An Experimental Investigation of the Mode Group Diversity Multiplexing Technique

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Mode group diversity multiplexing (MGDM) has been proposed as a means to create independent, transparent communication channels over a multimode fibre in short reach optical networks. In this paper we provide an experimental investigation of the MGDM technique focusing on the linearity of the fibre's response and the temporal variations of the transmission matrix coefficients, which describe the signal transfer from the N transmitters to the M receivers of an MGDM system. The analysis presented is a key step towards the demonstration of this novel multiplexing technique.

1 Introduction

Multimode fibre (MMF), especially graded index MMF (GI-MMF), has been the preferable transmission medium in campus and in-premise networks, as an easier-to-install alternative to single-mode fibre. As the need for higher bandwidth increases, MMF links reach their performance limit due to differential mode delay (DMD). A simple way to upgrade these links is with the offset launch technique [1]. As a step further different offset beams can be used to excite different groups of modes allowing several (N) communication channels over the same MMF. This is the objective of the Mode Group Diversity Multiplexing (MGDM) technique [2]. MGDM requires electronic processing of the received signals to mitigate the crosstalk among the channels. In general M received signals are related to the N transmitted ones via an MxN transmission matrix (**H**), whose elements h_{ij} describe the signal transfer from source j to detector i. The signal processing unit recovers the N transmitted signals when the transmission matrix is known. Recently a design for an MGDM transceiver has been proposed [3].

Furthermore, MMF may also play an important role in future in-house networks, meant to provide the residential user with large bandwidth and a diversity of services, with Plastic Optical Fibres (POF) being of particular interest due to their ease of handling. Especially in the case where PMMA-based GI-POF is used [4], featuring low fabrication cost and a very large core diameter, MGDM can be proved a key way of multiplexing transparent channels due to the narrow attenuation spectrum of the PMMA material which limits the implementation of CWDM.

Transparency and robustness are two important requirements for such a system. In this paper we present an experimental investigation of the MGDM technique. The objective is to examine the linearity of the system as well as the temporal variations of the transmission matrix coefficients; both these features have a strong impact on the electronics design required for a transparent and robust system.

2 Experimental set-up

A fibre concentrator (FC) was used at the transmitting side of the system (fig. 1). The FC transforms waveguides from the standard pitch of 125 μm into 30 μm. Each

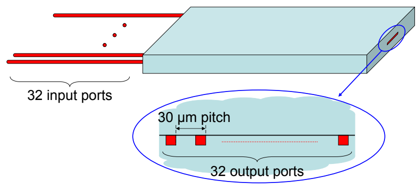


Fig. 1 Fibre Concentrator.

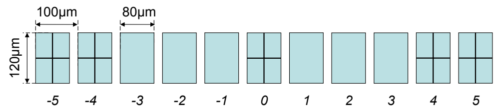


Fig. 2 PDIC photodiodes.

waveguide has a single-mode cut-off wavelength of approximately 1200 nm. The concentrated side of the FC was butt-coupled to a 2 km long silica GI-MMF with 148 µm core diameter and 200 µm core-cladding diameter, allowing light from two uncooled 635 nm lasers to be launched simultaneously into the GI-MMF with radial offsets 0 and 30 µm – corresponding to transmitter 1 and 2 – and thus exciting two different groups of modes. The lasers were followed by variable optical attenuators (VOAs) to control the level of the optical power. At the receiving end of the system an optoelectronic IC which contains Photo-Detectors and pre-amplifiers (PDIC) was used [5]. The PDIC was originally designed for optical storage systems and has highest responsivity at red light. The geometry of its integrated photodiodes is illustrated in fig. 2. Each segment consists of four sub-segments and has one RF output which gives the total response from the four sub-segments. Additionally, segments -5, -4, 0, 4 and 5 have four more RF outputs, one from each of the four sub-segments. A lens was used to project the Near Field Pattern (NFP) at the fibre output on the PDIC. The RF outputs of the PDIC were sent to a computer via A/D converters for further analysis of the received signals. The set-up is illustrated in fig. 3.

