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MDM transmission using air-clad photonic lanterns

Neethu Mariam Mathew, Lars Grüner-Nielsen, *Member, IEEE*, Michael Galili, Mads Lillieholm, and Karsten Rottwitt

Abstract—MIMO less few mode transmission is performed using two spatial channels transmitted through 1 km of two mode graded index fiber at 10 Gb/s modulation rate. The multiplexing and de-multiplexing of the spatial channels are done using air clad photonic lanterns. The power in the two degenerate LP_{11} modes are added electrically and counted as a single channel. The Q values calculated for the LP_{01} and LP_{11} channels are 5.4 and 4.7 respectively. We also show that, the signal degradation due to modal interference can be mitigated by using different laser sources for different spatial channels with some wavelength spacing. The wavelength separation increases the modal beat frequency beyond the detector bandwidth, thus improving the transmission performance. Using two laser sources with a wavelength spacing of 0.2 nm between the spatial modes could improve the Q compared to the case where a single laser source is split between the spatial channels with some extra length of fiber in one of the paths for optical decorrelation.

Index Terms—Optical fiber devices, Optical fiber communication, Intensity modulation

I. INTRODUCTION

MODE division multiplexing (MDM) using few mode fibers has been a very active research field in the last decade. Usually, coherent detection and multiple input multiple output (MIMO) digital signal processing is used to mitigate the modal crosstalk in these few mode transmission systems. However, MIMO processing is computationally complex and energy consuming which limits the practical applications of MDM. There are ways to reduce this complexity. For example, in a weakly coupled Few Mode Fiber (FMF), the inter channel distortion due to mode coupling is reduced by increasing the effective index difference between the linearly polarized (LP) modes in the fiber. This could reduce the MIMO complexity to 2×2 MIMO for the non degenerate modes and 4×4 MIMO for the degenerate modes [1]. If the two polarization channels and the degenerate spatial channels are not separated, and counted as a single channel, then MIMO processing can be fully avoided. The interests in this kind of MDM without MIMO has emerged lately in short reach applications like data center networks and interconnections for high performance computers [2] [3]. Conventional intensity modulation and direct detection (IM-DD) are preferred in these short reach applications due to the simple structure and low cost. MDM without MIMO requires mode multiplexers that can specifically excite the required spatial mode in the fiber, and mode de-multiplexers that can transform light back from different

higher order modes. Fiber based mode selective couplers (MSC) can perform these functions and IM-DD transmission using such couplers has been reported [4]. Mode selective couplers excite one LP mode at a time. Thus for each LP mode group a separate MSC is required. Furthermore, MSC can only detect one of the degenerate modes in a specific mode group. A mode selective photonic lantern can overcome this limitation as it can excite different LP modes in a FMF at the same time. The power in both degenerate modes in the FMF can be also be simultaneously detected. Mode selective photonic lanterns that can excite up to 15 spatial modes has been reported [5]. 3×10 Gb/s mode group transmission over 20 km of FMF has been demonstrated using five port photonic lanterns. [6]. We have earlier reported the fabrication and characterization of an air clad mode group selective lantern that could excite the first two LP mode groups [7]. These air clad lanterns are fabricated without the use of the fluorine doped low index outer cladding which surrounds the single mode fibers (SMFs) in the usual fabrication technique. In our technique, one standard SMF (SSMF) and two Corning HI1060 (smaller core diameter of 5.3 μm) fibers are stranded together and tapered down. The tapered fiber bundle is cleaved and spliced to an OFS Two Mode Step Index (TMSI) fiber. TMSI fiber is preferred here as it has larger mode field diameters for the LP_{01} and LP_{11} modes compared to the graded index fiber used for transmission and hence the single mode fiber bundle does not have to be tapered down below 22 μm .

In this paper we report the results of the MDM transmission using two fabricated lanterns. MIMO less 2×10 Gb/s transmission over 1 km of FMF and 2×25 Gb/s transmission over 7 m of FMF are reported here. We also show that the signal degradation due to modal interference can be reduced by using different lasers with a small wavelength spacing for the two spatial channels [8].

