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 sources, each exciting a different group of modes and at the receiving side detectors selectively respond to a different part of the near-field pattern (NFP) at the fiber output. In MIMO systems 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 $j$th source and received by the $i$th detector. The signal processing unit recovers the 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 ($\eta$) and simplicity. A significant part of the analysis is based on an experimental estimation of the optical crosstalk among the channels, for a $62.5/125 \mu$m 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 $\eta$. The set of excited modes depends on the launch conditions, i.e., the beam waist radius, as well as the radial $\rho_0$, angular $\theta_0$, 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 $\rho_0$ [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 $\eta$ for large $\rho_0$ and, as it will be shown, yields a design independent of the GI-MMF length.

In the following, a $3 \times 3$ 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.
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

$$h_{i,j} = \frac{\int_{0}^{2\pi} \int_{0}^{\alpha} I_j(r, \phi)r \, dr \, d\phi}{\int_{0}^{2\pi} \int_{0}^{\alpha} I_j(r, \phi)r \, dr \, d\phi}$$

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

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

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 x 3 link minimize the crosstalk, given the input beams. For the 75-m fiber, crosstalk at channel 1, 2, and 3 is $\approx -3.1, \approx -0.3,$ and $\approx -5.4$ 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 $i$th channel between $r_{i-1}$ and $r_i$. Annular NFPs can be observed by introducing an angular offset $\theta_0$ 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 x 3 system, introducing an angular offset to $T_3$ would result in very low $\eta$ 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 $\delta r(t) = \bar{H}(t) s_R(t) + y(t)$ or $\delta r(t) = \bar{H}(t) (\bar{H}(t) s_R(t) + x(t)) + y(t),$ where $\bar{H}(t)$ represents the noise from the demultiplexing unit and $\bar{H}(t)$ is an estimate of the inverted matrix $H(t) = \{ h_{i,j}(t) \}.$ Assuming ideal channel estimation, i.e., $\bar{H}(t) = H(t), \delta s(t) = s_R(t) + \bar{H}(t) x(t) + y(t),$ it is clear that, although matrix inversion recovers the transmitted signals, noise increases. The two noise terms $x(t)$ and $y(t)$ depend on the specific implementation of the receiver. To calculate the power penalty, we focus on the term $\bar{H}(t) x(t),$ since this term expresses the noise enhancement due to the demultiplexing algorithm. The variance of the noise at the $i$th channel is $\sigma_i^2 = \sum_{k=1}^{N} (h_{i,k})^2 \text{Var}(x_k),$ where $x_k$ are the statistically independent elements of the noise vector $x.$
The average and maximum power penalty and optical crosstalk for an MGDM system with 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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REFERENCES


AVERAGE (MAXIMUM) POWER PENALTY, OPTICAL CROSSTALK, AND GEOMETRIC DESIGN PARAMETERS FOR AN N x N MGDM SYSTEM

<table>
<thead>
<tr>
<th>N x N</th>
<th>Shot noise limit (dB)</th>
<th>Thermal noise limit (dB)</th>
<th>Optical crosstalk (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 x 2</td>
<td>2.3 (2.3)</td>
<td>1.2 (1.4)</td>
<td>-6.7 (-5.7)</td>
</tr>
<tr>
<td>3 x 3</td>
<td>5.7 (7.2)</td>
<td>2.9 (3.2)</td>
<td>-2.8 (0.4)</td>
</tr>
<tr>
<td>4 x 4</td>
<td>8.3 (10.3)</td>
<td>4.2 (4.7)</td>
<td>-0.8 (1.5)</td>
</tr>
<tr>
<td>5 x 5</td>
<td>11.3 (13.3)</td>
<td>5.6 (6.3)</td>
<td>0.8 (2.7)</td>
</tr>
</tbody>
</table>

where \( P_j^o \) 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 x N system with N = 2, 3, 4, 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 \( h_{k,j} \) have been measured using the 75-m fiber.

A feature of MMF links is tolerance in alignment. In order to maintain this feature, the radial offset should be set at \( \rho_{max} = \rho_0 - d_{col} \), where \( \rho_0 \) is the maximum radial offset ensuring a desired coupling efficiency, and \( d_{col} \) is the required tolerance in alignment. However, misalignments will change the spectrum of the 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 = 4 and N = 5. The same tolerance \( d_{col} = 2 \mu m \) has been used at the transmitting and the receiving side. The 3 x 3 link is much more robust than the 4 x 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.

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

\[
\text{SNR}_j = \frac{P_j}{\sigma_j^2},
\]

where \( P_j \) is the average power defined by the bias of the lasers. In the following, we assume that \( P_j \) = \( P_i \sqrt{v_j} \). The noise variance at the shot noise limit is

\[
\text{Var}_j(\eta_k) = \sum_{k=1}^{N}(h_{k,j}^*)^2 h_{k,j},
\]

and at the thermal noise limit

\[
\text{Var}_j(\eta_k) = \sum_{k=1}^{N}(h_{k,j}^*)^2.
\]

The power penalty at the jth channel of an MGDM link is

\[
\frac{P_j^o}{P_j^\text{shot}} = \left( \frac{\text{N}}{\text{N}^2} \right) \sum_{k=1}^{N}(h_{k,j}^*)^2 h_{k,j},
\]

\[
\frac{P_j^o}{P_j^\text{thermal}} = \left( \frac{\text{N}}{\text{N}^2} \right) \sum_{k=1}^{N}(h_{k,j}^*)^2.
\]