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Mode Multiplexing at 2×20Gbps over 19-cell Hollow-Core Photonic Band Gap Fibre

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Abstract: This paper demonstrates the first mode-multiplexed system over 19-cell hollow-core photonic band gap fibre, at 2×20Gbps using the $LP_{0,1}$ and $LP_{2,1}$-like modes.

OCIS codes: 060.0060 (Fiber optics and optical communications), 060.5295 (Photonic crystal fibers)

1. Introduction

Mode division multiplexing (MDM) has been recognized as a promising candidate for extending the capacity limit of single mode fibres (SMFs) [1-3] by utilizing the spatial dimension of optical fibres. MDM has been demonstrated previously using Graded-Index Multi-Mode Fibres (GI-MMFs) for short-range high-speed applications [4-5]. MDM targeting long-haul communication has been demonstrated so far in some Few-Mode Fibre (FMF) prototypes [1-3], which are all solid-core fibres. One of the well-known practical limitations of solid core fibres is fibre nonlinearities. Hollow-Core Photonic BandGap Fibres (HC-PBGFs) can greatly reduce nonlinearities as in excess of 90% of the power propagates through air [6]. For the same reason, these fibres also have the potential to offer decreased loss over solid fibres [7]. Increasing the dimension of the air core reduces loss but also results in an increase in the number of supporting modes [6]. This would be seen as undesirable if not for the potential of MDM to exploit this larger modal diversity. In [8] we explored MDM in a 7-cell HC-PBGF that only supports $LP_{0,1}$ and $LP_{1,1}$ modes. In this work, the air core of the HC-PBGF used for the mode transportation increases to 19 cells which supports approximately 20 degenerate modes per polarisation [6]. In addition, HC-PBGFs can be used for opening new transmission windows around 2 µm where they have been theoretically predicted to have minimum loss [9] that is significantly lower than that of solid-core silica fibres in the same wavelength range.

In this work, a 2×20 Gbps two-mode system, employing the $LP_{0,1}$ and $LP_{2,1}$ modes, is demonstrated over a section of 19-cell HC-PBGF. Accurate mode excitation is enabled by a binary phase Spatial Light Modulator (SLM) and more than 10 dB crosstalk suppression is achieved by a standard 50/50 50µm graded-index core multimode coupler. The experimental results reveal the possibilities, as well as challenges, of MDM in many-mode HC-PBGF.

2. Modal Multiplexing and demultiplexing

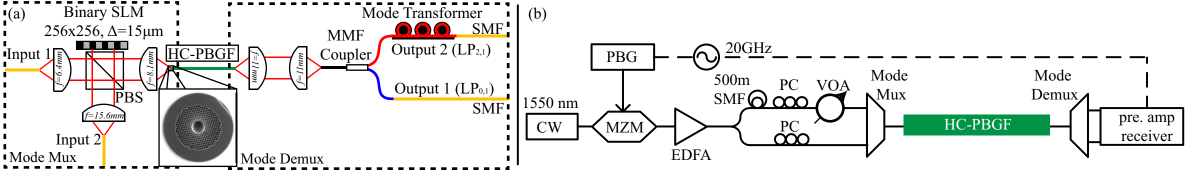

Fig. 1. (a) Modal multiplexing/demultiplexing mechanism. (b) System overview.

The system multiplexes channels on two separate modes of the fibre. The first channel propagates using the $LP_{0,1}$ mode and is launched simply by resizing the fundamental mode of the input Single-Mode Fibre (SMF) as illustrated in Fig. 1(a). The second modal channel is launched by way of a binary phase SLM which displays a phase mask designed to generate the desired mode in the far-field [10]. The SLM can be programmed to excite any mode of the fibre at any orientation. The modes travel through a relatively short distance of fibre of 75cm. The limited distance is a consequence of the high Differential Mode Attenuation (DMA) of the fibre which can be several dB/m [11]. For instance, at equal launch power there was a measured difference of 2.7dB/m between the $LP_{0,1}$ and $LP_{2,1}$ modes used for this experiment. At the receiving end, the similarity between the modes of the HC-PBGF and that of a standard multimode fibre is exploited by using a 50µm GI-MMF coupler, nominally rated as a 50/50 split at 850/1310nm, as the demultiplexer. Using a multimode coupler as a modal demultiplexer is a common method [5] of achieving the required modal diversity but is used in a slightly unusual fashion in this instance. First, rather than physically butt-coupling the two fibre cores together, the HC-PBGF core is imaged onto the coupler's core. The primary reason for employing this technique is to avoid physically touching the core of the HC-PBGF and so the two cores can be precisely aligned. This also allows a mirror to be inserted between the lenses to observe the far-field exiting the HC-PBGF and being imaged onto the coupler at any given moment without moving the fibre and hence changing the mode profile. The MMF coupler itself as shown in Fig. 1(a) has two output ports labeled 1 (blue) and 2 (red) respectively. Any mode can couple to the first port but only the $LP_{0,1}$ can couple through the SMF attached to it. The $LP_{0,1}$ mode however cannot strongly couple to the second port which only transmits the higher-order modes. Because the desired system requires single-mode outputs, the second output port of the coupler is threaded through a polarisation controller which is used as a crude mode converter to maximize the coupling into the output single-mode fibre.

