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Published in:

Proceedings of the European Conference on Optical Communication (ECOC) 2011

Publication date:

2011

Document Version

Publisher's PDF, also known as Version of record

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Citation (APA):

Xu, J., & Peucheret, C. (2011). Two-Mode Multiplexing at 2×10.7 Gbps over 7-Cell Hollow- Core Photonic Band Gap Fiber. In *Proceedings of the European Conference on Optical Communication (ECOC) 2011* (pp. We.10.P1). Optical Society of America. <http://www.ecoc2011.org/>

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Two-Mode Multiplexing at 2×10.7 Gbps over 7-Cell Hollow-Core Photonic Band Gap Fiber

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Abstract: We demonstrate two-mode multiplexing at 2×10.7 Gbps over 7-cell hollow-core photonic band gap fiber. BER performances below FEC threshold limit (3.3×10^{-3}) are shown for both data channels.

OCIS codes: (060.2270) Fiber characterization; (060.2330) Fiber optics communications

1. Introduction

It has been generally realized that current technologies are fast approaching the capacity limit of single mode fibers (SMFs). Mode division multiplexing (MDM) has been recognized as a promising candidate for overcoming the fast approaching capacity limit by utilizing the spatial dimension of cylindrical optical waveguides. MDM has been realized through graded-index multi-mode fibers (GI-MMFs) [1, 2] and few-mode solid-core fibers [3-6], targeting short-range and long-haul applications, respectively. However, one of the fundamental reasons that limit the information capacity of solid core fibers is fiber nonlinearities. Hollow-core photonic band gap fibers (HC-PBGFs), on the other hand, may greatly relieve such impact by supporting light transmission in air for up to 90% or more [7].

So far MDM using HC-PBGFs has never been demonstrated. In this work, we demonstrate a preliminary two-mode multiplexing system over a 7-cell HC-PBGF. LP_{11} modes are excited by offset launching light at the input of the HC-PBGF. Different LP_{11} can be selectively excited by changing the polarization of the input light. Mode demultiplexing is realized by carefully selecting the detection position on the output mode profile. Two 10.7 Gbps non-return to zero (NRZ) signals are transmitted by different LP_{11} modes, namely LP_{11a} and LP_{11b} . Up to 3 dB power penalty are observed for transmitting only one LP_{11} mode at a bit error ratio (BER) of 10^{-9} . BER performance of transmitting two LP_{11} modes simultaneously stays below the FEC threshold (3.3×10^{-3}) for concatenated codes assuming 7%-overhead coding. The reasons for the large sensitivity degradations are believed to be the restricted mode de-multiplexing conditions, which can be improved greatly by optimising the detection method.

2. Two-mode multiplexing and demultiplexing

Fig. 1(a) shows the schematic view of the two-mode multiplexing and demultiplexing method. The input signal is launched into the HC-PBGF via a piece of tapered SMF. The minimum spot size at the output of the tapered SMF is $2.5 \mu\text{m}$. The core diameter of the 7-cell HC-PBGF is $10.6 \pm 0.3 \mu\text{m}$ [7]. Five modes (LP_{01} and four LP_{11} modes) are well supported by the HC-PBGF. The mode profile at the output of the HC-PBGF is firstly imaged by a 40 times microscope objective and then focused by a 10 times microscope objective into another tapered SMF. Therefore, the mode profile seen by the second tapered SMF is roughly 4 times larger than that at the output of the HC-PBGF. In the light path between the two microscope objectives, 50% of the light is reflected by a beam splitter into an infrared camera. The fundamental mode, LP_{01} , can be excited by aligning the tip of the tapered SMF to the center of the HC-PBGF, as shown in Fig. 1(b) representing the mode profile captured by the camera. LP_{11} modes can be excited, on the other hand, by offsetting the first tapered SMF $6 \mu\text{m}$ away from the center of the HC-PBGF. By changing the polarization of the input light to the HC-PBGF, two different modes, namely LP_{11a} or LP_{11b} , mode can be excited, as shown by Fig. 1(c) and (d).

