Wavefront-matching-method-designed six-mode-exchanger based on grating-like waveguide on silica-PLC platform

Takeshi Fujisawa[1], Taiji Sakamoto[2], Masashi Miyata[3], Takashi Matsui[2], Toshikazu Hashimoto[3], Ryoichi Kasahara[3], Kazuhide Nakajima[2], and Kunimasa Saitoh[1]

[1] Graduate School of Information Science and Technology, Hokkaido University North 14, West 9, Kita-ku, Sapporo 060-0814, Japan
[2] NTT Access Network Service Systems Laboratories, NTT Corporation, Tsukuba, Ibaraki, 305-0805 Japan
[3] NTT Device Technology Laboratories, NTT Corporation, Atsugi, Kanagawa, 243-0196 Japan,
Email: fujisawa@ist.hokudai.ac.jp

Abstract: A first six-mode exchanger based on one sidewall grating-like waveguide is successfully designed with the help of strong optimization algorithm. Fabricated device compensates for mode-dependent-loss caused by fiber-waveguide junctions, showing the proof-of-concept operation. © 2020 The Author(s)

1. Introduction

A mode-division-multiplexing (MDM) technique has attracted a lot of attentions to increase the capacity of optical fiber transmission system. In MDM system, a MIMO technique is usually used to undo the mode mixing occurred in few-mode fibre (FMF) at the receiver. In MIMO processing, so-called differential mode delay (DMD) and mode-dependent loss (MDL) deteriorates the receiver performance. Too large DMD and MDL make it difficult to recover the signal. To overcome these problems, a mode exchanging or mixing technique at a relay point between two FMFs is useful [1]. In a mode-exchanger (mode-EX) or mode mixer, various mode converting operations are necessary and a long-period grating (LPG) waveguide is one of the promising candidates for them. By properly designing the grating pitch, it is possible to exchange arbitrary two modes. In [2], a six-mode mixer based on two cascaded long-period fiber grating (LPFG) was proposed and no MDL degradation originating from the device was demonstrated. However, to mixing six-modes, two kinds of LPFGs are necessary and the total size of two LPFGs was over 60 mm and the size reduction is preferable. For that purpose, an integrated type mode-EX is useful due to its small size and mass productivity. In [3,4], LPG based mode converters were proposed for polymer waveguide platforms and successful mode conversion for three modes are demonstrated. However, to convert LP_{11a} and LP_{11b} modes separately, the sidewall and the surface gratings have to be formed, leading to difficult fabrication process. Recently, a three mode-EX based on Si-wire LPG-like waveguide was demonstrated [5,6]. Although the size of the mode-EX is ultrasmall (~50 μm in length), the modes are not similar to fiber LP modes.

In this paper, a six-mode-EX designed by wavefront matching (WFM) method [7] based on only one sidewall grating-like waveguide with short and adiabatic taper waveguides on silica-PLC platform is proposed for MDM transmission. The use of optimization algorithm makes it possible to generate complex waveguide geometry, which cannot be reached by human design. Quasi-six-mode exchanging operation is possible without surface grating and the cascade of two gratings is not necessary as in previous studies [2-4]. Furthermore, the effect of fiber-waveguide junctions on MDL degradation is investigated, and the importance of low-loss and low-MDL connection between fiber and waveguide is pointed out. Fabricated device partly compensates for MDL caused by the fiber-waveguide junctions, showing the proof-of-concept operation. This is the first demonstration of MDL reduction by the mode mixing device based on PLC.

