200Gb/s Transmission over 20km of FMF Fiber using Mode Group Multiplexing and Direct Detection

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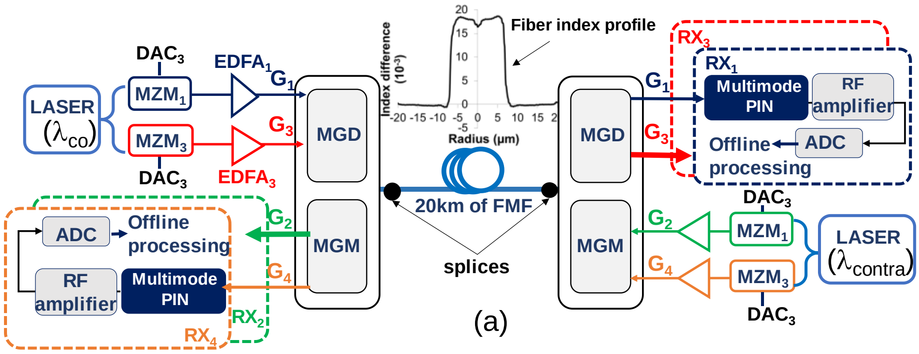
Abstract: *We demonstrate 200Gb/s bidirectional transmission over 20km of step-index FMF fiber using selective excitation of 4 mode groups, direct detection and a single laser in each propagative direction.*

Introduction

Mode multiplexing is an attractive way to increase the total bitrate that can be transported over a Few Mode Fiber (FMF). Most of experimental demonstrations use coherent detection with massive multiple input multiple output (MIMO) signal processing[1]. With specially designed FMF and mode multiplexer with low modal crosstalk it is possible to use low complexity 4x4MIMO processing over reduced reach (below 40km)[2]. However, this type of coherent receiver is still too complex for low cost transmissions where intensity modulation and direct-detection (IM-DD) solution is preferred. Recently, mode group multiplexing has been used over conventional OMx fibers for short reach IM-DD transmission[3-6], and also using FMF for long reach (20km)[7]. In this case, groups of modes (instead of independent modes) are demultiplexed. For each mode group, a single multimode photodiode is used at the receiver side. In our previous work[5], due to high modal crosstalk in the mode multiplexer and in the OM2 fiber, we used independent wavelengths for the co-propagative mode groups even if some spectrum overlap was possible. In this paper, we demonstrate bidirectional transmission over 20km using a specially designed FMF and mode group multiplexer with low modal crosstalk using a single laser in each direction. Achievable bitrates using DMT and PAM4 are experimentally compared. Finally, using DMT modulation format a total net bitrate of 200Gb/s is achieved.

The Few mode fiber and the Mode group multiplexer and de-multiplexer

The fiber used in this work is a weakly-coupled FMF[8-9] that supports 10 spatial modes: 2 non-degenerate LP modes (LP01 & LP02) and 4 two-time-degenerate LP modes ($LP11_{a,b}$, $LP21_{a,b}$, $LP31_{a,b}$ & $LP12_{a,b}$). This FMF has a standard glass diameter of 125µm and has been fabricated with standard manufacturing processes that allow for large-scale production. The minimum effective index difference between the LP modes ($\min|\Delta n_{eff}|$) is as high as 1.5×10^{-3}, which limits mode coupling, the effective areas are between 84 and 100µm² and the attenuations ~0.25dB/km at 1550nm for LP_{01}[8]. Improved trade-off between high $\min|\Delta n_{eff}|$ and effective areas & attenuations compared to step-index profiles with same number of LP modes has been obtained by introducing an optimized depressed zone in the center of the step-index core.This allows to reduce the n_{eff} of the cylindrically-symmetric non-degenerate LP0X modes with limited impact on the other modes. Finally, the maximum differential mode group delay between the six LP modes has been measured at 23.7ps/m. The mode group multiplexer is based on the MPLC technology[10]. We use the first four LP modes for transmission. In one direction two groups of modes are used: mode group 1 (G_1) with LP01 mode and mode group 3 (G_3) with $LP21_{a,b}$ modes. In the reverse direction mode group 2 (G_2) with $LP11_{a,b}$ modes and mode group 4 (G_4) with LP02 modes are used. Considering the refractive index profile indicated in Fig1.a, the chromatic dispersions obtained by simulation for G_1, G_2, G_3 and G_4 are respectively 20.5, 25.35, 26.95 and 31.25ps/nm/km. With this FMF we use lower number of modes compared to our previous work where we used OM2 fiber. Therefore, mode group multiplexer (MGM) and the mode group demultiplexer (MGD) handle lower number of modes and have reduced modal crosstalk, the average modal crosstalk in a B2B configuration is -19.2 dB. Fig1.b shows the loss and the modal crosstalk of the MGD and the MGM with 20km of transmission fiber. We have estimated that a part of this modal crosstalk comes from unperfect splices and it could be improved by 3dB for the worst mode group (G_2) with better splicing.



