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Design Considerations for a Transparent Mode Group Diversity Multiplexing Link

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Abstract—**Mode group diversity multiplexing (MGDM) is an optical multiple-input–multiple-output technique that aims at creating independent communication channels over a multimode fiber, using subsets of propagating modes. This letter deals with the analysis of an MGDM point-to-point link, transparent to the transmission format. The geometry of a mode-group selective multi/demultiplexer is optimized in order to minimize the crosstalk among the channels. The power penalty is calculated when a zero-forcing algorithm is used to mitigate the crosstalk.**

Index Terms—**Graded-index multimode fiber (GI-MMF), mode group diversity multiplexing (MGDM), optical multiple-input–multiple-output (MIMO), transparent optical link.**

I. INTRODUCTION

IN SHORT-REACH optical networks, multimode fiber (MMF), primarily graded-index (GI) MMF, has been the medium of choice. Its large core diameter makes MMF splicing easier than that of single-mode fiber (SMF). On the other hand, the bandwidth of an MMF is significantly lower than that of an SMF in the classical intensity-modulation direct-detection approach. This is due to the differential mode delay (DMD) among the propagating modes. To enhance the performance of GI-MMF links, techniques such as selective mode launch [1] and spatially resolved equalization [2] can be applied. As a step further and aiming at the integration of several services—such as analog/digital TV, Internet traffic and voice—over a common optical infrastructure, different groups of modes can be excited and used as independent, parallel communication channels. This is the objective of the mode group diversity multiplexing (MGDM) technique [3].

MGDM is an optical multiple-input–multiple-output (MIMO) scheme that requires electronic processing of the received signals to mitigate the crosstalk among the channels. MIMO is a well-known principle in wireless communications to provide larger robustness and capacity. At the transmitter, there are N sources, each exciting a different group of modes and at the receiving side M detectors selectively respond to a different part of the near-field pattern (NFP) at the fiber output. In MIMO systems $M \geq N$. The more receiving antennas, the larger the total received power. However, when the transmission medium is an MMF, the total received power remains constant

and is simply split among the detectors. This is why preferably $M = N$ in the case of MGDM.

In general, the relation between the received and the transmitted electrical signals is not simple. Propagation in the MMF introduces dispersion and mode mixing. However, in some cases this relation can take the form of a simple matrix [4]. In other words, the received electrical signals vector $\mathbf{s}_R(t)$ is related to the transmitted electrical signals vector $\mathbf{s}_T(t)$ via matrix $\mathbf{H}(t)$, i.e., $\mathbf{s}_R(t) = \mathbf{H}(t)\mathbf{s}_T(t) + \mathbf{x}(t)$, where $\mathbf{x}(t)$ is a noise component. If dispersion can be neglected, the transmission matrix elements $h_{i,j}$ are real-valued, expressing the proportion of the power transmitted by the jth source and received by the ith detector. The signal processing unit recovers the N transmitted signals by matrix inversion, when $\mathbf{H}(t)$ is known. Electronic processing and fiber dispersion bound the bandwidth of the link. However, the format of $\mathbf{s}_T(t)$ can be arbitrary. In this sense, the link is transparent.

In this letter, a transparent MGDM point-to-point link is analyzed, yielding a scheme consistent with high coupling efficiency (η) and simplicity. A significant part of the analysis is based on an experimental estimation of the optical crosstalk among the channels, for a $62.5/125$ μm silica GI-MMF, the most commonly installed type of MMF.

II. GEOMETRIC CONSIDERATIONS AND CROSSTALK ESTIMATION

One way to selectively excite a GI-MMF is by launching a Gaussian beam at its front facet. Compared with other techniques, such as using a mask at the input of the GI-MMF [5] or side launch through a prism [6], excitation with a Gaussian beam is simple and provides high η. The set of excited modes depends on the launch conditions, i.e., the beam waist radius, as well as the radial ρ_0, angular θ_0, and axial offsets. These offsets refer to the radial and angular displacement of the beam with respect to the GI-MMF axis and the distance of the beam waist from the input facet of the GI-MMF. In order to obtain the narrowest possible mode spectrum, the beam waist should lie on the fiber facet (zero axial offset) with its radius varying according to the wavelength, the index profile, and the radial offset ρ_0 [7]. A good compromise is to use a standard (for a given wavelength) SMF. The angular offset is chosen $\theta_0 = 0$ since this ensures high η for large ρ_0 and, as it will be shown, yields a design independent of the GI-MMF length.