II. MDM TRANSMISSION

The experimental set up used for data transmission is shown in figure 1. A DFB laser is modulated using a Mach Zehnder modulator to generate a non-return-to-zero signal. A pseudo random bit sequence (PRBS) of length of $2^{31} - 1$ is used for transmission. The amplified signal is split into two paths using a 3 dB coupler. The laser has a line width of a few MHz, corresponding to a coherence length of around 100 m. A 2 km SMF + 300 m dispersion compensation fiber is included in one of the paths to decorrelate the optical paths. The two paths are separately amplified and fed into the LP_{01} and LP_{11} inputs of the multiplexing lantern. Variable attenuators are connected to each paths to balance the powers in the two modes, so the received power is the same in both channels. There is 7

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Fig. 1. a) Setup used for MDM transmission using two LP channels at 10 Gb/s and 25 Gb/s. DFB: DFB laser, PG: Pattern Generator, MZM: Mach Zehnder Modulator, 3 dB: 3 dB splitter, EDFA: Erbium Doped Fiber Amplifier, VOA: Variable Optical Attenuator, PL: Photonic Lantern, PC: Polarization controller, TMGI: Two Mode Graded Index fiber, PD: Photo Diode. b) The aligned LP₁₁ traces before adding.

m of TMSI fiber between the two lanterns, and a polarization controller is set on the TMSI fiber. A 1 km long OFS two mode graded index fiber (TMGI) is also spliced between the two lanterns. Depending on the input polarization, the orientation of the LP₁₁ mode in the FMF changes and hence the overlap with the lantern modes of the de-multiplexing lantern also changes. The polarization controller at the TMSI fiber can rotate the LP₁₁ mode to get the lowest de-multiplexing cross talk. At the output lantern, the SSMF shown in thick line, delivers the de-multiplexed LP₀₁ power. The two small core HI1060 fibers, each give an orthogonal linear combination of powers in LP_{11a} and LP_{11b} modes. Hence the total LP₁₁ power is the sum of the two HI1060 outputs. Three photodiodes detect the output powers and the signals are acquired by an oscilloscope. The powers from the two HI1060 fibers are electrically added in the oscilloscope to get the total power in the LP₁₁ channel. A free space delay is introduced at one HI1060 fiber to align the traces together before they are added, alternatively this delay could be added in the electrical signal processing by finding the delay that gives the maximum correlation between the traces, and shifting one of the traces accordingly. An example of the aligned output traces from the two HI1060 fibers for a modulation rate of 25 Gb/s is shown in Figure 1b. The sampling speed of the oscilloscope is 80 GS/s and the bandwidth is 33 GHz. The real time traces from the three output fibers are saved and there are 10⁶ points in each trace.

The polarization dependent crosstalk for the multiplexing lantern is measured using S² set up as 12 dB - 16.1 dB for the LP₀₁ mode and 12.4 dB - 14.9 dB for the LP₁₁ mode [9]. For the demultiplexing lantern, when LP₀₁ mode is launched to the TMSI fiber, the PDL for LP₀₁ and LP₁₁ modes are 2.6 dB - 2.7 dB and 14.2 dB - 15.2 dB respectively and when LP₁₁ mode is launched into the TMSI fiber, the PDL for the LP₀₁ and LP₁₁ modes are 12 dB - 20 dB and 3.3 dB - 4.4 dB respectively. The polarization dependent mode crosstalk matrix for the two lanterns connected back to back with 7 m of TMSI fiber between them is shown in table I. The splice between the TMSI fibers introduce some extra mode coupling here.