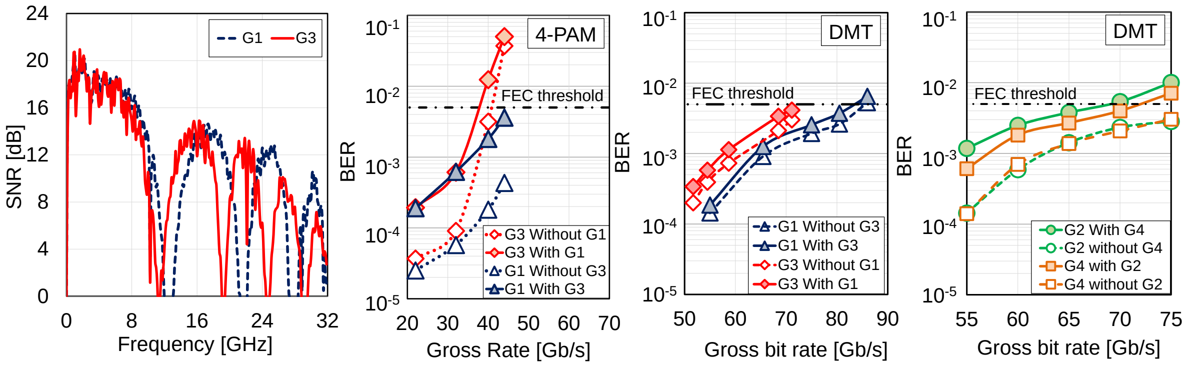
	MGM+MGD+ 20 km FMF + 2 splices	
	LOSS (dB)	Crosstalk (dB)
G_1	-10	-23
G_3	-11,7	-17
G_2	-10,5	-10,1
G_4	-12,4	-16,6

(b)

Fig. 1. a) loss and modal crosstalk b) Bi-directional configuration of the mode group (de-)multiplexer (MGM/MGD), thick lines represent the OM2 fiber and thin lines represent the SMF fiber

