<td>6.0</td>
</tr>
<tr>
<td>$W_{Bmin}$</td>
<td>16.0</td>
<td>11.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$W_{Bmax}$</td>
<td>20.0</td>
<td>16.0</td>
<td>11.0</td>
</tr>
<tr>
<td>$d_m$</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>$d_e$</td>
<td>12.0</td>
<td>12.0</td>
<td>24.0</td>
</tr>
<tr>
<td>$d_s$</td>
<td>1.9</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>$L$</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>$L_1$</td>
<td>250</td>
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*Fig. 4. Result of beam propagation analysis*
the fabrication error $\delta$. Here, negative values were adopted to $\delta$, since the waveguide width tends to be narrowed from the designed value due to the side etching in the etching process. The waveguide parameters of the first order branching region which are shown in Table I were used for the evolutional mode demultiplexer and those represented in Fig. 6 were used for the asymmetric coupler in the calculation using beam propagation method. It is seen from Fig. 6 that the wavelength dependence of the mode evolutional demultiplexer is much smaller than that of the asymmetric coupler. The circular and triangular dots correspond to the minimum crosstalk values of the mode evolutional demultiplexer and the asymmetric coupler, respectively. The minimum crosstalk value was increased by only 0.1% for the fabrication error of 0.2 $\mu$m in the mode evolutional demultiplexer. On the other hand, that was deteriorated to 18.4% from 0.8% in the asymmetric coupler.

3 Fabrication and loss measurement

In this work, the SBMM was fabricated by the spin-coating of polymer materials and photolithography process [13]. The core was made of PMMA ($n = 1.495$
@λ = 1550 nm, and the cladding was made of UV-cured epoxy resin (supplied by NTT-AT, n = 1.479 @λ = 1550 nm). The fabrication process is summarized as follows. (1) The under cladding layer was formed by the spin-coating of the UV-cured epoxy resin on an Si substrate, followed by the UV-curing and the baking (90 °C). (2) The PMMA solvent which is dissolved by chlorobenzene (C₆H₅Cl) was spin-coated on the substrate as a core layer. (3) Polyvinyl alcohol (PVA) which is hydrophilic resin layer was formed by spin-coating for the water lift-off process. Here, to prevent the dissolution of PVA layer at the photolithography process, the non-hydrophilic resin (OMR-100, by Tokyo Ohka Kogyo Co, Ltd.) was formed on the PVA layer. (4) The waveguide pattern was formed by photolithography using a silicone-based photoresist (FH-SP3CL, by FUJIFILM) and reactive ion etching using oxygen gas. (5) The photo-resist layer was removed by the lift-off process using water. (6) The over cladding layer was formed by the spin-coating and the UV-curing of the UV-cured epoxy resin. The microscopic image of the substrate surface of the fabricated device is shown in Fig. 7. This figure corresponds to the 1st order mode branching part. It can be seen that the waveguides were well formed and the gap between the bus line and the drop line was successfully etched.

Next, the insertion losses of respective ports were measured. The SBMM was used as a multiplexer and the incident light was launched into each input end of the port #0–3 using a polarization maintaining fiber. Here, the input end of the bus line which is single mode waveguide corresponds to port #0, and that of the add line for the n-th order mode branching region correspond to port #n, respectively. The output power was received at the output end of the multimode bus line waveguide using a graded index multimode fiber (core diameter = 50 µm). The wavelength of the incident light was varied ranging from 1530 to 1630 nm with the increment of 1 nm using tunable laser (Anritsu, MG9541A) and output power was received using a spectrum analyzer (Anritsu, MS9710C). Fig. 8 shows the measured results. The insertion loss of the port #0–2 for both TE and TM polarization modes were less than −10 dB within the CL-band, while that of port #3 ranged from −8.2 to −14.4 dB. These losses include the absorption loss of the polymer materials (about −2 dB [13]) and the coupling loss (~1.7 dB) from the polarization maintaining fiber (MFD = 10.5 µm) to the input end of bus line and add line waveguides (MFD = 6.6 µm x 4.8 µm).
It can be seen that the insertion losses of 3rd order mode was much larger than those of other modes. This increase of loss is attributed to the increase of the scattering loss resulting from the narrowing of the add line waveguide of port #3. The insertion loss will be improved by adopting the dielectric materials such as SiO₂.