The transmission quality is assessed from the Q value of the output traces evaluated from the intensity distributions and standard deviations of the 1 and 0 bits. The data is transmitted simultaneously through the LP₀₁ and LP₁₁ channels at 10 Gb/s and 25 Gb/s. The frequencies present in the output traces are first determined using a Fourier transform. The Fourier

TABLE I
THE MODE CROSSTALK MATRIX WHEN TWO LANTERNS ARE CONNECTED BACK TO BACK WITH 7 M OF TMSI BETWEEN THEM

	output LP ₀₁ [dB]	output LP ₁₁ [dB]
Input LP ₀₁	2.5 - 4.2	6.9 - 12.7
Input LP ₁₁	11.4 - 19.5	4.8 - 6.4

Fig. 2. The frequencies present in the saved LP₀₁ trace with a modulation rate of 10 Gb/s. The Gaussian filter used on the output trace is shown in orange line.

transform of the LP₀₁ channel trace, for 10 Gb/s modulation rate is shown in figure 2. As the receiver bandwidth is much larger than the modulation frequency, a Gaussian filter is used on the saved traces. A nearly ideal 16th order super Gaussian filter is used to emulate the receiver bandwidth. The filter is shown in orange line in figure 2. The Q values are calculated at different filter bandwidths and shown in figure 3. These are for the LP₀₁ channel at modulation rates of 10 Gb/s and 25 Gb/s. It can be seen that the best transmission performance is obtained when the receiver bandwidth is close to the modulation frequency. Hence the bandwidth of the Gaussian filter is set same as the modulation frequency and the eye diagrams and Q values are evaluated for each channel. The evaluated Q values and the corresponding eye diagrams for the LP₀₁ and LP₁₁ channels are shown in figure 4a for a modulation rate of 10 Gb/s and in figure 4b for 25 Gb/s. Here, there is 7m of TMSI between the multiplexing and de-multiplexing lanterns. The Q values of the input signal fed into the multiplexing lantern is also shown for comparison. For 10 Gb/s, the Q values are high, but for 25 Gb/s the Q value has reduced showing signal degradation.

As the next step, a 1 km TMGI fiber is spliced between the two lanterns. The TMGI fiber is preferred over the TMSI fiber because it has a much lower distributed mode coupling of -25 dB for a 30 km length [10]. Data is transmitted simultaneously

Fig. 3. Q values for the LP_{01} channel at different receiver bandwidth at modulation rates of a) 10 Gb/s and b) 25 Gb/s.

Fig. 4. Evaluated eye diagrams for the input signal and the two spatial channels for 7m long transmission at a modulation frequency of a) 10 Gb/s b) 25 Gb/s c) for 1 km long transmission at 10 Gb/s.

through the two channels at 10 Gb/s. The calculated Q and the eye diagrams for this 1 km transmission is shown in figure 4c. It is seen that for 1 km transmission, the Q value obtained is smaller than for the 7 m transmission shown in figure 4a at the same modulation rate of 10 Gb/s. The LP_{11} mode rotates along the length of the fiber and its overlap with the lantern modes in the demultiplexing lantern changes. This changes the polarization dependent de-multiplexing crosstalk as well. The longer the fiber, the faster this change will be. Hence, the polarization controller used on the FMF shown in figure 1 cannot be tuned fast enough for 1 km transmission. Mode coupling in the two splices between the TMSI and TMGI fibers also affects the transmission performance here.

Further investigation shows that there are two sources for signal degradation in this MIMO less MDM transmission. One is the pure crosstalk where the field in one spatial mode adds itself to the field in the other mode, and the other is the interference where the modes beat with each other. This modal noise is worse when there are only two modes in the fiber [11]. Usually, in the laboratory set ups this modal noise is reduced by using a delay in one of the spatial paths by connecting some extra fiber whose length exceeds the coherence length of the source. Another way to mitigate this modal interference is by using different wavelengths for the two modes, where

the wavelength spacing is large enough that the beat frequency becomes much larger than the detector bandwidth. This kind of wavelength interleaving to mitigate modal crosstalk in FMF transmissions has already been reported [2] [12] [13]. In the next section we include an experimental study of these modal interference effects on FMF transmission.