Transmission experiment

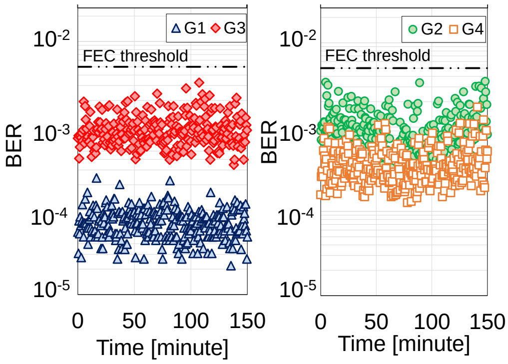
Fig1.a depicts the experimental set-up. At the transmitter, a single laser source is split by a polarization maintaining 3dB coupler. Each output is then modulated with a dedicated Mach-Zehnder modulator driven by an 88Gs/s CMOS digital to analog converter (DAC), such that independent data are used for co-propagative mode groups. A different wavelength is used for each direction due to non-optimized return loss in the MGD/MGM. To partially compensate for the losses of the MGM/MGD and the FMF given in the table of Fig1.b, a single-mode EDFA is used after each modulator. The input power of each photodiode is set to +1dBm by tuning the output power of each EDFA. The output power of EDFA 1,2,3 and 4 are respectively 10.9, 11.7 ,12.6 and 13.2 dBm. At the receiver, the signal is detected with a multimode PIN photodiode with 28GHz bandwidth followed by a 32GHz linear amplifier. The use of a PIN-TIA could be beneficial to remove the EDFA. Signal is then sampled by a 92Gs/s analog-to-digital converter (ADC), followed by off-line signal processing. We investigate two different modulation formats, *i.e.,* PAM4 and DMT. In the case of PAM4 format, a root raised cosine filter with roll-off factor of 0.2 is used, and a T/2-spaced feed forward equalizer with 51 taps is applied for equalization. In the case of DMT format, the FFT length is set to 512, with 30% maximum amplitude clipping and a cyclic prefix composed of 16 symbols. Optimal bit loading adapted to the channel response is applied to maximize the rate for a BER target of 5×10^{-3}. The latter, corresponds to the threshold of a hard decision FEC with 7% overhead[11]. Firstly, the performance in the absences of the co-propagating modes is measured (blank markers). Fig2.a shows an example of the measured Signal to Noise Ratio (SNR) response using DMT after 20km transmission for the two co-propagating mode groups G_1 and G_3 . It is observed that the power fading arising from the cumulated fiber chromatic dispersion is different for each mode group because each mode group has a different chromatic dispersion value. This explains the results in Fig2.b and c where the achievable rates for each group will also be different. Fig2.b and c display respectively the BER as a function of the transmitted bitrate (without assuming 7% overhead) for G_1 and G_3 considering PAM4 and DMT format. For each value, 20 waveforms have been processed. It is observed that DMT achieves higher bitrates compared to PAM4 for both G_1 and G_3. Moreover, for G_3 as the bit rate increases the BER of PAM4 increases much faster than the BER of DMT. This shows the resilience of DMT to chromatic dispersion achieved by adapting the bit loading to the channel response. Furthermore, using DMT, the achievable bitrate per mode group is different, and the BER degradation when the bitrate increase is different for this two mode groups. Secondly, the BER is measured considering the propagation of the co-propagating modes group with the same wavelength (filled markers). Fig2.b shows that PAM4 is highly impacted by modal crosstalk. In this case, using PAM4 format, the net bitrate is limited to 38Gb/s considering BER threshold of 5×10^{-3}. Contrary to PAM4, DMT modulation scheme shows good resilience to modal crosstalk for the all mode groups. In fact, G_1, and G_3 present only a small penalty due to their low crosstalk values displayed in the table of Fig1.b, achievable bitrate for G_1, and G_3, are respectively 80Gb/s, 70Gb/s. Therefore, we consider only DMT modulation for the reverse direction (G_2 and G_4). Fig2.d shows the BER as a function of the transmitted bitrate for G_2 and G_4. It is observed that G_2 has the highest BER penalty due to its high modal crosstalk value. Achievable bitrates for G_2, and G_4 are respectively 65Gb/s and 70Gb/s. This results in a total of 285Gb/s gross bit rate (265Gb/s net) using the four mode groups. However, reference[12] has shown that for multicore fiber the modal crosstalk of carrier-supported signals can encounter time fluctuation.



(a) (b) (c) (d)

Fig. 2. a) SNR response after 20km transmission for G_1 and G_3. Measured BER after 20km : b) for G_1 and G_3 using 4PAM c) G_1 and G_3 using DMT d) for G_2 and G_4 using DMT

Hence, to ensure margin in our system we choose to modulate all the mode group at 55Gb/s, resulting in a total of 220Gb/s (205Gb/s net bitrate) and measured BER fluctuation over 150 minutes. Results are displayed in Fig3.a and b showing the BER as a function of time for all mode groups. The BER performance of all mode groups stays below the FEC threshold, with G_1 giving the largest margin such that its corresponding rate could be set higher than 55Gbit/s due to its lowest modal crosstalk and dispersion value.



(a) (b)

Fig. 3: BER stability due to variations in modal crosstalk for all mode groups modulated at 55Gb/s: a) for G_1 and G_3 b) for G_2 and G_4

Conclusion

We demonstrated a total net bitrate greater than 200Gbit/s for bidirectional transmission over 20km of a specially designed FMF fiber using DMT modulation scheme and direct detection. We achieved this result by using selective excitation of 4 mode groups and the same laser source for the two co-propagating mode groups in each direction. The stability of the BER performance has been assessed during 150 minutes.

Acknowledgements

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