Discrete Multitone Transmission over 4.4km Graded-Index Multimode Fiber with Center and Offset Launching for Mode Group Division Multiplexing

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35.4Gbit/s discrete multitone (DMT) transmission over 4.4km graded-index multimode fiber by center launching is demonstrated. Feasibility of a 62.9Gbit/s 3 × 3 DMT Mode Group Division Multiplexing system with center and offset launching is discussed.

1. Introduction

The data transmission capacity of graded-index multimode fiber (GI-MMF) in short-range optical communication links such as local and storage area networks is restricted due to the influence of modal dispersion. However, many techniques have been proposed to remove this limitation, such as: adaptive optics [1], electrical dispersion equalization [2], subcarrier multiplexing [3], offset launching (OL) [4], and center launching (CL) [5].

In this paper, the enlarged bandwidth of MMF when using CL is shown and 35.4Gbit/s discrete multitone (DMT) [6] transmission over 4.4km GI-MMF is successfully demonstrated. By employing CL it is easy to upgrade existing MMF networks: just exchange the transmitters with MMF pigtails to SMF pigtailed ones, and directly couple these SMF pigtails to the transmission MMF. In addition, OL has been investigated to provide more parallel channels in MMF, by means of Mode Group Division Multiplexing (MGDM) [7]. In this paper it is proven that with a bit- and power-loading algorithm, DMT can minimize the influence of modal dispersion in mode groups with OL and provides the potential for a 3 × 3 long distance and high speed MGDM system.

2. Modal Dispersion

The frequency response of MMF is determined by modal and chromatic dispersion. Compared to modal dispersion, chromatic dispersion is much smaller and often negligible. Therefore, neglecting attenuation in each mode (which is justified as the fibre length is short), the frequency response of the MMF with N guided mode groups can be written as:

$$H_{MMF}(f) = \sum_{n=1}^{N} e^{-j2\pi f t_n} \qquad (1)$$

where t_n is the group delay of the n^{th} mode. It was highlighted in [7] that the differential dispersion among the excited modes greatly increases with larger SMF-to-MMF radial offsets. This is also demonstrated in Fig. 1(a) where the normalized frequency response at λ=1310nm for a 4.4km long GI-MMF (50/125μm) with various radial OL by translating the launching SMF by means of a computer-controlled micro-positioner is shown. The bandwidth distance product for the 4.4km GI-MMF, used in the experiment, is 1604MHz*km at 1310nm. The generation of higher-order modes in the 20µm offset case, obviously causes more modal dispersion. In comparison, the frequency response for CL is flat. Fig. 1(b) shows the normalized frequency response of this GI-MMF with CL at λ=1310nm and λ=1550nm. It can be seen that with CL, the -3dB bandwidths at both wavelengths exceed 12GHz. This clearly indicates that the differential dispersion among the lower-order modes excited with CL is clearly smaller than the differential dispersion with OL.