2. Device structure and results

Figure 1 shows the schematic of the mode-EX waveguide considered here. The waveguide is made of silica and the relative index difference and the thickness are 1.1% and 10 μm. The proposed device consists of three parts, namely, input short taper waveguide (Taper1), grating-like waveguide designed by WFM method (WFM grating), and output adiabatic taper waveguide (Taper2). Figure 2 shows the intended mode conversion process in the proposed mode-EX. The device input is six LP modes in FMF. In Taper1, LP_{21b} and LP_{02} modes are mixed and converted to E_{31} and E_{13} modes by using the short taper [8]. In the square waveguide, there exist LP_{21b}- and LP_{02}-like modes as a hybrid mode of E_{31} and E_{13} modes. Therefore, LP_{21b} and LP_{02} modes coming from FMF are converted to the mixture of E_{31} and E_{13} modes in the short taper due to the abrupt change in the waveguide width. The length of short taper is 100 μm. The input waveguide width of Taper1 is 10 μm and it is tapered up to 11 μm.

In the WFM grating, only one-side of the waveguide is corrugated to convert modes with different parity. The intended mode conversion is shown in Fig. 2. Since the function is very complex, it is difficult to obtain the waveguide geometry by manual design. Here, we used a WFM method for multimode waveguides [7]. The WFM method is a deterministic optimization algorithm for PLC based on physics and have been used for reducing the loss and wavelength dependence of PLC devices [5,6,7]. The optimization is carried out for the wavelength of λ = 1550 nm. The initial structure is simple straight waveguide with the length of 10 mm and the width of 11 μm. One side of the waveguide is corrugated based on the WFM algorithm and the optimized geometry is shown in Fig. 1 and complex grating-like geometry is obtained. Finally, in Taper 2, E_{13} and E_{31} modes coming from the grating are converted to LP_{21b}- and LP_{02}-like modes without mode mixing by using adiabatic mode conversion, as in the row of "Taper2" in Fig. 2. The adiabatic taper employs two-stage tapering [8] and the total length is 6 mm. The waveguide width is tapered down from 11 to 10 μm. The total length of the device is 16.1 mm.

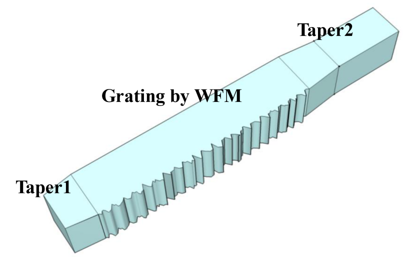


Fig. 1 The schematic of six-mode-EX designed by WFM method.

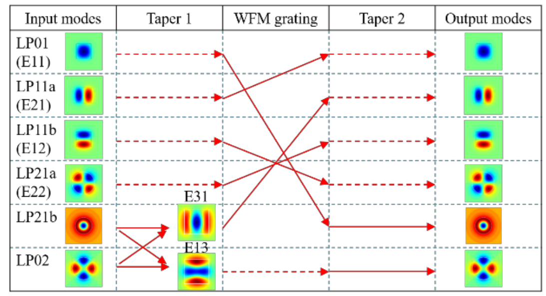


Fig. 2 Designed mode conversion process in the proposed device.

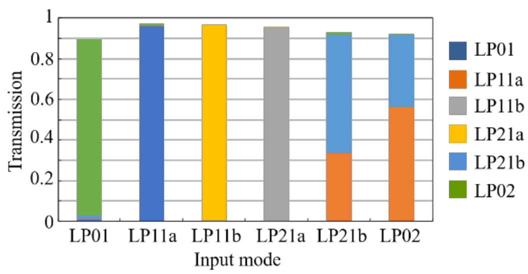


Fig. 3 Calculated output modal powers of proposed six-mode-EX for different input modes.

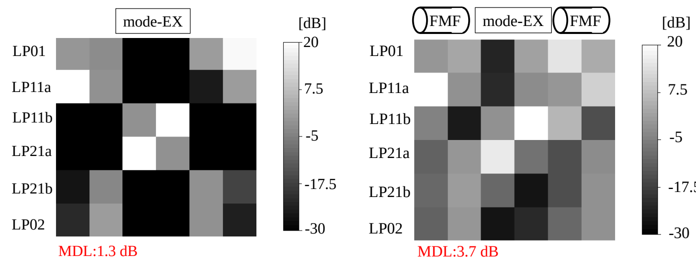


Fig. 4 Calculated 6×6 coupling matrices of (left) proposed device only and (right) the proposed device with two fiber-waveguide junctions.