In the following, a 3×3 link will be discussed, serving as an example for the design of an $N \times N$ one. The multiplexer consists of three radially offset beams. At the receiving side, a three-segment receiver geometry is proposed. The segment areas are chosen so as to minimize the crosstalk among the channels.
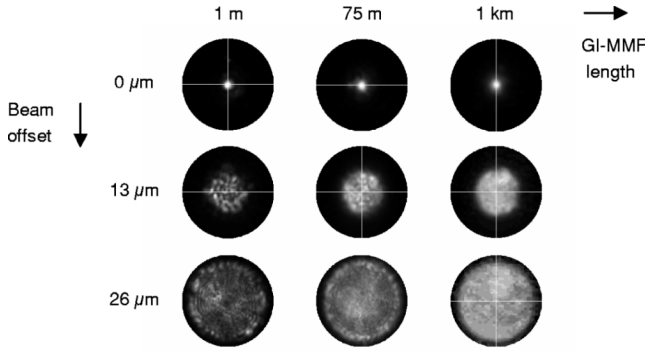
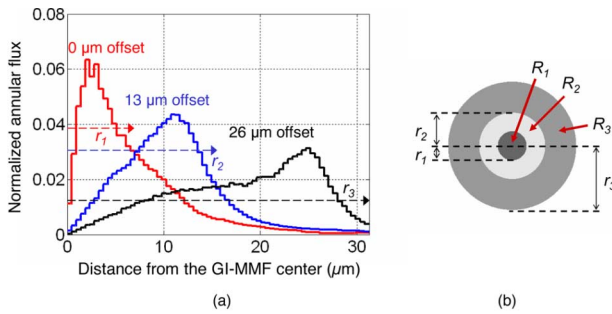Fig. 1. NFP at the output of a $62.5/125$ μm silica GI-MMF under selective excitation with a radially offset beam.

Fig. 2. (a) Normalized annular flux of the NFP at the output of a 75-m $62.5/125$ μm silica GI-MMF, when the latter is excited by a radially offset beam. (b) Three-segment MGDM receiver geometry based on (a).

A 660-nm Fabry–Perot laser diode pigtailed to a 1 m SMF with mode field diameter 4.2 μm and numerical aperture (NA) 0.12 was used to selectively excite three samples of $62.5/125$ μm silica GI-MMF, with central NA 0.275, of lengths 1 m, 75 m, and 1 km. The SMF output was launched on the input facet of the GI-MMF with radial offsets of 0, 13, and 26 μm, corresponding to beams $T_1, T_2,$ and T_3 of the investigated multiplexer scheme. The position of the SMF was controlled by computer-driven translational stages. The NFP at the GI-MMF output was observed through a microscope ($50\times$, NA 0.75) with a charged-coupled device (CCD) camera. The laser was operating above threshold and the 75-m and 1-km fibers were placed around a 15-cm diameter drum. In a real MGDM link, the three beams should be launched simultaneously. This can be achieved by means of a laser array or a planar waveguide [8].

The NFP has a disk shape whose radius length is similar to the radial offset of the launched beam (Fig. 1). It is evident that the disk radius is practically independent of the GI-MMF length, indicating that mode mixing is limited. Similar NFPs have been observed at 1300-nm wavelength [8]. Fig. 2(a) depicts the spatial overlap among the normalized annular flux of the three MGDM channels for the 75-m fiber. The result is similar for the other two fibers. The annular flux is the integrated intensity between radii r and $r + \mathrm{d}r$ over the fiber facet [9]. Due to the circular symmetry of the GI-MMF, a circular three-segment receiver geometry is proposed, consisting of three annular segments [Fig. 2(b)]. The three radii that define the receiver segments are $r_1 = 7$, $r_2 = 16$, and $r_3 = 31.25$ μm. In legacy GI-MMF, defects may occur in the refractive index profile, primarily close to the GI-MMF axis. This may mainly affect the

value of r_1. Assuming linear superposition of the three power distributions at the GI-MMF output, the $h_{i,j}$ coefficients can be estimated by

$$h_{i,j} = \frac{\iint_{R_i} I_j(r,\phi) r \, \mathrm{d}r \, \mathrm{d}\phi}{\int_0^{2\pi} \int_0^\alpha I_j(r,\phi) r \, \mathrm{d}r \, \mathrm{d}\phi}$$

where $I_j(r,\phi)$ is the intensity distribution of the NFP caused by T_j, (r,ϕ) the polar coordinates on the fiber facet with $r = 0$ on the fiber axis, R_i is the area of the ith receiver segment, and α the core radius of the GI-MMF. The resulting matrix is

$$\mathbf{H} = \begin{pmatrix} 0.64/0.67/0.61 & 0.23/0.23/0.19 & 0.08/0.07/0.07 \\ 0.30/0.26/0.29 & 0.65/0.63/0.63 & 0.30/0.30/0.29 \\ 0.06/0.07/0.10 & 0.12/0.14/0.18 & 0.62/0.63/0.64 \end{pmatrix}$$

presented in the form $h_{i,j}\{75 \text{ m}/1 \text{ m}/1 \text{ km}\}$. The matrix was similar for laser operation below threshold.

