Dispersion-supported direct-detection mode group division multiplexing using commercial multimode fiber couplers

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In this Letter, an intensity-modulation direct-detection mode group multiplexing system is investigated. The system does not use highly modally selective optics: multiplexing and demultiplexing is done in commercial multimode couplers and modal diversity is enhanced by modulation rates far beyond the length–bandwidth product of the fiber. Experimental and theoretical results shown for OM1 and OM2 fibers fully confirm this theory.

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Multimode fibers (MMFs) are attractive transmission media for short-reach connections. Their application receives most attention in local area networks and in data center interconnects, where the MMFs of older types (OM1/OM2) already dominate the existing infrastructure and the new types (OM3/OM4) are being installed. In these applications, the cost of the link and the compactness of the hardware are vital issues. Consequently, uncomplicated transceiver optics and direct detection is preferred. For many years, MMFs have been considered inferior to single-mode fibers due to modal dispersion, which causes intersymbol interference (ISI) and restricts the achievable bit rates. On the other hand, it is possible to exploit the orthogonality of MMF modes and multiplex different data streams into different fiber modes.

Although multiple-input multiple-output (MIMO) MMF systems had been studied in the 80s [1], the first systems with actual data transmission at competitive bit rates were reported only few years ago [2,3]. Due to the difficulty of launching and detecting individual modes, different signals were carried by a number of neighboring mode groups, but not truly single modes of the fiber. To overcome the optical crosstalk resulting from imperfect optical demultiplexing and mode mixing in the fiber, a simple signal processing scheme at the receiver was employed. It involved combination of the signals received by spatially resolved photodiodes with different weighting factors. The coefficients were calculated to inverse the crosstalk matrix of the system [2,3]. These setups required complicated transceiver optics and energy-inefficient spatial filtering at the fiber output. For example, the setup [3] required 2 erbium-doped fiber amplifiers (EDFAs) for its operation and yet simultaneous detection of both channels was not demonstrated. The problem of poor conditioning of the channel matrix was solved by upconverting the signal to a RF carrier [4]. The intermodal dispersion actually supported the transmission, in a similar way to which multipath propagation is exploited in MIMO radio systems. The channel coefficients differ in both amplitude and phase, which results in lesser noise amplification when the channel matrix is inverted. This enabled transmission of up to four channels in an optically very simple setup, where just MMF couplers served as multiplexers and demultiplexers [5]. However, as the signal was transmitted in one of the passbands of the MMF frequency response, the signal's bandwidth was low, which resulted in poor bit rates. The rapid progress in mode multiplexing accompanied the introduction of few mode fibers (FMF) [6]. FMF transmission systems use coherent detection and an adaptive MIMO equalizer in a butterfly structure of finite impulse response (FIR) filters at the receiver [6]. This processing also eliminates the crosstalk coming from the time-delayed tributaries of different channels [7]. In addition, coherent detection facilitates MIMO operation, by introducing phase dependencies into the processing. This type of MIMO has been demonstrated for very high bit rates also in MMF [8,9]. However, in [8,9], coherent detection and selective optics at the reciever were employed [8]. To the author's best knowledge, only one direct-detection MIMO system in MMF has been demonstrated so far [10] that uses advanced digital signal processing rather than highly mode selective optics. However, the work in question lacks many details on the experimental configuration, and the operation principle of the system has not been explained.

In this Letter an intensity-modulated direct-detection mode group diversity system is described and experimentally demonstrated. The system configuration is extremely simple and low-cost. An off-the-shelf MMF coupler is used as a multiplexer and another one is used as a demultiplexer. The modal diversity is enhanced by modulation rates far beyond the bandwidth–length product of the MMF.

The physical configuration of the system is shown in Fig. 1. A MMF coupler is used to multiplex different signals into different modes of the fiber. The unconnected arm of the input coupler introduces a 3 dB loss to the system, but at the MMF output all the power is collected by the receivers. MMF coupler is a mode-selective device, i.e., if all modes are excited on its input, the lower-order modes tend to stay in the forward arm and the higher-order modes tend to couple to the lateral arm. Unfortunately, this selectivity is not high enough to avoid

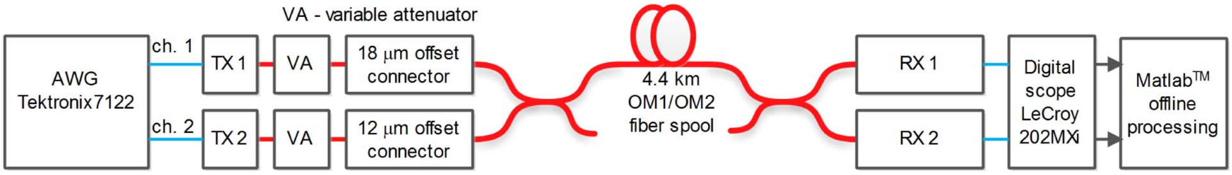

Fig. 1. Experimental setup.

