Abstract: We investigate experimentally the feasibility of a 2x2 MIMO system based on Mode Group Diversity Multiplexing to enlarge the bandwidth distance product of MMF. A data rate of 10.7 Gb/s over 300m GI-MMF is achieved.

1. Introduction

Multimode fibre (MMF) is a very attractive transmission medium due to low cost components compared to single mode fibre (SMF) in broadband local area networks (LANs) [1]. However, MMF is characterized by a low bandwidth distance product compared to SMF due to its multi mode character which implies mode dispersion as main limiting transmission effect. Several approaches like different multiplexing methods (Coarse-WDM), mode group diversity multiplexing (MGDM)) or equalization [2] were discussed in the last years to overcome this bandwidth limitation. Thereby, the MGDM approach is characterized by a high potential to increase the data rate [3]. Until now, a large research effort has been made to investigate possible transmitter and receiver setups to realize MGDM in high speed transmission systems [1,4]. In this paper, we investigate the feasibility of a complete MGDM system using mode multiplexing at the transmitter and demultiplexing at the receiver side. We show by experiments in the first part of the paper that the limiting effect of mode dispersion can be overcome by using a 2 x 2 MGDM system at a total data rate of 10.7 Gb/s over 300 m GI-MMF. In the second part, the crosstalk between the two copropagating channels is analysed by BER measurements.

The paper is structured as follows: Section 2 describes briefly the general idea of MGDM followed by section 3 which shows our experimental setup. The feasibility of MGDM and the investigation of the crosstalk between the propagating signals are presented in section 4.

2. General Setup of MGDM

Fig. 1a shows the general setup of the investigated 2 x 2 MIMO system consisting in two input signals s1(t) and s2(t), an optical transmission line characterized by four transmission coefficients and two output signals y1(t) and y2(t). Based on the mode multiplexing approach, s1(t) and s2(t) are assigned to different mode groups which are copropagating in the MMF [1]. The excitement of the different mode groups is realized by two different restricted launch positions (position 1 (P1); position 2 (P2)) as shown in fig. 1b. Thereby, P1 excites low order modes which are travelling mostly in the centre of the core whereas P2 excites high order modes which are travelling close to the core cladding interface [4]. This intensity distribution between the excited mode groups gives the possibility to separate the signals by two detection areas as shown in fig. 1d. Thereby, area 1 detects the low order mode groups and area 2 the high order mode groups [5].

Fig: 1a: General setup of the 2 x 2 MIMO system with four transmission coefficients h11, h12, h21, h22; b) mode multiplexing by two restricted launch positions (P1 and P2); c) demultiplexing by two different detection areas (area 1: low order modes, area 2: high order modes)

MMF links are mainly limited by the disturbing influence of mode dispersion which is linearly dependant on the data rate. This means that the influence will be significantly reduced by using a 2 x 2 MIMO system based on MGDM consisting in two data streams each with half of the total bit rate. However, these signals are disturbed by each other due to the effect of crosstalk indicated by the transmission coefficients h21 and h12 in fig. 1a. This effect becomes more important in MMF with smaller core diameter.
3. Experimental Setup

Fig. 3 shows the experimental setup for investigating a 2 x 2 MIMO system. The MGDM technique was shown with two different fibres of core diameter 62.5 um (fibre 1) and 50 um (fibre 2).

The coherent light of the single mode laser ($\lambda=1540\,\text{nm}$) is split into two arms and modulated by two Mach Zehnder Modulators (MZMs). These are driven with two PRBS sequences of length $2^{23}-1$. The data rate in each arm is set to 5.35 Gb/s which gives a total data rate of 10.7 Gb/s (including a standard FEC overhead). Both streams were decorrelated by means of different delays. After amplification with EDFAs and attenuation with variable optical attenuators (VOAs) the upper arm was launched with 0 um offset at the centre of the MMF. This was realized with a centre launch connector (CLC, fig.3a) with a direct connection between SMF (thin line) and MMF (thick line). The lower arm was launched with an offset of 20 um which was realized by an offset launch connector consisting in a patch cord from SMF to MMF (OLC, fig. 3b). Afterwards the signals were coupled together by a mode preserving 2 x 1 coupler (fig. 3c). Finally, the multiplexed signal was transmitted over one of the two tested GI-MMF. The demultiplexing was realized by a micropositioner which gives the possibility to detect a part of one of the two detection areas (see fig. 1c) by a movable SMF (core diameter: 9um). Afterwards the signal is amplified (necessary due to the loss (15 dB) resulting from the small detection area), detected by a photodiode and analyzed with oscilloscope and BER tester.