The total optical crosstalk at R_i is $10\log_{10}(\sum_{j\neq i} h_{i,j})/(h_{i,i})$ (dB). The receiver radii of the investigated 3×3 link minimize the crosstalk, given the input beams. For the 75-m fiber, crosstalk at channel 1, 2, and 3 is -3.1, -0.3, and -5.4 dB, respectively. The $h_{i,j}$ coefficients vary very moderately with the GI-MMF length. Therefore, the dependence of the power budget of the proposed MGDM link on the fiber length will be mainly due to the fiber loss.

Crosstalk could be reduced by bounding the propagating power in the ith channel between r_{i-1} and r_i. Annular NFPs can be observed by introducing an angular offset θ_0 to the input beams, in accordance with the launch of helical rays [10]. However, the thickness of such patterns varies with the fiber length. In addition, clear annular patterns appear when the coherence time of the source is very small, as in LEDs. Furthermore, in the case of the investigated 3×3 system, introducing an angular offset to T_3 would result in very low η due to the small local NA.

III. POWER PENALTY ANALYSIS

A mode-group selective multi/demultiplexer has been hitherto proposed and the optical crosstalk among the channels has been estimated. To recover the input signals, electrical processing is required. For MGDM, the simplest receiver architecture is matrix inversion, a zero-forcing method in line with the requirement of service transparency [11]. In this section, we calculate the power penalty as a result of matrix inversion, and we examine its sensitivity to misalignments.

After matrix inversion, the estimated transmitted signals are $\hat{\mathbf{s}}_T(t) = \hat{\mathbf{H}}^\dagger(t)\mathbf{s}_R(t) + \mathbf{y}(t) \Rightarrow \hat{\mathbf{s}}_T(t) = \hat{\mathbf{H}}^\dagger(t)(\mathbf{H}(t)\mathbf{s}_T(t) + \mathbf{x}(t)) + \mathbf{y}(t)$, where $\mathbf{y}(t)$ represents the noise from the demultiplexing unit and $\hat{\mathbf{H}}^\dagger(t)$ is an estimate of the inverted matrix $\mathbf{H}^\dagger(t) = \{h_{i,j}^\dagger(t)\}$. Assuming ideal channel estimation, i.e., $\hat{\mathbf{H}}^\dagger(t) = \mathbf{H}^\dagger(t)$, $\hat{\mathbf{s}}_T(t) = \mathbf{s}_T(t) + \mathbf{H}^\dagger(t)\mathbf{x}(t) + \mathbf{y}(t)$. It is clear that, although matrix inversion recovers the transmitted signals, noise increases. The two noise terms $\mathbf{x}(t)$ and $\mathbf{y}(t)$ depend on the specific implementation of the receiver. To calculate the power penalty, we focus on the term $\mathbf{H}^\dagger(t)\mathbf{x}(t)$, since this term expresses the noise enhancement due to the demultiplexing algorithm. The variance of the noise at the jth channel is $\sigma_j^2 = \sum_{k=1}^N (h_{j,k}^\dagger)^2 \mathrm{Var}(x_k)$, where x_k are the statistically independent elements of the noise vector $\mathbf{x}$.

TABLE I
AVERAGE (MAXIMUM) POWER PENALTY, OPTICAL CROSSTALK, AND
GEOMETRIC DESIGN PARAMETERS FOR AN $N \times N$ MGDM SYSTEM

$N \times N$	Shot noise limit (dB)	Thermal noise limit (dB)	Optical crosstalk (dB)
2×2	2.3 (2.3)	1.2 (1.4)	-6.7 (-5.7)
3×3	5.7 (7.2)	2.9 (3.2)	-2.8 (-0.4)
4×4	8.3 (10.3)	4.2 (4.7)	-0.8 (1.5)
5×5	11.3 (13.3)	5.6 (6.3)	0.8 (2.7)

| $N \times N$	Radial offsets (μm)	Segment-radii (μm)
2×2	0, 26	12, 31.25
3×3	0, 15, 26	7, 17, 31.25
4×4	0, 10, 19, 26	5, 12, 20, 31.25
5×5	0, 10, 15, 21, 26	5, 10, 16, 22, 31.25

Fig. 3. Influence of misalignments on the power penalty of the mostly affected channel of (a) a 3×3 and (b) a 4×4 MGDM link. A1 corresponds to no misalignment (Table I). B1 and C1 correspond to $+2$ μm and -2 μm misalignment at the transmitting side. A2, B2, and C2 correspond to A1, B1, and C1 with 2 μm misalignment at the receiving side.