significant interchannel crosstalk. For example, the measured output powers for different transmitters are given in Table 1(a) for a 4.4 km OM1 fiber link. This gives the MIMO power matrix

$$H = \begin{pmatrix} 0.44 & 0.36 \\ 0.56 & 0.64 \end{pmatrix}, \tag{1}$$

where h_{ij} denotes the measured power in the ith output when only the jth signal at the input is present. The matrix in Eq. (1) is too badly conditioned for a system based solely on matrix inversion like [2,3]. We propose to exploit modal dispersion to support the transmission [4,5,9], but here we use neither a RF carrier nor coherent detection to diversify the channel matrix coefficients; rather, we increase the bit rate far above the 3 dB bandwidth of the fiber. The crosstalk then becomes time-resolved, as different mode groups arrive at different times to the receivers and are differently filtered in the output coupler. The uneven division of power carried in each mode group, which takes place in the output splitter, leads to four different impulse responses in the system. This is shown in Fig. 2, where the measured

Table 1. Measured Output Powers (dBm) for Different Inputs in a 4.4 km Link in (a) OM1 and (b) OM2 Fiber

OM1		TX1	TX2
	RX1	−6.0	−6.1
	RX2	−4.9	−4.3
OM2		TX1	TX2
	RX1	−4.1	−3
	RX2	−3.6	−2.2

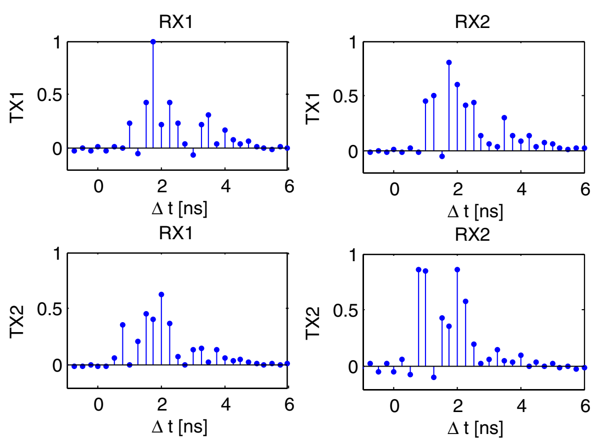

Fig. 2. Measured cross-correlation of the send and received symbol sequences for the OM1 fiber at 2×4 Gbit/s.

exemplary cross-correlations of the input (send) and received sequences have been shown for the discussed case of OM1 fiber. On one hand, the increased bit rate provides better diversity; on the other hand, it causes ISI. Therefore, we use a butterfly configured decision feedback equalizer (DFE) at the receiver to combine the time-resolved energy of signals carried by different mode groups and compensate the ISI. The DFE has a significant advantage over feed forward equalizer (FFE) in that it subtracts crosstalk and ISI without noise enhancement, which results in a higher transmission quality.

The structure of the employed equalizer is shown in Fig. 3. Its operation (in symbol-spaced fashion) is described by the equation

$$y_i(n) = \sum_{j=1}^{2} \sum_{l=0}^{L1-1} w_{ij}^f(l) x_j(n-l) - \sum_{j=1}^{2} \sum_{l=1}^{L2} w_{ij}^b(l) \hat{y}_j(n-l), \tag{2}$$

where $x_j(n)$ are the samples of the signal at the jth receiver; $y_j(n)$ and $\hat{y}_j(n)$ are the samples of the output signal prior to and after the slicer, respectively; and $L1$ and $L2$ are the lengths of the forward and feedback sections, respectively. The first term in Eq. (2) refers to the FFE and the second term refers to the DFE. The equalizer weights were calculated with the least mean squares algorithm, which also allows adaptive tracing of the crosstalk.

To prove the theory, a MATLAB simulation of a 2×4 Gbit/s transmission has been performed. The four impulse responses used for simulation came from the measurement for the OM1 fiber. First, the influence of power division in MIMO was investigated and compared with a system having ideal, delta responses. The MIMO power matrix was parameterized with ρ as

$$H = \begin{pmatrix} \rho & 1-\rho \\ 1-\rho & \rho \end{pmatrix}. \tag{3}$$

The results of simulation of transmission for SNR of 25 dB at both receivers have been shown in Fig. 4(a). For the ideal memoryless channel, the quality of

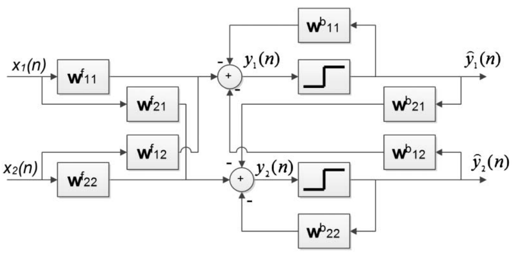

Fig. 3. Equalizer structure.