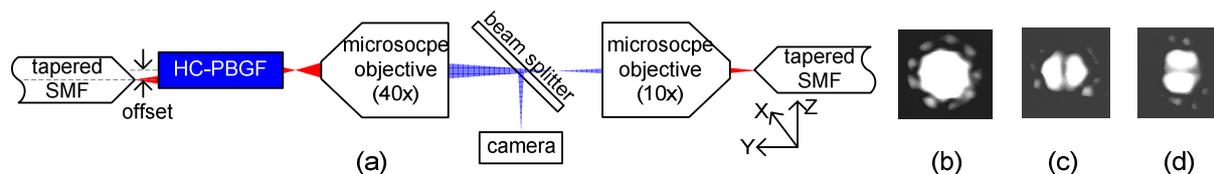


Fig. 1 (a) Schematic view of the two-mode multiplexing and demultiplexing method; (b)~(d) Mode profiles captured by the camera, corresponding to LP_{01} , LP_{11a} , and LP_{11b} respectively.

Mode de-multiplexing is realized by carefully selecting the detection point on the received mode profiles using the second tapered SMF. Fig. 2 shows the contour plots of power collected by the second tapered SMF at different X and Z locations. Fig. 2(a) and (b) are measured when LP_{11a} or LP_{11b} is excited, respectively. Two optimum detection points can be found, as marked by the green and red spot, for receiving LP_{11a} and LP_{11b} mode, respectively. The contrast ratio for detecting LP_{11a} is 11.2 dB and 11.3 dB for LP_{11b}. However, the contrast ratio drops rapidly away from the optimum positions. For example, there is more than 5 dB drop on the contrast ratio by moving 2 μm from the red spot in the Z direction. Therefore, the detection margin for optimized performance is quite small.

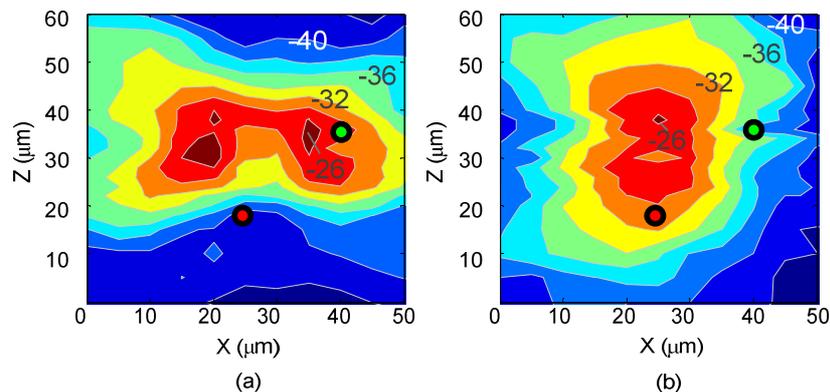


Fig. 2 Contour plots of power collected by the second tapered SMF while (a) LP_{11a} and (b) LP_{11b} are excited, respectively. The power is measured in dBm. The X and Z distances refer to the directions shown in Fig. 1(a).

3. Experimental setup and BER performances

The experimental setup is shown in Fig. 3. A 10.7 Gbps non-return to zero (NRZ) signal is generated by sending a continuous-wave (CW) light at 1550 nm into a Mach-Zehnder modulator (MZM). A 2^7-1 pseudo-random sequence length is used. Two data channels are formed by splitting the signal at the output of the MZM into two branches. Each path is controlled by a polarization controller (PC). A 500 m standard SMF is added into one of the light paths to de-correlate the two data channels. The length of the used HC-PBGF is 30 m. The total loss of the HC-PBGF link, including transmission loss and coupling losses from the alignment setup shown in Fig. 1(a), is measured to be 25 dB for the LP₀₁ mode and 40 dB for the LP₁₁ mode. The nominal loss of the LP₀₁ mode is ~ 11 dB/km [7]. Therefore, the coupling loss of the alignment setup is estimated to be around 24.7 dB. After transmission through the HC-PBGF link, the received signal is sent into a pre-amplified receiver for BER measurements. Fig. 4(a) and (b) show the eye diagrams of the received LP₁₁ mode without and with the other channel switched on at a BER of 10^{-9} and 10^{-3} , respectively. For comparison, the eye diagram of the received LP₀₁ mode is shown in Fig. 4(a) at a BER of 10^{-9} .

Fig. 4(d) shows the BER performances of the two-mode multiplexing system. The back to back case is obtained by sending the signal at the output of the MZM into the pre-amplified receiver directly. By switching off the other channel, a power penalty of 1 and 3 dB are observed for LP_{11a} (ch1) and LP_{11b} (ch2), respectively. However, the BER performance degrades greatly when the other channel is switched on. Nevertheless, in both cases, BER below the FEC threshold (3.3×10^{-3}) assuming 7% overhead coding have been achieved. Such BER degradation as well as the non-uniform performance between the two channels is believed to be largely due to the non-optimized detection position in the de-multiplexing stage, as discussed in Section 2. The performance of the fundamental mode, LP₀₁, is also measured. The power penalty in this case is 1.5 dB at a BER of 3.3×10^{-3} . However, almost no power penalty has been achieved in this case at a BER of 10^{-9} , indicating excellent performance of the transmission using the fundamental mode at 10.7 Gbps.