It is primarily the modal characteristics of the MMF coupler and the requirement for single-mode outputs which defines which mode is best for multiplexing the second channel. There are two contradictory requirements; the second channel must be sufficiently different from the fundamental so it is unlikely to couple to the SMF attached to the first output, but sufficiently similar to the fundamental that the simple mode transformer on the second port can be manipulated to provide adequate power to the SMF attached to that port and preserve the modal diversity between the two channels. Without the SMF attached to the second port, the isolation of the $LP_{1,1}$ mode is between 10.5 and 12.5dB depending on the orientation whereas the $LP_{2,1}$ mode provides between 15.4 to 18dB. Higher-order modes provide similar isolation to that of the $LP_{2,1}$ but suffer more loss, both through the HC-PBGF itself but more importantly, when an SMF is attached to the second port. The $LP_{2,1}$ mode could be coupled to the SMF with 6dB loss leaving 11-12dB of isolation between the ports for that mode. Although the use of a SMF on the second port is an impediment to the isolation for the higher-order modes any additional loss through the second port serves to better isolate the $LP_{0,1}$ channel. The leakage of the fundamental to the second port was measured to be around 21dB.

The Differential Mode Delay (DMD) of the fibre is very large, with just 75cm of HC-PBGF having similar DMD to hundreds of metres or a few kilometres of graded-index multimode fibre and possesses even larger delays than step-index fibres designed specifically with large DMD for mode-multiplexing [12].The large difference in propagation constants of the modes serves to reduce the beat length and keep the propagating modes isolated. However the single-mode fibre on the second port preferentially couples lower order modes and tends to skew the final modal power distribution which can effectively amplify the modal dispersion for the secondary port. For example, if a channel is propagated using the $LP_{2,1}$ mode, but some small mode-coupling occurs to the $LP_{1,1}$ mode either at the launch or along the length of the fibre, the fact that the $LP_{1,1}$ component of the power is more likely to couple to the single-mode output than is the $LP_{2,1}$ may serve to boost the relative power of the $LP_{1,1}$ mode and hence increase the modal dispersion. This also leads to an effect whereby adjusting the mode transformer to maximize the power out of the secondary port, also tends to make the modal dispersion worse, and in a similar fashion, rotating the orientation of the launched mode at the input of the fibre to maximise the power also tends to degrade isolation.

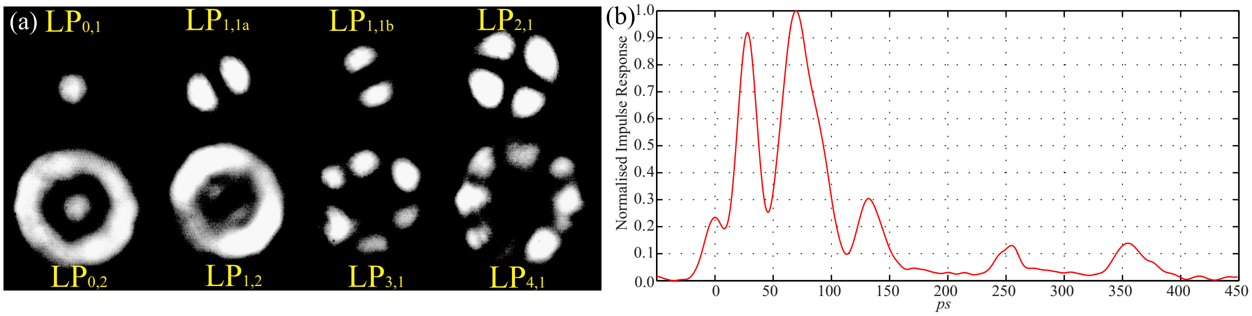

Fig. 2. (a) Far-field of the HC-PBGF at the receiving end (b) Impulse response after 75cm with multiple modes excited simultaneously.