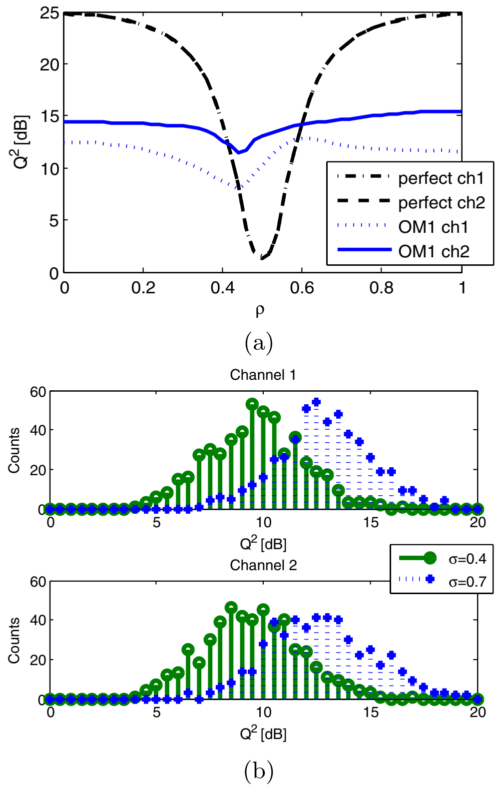

Fig. 4. (a) Influence of MIMO power matrix and (b) difference in impulse responses on the transmission quality.

transmission drops dramatically when ρ approaches 0.5 and the matrix in Eq. (3) becomes singular. This is not the case in the OM1 system, where the Q parameter drops only a little bit when ρ nears 0.5. However, even if the channels are fully separated, the highest Q is at least 10 dB below the ideal case. This gap is attributed to the equalization penalty. Furthermore, the overall behaviour of Q in terms of ρ depends on the balance between ISI and crosstalk, which explains the fact that the plot does not have symmetry in $\rho = 0.5$, and that Q may actually drop for increasing ρ.

The influence of the output coupler's modal diversity was studied in a Monte Carlo simulation, where the $h_{11}(n)$ and $h_{22}(n)$ impulse responses measured for OM1 fiber were used, but the cross-responses were randomly generated for each of the 500 transmission cases according to the formula $h_{21}(n) = h_{11}(n) + |N(0, \sigma|h_{11}(n)|)|$, where $N(m, \mu)$ defines a random variable from normal distribution with mean m and standard deviation μ. This choice of cross-responses is intended to show that the difference between the response and the cross-response affect transmission quality. The histograms of Q^2 for SNR of 25 dB have been shown in Fig. 4(b). Clearly, by increasing the diversity in the output coupler, the quality of transmission is enhanced.

The experimental setup is shown in Fig. 1. An arbitrary waveform generator (AWG) generates two separate random binary data channels of length 10^5 symbols each. The signals from AWG separately modulate two transmitters (Zonu OZ450), having a directly modulated 1310 nm Fabry–Perot laser ended with a single-mode pigtail. The modal control is achieved by using fusion-spliced single mode to multimode patch-cords with offsets of 12 and 18 μm. Pulling one of the laser pigtails out of the connector was another way to achieve modal diversity. This second type of launch excites many modes in one arm and a few mostly low-order modes in the second. Interestingly, for this type of launch, the results were better in terms of achievable bit rate than for the offset launch. However, we focus on the offset launch only, as it has produced more even power division in the splitters, and the power MIMO matrix was more badly conditioned (Table 1). After transmission, the signal is split in a MMF coupler to two p-i-n photoreceivers (Thorlabs PDA8135). The signal is then sampled at a rate of 10 Gs/s in a digital scope, and further processing takes place in MATLAB. The 3 dB bandwidth of the transmitters and receivers is 3.3 and 9.6 GHz, respectively. The overfilled bandwidth of both OM1 and OM2 fiber was 500 MHz · km (or approx. 120 MHz for 4.4 km). The equalizer used was $T/2$ spaced and had 40 feed forward and 15 feedback taps. The initial 10^4 symbols are used as a training sequence and the transmission quality is evaluated for the remainders of the sequences.

