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Perspective on mode-division multiplexing

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ABSTRACT

We review the current status of mode-division multiplexing (MDM) techniques in fibers and on chips. Three system applications are introduced, including quasi-single mode transmission, multicore few-mode amplifier, and fiber sensing. We also discuss the technology development trend in terms of multiple-input-multiple-output-free MDM, economics of MDM, and quantum information processing. Finally, we provide perspectives on emerging applications beyond communications by leveraging the optical properties of high order modes, e.g., nonlinear optics in the visible regime, broadband frequency comb generation, and super resolution endoscopy.

I. INTRODUCTION

Multiplexing is an essential function in optical signal processing for a variety of applications, covering communications, computing, quantum information processing, imaging, sensing, etc. Among the available physical dimensions of an optical carrier, space may be the last dimension to explore, and space division multiplexing (SDM) has received tremendous interest in recent years.[1] SDM can efficiently utilize the cross section area of a fiber or an on-chip waveguide. It has been achieved mainly by two approaches: The first one is by fabricating multiple cores in a fiber[2] or a densely packed waveguide array on chip.[3] The second approach uses mode-division multiplexing (MDM) in a few-mode/multimode fiber (FMF/MMF) or a multimode waveguide on chip, which supports high order modes. There may be overlap between the two categories, such as a coupled core fiber.[4]

Recently, many applications have emerged using spatial modes as a resource, which can be divided into two categories. The first category includes applications that utilize the linear properties of spatial mode in few-mode fibers (FMFs) and multimode waveguides, including mode-division multiplexing such as lossless combining in a passive optical network (PON) because of the extra degree of freedom. The second category involves nonlinear applications. For example, mode orthogonality can be used to suppress nonlinear inter-channel interference. Large mode area and mode orthogonality together lead to applications in microwave photonic links and long-haul transmission using quasi-single-mode techniques. All these applications, when applied in a straightforward manner, are based on mode orthogonality. But there is a fundamental challenge, i.e., only ideal fibers or waveguides offer mode orthogonality. Real fibers and waveguides have practical limitations, such as mode coupling and mode crosstalk. They have significant impact on the applications listed above.

In this Perspective, we first review the current status of the MDM technologies and their integration approaches, covering multimode fibers, coupled core fibers, MDM on chip, and fiber-chip coupling. Technical advances in the system aspect of MDM are addressed, including quasi-single-mode transmission, multicore few-mode amplification, and fiber sensing. In addition, we discuss the technology development trend in terms of MIMO-free MDM, economics of MDM, and quantum information processing-based MDM. Finally, perspectives on emerging applications beyond communications are provided.

II. CURRENT STATUS OF MDM TECHNOLOGIES

In this section, we review the current status of MDM technologies and related device advances in fibers and integrated chips.

A. Multimode fibers

Multimode fiber (MMF) supporting spatially overlapped modes is attractive in communications and other applications. Mode coupling and modal dispersion are the two main impairments need to be dealt with. Modal dispersion is introduced by the propagation constant differences between the modes. In telecommunications, full field of the mode-multiplexed signal is commonly captured by employing optical coherent receivers which detect the field directly by interfering the signal with a continuous wave light as a local oscillator (LO).[5] Full field reconstruction can also be accomplished using intensity-only measurements while mitigating LO with the aid of complementary projections and a phase retrieval algorithm.[6] Modal dispersion and mode mixing are digitally reversed at the receiver using multiple-input-multiple-output (MIMO)-based digital signal processing (DSP)[5] which employs pilot symbols as part of the transmitted signal to determine the MMF's complex coupling matrix and recovers the transmitted information stream after inversing the detected scrambled signal. High-performance spatial multiplexers supporting up to 200 spatial modes[7–9] enable the large-capacity transmission trials using MMFs.[10–12] Mode-multiplexed 90 × 90 MIMO transmission over all nine mode groups of a graded-index MMF was demonstrated, achieving a record spectral efficiency of 202 bit/s/Hz over a single optical fiber core.[12]

For the multimode fibers, the bending losses have been extensively studied.[13] The critical radius of the curvature with a 3-dB insertion loss is equal to the core diameter divided by the index difference between the core and the cladding of the optical fibers, which is about 1 cm for an index difference of 1% and a core diameter of 100 μm. In practice, sharp bends of multimode fibers should be carefully taken care of to avoid extra losses, while the crosstalk may be eliminated by introducing MIMO processing as long as the transmission matrix of the fiber is unitary.

