# Mode Division Multiplexing over 19-cell Hollow-core Photonic Bandgap Fiber by Employing an Integrated Mode Multiplexer

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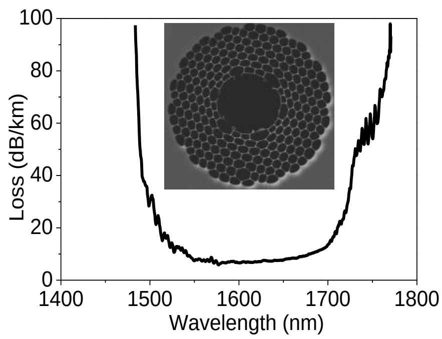
A photonic integrated mode coupler based on Silicon-on-Insulator (SOI) is employed for mode division multiplexing (MDM) over a 193m 19-cell hollow-core photonic bandgap fiber (HC PBGF) with a 3dB bandwidth > 120nm. Robust $LP_{01}$ and $LP_{11}$ modes, and two degenerate $LP_{11}$ modes ($LP_{11a}$ and $LP_{11b}$) MDM × 20Gbaud QPSK transmissions are both experimentally verified.

*Introduction:* With the continuous concern about the exhausting capacity of single-mode fiber (SMF) links due to the limitations induced by fiber nonlinearities, mode division multiplexing (MDM) [1] was proposed to avert this bottleneck through utilizing the last unexplored dimension: space. Utilizing multiple fiber modes as separate transmission channels, MDM is able to enhance the fiber capacity in the spatial domain. Mode coupling, differential group delay (DGD) and other fiber imperfections are compensated with Digital Signal Processing (DSP) at the receiver side. Promising MDM combined with WDM transmissions over few-mode fibers (FMFs) [2]–[4] and conventional multi-mode fiber (MMF) [5] have been demonstrated. Hollow-core photonic bandgap fiber (HC PBGF) was also proposed as a candidate to enhance the capacity of optical networks, since HC-PBGF has a lower nonlinearity than the solid-core fibers [7]. In [8], MDM transmission over HC PBGF was demonstrated, where phase-plate based mode multiplexer (MUX) and demultiplexer (DEMUX) were utilized.

In this letter, a photonic integrated mode coupler based on Silicon-on-insulator (SOI) [6] is employed as a mode MUX for MDM (2×20Gbaud QPSK) transmissions over a 193m 19-cell HC PBGF. It is for the first time that SOI based integrated circuit is implemented into PBGF transmission.

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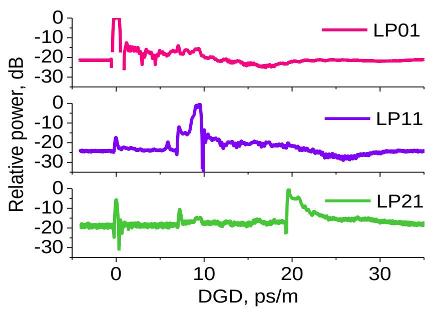


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**Fig. 1** *Transmission loss spectrum and SEM picture of the 19c HC-PBGF (Fig. 1a), and time-of-flight measurement for pure $LP_{01}$, $LP_{11}$ and $LP_{21}$ mode (Fig. 1b).*

*Hollow-core photonic bandgap fiber:* HC PBGF guides the light in the central air core, which is surrounding with regular lattice of air holes to generate a photonic bandgap. The dominant loss from the HC PBGF comes from surface scattering [7], induced by the overlap of the fiber modes with the air-glass interface. A 19-cell thin-core-surround HC PBGF design is able to decrease significantly the surface scattering. Fig. 1a shows the transmission loss spectrum and Scanning electron microscope (SEM) picture of the fiber. It has a 3dB bandwidth larger than 120nm with a minimum loss of 5.86dB/km. Fig. 1b shows the results with time-of-flight measurement [8] for pure $LP_{01}$, $LP_{11}$ and $LP_{21}$ modes. The DGD between $LP_{01}$ and $LP_{11}$ modes is around 9ps/m, which results in 1.7ns modal delay after 193m transmission.