The measured Q factor at different bit rates is shown for 4.4 km OM1 and OM2 fibers in Fig. 5. Increasing the bit rate results in greater diversity in the impulse responses in the system and supports the transmission, at least to the point where the diversity is offset by higher ISI. In both fibers, transmission below 500 Mbit/s per channel was hardly possible, whereas the best results were achieved for 2–2.5 Gbit/s, and operation above 8.5 dB forward error correction threshold level was still possible for 5 and 4 Gbit/s per channel for OM2 and OM1, respectively. The DFE, which is particularly effective at suppression of ISI, performs better than FFE, especially at high bit rates at which ISI dominates the crosstalk. Furthermore, Ch. 1, launched into OM2 with 18 μm offset, undergoes much higher delay spread than Ch. 2, and FFE is not able to suppress the ISI for this channel. Hence, lower Q is measured in Ch. 1 than in Ch. 2 for FFE. This is not the case for OM1, where the channel response lengths are comparable (Fig. 2). The transmission distance should have a similar impact on Q as the bit rate: its increase resolves mode groups in time due to the increased differential mode delay. However, at some point, ISI and attenuation in the fiber become too high and prohibit the reception.

The system performance is investigated for OM2 in terms of received power in Fig. 6. In the single input

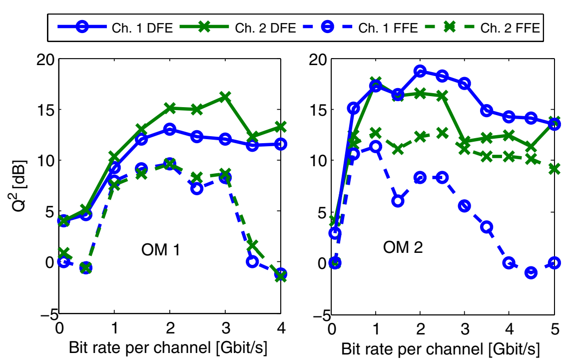

Fig. 5. Measured Q^2 [dB] for different bit rates.

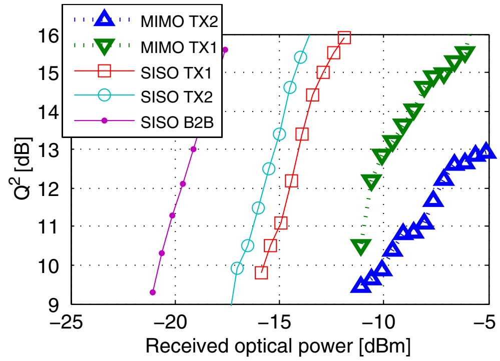

Fig. 6. Average Q^2 [dB] versus receiver input power for OM2 at 3 Gbit/s per channel.

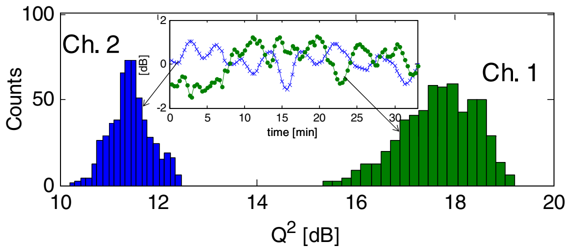

Fig. 7. Measured Q^2 [dB] histogram for OM2 at 3 Gbit/s with relative time changes recorded for 35 minutes.

single output (SISO) case, TX2 and TX1 have a penalty of about 4 and 5 dB with respect to B2B case. The MIMO system has a further penalty of approximately 5 dB. Also, the rise in Q with increasing power is slower for MIMO than for SISO. This is attributed to additional noise enhancement caused by crosstalk compensation at the equalizer. Due to environmental changes, the speckle pattern at the splitter input varies in time, causing slight changes in the mode group filtering at the coupler; this may cause a statistical variation of Q. To study this effect, Q was evaluated every 20 s for 2×3 Gbit/s in OM2 (Fig. 7). The changes were relatively slow and moderate, especially if compared to a 2×2 system based on strong spatial filtration at the output [11].

We report on a successful experimental transmission of 2×4 Gbit/s in a 4.4 km OM1 fiber and 2×5 Gbit/s in an OM2 fiber, which is approximately 80 times higher than their bandwidth–length products. Unlike previous experiments, we achieved this result with off-the-shelf components only, without the use of free-space optics or optical amplification. The modal diversity was enhanced by transmission at a bit rate exceeding the 3 dB bandwidth of the fiber and use of DFE. We believe that this method may become a viable means of coarse multiplexing in legacy MMF, especially if more modally selective couplers are used. The scalability of the system for higher number of channels is yet to be determined.

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