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# Effectiveness of mode-selective spatial filtering in mode group diversity multiplexing links

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***Abstract*—**Mode-selective spatial filtering (MSSF) is a new optical method of combating the cross-talk among the channels of a mode group diversity multiplexing link. MSSF can greatly improve the robustness and scalability of the link.

## I. Introduction

Light in multimode fibers (MMFs) propagates in a multitude of spatial modes. These modes offer spatial degrees of freedom that can be used in transmission. Although this principle is known, the way of realizing such a transmission scheme is non-trivial. Especially in intensity-modulation direct-detection (IM-DD) links, the utilization of the spatial modes becomes very challenging, since the modes are orthogonal with respect to their field and not their intensity profiles. Multiple-input multiple-output (MIMO) techniques used to increase the spectral efficiency and reliability of wireless communication links can be also applied in IM-DD transmission over MMF [1,2]. In this approach, electrical processing of the received signals is used to recover the transmitted signals, and thus no orthogonality at the optical intensity domain is required.

Mode group diversity multiplexing (MGDM) [2] is an IM-DD MIMO technique that aims at realizing parallel communication channels, transparent to the transmission format. MGDM supports the integration of various broadband services over a common MMF infrastructure [2]. When the link is not limited by dispersion, vector $\mathbf{s}_R(t)$ of the $M$ received electrical signals is related to vector $\mathbf{s}_T(t)$ of the $N$ transmitted electrical signals via an $M\times N$ real-valued matrix $\mathbf{H}(t)$, i.e. $\mathbf{s}_R(t)=\mathbf{H}(t)\mathbf{s}_T(t)+\mathbf{n}(t)$, where $\mathbf{n}(t)$ is a noise vector [3,4]. In silica graded-index (GI) MMFs, a bandwidth of several GHz can be achieved below the dispersion limit [5]. To recover the input signals irrespective of their format, matrix inversion can be used. However, at the same time, this enhances the noise and induces a power penalty in order to maintain the signal-to-noise ratio of the 1×1 case [4]. The more diagonal the matrix $\mathbf{H}(t)$, i.e. the larger the spatial diversity, the smaller the power penalty due to the electronic matrix inversion and the more robust the link. Higher robustness allows the link to be more scalable to the number of channels [4]. We have recently introduced mode-selective spatial filtering (MSSF) as an optical way to combat the cross-talk among MGDM channels and increase the spatial diversity of the link [6]. A 2×2 link was demonstrated [6]. In this paper, we show experimentally the high effectiveness of MSSF in links with a larger number of channels.

## II. MSSF principle

A simple way to selectively excite a GI-MMF is to use radially offset Gaussian-like beams at its input face. Each beam excites a different group of modes which yields a distinguishable near-field pattern (NFP) on the output face of the GI-MMF [4]. Given the NFPs, the geometry of the detectors can be chosen to minimize the cross-talk [4]. This approach for an $N\times N$ link is simple (see references within [4,6] for comparison), however, for $N>3$ the link is very sensitive to changes in the elements of $\mathbf{H}(t)$.

MSSF is a new optical technique that improves the condition number of $\mathbf{H}(t)$ [7], and therefore increases the robustness of an MGDM link. Fig. 1 illustrates the MSSF principle. In Fig. 1b, two propagating rays in a GI-MMF are shown. The exit points of the rays on the end face of the GI-MMF fall within the area that would be detected by a single segment $R_\mathrm{i}$ of a multisegment MGDM detector (Fig. 1a). However, the angular divergence ($\theta$) of the rays when coming out of the GI-MMF is significantly different. In particular, at the GI-MMF output, ray 1 forms an angle $\theta_1$ with the fiber axis smaller than the angle $\theta_2$ between the fiber axis and ray 2. Let us assume that a lens is used to project the NFP onto the multisegment MGDM detector. If the numerical aperture (NA) at the object side of the lens (GI-MMF output face), $\mathrm{NA}_\mathrm{lens}$, corresponds to $\theta_\mathrm{lens}$ such that $\theta_1\leq\theta_\mathrm{lens}<\theta_2$, then only ray 1 is gathered by the lens and subsequently projected onto the detector. In the example of Fig. 1, if $\mathrm{NA}_\mathrm{lens}$ is sufficiently low, $R_2$ ($R_3$) detects light related to ray 1 (2), while $R_1$ does not receive light associated with rays 1 and 2.

In GI-MMFs, the NA has a maximum value on the fiber axis and gradually drops to zero at the core-

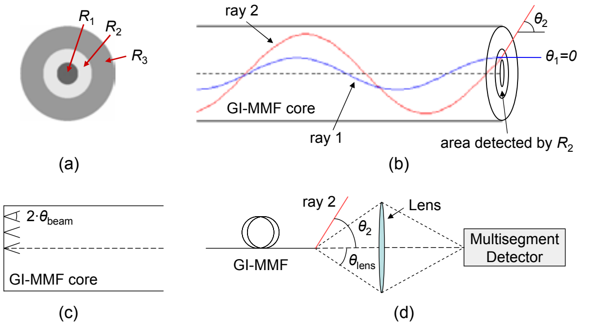

**Fig. 1** (a) Geometry of a three-segment detector for a 3×3 MGDM link [4]. (b) Two propagating rays in a GIMMF. (c) Three input beams with different radial offset at the GI-MMF input. (d) A lens projects light on the GI-MMF output face onto a multisegment detector.