4 Demonstration of selective mode excitation and evaluation of mode crosstalk

Fig. 9 shows the experimental setup of the selective mode excitation using the fabricated SBMM. In this experiment, the fabricated SBMM was used as a multiplexer. The TE polarized incident light was launched into the input end of each port of the multiplexer using polarization maintaining fiber (PMF) and the near field pattern (NFP) of the light radiated from the output end, i.e. bus line output end, was observed using an InGaAs infra-red camera (HAMAMATSU Photonics A4859-01). The NFPs observed using this setup and the analytical field profiles calculated using finite element method (FemSIM by Rsoft) of modes are shown in Fig. 10. It can be seen from Fig. 10 that the selective mode excitation was successfully demonstrated.

Fig. 8. Wavelength dependence of insertion loss

Fig. 9. Experimental setup of selective mode excitation
The crosstalk characteristics were measured using the measurement setup shown in Fig. 11. The demultiplexer was directly connected to the multiplexer, which was fabricated simultaneously using the same photo-mask pattern. Actually the mode multiplexer used in the measurement of the insertion loss and the NFP observation of selective mode excitation was cut out from this device after the measurement of the crosstalk. The port to port crosstalks (see Appendix) were measured using the PMF. The polarization was controlled to TE or TM mode using a polarization locker (Thorlab, PL100P). The evaluated crosstalks of individual modes are shown in Fig. 12. Most of the crosstalks were less than $-10$ dB, except for the crosstalks form port #3 to port #2. This combination is that between neighboring modes, and the deterioration of crosstalk seems to be attributed to some kind of fabrication error resulting from the narrowing of waveguide width during the etching process. In addition, since the differences of the propagation constants between neighboring modes are small, the mode conversion between neighboring modes easily occurs. Thus, it seems that the modes were converted to the neighboring order modes due to the scattering caused by the roughness of the side wall of the waveguide. The oscillation of the measured crosstalk values were attributed to the interference between the guided mode and the cladding mode guided in-between the top surface of cladding and the boundary between the cladding and the Si substrate.
5 Conclusions

The selective mode excitation of four modes was successfully demonstrated using an SBMM fabricated using polymer materials. The insertion loss would be improved by adopting dielectric materials as the waveguide materials. In this work, we focused on the demonstration of the function of the proposed multiplexer, i.e. selective four mode excitation, so that the waveguide materials are not suitably adopted. Thus, the characteristics of the multiplexer such as the large loss and the crosstalk deterioration would be improved by adopting proper materials such as silica based materials used in PLC devices.

The crosstalk from higher order modes to the fundamental mode is negligible since the higher order modes are cutoff due to the tapering structure.

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Appendix

To describe the measurement results, the analytical expression of crosstalk of the mode evolutional multimode/multiplexer needs to be derived. First, the physical model of the mode evolutional multiplexer is illustrated in Fig. A1. Here, the crosstalk
between two modes (two ports) is considered for the simplicity of analysis. The transfer matrix of this model can be expressed by the following equation,

$$
\begin{bmatrix}
E_4 \\
E_5 \\
E_6
\end{bmatrix}
= 
\begin{bmatrix}
\sigma_{41} & \sigma_{42} & 0 \\
\chi_{51} & 1 - \sigma_{42} - \chi_{62} & 0 \\
1 - \sigma_{41} - \chi_{51} & \chi_{62} & 0
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3
\end{bmatrix}
= [M]
\begin{bmatrix}
E_1 \\
E_2 \\
E_3
\end{bmatrix}
$$