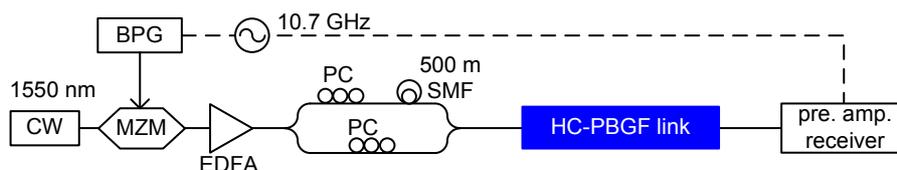


Fig. 3 Experimental setup.

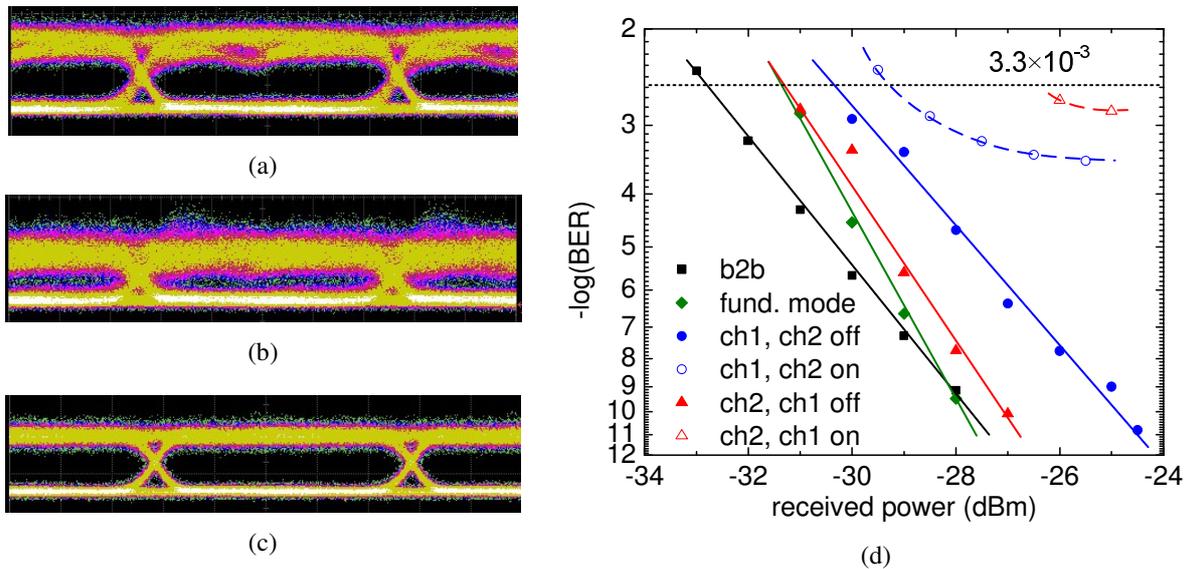


Fig. 4 Eye diagrams (a) ch1 (LP_{11a}) on, ch2 (LP_{11b}) off; (b) ch1 on, ch2 on; (c) fundamental mode; (d) BER performance.

4. Conclusion

We have demonstrated for the first time a two-mode multiplexing system in a section of hollow-core photonic band gap fiber. BER performances below the FEC threshold limit (3.3×10^{-3}) are shown for both data channels. Error free performances (at a BER of 10^{-9}) are achieved for transmitting only one LP_{11} mode with a power penalty of up to 3 dB. The fundamental mode is also measured for comparison and shows about 1.5 dB power penalty at a BER of 3.3×10^{-3} and almost no power penalty at a BER of 10^{-9} . These preliminary experimental results are believed to be improved greatly by upgrading the mode multiplexing and demultiplexing method. As discussed in Section 2, the detection margin on the received mode profile is tight and suffers from system instability strongly. In addition, the mode excitation at the input of the HC-PBGF can be also improved by using better mode-matching techniques [3-6].

The authors would like to thank NKT photonics and especially Jens Kristian Lyngsø and Lasse Leick for providing the HC-PBGF. The authors would also like to thank Radu Malureanu for providing the infrared camera. This work is supported by the Danish Council for Technology and Productions Sciences (project 10-093299).

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