*Transmission results:* Fig. 2a shows the experimental setup for MDM transmission over the 193m 19-cell HC-PBGF. An external-cavity laser (ECL) operating at 1555.75nm is split into two outputs. The first is amplified and utilized as Local Oscillator (LO) for coherent detection. The other is modulated by a $LiNbO_3$ IQ-Modulator driven by two digital-to-analog convertors (DACs) operating at 20GS/s. A sequence with a length of $2^{15}$ symbols is used for the in-phase (I) component and a copy with a delay of $2^{14}$ symbols is for the quadrature (Q) component of the 20Gbaud QPSK signal. After amplification, the signal is split into two tributaries with a delay of 1960 symbols. These two decorrelated signals are sent to different input ports of the mode MUX, which is the integrated mode coupler. The input ports of the chip have been packaged with an SMF fiber array and the FMF side is free to allow the launching into optical fibers with different designs, as shown in Fig. 2b. Due to the availability of laboratory resources, two modes out of three spatial modes (In this letter, only the single polarization case is investigated) are transmitted simultaneously in each test. At the mode DEMUX side, binary phase plates are employed for separating two different modes. $LP_{01}$ and $LP_{11a}$, and both degenerate $LP_{11}$ modes ($LP_{11a}$ and $LP_{11b}$) are transmitted respectively. In the mode DEMUX, depending on the transmitted modes, the phase plate at port A is inserted or taken away and the one at port B is rotated by 90 degrees where appropriate to select the corresponding $LP_{11}$ mode, as shown in the DEMUX block in Fig. 2a. Two outputs of the mode DEMUX are fed into the coherent receivers. 4 electrical signals from the Balanced Photo-detectors (BPDs) are captured by a digital real-time oscilloscope sampling at 40GS/s. The captured data is off-line processed with multiple-input multiple-output (MIMO) based DSP to recover the signals.

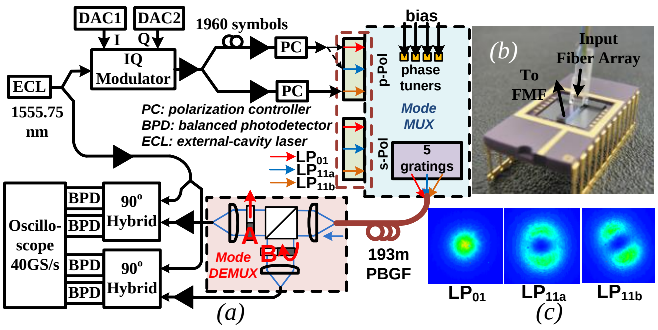
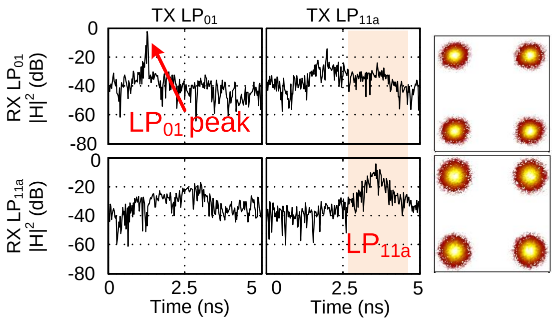



**Fig. 2** *Experimental setup for MDM transmissions (Fig. 2a), picture of the packaged SOI mode coupler (Fig. 2b) and captured pure fiber modes excited by the SOI mode MUX (Fig. 2c).*

The equalizer taps after convergence and constellations for the transmission of $LP_{01}$ and $LP_{11}$, and degenerate $LP_{11}$ modes ($LP_{11a}$ and $LP_{11b}$) can be seen in Fig. 3a and Fig. 3b, respectively. Robust transmission is demonstrated for both cases. In $LP_{01}$ and $LP_{11}$ transmission case, the DGD two modes after 193m 19c HC PBGF can be seen in Fig. 3a) where no obvious mode coupling can be found. It demonstrates that the SOI mode coupler is able to provide high mode extinction ratio. For degenerate $LP_{11}$ modes transmission, the DGD of $LP_{11}$ modes is negligible, as shown in Fig. 3b. The wide plateau of the equalizer taps for $LP_{11}$ modes means a large distributed mode coupling for the $LP_{11}$ modes [9]. The measured 3dB wavelength bandwidth of the SOI mode coupler is larger than 40nm, which covers the whole C-band and has been demonstrated to be compatible to wavelength division multiplexing (WDM) [10]. The chip insertion loss is around 20dB for $LP_{01}$ and $LP_{11}$ modes in the optimal wavelength. Main loss comes from FMF coupling region, which is expected to be minimized in future optimization of the small vertical grating design.

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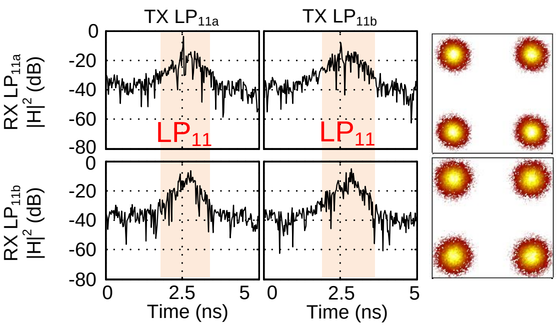


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**Fig. 3** *Equalizer taps (left) and constellations (right) after transmission for $LP_{01}$ and $LP_{11}$ modes (Fig. 3a), and $LP_{11a}$ and $LP_{11b}$ (Fig. 3b).*

*Conclusion:* MDM (2×20Gbaud QPSK) transmission over a 193m 19-cell HC PBGF was experimentally demonstrated by employing an integrated mode coupler. The SOI mode coupler is able to selectively excite $LP_{11}$ and $LP_{01}$ modes through push-pull and center launch. It demonstrates a compact and low-cost solution for mode multiplexing and the results are promising for further MDM transmission over HC PBGF with lower nonlinearity.