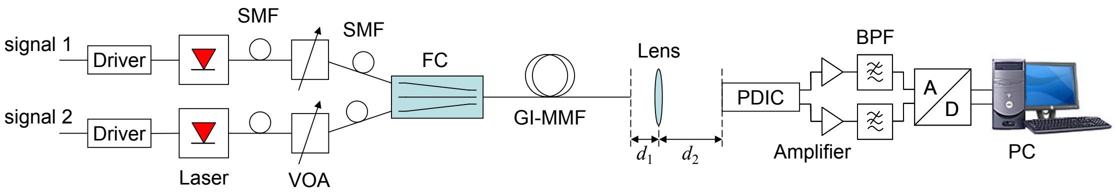


Fig. 3 Experimental set-up.

The distances d_1, d_2 depend on the desired magnification (m) and the focal length of the lens. The magnification was m=2, allowing for the realization of a 2x2 system while minimizing the coupling losses at the receiving side (fig. 5). Two FC ports and three PDIC segments were used; one to detect the lower order modes and two (with one combined output) for the higher order modes. Fig. 4 illustrates the NFP yielded when light is launched separately in each FC port as well as when the two ports are used simultaneously.

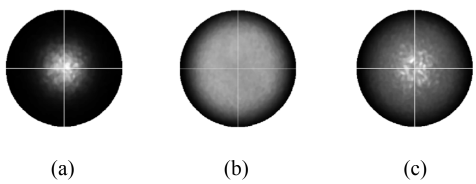


Fig. 4 Near Field Pattern at the output of the GI-MMF for (a) central launch (b) offset launch (c) central and offset launch simultaneously.

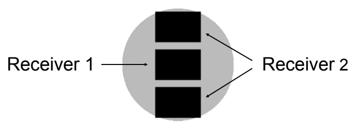
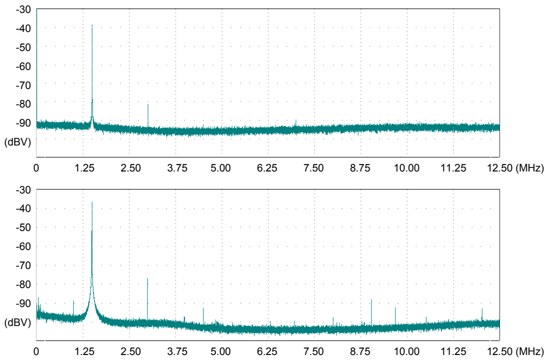


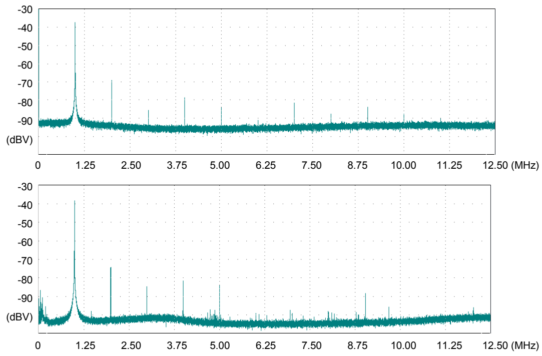
Fig. 5 Geometry of the receiving side of the 2x2 system where three segments of the PDIC are used. Black colour has been used for the PDIC segments and gray for the magnified fibre core.

3 Results

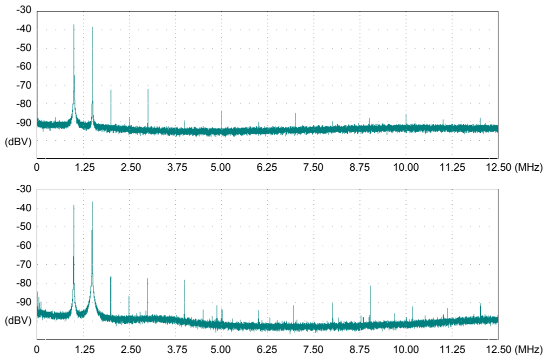
To study the linearity of the system the two lasers were intensity modulated by two sinusoidal signals; 1 and 1.5 MHz were used at the lower and the higher order modes respectively. The bias point of the lasers and the modulation depth were chosen so as to provide the most linear possible output. The Fourier transform of the received signals is depicted in fig. 6. No evident harmonics are introduced due to the simultaneous propagation of the two signals. The MMF having a linear response, the system linearity depends on the linearity of the lasers, the photodiodes and the electronic circuits used.