(1)

where $E$, $E'$, $\sigma$, and $\chi$ are the input electromagnetic field, the output electromagnetic field, the radiation loss coefficient, and the crosstalk coefficient, respectively. Here it is assumed that $\sigma \ll 1$ and $\chi \ll 1$. It should be noted that there are radiation ports in the mode evolutional multi/demultiplexer in principle. Third column element of the matrix should be zero since the incident radiation mode, $E_3$, is not incident on the multiplexer. Next, the physical model of the demultiplexer is shown in Fig. A2 and the transfer matrix of the demultiplexer can be written as follows

$$
\begin{bmatrix}
E'_1 \\
E'_2 \\
E'_3
\end{bmatrix}
= 
\begin{bmatrix}
0 & \chi_{15}' & 1 - \sigma_{36}' - \chi_{26}' \\
0 & 1 - \sigma_{35}' - \chi_{15}' & \chi_{26}' \\
0 & \sigma_{35}' & \sigma_{36}'
\end{bmatrix}
\begin{bmatrix}
E'_4 \\
E'_5 \\
E'_6
\end{bmatrix}
= [N]
\begin{bmatrix}
E'_4 \\
E'_5 \\
E'_6
\end{bmatrix}
$$

(2)

In the demultiplexer, there is no input into the drop line so that the 1st column elements of the demultiplexing matrix should be zero. In the case that the multiplexer and the demultiplexer are cascaded, the transfer matrix of this system can be expressed by the following equation,

$$
\begin{bmatrix}
E'_1 \\
E'_2 \\
E'_3
\end{bmatrix}
= [N][M]
\begin{bmatrix}
E_1 \\
E_2 \\
E_3
\end{bmatrix}
$$

(3)

Then, we obtain

$$
\begin{bmatrix}
E'_1 \\
E'_2 \\
E'_3
\end{bmatrix}
= 
\begin{bmatrix}
n_{13}m_{31} & n_{12}m_{22} + n_{13}m_{32} & 0 \\
n_{22}m_{21} + n_{23}m_{31} & n_{22}m_{22} & 0 \\
n_{33}m_{31} & n_{32}m_{22} & 0
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3
\end{bmatrix}
$$

(4)
where the matrix elements $m_{ij}$ and $n_{ij}$ are defined in eqs. (a1) and (a2). Here, eq. (a4) can be solved for $E_1'$,

$$E_1' = n_{13}m_{31}E_1 + (n_{12}m_{22} + n_{13}m_{32})E_2. \quad (a5)$$

The second term of the right-hand side of eq. (a5) is the crosstalk component. Therefore, the crosstalk of this system can be written by,

$$XT_{12}^2 = |\chi_{15}'(1 - \sigma_{42} - \chi_{62}) + \chi_{62}'(1 - \sigma_{36}' - \chi_{26}')|^2$$

$$\approx |\chi_{15}' + \chi_{62}'|^2 \approx (\chi_{15}' + \chi_{62}')^2 \quad (a6)$$

where, $XT_{ij}$ is the crosstalk from the input of the multiplexer ($E_j$) to the output of the demultiplexer ($E_i'$). Here, let us consider the scattering matrix of the system of the multi/demultiplexer shown in Fig. A3.

$$\begin{bmatrix} E_1' \\ E_2' \\ E_3' \\ E_4 \\ E_5 \\ E_6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & N \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ M & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4' \\ E_5' \\ E_6' \end{bmatrix}. \quad (a7)$$

Since the $S$ matrix should be Unitary for the loss less system, the following equation should hold,

$$\begin{bmatrix} 0 & M^T \\ N^T & 0 \end{bmatrix} = \begin{bmatrix} 0 & N \\ M & 0 \end{bmatrix} = \begin{bmatrix} M^TM & 0 \\ N^TN & 0 \end{bmatrix} = I \quad (a8)$$

From this condition, the following equation is derived.

$$|\chi_{15}'| = |\chi_{62}| \quad (a9)$$

It can be seen by solving the eq. (a8) that $\chi_{15}'$ is equal to $\chi_{62}$, so that,

$$XT_{12}^2 \approx 2\chi_{62}^2. \quad (a10)$$

Equation (a10) implies that the crosstalk from the bus line input $E_2$ to the drop line output $E_1'$ of the cascaded multi/demultiplexer is twice as the crosstalk from bus line input $E_2$ to the higher order mode output $E_6$ of the multiplexer. Therefore, the crosstalk of the multiplexer can be evaluated by measuring the port to port crosstalk of the cascaded multi/demultiplexer.