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## References


[1] R. Ryf, S. Randel, A. H. Gnauck, C. Bolle, A. Sierra, S. Mumtaz, M. Esmaeelpour, E. C. Burrows, R. Essiambre, P. J. Winzer, D. W. Peckham, A. H. McCurdy, and R. Lingle, "Mode-Division Multiplexing Over 96 km of Few-Mode Fiber Using Coherent 6 6 MIMO Processing," *J. Light. Technol.*, vol. 30, no. 4, pp. 521–531, 2012.

[2] R. Ryf, S. Randel, N. K. Fontaine, M. Montoliu, E. Burrows, S. Chandrasekhar, A. H. Gnauck, C. Xie, R.-J. Essiambre, and P. Winzer, "32-bit/s/Hz Spectral Efficiency WDM Transmission over 177-km Few-Mode Fiber," in *Optical Fiber Communication Conference*, 2013.

[3] R. Ryf, N. K. Fontaine, M. Montoliu, S. Randel, B. Ercan, H. Chen, S. Chandrasekhar, A. Gnauck, S. G. Leon-Saval, J. Bland-Hawthorn, J. R. Salazar Gil, Y. Sun, and R. Lingle, "Photonic-Lantern-Based Mode Multiplexers for Few-Mode-Fiber Transmission," in *Optical Fiber Communication Conference*, 2014, p. W4J.2.

[4] V. A. J. M. Sleiffer, H. Chen, Y. Jung, P. Leoni, M. Kuschnerov, A. Simperler, H. Fabian, H. Schuh, F. Kub, D. J. Richardson, S. U. Alam, L. Grüner-Nielsen, Y. Sun, A. M. J. Koonen, and H. de Waardt, "Field demonstration of mode-division multiplexing upgrade scenarios on commercial networks," *Opt. Express*, vol. 21, no. 25, p. 31036, Dec. 2013.

[5] R. Ryf, N. K. Fontaine, H. Chen, B. Guan, S. Randel, N. Sauer, S. J. B. Yoo, A. M. J. Koonen, R. Delbue, P. Pupalaikis, A. Sureka, R. Shubochkin, Y. Sun, and R. Lingle, "23 Tbit/s Transmission over 17-km Conventional 50-μm Graded-Index Multimode Fiber," in *Optical Fiber Communication Conference*, 2014, p. Th5B.1.

[6] A. M. J. Koonen, H. Chen, H. P. A. Van den Boom, and O. Raz, "Silicon Photonic Integrated Mode Multiplexer and Demultiplexer," *IEEE Photonics Technol. Lett.*, vol. 24, no. 21, pp. 1961–1964, 2012.

[7] F. Poletti, N. V. Wheeler, M. N. Petrovich, N. Baddela, E. Numkam Fokoua, J. R. Hayes, D. R. Gray, Z. Li, R. Slav k, and D. J. Richardson, "Towards high-capacity fibre-optic communications at the speed of light in vacuum," *Nat. Photonics*, vol. 7, no. 4, pp. 279–284, Mar. 2013.

[8] Y. Jung, V. Sleiffer, N. Baddela, M. Petrovich, J. R. Hayes, N. Wheeler, D. Gray, E. R. Numkam Fokoua, J. Wooler, N. Wong, F. Parmigiani, S.-U. Alam, J. Surof, M. Kuschnerov, V. Veljanovski, de, Hugo Waardt, F. Poletti, and D. J. Richardson, "First Demonstration of a Broadband 37-cell Hollow Core Photonic Bandgap Fiber and Its Application to High Capacity Mode Division Multiplexing," in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*, 2013, p. PDP5A.3.

[9] J. W. Nicholson, A. D. Yablon, J. M. Fini, and M. D. Mermelstein, "Measuring the Modal Content of Large-Mode-Area Fibers," *IEEE J. Sel. Top. Quantum Electron.*, vol. 15, no. 1, pp. 61–70, 2009.

[10] H. Chen, V. Sleiffer, B. Snyder, M. Kuschnerov, R. van Uden, Y. Jung, C. M. Okonkwo, O. Raz, P. O'Brien, H. de Waardt, and T. Koonen, "Demonstration of a Photonic Integrated Mode Coupler With MDM and WDM Transmission," *IEEE Photonics Technol. Lett.*, vol. 25, no. 21, pp. 2039–2042, 2013.