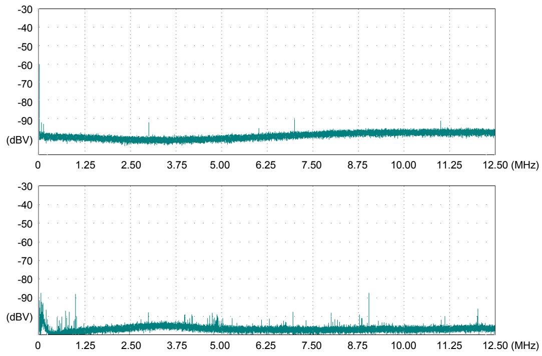
Higher order modes detected by the central (upper graph) and the two edge segments (lower graph) of the PDIC.



Lower order modes detected by the central (upper graph) and the two edge segments (lower graph) of the PDIC.



Lower and higher order modes detected by the central (upper graph) and the two edge segments (lower graph) of the PDIC.



System response without any input signals.

Fig. 6 Fourier transform of the two outputs of the MGDM set-up.

The time variations of the transmission matrix coefficients were examined by measuring the power level at the two pilot frequencies (1 and 1.5 MHz) at both outputs of the system and they are shown in fig. 7. The average values – normalized to the power received by the two PDIC segments associated with the higher order modes – give the following transmission matrix

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \begin{bmatrix} 0.55 & 0.37 \\ 0.40 & 0.60 \end{bmatrix}$$

It becomes clear (fig. 7) that the time variations of the transmission matrix coefficients are very moderate. The observed fluctuations do not necessarily indicate variations in the mode spectrum of each channel. The lasers operated uncooled and without any optical power feedback control loop; consequently the output power of the lasers fluctuates with time. Depending on the length of the fibre, the coherence time of the sources and the number of excited modes, speckles will occur at the NFP. In our set-up (fig. 3) this may yield modal noise due to the spatial filtering at the receiving side, especially at the lower-order-modes channel where the speckle pattern is stronger (fig. 4). As it can be seen from fig. 7 the stronger fluctuations appear in the h_{11} coefficient, which describes the power transmitted in the lower order modes and detected by the central segment of the PDIC. In a properly designed system [3], although there is spatial selectivity, the total power at the MMF end is detected and thus the power variations at every channel due to mode selectivity can be mitigated by continuously updating the transmission matrix, e.g. by assigning an out-of-band pilot signal at each channel.

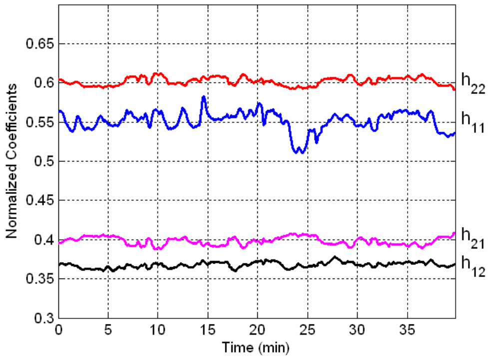


Fig. 7 Time variation of the transmission matrix coefficients (normalized to the power received by the two PDIC segments associated with the higher order modes).

Expanding the experimental set-up of fig. 3 to include a demultiplexing unit will allow the first demonstration of a transparent MGDM system.

4 Conclusions

We have designed and realized an experimental set-up that can be used to investigate and subsequently demonstrate the MGDM technique. Since the response of the MMF is linear the requirements on the system linearity are similar as in any other analog optical system. The investigated 2x2 system shows robustness since the transmission matrix coefficients do not fluctuate significantly in time. Uncooled lasers have been used to keep the system simple and cost-effective.

5 Acknowledgement

Funding from the Freeband Impulse programme by the Dutch Ministry of Economic Affairs is gratefully acknowledged.

6 References

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