Figure 3 shows the calculated output modal powers of the WFM-designed six-mode-EX. The intended mode exchanging operation can be seen. For LP_{01}, LP_{11a}, LP_{11b}, and LP_{21a} inputs, almost perfect mode conversions with only one grating-like structure are possible. For LP_{21b}, and LP_{02} mode inputs, the output is the mixture of LP_{11a}, and LP_{21b} modes as designed. The maximum insertion loss is about -0.5 dB for LP_{01} input. Left panel of Fig. 4 shows the calculated 6×6 coupling matrix of the device. The row and column of the matrix correspond to input and output modes. The mode order is the same for row and column. In each row, the power of the input mode is set to 0 dB. The MDL, which is calculated from the maximum and minimum singular values of the transmission matrix [9], is only 1.3 dB, showing the usefulness of the device as mode-EX at the relay point. In the experimental situation, however, there are junctions between fiber and waveguide and the effect has to be taken into account. As shown later, we use six-mode FMF reported in [10] for the input and output fibers for PLC in the experiment. The calculated coupling losses at the junction of the FMF and PLC are -0.37, -1.25, -1.25, -2.09, -2.60, and -2.62 dB for LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02} mode inputs. Calculated MDL of two junctions is 4.7 dB and is much larger than that of isolated six-mode-EX. Right panel of Fig. 4 shows the calculated 6×6 coupling matrix of the device, with taking into account the effect of two junctions. The matrix shows a mode mixing operation, rather than mode exchanging. Calculated MDL is 3.7 dB and this value indicates that the proposed WFM grating partly compensates for the MDL caused by two junctions (4.7 dB) by 1 dB.

Although a perfectly cyclic conversion of six modes is not achieved in this configuration, multiple mode-EX operations at the multiple relay points equalize the MDL and DMD in FMF, leading to reduced MDL in total, even if the device has finite MDL. To show the MDL reduction, we perform simple FMF transmission simulation. For the FMF, we consider 6-mode FMF and the losses of LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02} modes are assumed to be 0.15, 0.18, 0.18, 0.2, 0.2, and 0.23 dB/km. Here, we assume the loss of LP_{02} mode is maximum and the value is taken from [11]. Also, we assume that the loss of LP_{01} mode is similar to that of SMF. The losses of other modes are placed between them. The top panel of Fig. 5 shows the schematic of the simulation. We consider 150-km fiber and dividing it into $N + 1$ sections when N mode-EXs are placed between two FMFs. The transmission matrices of each section are multiplied, and the MDL is calculated from the transmission matrix of the whole system. The bottom panel of Fig. 5 shows the MDL of the system as a function of the number of exchanging points. Without the exchanging operation, the MDL of the system is 12 dB, corresponding to the loss difference of LP_{01} and LP_{02} modes after 150-km transmission. By increasing the number of exchanging operations, the MDL is decreased to 3.6 dB for

N = 3 if the effect of junctions is neglected. If the effect of the junction is considered, the MDL is 7.1 dB for N = 3 and the device is still effective for reducing the MDL of the system. These results indicate that MDL reduction is possible without perfectly cyclic conversion by proposed mode-EX based on simple grating-like waveguide with only side-wall corrugations.

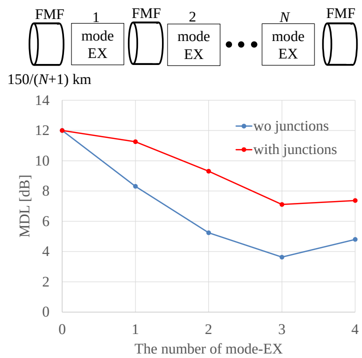


Fig. 5 (Top) A schematic of FMF transmission simulation with N mode-EX points and (bottom) MDL as a fucntin of N.

