Three-mode multi/demultiplexing experiment using PLC mode multiplexer and its application to 2+1 mode bi-directional optical communication

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Abstract: We demonstrate an optical three-mode multi/demultiplexing experiment without MIMO signal processing using two PLC mode multiplexers and a 10 m rectangular core fiber. 3×10 Gbps NRZ signals were transmitted in the fiber with a 1 dB OSNR penalty.

Keywords: PLC, mode multiplexers, flat-core fiber

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

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1 Introduction

With the development of the ability to undertake digital signal processing

on a massive scale, mode-division multiplexing (MDM) has been attracting increasing attention from the research community as an alternative way of keeping up with the capacity demands imposed on a single fiber [1]. Single-mode coherent receivers use 2x2 multiple input multiple output (MIMO) technology to separate polarization modes. In N-mode MDM transmission systems, the receivers need (2N)x(2N) MIMO processing to achieve mode demultiplexing, and the computational complexity increases quadratically with the number of modes. If the mode coupling is small enough and the modes are optically demultiplexed, a combination of 2x2 MIMO and 4x4 MIMO is needed for any value of N [2]. To eliminate the need for MIMO processing in mode demultiplexing, a sophisticated two-mode multiplexing transmission experiment was reported that incorporated fiber mode couplers [3].

Silica-based planar lightwave circuits (PLCs) can instead of the fiber couplers to compose or decompose propagation modes [4]. PLCs offer reproducibility, high stability and compatibility with silica single-mode optical fibers. However, PLCs are not compatible with the high order LP modes of optical fibers, which have a two-dimensional distribution. Therefore, we utilize optical fiber with a rectangular core to realize better mode matching with PLC mode multiplexers than provided by circular core fibers and describe a three-mode multi/demultiplexing experiment using PLC mode multiplexers. In the experiment, one of the three modes propagates in the opposite direction to the other two modes to reduce the mode crosstalk penalty.

2 Flat core fiber

In recent mode multiplexed communication, newly designed few-mode fibers (FMFs) were used, which limits the number of propagation modes. The difference between the propagation constants of each mode becomes large and so the mode crosstalk between the modes becomes small by limiting the number of propagation modes to just a few. There are mode crosstalk sources other than those in the FMFs. Mode crosstalk occurs at the interface between a fiber and a mode multiplexer when their mode fields differ. A misalignment between them causes severe mode crosstalk. Here we use rectangular core fiber to reduce the mode field mismatch between fibers and PLC mode multiplexers.

We use "top-hat" fiber [5] with a specially ordered core geometry as a transmission line. The fiber was fabricated from a fiber perform with a rectangular core profile. The core was not deformed during the drawing process and there is little residual stress on the core [6]. The fiber birefringence is dominated by the geometrical profile of the fiber and it can be evaluated by numerical simulation. Figure 1 shows the calculated differential group delay (DGD) values of the two polarization modes of the E_{00}, E_{10}, and E_{20} modes of the rectangular core fiber against core width. Two core heights of 8 and $10\,\mu$m are indicated by broken and solid lines, respectively. The DGDs of the E_{00}, E_{10}, and E_{20} modes are indicated by blue, red, and green lines, respectively. We selected a core height and width of 10 and $20\,\mu$m, respectively, to
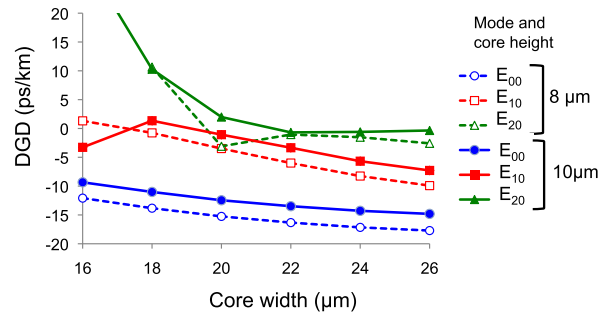
Fig. 1. Calculated DGD value of three fiber modes of the rectangular core fiber against core width.
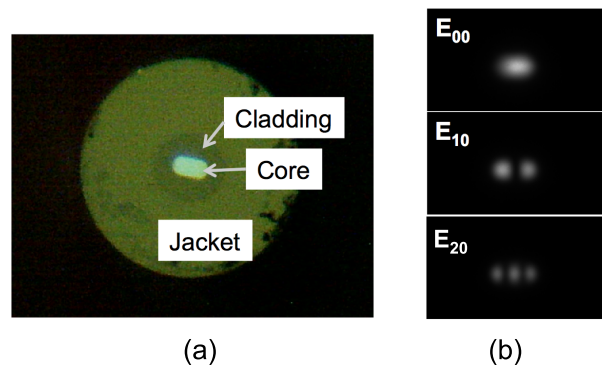

(a) (b)

Fig. 2. (a) Cross-section and (b) near field patterns of the flat-core fiber.

minimize the DGD value of the E_{00} mode and keep the DGDs of the other modes at a small value. The estimated worst DGD of the E_{00} mode was 13 ps/km when the two polarization modes of the E_{00} mode are not coupled. The 10 Gbaud signal can propagates upto a few kilometers with this DGD value. This fiber can be used for local service or interconnections within a data center.