A. MDM transmission using two lasers

To study the interference effects on FMF transmission, two laser sources are included in the experimental setup as shown in figure 5. Here, the two DFB lasers are separately modulated and used for the two spatial channels. One laser is set at a fixed wavelength of 1548.4 nm, and the other laser is tuned so that the wavelength spacing is 0.2 nm. Here we note that there is no wavelength filter on the photodiode as in the WDM transmission. The modulation frequency is 10 Gb/s and the modulation format is non-return-to-zero. There is 7m of FMF between the two lanterns. The evaluated eye diagrams and Q values for the two channels are shown in figure 6a. The polarization dependent crosstalk for the demultiplexing lantern is 4 dB to 5 dB higher than that of the lantern used in the set up in section II. In addition, in this set up, the MZM modulator used to modulate the DFB laser for the LP_{11} channel is not as good as that of the modulator used for LP_{01} channel. This could degrade the Q values of the output traces. Hence, the Q values evaluated for the input signals to both channels are given in figure 6 for reference. This FMF transmission is also repeated using a single laser, where a 1.7 km SMF is connected in one of the input paths. The corresponding Q values are shown in figure 6b. Comparing the results, it is seen that, using wavelength interleaving between the spatial modes can improve the Q value relative to using a single laser source and optical decorrelation in one of the paths. The wavelength spacing of 0.2 nm makes the modal beating much faster than the receiver bandwidth. This improves the transmission performance as seen in the evaluated Q values for the two cases.

III. DISCUSSION

In the above, we show that the fabricated air clad photonic lanterns could be used for MIMO less MDM transmission for short range applications. In [6], the powers from the two degenerate modes are combined optically using a third lantern, while in this work, the powers in the degenerate modes are combined in the electrical domain. In section II, a single laser source is used for transmission. 10 Gb/s and 25 Gb/s modulation rates are tried on 7m long TMSI fiber. For 25 Gb/s there is signal degradation due to the crosstalk in the lantern. 1 km long TMGI transmission is also tried at 10 Gb/s. The polarization dependent crosstalk in the fabricated lanterns is one of the main limiting factor for 1 km transmission. A follow up of this work would be to optimize the fabrication process to develop better lanterns with smaller crosstalk and polarization dependence and try longer MDM transmission with them. In section II-A, we show that signal degradation due to modal interference can be mitigated by using different laser sources with some wavelength spacing. The lanterns used in

Fig. 5. Transmission setup with two lasers. MZM: Mach Zender Modulator, EDFA: Erbium Doped Fiber Amplifier, PC: Polarization Controller, VOA: Variable Optical Attenuator, PL: Photonic Lantern, TMSI: Two Mode Step Index fiber, PD: Photodiode.

Fig. 6. Evaluated eye diagrams for the input signals and two spatial channels for 7 m long transmission at 10 Gb/s data rate using a) two lasers with 0.2 nm wavelength spacing between them and b) a single laser.

this part of the experiment have higher crosstalk, hence the transmission is done only at 10 Gb/s. For 10 GHz receiver band width, a wavelength spacing of 0.2 nm could significantly improve the transmission performance compared to the case where a single laser source is used, where the modal inference degrades the performance of both channels. This kind of wavelength interleaving is better than using a delay on one of the paths using a decorrelation fiber to mitigate the modal interference in transmission systems. Numerical studies shows that for a detector bandwidth of 10 Gb/s a minimum wavelength spacing of 0.2 nm is needed to mitigate the interference noise due to modal beating [14]. A more systematic experimental study of different wavelength spacing is difficult, as both the lantern crosstalk and the modal interference are polarization dependent.

IV. CONCLUSION

The multiplexing and demultiplexing capabilities of mode selective air clad photonic lanterns are tested using 2×10 Gb/s and 2×25 Gb/s MIMO-less MDM transmission. The evaluated Q values for 1 km transmission at 10 Gb/s through a two mode graded index fiber for the LP₀₁ and LP₁₁ channels are 5.4 and 4.7 respectively. We also show that the signal distortion due to modal interference can be mitigated by using different wavelengths for the two modes. For a receiver bandwidth of 10 GHz, a spacing of 0.2 nm could increase the Q compared to the case where a single laser is used.

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