4. Experimental setup and BER performance

The experimental setup is shown in Fig. 1 (b). A continuous-wave (CW) light at 1550 nm is modulated by a Mach-Zehnder modulator (MZM) and a 20 Gbps Non-Return to Zero (NRZ) signal with 2^{31}-1 pseudo-random sequence length is generated. Two data channels which are to be propagated by the $LP_{0,1}$ and $LP_{2,1}$ modes respectively, are formed by splitting the signal at the output of the EDFA into two branches and decorrelating the channels by passing the $LP_{0,1}$ path through a 500 m length of standard SMF. Polarisation controllers (PCs) are included in each path to align them to the polarisation required by the mode multiplexer. An attenuator is used in the $LP_{0,1}$ channel path to balance the power of the two channels to keep them approximately equal at the receiver. The demultiplexed signal is sent into a pre-amplified receiver for bit error ratio (BER) measurements.

Fig. 3 shows the BER performance of the 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. The eye diagram shown furthest to the left is measured in this case at -25 dBm received power. Compared to the back-to-back case, error-free single channel performances was achieved at BER=10^{-9} with a power penalty of 0.8 and 3.6 dB for $LP_{0,1}$ (up triangle) and $LP_{2,1}$ channel (down triangle), respectively. The 2.6 dB power penalty difference between $LP_{0,1}$ and $LP_{2,1}$ channels is due to modal dispersion as mentioned above. The modal performance of the demultiplexer is such that lower order modes can more easily couple to the single-mode outputs. This is not an issue for the modal bandwidth of the $LP_{0,1}$ channel, but decreases the bandwidth of the $LP_{2,1}$ as it effectively amplifies any modal mixing that has occurred to lower-order modes, due to the difference in modal attenuation when coupling from the MMF to the SMF.

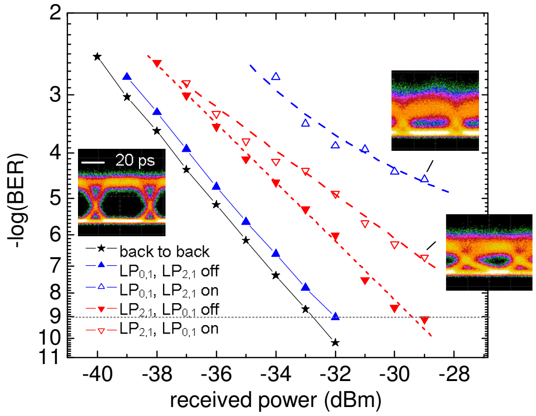

Fig. 3 BER performance. All eye diagrams are taken for a period of 30 seconds.

The maximum received power obtained in the experiment is -28.3 dBm, which is set by the maximum power rating of the SLM. The crosstalk measured for the $LP_{0,1}$ and $LP_{2,1}$ channel is 21.2 and 11.3 dB, respectively. With the both channels transmitting, BER down to 10^{-7} and $3{\times}10^{-5}$ has been confirmed for the $LP_{2,1}$ and $LP_{0,1}$ channels respectively at -29 dBm received power. The slope of the BER curve for $LP_{0,1}$ and $LP_{2,1}$ degrades heavily compared to the back-to-back case and indicates an error floor at higher received power levels for the $LP_{0,1}$ channel. Whilst the $LP_{2,1}$ channel's primary limitation is the exaggeration of modal dispersion by the demultiplexer, the $LP_{0,1}$ channel suffers from increased leakage of the $LP_{2,1}$, again due to the demultiplexing scheme where the increased loss introduced by attempting to couple from a multimode fibre to a single-mode output reduces the isolation between the channels.

5. Conclusions

Multiplexing and demultiplexing of two spatial modes of an HC-PBGF has been demonstrated with 2×20Gbps NRZ channels. BER of $3{\times}10^{-5}$ is achieved for the worst case. Although the multiplexing of modes by the SLM was very effective, demultiplexing by way of a standard multimode coupler to two single-mode fibre outputs was the primary limitation as it degrades the isolation between the channels as well as exaggerates modal dispersion.

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