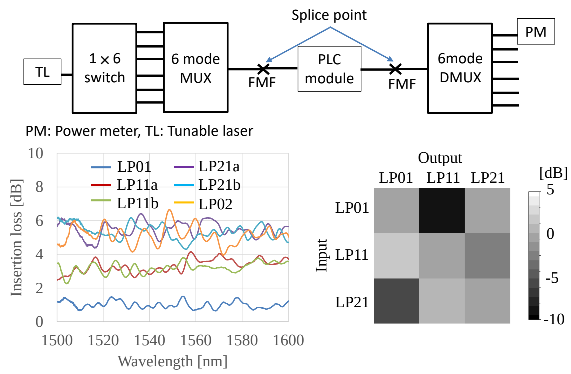
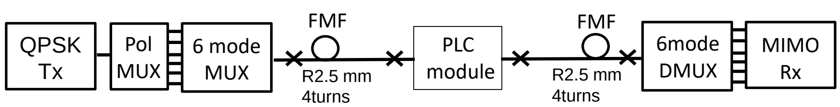


Fig. 6 (Top) Measurement setup and (Bottom left) the insertion loss spectra of straight waveguide module. (Bottom right) Measured mode coupling matrix of WFM grating module.



Measured MDL values

Straight waveguide module: 2.7 dB

WFM grating module: 1.9 dB

Fig. 7 MDL measurement setup of straight waveguide or WFM grating module and their relative MDL values.

We fabricated a reference straight waveguide and the designed device. Six-mode FMFs [10] are pigtailed to the PLC chip. We call them as "straight waveguide module" and "WFM grating module", hereafter. Lower left panel of Fig. 6 shows the insertion loss spectra of the straight waveguide module together with the experimental setup (top). Commercially available six-mode MUX from CaiLab is used to launch one of the six modes. The received power without PLC module is used as the reference power and subtracted. Therefore, the loss spectra shown in Fig. 6 correspond to sum of the coupling losses at two junctions. The loss differences are about 2 dB for LP_{01}-LP_{11} and 4.9 dB for LP_{01}-LP_{21} mode groups at 1550 nm. These values coincide with the calculated coupling loss. Here, LP_{11} mode group is LP_{11a} and LP_{11b} modes, and LP_{21} mode group is LP_{21a}, LP_{21b}, and LP_{02} modes. By using the same setup, we measured the coupling matrix of the "mode-group" because in our setup, we cannot launch and detect fiber degenerate modes separately (they are mixed in pigtailed FMFs). Lower right panel of Fig. 6 shows the measured 3×3 mode-group coupling matrices of the WFM grating module. In each row, the sum of the received mode powers of the input mode group is set to 0 dB. LP_{01} to LP_{21}, LP_{11} to LP_{01}, and LP_{21} to LP_{11} conversions (mode-group-EX operation) can be seen. Finally, we measured the approximate MDL of the device. Figure 7 shows the experimental setup. First, we measure the MDL without PLC modules as a reference. Polarization multiplexed QPSK signal is generated and 6 modes are multiplexed in the mode MUX. Strongly bent FMFs (R2.5 mm with 4turns) are spliced and the signals are fed into MIMO receiver via mode DMUX. By using offline processing, the MDL of the reference is obtained. Next, we insert PLC modules between two FMFs as shown in Fig. 7 and measured the relative MDL values to the reference. The measured relative MDL values are 2.7 and 1.9 dB for straight waveguide and WFM grating modules, respectively. Therefore, the MDL of the WFM grating module is about 1 dB smaller than that of straight waveguide module and the difference coincides with the calculated values.

3. Conclusion

We proposed a six-mode-EX with one sidewall grating-like waveguide designed by WFM method. The complex mode exchanging structure was successfully designed with the help of strong optimization algorithm. Fabricated device exhibits MDL compensating characteristics, showing the proof-of-concept operation.

4. Reference

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