We distinguish the two cases where either shot or thermal noise is the prevalent noise source. The first one gives a fundamental limit of the system performance, while the second one is practically always present. Other sources of noise, such as modal noise, do not have a fundamental limit and are more related to the temporal behavior of the system. The signal-to-noise ratio (SNR) at the jth channel is $\mathrm{SNR}_j = \bar{P}_j/\sigma_j^2$, where $\bar{P}_j$ is the average power defined by the bias of the lasers. In the following, we assume that $\bar{P}_j = \bar{P}, \forall j$. The noise variance at the shot noise limit is $\mathrm{Var}|_{\mathrm{shot}}(x_k) = \sum_{l=1}^{N} h_{k,l}\bar{P}$ and at the thermal noise limit $\mathrm{Var}|_{\mathrm{thermal}}(x_k) = \sigma_{\mathrm{thermal}}^2$. The power penalty at the jth channel of an MGDM link is

$$\left.\frac{\bar{P}_j^*}{\bar{P}}\right|_{\mathrm{shot}} = \sum_{k=1}^{N} \sum_{l=1}^{N} (h_{j,k}^{\dagger})^2 h_{k,l}$$

$$\left.\frac{\bar{P}_j^*}{\bar{P}}\right|_{\mathrm{thermal}} = \sqrt{\sum_{k=1}^{N} (h_{j,k}^{\dagger})^2}$$

where $\bar{P}_j^*$ is the average power required to maintain the SNR of the single-channel case. Table I shows the average and maximum power penalty and optical crosstalk for an $N \times N$ system with $N = 2, \ldots, 5$. It also gives the corresponding geometric parameters for the design of the multi/demultiplexer. Apart from optimizing the receiver radii, optimal offsets of the input beams have been approximated as well. The matrix elements $h_{i,j}$ have been measured using the 75-m fiber.

A feature of MMF links is tolerance in alignment. In order to maintain this feature, the radially offset-most beam should lie at $\rho_{\max} = \rho_\eta - d_{\mathrm{tol}}$, where ρ_η is the maximum radial offset ensuring a desired η and d_{tol} the required tolerance in alignment. However, misalignments will change the spectrum of excited modes, and consequently the NFP. This will affect the crosstalk and therefore the power budget. Fig. 3 shows the influence of misalignments on the power penalty of channel 1, which is the mostly affected channel of the proposed MGDM link with $N = 3$ and $N = 4$. The same tolerance $d_{\mathrm{tol}} = 2$ μm has been used at the transmitting and the receiving side. The 3×3 link is much more robust than the 4×4 one. The latter is primarily affected by the -2-μm misalignment at the transmitting end, since a smaller part of the fiber core is used to propagate the optical signals.
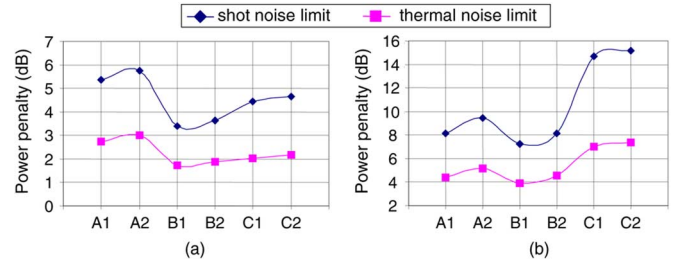
IV. CONCLUSION

In this letter, we have provided geometric considerations for an MGDM multi/demultiplexer, in the context of a simple transparent link. We have shown the tradeoff between the number of channels and the power penalty when a zero-forcing algorithm is used to demultiplex the received electrical signals. For the case of $62.5/125$ μm silica GI-MMF, to maintain robustness against small misalignments (~ 2 μm), the number of channels should not exceed three. The same approach can be applied to other types of GI-MMF, e.g., polymer optical fibers, viewed as suitable candidates for in-house networks [3].

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