Figure 2 shows the fiber cross-section and near field patterns of the flat-core fiber at a wavelength of 1.55 μm. The fiber has a pure silica core with a depressed cladding that has a relative index of about 1%. The corners of the core were intentionally rounded to maintain the same cladding thickness. The first three propagation modes of the fiber are shown in the figure. The propagation loss at a wavelength of 1.55 μm of the E_{00}, E_{10}, and E_{20} modes measured by the cut-back method were 9.06, 21.09, and 25.39 dB/km respectively. The mode crosstalk between the modes was neglected for simplicity. The loss of each mode can be reduced by increasing the cladding thickness.

3   Mode multi/demultiplexer using PLCs

Figure 3 shows schematics of the PLC mode multi/demultiplexer and the near field patterns of the modes at its multimode port. The PLC has three single mode ports, single mode waveguides corresponding to the E_{00}, E_{10} and E_{20} modes, and a multimode port, which is a multimode waveguide to support those modes. Mode multi/demultiplexing using a PLC is based on
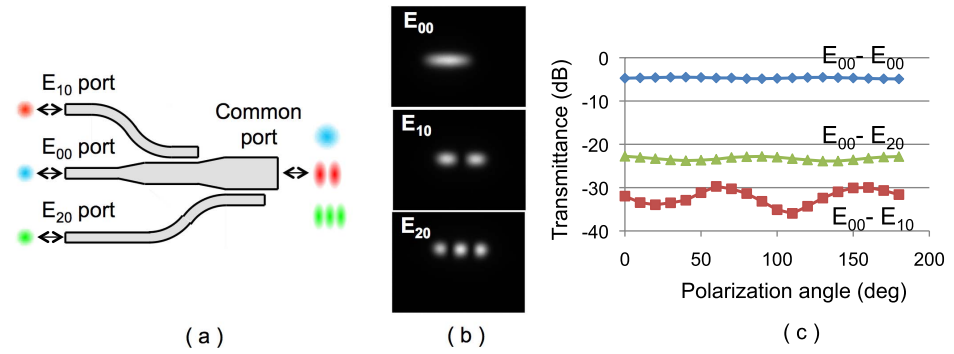
Fig. 3. (a) Schematics of the mode multi/demultiplexer, (b) near field patterns of the modes, (c) Polarization satability of demultiplexing on E_{00} port.

Table I. Overall coupling coefficient through two PLC mode couplers.

Input port	Output port		
	E_{00}	E_{10}	E_{20}
E_{00}	-4.28 (dB)	-29.88 (dB)	-22.93 (dB)
E_{10}	-31.68 (dB)	-5.1 (dB)	-28.28 (dB)
E_{20}	-21.98 (dB)	-30.98 (dB)	-6.28 (dB)

the index matching of a single mode waveguide and one of the modes of the multimode waveguide [4]. A single mode signal launched into a single mode port corresponding to E_{10} (or E_{20}) mode couples with the E_{10} (or E_{20}) mode of the multimode waveguide. The E_{00}, E_{10} and E_{20} modes are multi/demultiplexed to a multimode waveguide simultaneously.

The polarization dependence and mode crosstalk of the PLC multiplexers were evaluated by using two PLCs with facing multimode ports. Figure 3 (c) shows the polarization dependence of the multiplexer. A polarized cw light at a wavelength of $1.55\,\mu$m was launched into the E_{00} port of one PLC and the transmitted power was measured at each port of the other PLC. The through port (E_{00} to E_{00}) exhibited a small polarization dependence of less than $0.4\,$dB. While the crosstalk showed larger polarization dependences of 1 and $6\,$dB for E_{00}-E_{20} and E_{00}-E_{10}, respectively.

Table I summarizes the transmittance and crosstalk between three ports. The overall coupling loss includes that at the interface between multimode ports and the two interfaces between the single-mode ports of the PLCs and single-mode fibers, and the conversion efficiency of the PLC mode multiplexers. When the input power was the same for all modes, the E_{20} output port was a mixture of the values of $-22.93\,$dB for the E_{00} input port, $-28.28\,$dB for the E_{10} input port, and $-6.28\,$dB for the E_{20} input port. Thus, the mode crosstalk at the port was $-16.65\,$dB. The mode crosstalk values for the E_{10} to E_{00} mode and the E_{10} to E_{20} mode were better than -25 and $-23\,$dB, respectively. When the two PLCs have the same mode profile at the multimode port, the mode crosstalk can be further reduced by precise alignment. Table II shows the transmittance and crosstalk with a $2\,$m rectangular core

Table II. Overall coupling coefficient through two PLC mode couplers with 2 m rectangular core fiber.