4. Experimental results

In fig. 4a and fig. 4b, the experimentally determined eye diagrams are shown for the 2x2 MIMO system over 300 m of fibre 1 (core diameter: 62.5um). Thereby, input power was set to 5dBm in each arm. We observe wide open eyes for both detection areas. The power distribution of signal 2 (OLP) is spread out over a large part of the core area, thus with the SMF only a small fraction of the total power in area 2 is detected[4]. For comparison purposes, we show in fig. 4d the eye diagram for a system consisting in one 10.7 Gb/s signal which is launched in overfilled position and received with a MMF photo detector, which detects the complete power in MMF cross section (fig. 4c).

**Fibre 1: 2 x 5.35 Gb/s over 300 m**

**Fibre 1: 1 x 10.7 Gb/s over 300 m**

**Fibre 2: 2 x 5.35 Gb/s over 300 m**

![Eye diagrams for 2x5.35 Gb/s over 300m GI-MMF (Fibre1)](image1)

![Eye diagram for 1x10.7 Gb/s over 300m GI-MMF (overfilled launch position and complete detection area)](image2)

![Intensity distribution for 20 um and 0um offset](image3)

![Superposition of fig e,f with detection points](image4)

![Detected eye diagrams (fibre 2)](image5)
We observe a closed eye due to the strong influence of mode dispersion in fig. 4d. This is explained by a high number of excited modes (overfilled launch position) and a detection area that covers the complete core cross section [4,5].

The experimental results of MGDM including crosstalk investigations over fibre 2 are shown in the right part of fig. 4. In fig. 4e and fig. 4f the intensity distributions over the core cross section for fiber 2 after 300m transmission for P2 and P1 are shown, respectively. For launching at P2, low power levels in the centre of the core and high intensity levels formed as a ring are visible for larger radii. In contrast to that, we see a high intensity in the core centre and a low intensity for larger radii if we launch with 0 um offset. In fig. 4g the superposition of fig. 4e and fig. 4f is shown. Thereby, the white colour represents the area of higher intensity of signal 1. By detecting at the indicated points (grey circles), we see again wide open eyes for fibre 2 as shown in fig. 4h and fig. 4i. However, we observe a widened one level compared to the experiments with fiber 1 which indicates a higher crosstalk due to the lower core diameter. Therefore, we investigate in more detail the influence of crosstalk between the two signals for varying power levels by BER measurements. In fig.5a, the determined BER curves are shown over the received input power for the two detection areas by solid lines (grey for detection area 1 and black for detection area 2). The dotted lines in fig. 5a show the situation without crosstalk (separate transmission of signal 1 and signal 2).

For separate transmission of $s_1(t)$ and $s_2(t)$, we can see slightly better performance (ca.1dB) of reference signal 1 detected by area 1 compared to signal 2. In addition, it is visible by the solid lines in fig. 5a that the transmission quality of signal 2 is much more degraded by the crosstalk due to MGDM compared to signal 1. A 6 dB worse performance to the reference signal 2 is measured whereas the degradation for signal 1 is approximately 0.5 dB. This fact might be explained by high intensity values of signal 1 which are concentrated in much smaller area of the core’s centre compared the larger ring shaped area of signal 2. This assumption is confirmed by BER curves shown in fig. 5b for varying power levels of signal 1 and constant power level of signal 2. We can extract that the signal quality of signal 2 is significant improved for decreasing power values of signal 1. By using 9 dB less input power level in signal 1, we achieved an error free transmission of signal 2 with only -27.5 dBm received input power which means a reduced penalty of 2.5 dB to the reference signal. Even for this power ratio, we achieved error free transmission for signal 1. Thus we have shown 10.7 Gb/s error free transmission for both signals, different fibre types and different power ratios. However, we have to mention that the crosstalk will be larger if detecting close to the border between the two detection areas. For this case an equalization process using the transmission coefficients (see fig. 1a) will be unavoidable.

5. Conclusion
We show by experiments the feasibility of using a 2 x 2 MIMO system based on Mode Group Diversity Multiplexing (MGDM) to overcome the bandwidth limitation of mode dispersion in GI-MMF. We achieved an error free transmission over 300 m GI-MMF at 10.7 Gb/s. In addition, it was shown by BER measurements that the signal carried by high order modes suffers more from crosstalk compared to the signal carried by low order modes.

References