Shaping optical fibers to mode division multiplex without MIMO

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***Abstract*— MIMO complexity can be reduced or avoided completely by proper design of the few mode optical fiber used for mode division multiplexing. Our focus is high index contrast fibers that avoid the formation of scalar modes, to favor vector modes with more limited modal interactions.**

Keywords—spatial division multiplexing, mode division multiplexing, orbital angular momentum, SDM, MDM, OAM

I. Introduction

Spatial multiplexing in an optical fiber (rather than using fiber bundles) can take the form of multiple core fibers, multimode fibers, or some hybrid of the two. To maximize capacity in one core of a fiber, mode division multiplexing (MDM) is essential. Two different modal bases, linearly polarized (LP) scalar modes and vector modes, are under study for spatial division multiplexing [1-3]. The vector modes can be circularly polarized, as is the case with orbital angular momentum (OAM) modes, or can be linearly polarized vector modes (LPV). LP-MDM demonstrations tend to target long haul data transmission, while OAM-MDM and LPV-MDM systems target short reach applications. The interest in vector mode MDM is motivated by the search for a low modal crosstalk solution that eschews the use of multiple input, multiple output (MIMO) processing. In this paper we will discuss the implications for both transceiver and network architectures when using MIMO processing for MDM.

II. Implications of MIMO Use

Consider an MDM system exploiting M modes in two polarizations, supporting a total of $2M$ data channels. For most demonstrated LP-MDM systems this would involve $2M\times 2M$ equalizers in the receiver digital signal processing (DSP), or what we refer to as full-MIMO. These equalizers undo effects of heavy crosstalk between modes. Another approach is to design systems that have low crosstalk between LP mode groups, only requiring MIMO processing within mode groups. In this case, somewhere between $4M$ and $16M$ equalizers would be required, partial MIMO. Exploitation of vector modes for MDM targets the use of minimal MIMO. For instance, OAM modes and some LPV mode MDM systems rely only on 2×2 MIMO, a staple of today's commercial coherent detection DSP. Polarization maintaining fibers for LPV [4] and OAM fibers using optical MIMO [3] can avoid all electronic MIMO and are referred to as MIMO free. This should not be confused with systems that achieve MIMO-free operation by forgoing polarization multiplexing or the exploitation of individual modes; the number of data channels would be much less than $2M$. We only discuss MDM systems that exploit all targeted individual modes in order to achieve maximal capacity.

A. Transciever configurations

In Fig. 1 we provide schematics to illustrate the impact of the level of MIMO processing on MDM transceiver configurations. The lower section of Fig. 1 refers to the receiver front end architecture, whereas the upper section refers to the DSP. Each column refers to one of the four types of MDM discussed: full, partial, 2×2, and no MIMO.

The sketches in the upper section of Fig. 1 indicate the number of equalizers (shaded boxes in the matrix). Each equalizer has complexity determined by the differential group delay (DMGD) for the MDM system. The blue time traces are meant to evoke the impact of DMGD. The total DSP complexity, both in hardware size and power consumption) is related to both equalizer number and memory depth. Shorter fiber lengths would, of course, lead to less DMGD.

The receiver front ends of these system vary due to the requirement for synchronization. A full MIMO system would

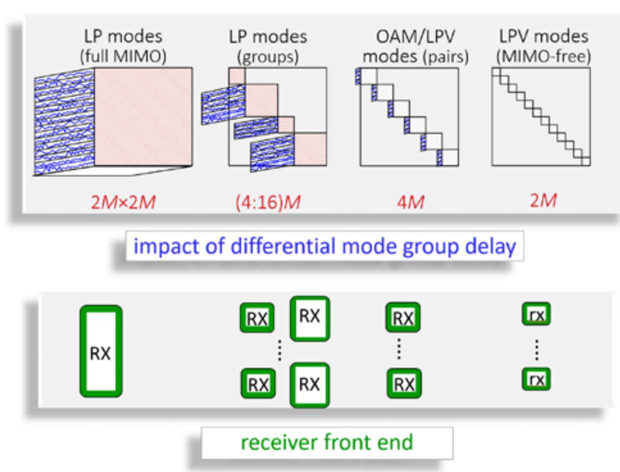

Fig. 1 Illustration of MIMO processing complexity (upper section) and receiver front end complexity (lower section) for various MDM solutions.

require that all 2*M* channels be captured simultaneously and treated in concert. The 2×2 MIMO solution would use one conventional coherent receiver for each MDM channel. These receivers would not even require collocation; collocation would, however, enable DSP complexity reduction by sharing carrier phase and frequency recovery, similar to full MIMO systems. The partial MIMO would typically involve a collection of 2×2 or 4×4 MIMO front ends, and MIMO free would have only coherent detection without requiring polarization recovery.