Input port	Output port		
	E_{00}	E_{10}	E_{20}
E_{00}	−5.6 (dB)	−24.3 (dB)	−15.5 (dB)
E_{10}	−23.5 (dB)	−7.5 (dB)	−19.5 (dB)
E_{20}	−15.8 (dB)	−22.8 (dB)	−10.5 (dB)

fiber placed between multimode ports. In this setting, the two multimode interfaces cause the mode crosstalk to deteriorate. Furthermore, the mode field mismatch induces mode crosstalk between the E_{00} and E_{20} modes, which, in this case, was as much as −5 dB.

4 Experiments

Figure 4 shows schematics of the experimental setup. Three lines of 10 Gb/s NRZ signals at a wavelength of 1548 nm were generated by dividing a single signal source, and different delays were applied to decorrelate the signals. The power launched into the fiber was −6 dBm/mode. The E_{00} and E_{20} modes propagate in opposite directions in the fiber to reduce the mode crosstalk penalty. The E_{10} mode can propagate in either direction. Here we propagate the mode in the same direction as the E_{00} mode and we align the PLC and the fiber by minimizing the mode crosstalk between the E_{00} and E_{10} modes.

Figure 5 shows eye diagrams of back-to-back (B2B), and E_{00}, E_{10}, E_{20} modes after 10 m propagation. The E_{00} mode and the E_{20} mode were propagated in opposite directions. The E_{10} mode induces no mode crosstalk with
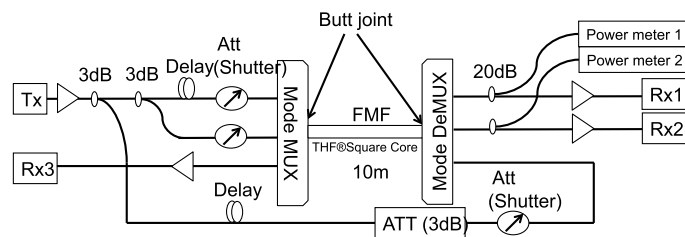

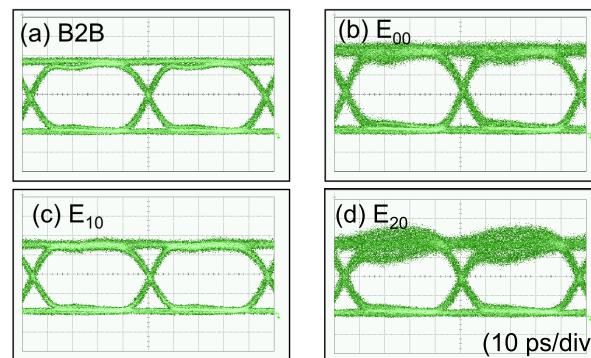**Fig. 4.** Schematics of experimental setup.

Fig. 5. Eye diagrams of back-to-back, and E_{00}, E_{10}, E_{20} modes after 10 m propagation.
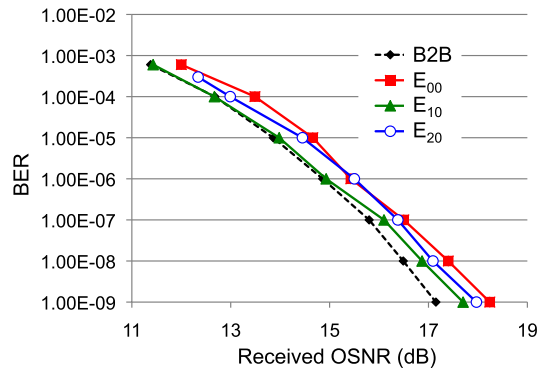
Fig. 6. BER vs. received OSNR.

other two modes at the interface between the fiber and the PLC when they are perfectly aligned. In contrast, the E_{00} and E_{20} modes suffer mode crosstalk from each other at the interface even when the alignment is perfect because the mode profiles of the PLC and the fiber are different. The two modes propagate in opposite directions but the reflection at the interface may cause the mode crosstalk to degrade the eye diagram.

Figure 6 shows BER as a function of received OSNR. The E_{10} mode exhibits a smaller OSNR penalty than the other two modes. The broken black line shows the B2B BER performance and the blue, green, and red lines show the BER performance of the E_{00}, E_{10}, and E_{20} modes, respectively. 1 dB OSNR penalties were observed for the E_{00} and E_{20} modes while the E_{10} mode exhibits a smaller penalty than the other two modes reflecting the eye-opening deterioration shown in Fig. 5.

Only a 10 m fiber was used in this experiment because we cannot achieve a mode crosstalk of better than 10 dB in a 100 m fiber. The main reason for the crosstalk was that the fiber we used supports more than 7 modes because of its high relative index. In addition, a large mode dependent loss resulting from the thin cladding degrades the mode crosstalk of the high loss modes. We think propagation distances more than 1 km will be possible by using properly designed FMFs with PLC mode multiplexers.

5 Conclusion

We described a three-mode multi/demultiplexing experiment without MIMO signal processing using a 10 m rectangular core fiber and two PLC mode multiplexers. An OSNR penalty of 1 dB was caused by the mode crosstalk at the two interfaces between the fiber and the PLCs.

Acknowledgments