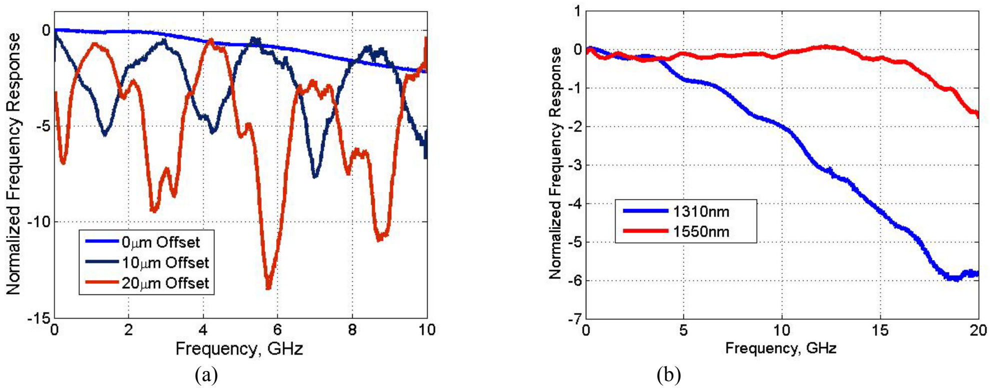


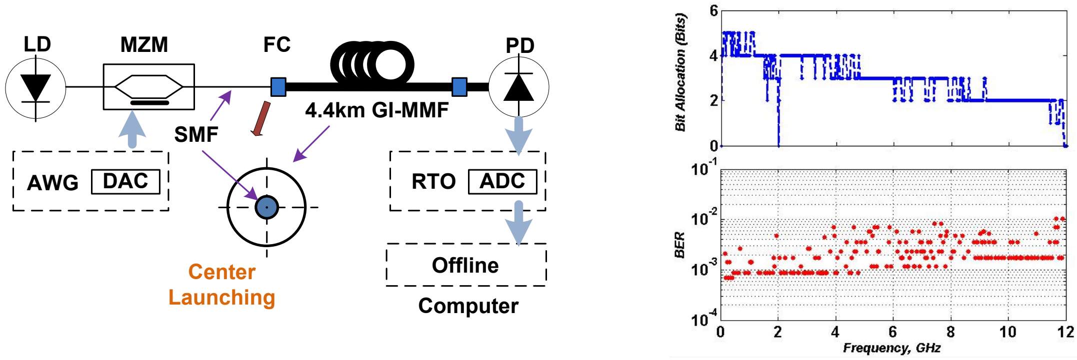
Fig. 1: Normalized frequency response of a 4.4km GI-MMF with (a) radial OL at 1310nm and (b) CL at 1310nm and 1550nm.

3. Experimental Results

The experimental setup is shown in Fig. 2(a). Light from a 1550nm wavelength laser diode (LD) is externally modulated by a DMT signal generated by an arbitrary waveform generator (AWG) using a 40Gbit/s Mach-Zehnder Modulator (MZM). The SMF pigtail of the MZM is connected with a 4.4km GI-MMF link by means of a fiber connector (FC), which realizes the CL. A 50/125µm GI-MMF pigtailed PD is used to detect the light from the transmission MMF. The PD has a bandwidth of 25GHz. The electrical signal after photo-detection is recorded by a real-time oscilloscope (RTO) sampling at 50GS/s and then sent to a computer for offline signal processing in Matlab. An adaptive bit- and power-loading algorithm is utilized to maximize system's bit rate and bandwidth efficiency. This algorithm measures the signal-to-noise-ratio (SNR) for a specified frequency range and uses this information to adjust the bit allocation for each subcarrier [6].

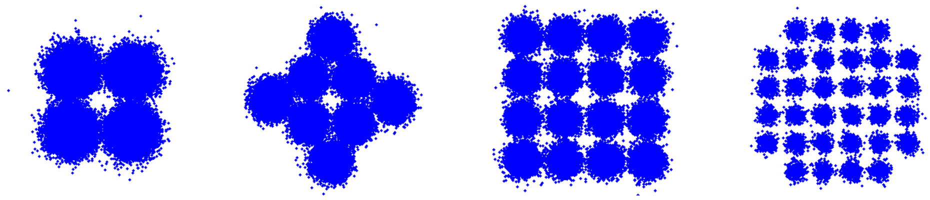
In the experiment, 512 subcarriers are used in the DMT signal and the AWG is sampling at 24GS/s so the DMT signal has a bandwidth of 12GHz. The optical power received at the PD is 0dBm. The transmission performance for the 35.4Gbit/s transmission over 4.4km GI-MMF is shown in Fig. 2(b), which gives the results about the bit allocation and bit-error-rate (BER) for all subcarriers. The achieved 35.4Gbit/s bit rate includes 7% forward error correction (FEC) bits, cyclic prefix and preamble. The net bit rate is 32.1Gbit/s. Although not all subcarriers achieve a BER better than 10-3 (the BER target which is based on the FEC limit for error-free operation), the overall BER could still be below 10-3 so that signals can be correctly recovered. Fig. 3 gives the different recovered constellations for subcarriers with the same modulation levels. The bit rate for electrical back-to-back and optical back-to-back is 52.1Gbit/s (BER=6.57e-4) and 38.7Gbit/s (BER=9.21e-4), respectively. It can be seen that the negative impact of the MMF with CL on the system's performance is very small. So

MMF with CL clearly has the potential to be utilized for long distance and high speed transmission.