cladding interface. This means that MSSF will be effective on the area of the output face of the GI-MMF defined by $NA_{GI\text{-}MMF}(r)>NA_{lens}$, where $NA_{GI\text{-}MMF}$ is the local NA of the GI-MMF and $r$ the distance from the fiber axis. If $NA_{beam}$ denotes the NA of the radially offset input beams, the following relation will generally hold for $NA_{lens}$, $NA_{beam}<NA_{lens}<NA_{GI\text{-}MMF}(0)$. The upper bound expresses the condition for MSSF to take effect, while the lower bound gives a practical rule for GI-MMFs with limited mode mixing. In such GI-MMFs, light launched with a beam of $NA_{beam}$ at radial offset $\rho_0$ will propagate with similar NA around $\rho_0$ and larger NA at points closer to the GI-MMF axis (Fig. 1b). In general, $NA_{lens}$ will decrease as the number of channels increases. However, the lower the $NA_{lens}$, the higher the power penalty due to MSSF (not all the optical power is gathered by the lens). For a certain $N$, the value of $NA_{lens}$ is chosen as a trade-off between the total power penalty and the condition number of $\mathbf{H}(t)$.

## III. Experimental results

In [6], the first demonstration of MSSF was performed with a 2×2 link that exhibited remarkable stability over a 25-h period. Here, we show the effectiveness of MSSF in links with a larger number of channels. Fig. 2 shows our experimental set-up. A 635-nm Fabry-Pérot multi-quantum-well laser diode was used to selectively excite a GI-MMF with core/cladding diameter of 62.5/125 $\mu$m and central NA 0.275. The laser is pigtailed to a single-mode fiber (SMF) with mode field diameter (MFD) 4.2 $\mu$m and NA 0.12. A variable optical attenuator (VOA) with SMF pigtails, of similar MFD and NA with the laser pigtail, was used to control the level of the optical power. A microscope projected the NFP at the GI-MMF output onto a charge-coupled device camera. An image of the NFP was grabbed with video processing software. Two GI-MMFs were tested, of lengths 1 m and 1 km, under excitation with the SMF of the VOA at 0, 10, 15, 21, and 26 $\mu$m radial offset, following the design parameters in [4]. The radial offset of the SMF axis from the GI-MMF axis was set by means of computer-controlled translational stages. Two microscope objectives were used. A 50× one with NA 0.75, capturing all the NFP, and a 5× one with NA 0.10, achieving MSSF, its NA being close to the limit $NA_{beam}=0.12$. The results are shown in Fig. 3. The NFP (50× objective) is confined within a disk which is transformed into a doughnut when the 5× objective is used. It is clear that MSSF can be highly effective and a robust link with five channels could be realized. For a smaller number of channels, MSSF could fully mitigate the cross-talk. Quantitative evaluation of MSSF would require a careful analysis that takes into account both the power penalty due to the electronic processing [4] and the one due to MSSF. The optimal value of $NA_{lens}$ should be also defined for a given $N$. This could be done either with an experimental set-up where the NA can vary over a large range, or with simulations. The low magnification of 5× does not allow for a good estimation of the power penalty due to the electronic matrix inversion, since the obtained images have a low resolution. The results of Fig. 3, though, undoubtedly show the effectiveness and great potential of MSSF.

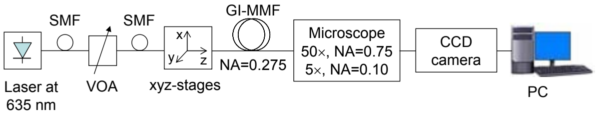

**Fig. 2** Experimental set-up for the investigation of the effect of MSSF.

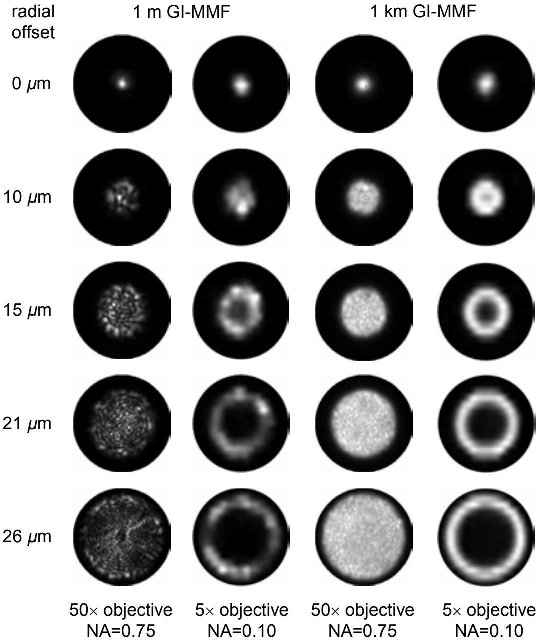

**Fig. 3** Observed pattern at the output of a 1-m and a 1-km long 62.5/125 $\mu$m silica GI-MMF under selective excitation.

## IV. Conclusion

MSSF is a very simple, easily realizable and highly effective optical technique to increase the robustness and scalability of MGDM links. We have shown that for short wavelengths, a five-channel link is well-supported, while for a smaller number of channels, MSSF could eliminate the need for electronic demultiplexing.

## Acknowledgment

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