B. *Optical network configurations*

Combining mode and wavelength division multiplexing (WDM) is crucial to maximizing the capacity of optical fiber, particularly in reconfigurable optical networks. The left of Fig. 2 gives sketches of four WDM/MDM architectures with wavelengths across the top and modes along the side. Vector mode multiplexing is compatible with all architectures, while full MIMO would only apply to the first example of wavelength switching: all modes on a given wavelength must traverse the network as a unit. This leads to coarse flexibility in switching. A partial MIMO system (the second or hybrid network architecture) would allow greater switching flexibility as only subgroups of modes would be required to be routed as a unit. These two architectures would require a new generation of channel drop devices, not standard wavelength selected switches (WSS). Research is underway for devices that combine a high-port-count conventional WSS with a mirror designed to gather all modes at a given wavelength and switch them together [5]; such devices are illustrated with 3D WSS arrows in Fig. 2.

While vector mode systems are fully compatible with the first two architectures, they offer the possibility of also working with the remaining two architectures. In the case of full granularity, *M* modes and wavelengths could be freely routed; this offers the greatest flexibility in routing, but of course with a commensurate increase in the number of switch components. The use of space switching (all wavelengths routed together on a given mode), gives coarse granularity in routing, but with greatly reduced hardware complexity. Most importantly, the last two architectures are fully compatible with existing switch hardware, only requiring a spatial demultiplexer to separate the modes.

III. Fibers for Vector Mode MDM

To shape optical fibers to mode division multiplex without MIMO, we target a fiber geometry that works against the formation of scalar LP modes. This is achieved first my working with high contrast fibers where the weakly guiding approximation is violated, that is, where the cladding and core have disparate indices of refraction. In the case of OAM modes, ring core fibers with circular symmetry are used for effective coupling of these modes; OAM modes are characterized by a shaped intensity profile. In the case of LPV modes, an elliptical waveguide is called for, either solid core or elliptical.

We have successfully demonstrated kilometer scale data propagation when using either a graded index core fiber or a step index ring core fiber [6]. In both cases only 2×2 electrical MIMO was required, and no optical MIMO. We have also demonstrated the compatibility of this fiber with commercial transceivers [7]. Our ring core fiber with an air core afforded the

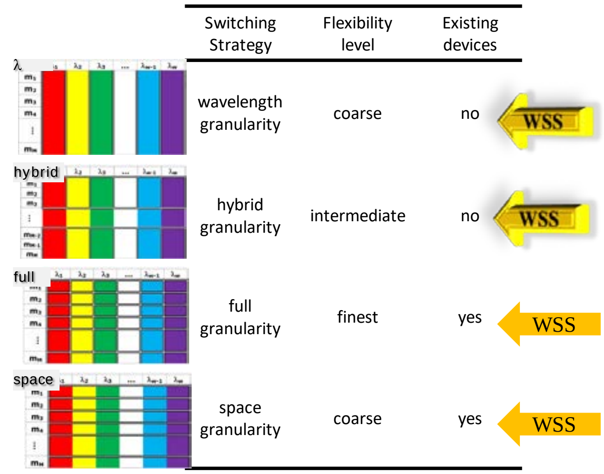

Fig. 2 WDM-MDM switching architectures and their attributes; full and partial MIMO systems compatible with wavelength and hybrid architectures, respectively; 2×2 MIMO and MIMO-free compatible with all architectures

greatest contrast between core and cladding and led to a record-breaking 9 OAM modes, capable of supporting up to 36 information channels [8].

Our LPV demonstration of an elliptical ring core fiber [4] exhibited good polarization maintaining properties over eight modes, each having effective index difference (with its nearest neighbor) larger than 10^{-4}. These fibers displayed stable mode power and polarization extinction ratio even under external perturbation. Data recovery did not require any MIMO or polarization-division multiplexing (PDM) signal processing even after .9 km transmission. We have also designed fibers with solid, elliptical cores supporting five spatial modes with twofold polarization degeneracy (ten channels) [9]. This design would be compatible with 2×2 electrical MIMO receiver.

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