(a) (b)

Fig. 2: (a) Experimental Setup (AWG: arbitrary waveform generator,; RTO real-time oscilloscope, (b) Transmission performance: bit allocation and BER for all subcarriers



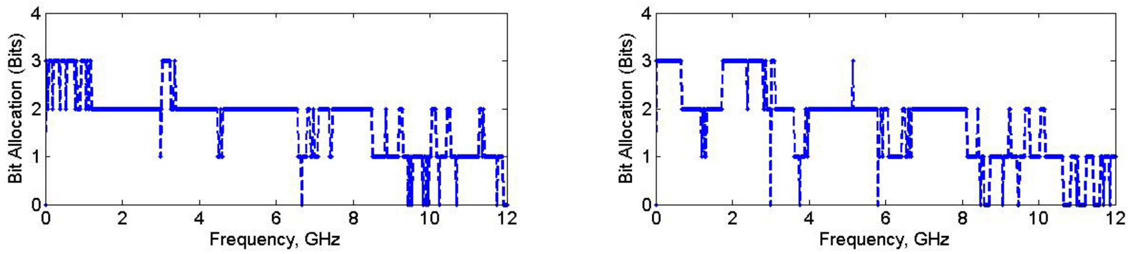
(a) (b) (c) (d)

Fig. 3: Constellations of received signal for subcarriers with (a) 4QAM, (b) 8QAM, (c) 16QAM, (d) 32QAM

4. Feasibility of a 62.9Gbit/s 3 × 3 DMT MGDM System.

Mode Group Division Multiplexing (MGDM) [7] has been demonstrated as an efficient way to increase MMF's capacity, which utilizes different mode groups to transmit different signals in parallel. In MGDM, CL can launch one mode group with negligible impact from modal dispersion, as discussed before. Higher-order mode groups launched by OL suffer from modal dispersion. Compared to other modulation schemes, by using an adaptive bit- and power-loading algorithm, DMT is not sensitive to the modal dispersion in these OL mode groups. Therefore, the application of DMT in MGDM systems can extend transmission lengths and increase capacity further.

Fig. 4 (a) and (b) give the bit allocation results in case of 10μm and 20μm offset launching over 4.4km GI-MMF. The subcarriers with higher SNR are loaded with more bits. The bit rate for 10μm and 20μm OL is 14.0Gbit/s (BER=4.65e-3) and 13.5Gbit/s (BER=9.11e-2), respectively. The high BER, especially for the 20μm case can be explained by the fast frequency response change which is Rayleigh time-varying and cannot be adequately followed by the offline signal processing. The calculation process of bit- and power-loading in our offline processing takes 5 to 6 seconds. However, this problem can be solved by real-time processing with a field-programmable gate array (FPGA) or an application specific integrated circuit (ASIC). Therefore, when DMT is utilized, it is feasible to realize a 62.9Gbit/s 3 × 3 MGDM system over 4.4km GI-MMF with BER less than 1e-3 by a combination of CL, 10μm OL and 20μm OL. The mode groups separation at the receiving side can be realized through mode selective spatial filtering [7] followed by signal processing algorithms similar to those used in wireless MIMO systems.



(a) (b)

Fig. 4: Bit allocation in case of (a) 10µm and (b) 20µm offset launching.

5. Conclusion

35.4Gbit/s Discrete Multitone Transmission (DMT) over a 4.4km GI-MMF link with central launching (CL) was demonstrated. DMT also proves to be a useful solution to minimize the influence of modal dispersion for mode groups with offset launching (OL) in a Mode Group Diversion Multiplexing (MGDM) system. The feasibility of a 62.9Gbit/s 3 × 3 MGDM system over the GI-MMF link was discussed.

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6. References

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