B. Coupled-core fibers

Multicore fiber (MCF) is another effective approach to improve the spatial density, which has different optical paths defined by distinct single-mode fiber cores.[1] Various studies have been reported such as the 7-core,[2] 12-core,[14] and 22-core[15] MCFs, the highest transmission capacity per fiber can reach 2 Pbit/s.[15]

Recently, coupled core fibers are proposed to further improve the aggregate transmission capacity of the optical fiber. It offers many prominent features such as higher spatial density compared with uncoupled MCFs,[16] reduced impulse responses relative to multimode fibers (MMFs),[17] large effective areas,[18] and nonlinear impairments mitigation.[19] The coupled MCF was first proposed to accommodate more fiber cores inside a limited size cladding by reducing the core-to-core spacing,[16] multiple-in-multiple-output (MIMO)-based DSP is used to tackle the mode mixing. For the coupled MCFs with single-mode cores, the number of the guided modes is equivalent to that of the fiber cores. By optimizing the fiber design parameters such as core-to-core spacing,[17] twist rate and core arrangement,[20] the effective index differences between the modes are comparable to the index variations caused by the perturbations such as bending, twisting and other fiber deformations,[21] as illustrated in Fig. 1. Therefore, all the guided modes of the coupled MCF can be continuously scrambled along the propagation, which is referred to as strong coupling regime. The accumulated differential group delay (DGD) and mode-dependent loss (MDL) both grow with the square root of the fiber length,[22] resulting in a shorter impulse response after long-distance transmission and helping to improve system performance. Moreover, strong mode mixing enables nonlinear impairments mitigation, which may be regarded as the most compelling benefit provided by the coupled MCFs.[19,23,24] It has been experimentally confirmed that the coupled MCFs outperform the single-mode fiber with an identical core design and are more tolerant to nonlinear distortions.[25] Similar to the uncoupled MCFs, signals can be launched directly into the cores of the coupled MCFs, which can avoid delicate mode conversion section inevitable for the MMFs and significantly simplify the component fabrication. Enormous advantages together with the reported high-performance components such as spatial multiplexers[26] and optical amplifiers[27] make the coupled MCF as one of the top SDM schemes for long-haul and submarine applications.[28] In contrast to the coupled MCFs, MMFs have weak inter-mode-group coupling due to large effective index differences between the mode groups. The DGD accumulation of the MMFs scales linearly with the distance. Efforts have been devoted to transforming the MMFs into the strong mixing regime by introducing mode scramblers.[29–31] Further performance enhancement to lower the insertion losses and MDL is still needed to sustain long-distance transmission with dense deployment of the mode scramblers along the MMF link.

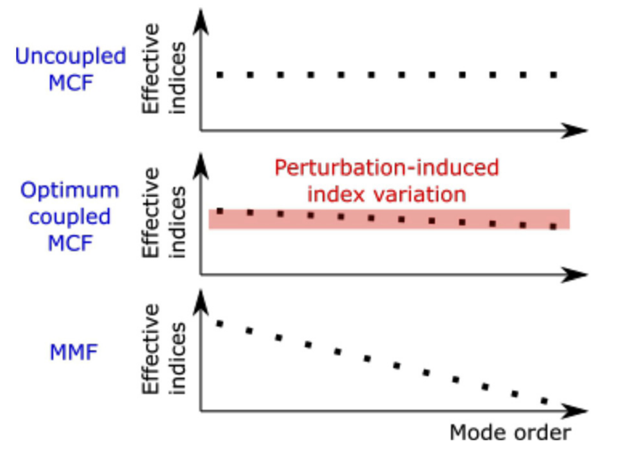

FIG. 1. Illustration of the effective indices for the modes supported by uncoupled MCF, coupled MCF, and MMF.

C. MDM based on integrated photonic circuits

Compared with optical fibers, a silicon-on-insulator (SOI) platform is attractive for its property of high density integration[32,33] and complementary metal-oxide-semiconductor (CMOS)-compatible fabrication. By employing the orthogonal TE/TM modes in silicon waveguides, many on-chip MDM devices have been reported.[34] Although in theory the number of mode channels can be scaled by cascading multiplexing stages, the performance degradations originated from the fabrication errors severely limit the scalability. Conventional MDM devices based on asymmetric directional couplers (ADCs) are sensitive to the waveguide width variations due to the different dispersion slopes of the bus waveguide and the access waveguide. This problem can be effectively solved by engineering the access waveguide with a subwavelength grating (SWG) structure such that its dispersion slope matches with that of the bus waveguide. A record high channel count of 11 was achieved for such an SWG based MDM device;[35] mode channels can be expected using the similar structure. The microscope image of the device is shown in Fig. 2.

A transmission experiment is carried out to characterize the performance of the on-chip MDM devices. A low-coherence matched detection method is employed to transmit a 30-Gbaud 8-PSK signal over a 11-channel integrated MDM circuit.[36] The aggregate data rate can reach 900 Gbit/s while maintaining an acceptable BER value. This work proves the feasibility of employing on-chip MDM for future high-capacity optical interconnects for computing systems.

Another important building block is multimode bends, which are necessary for interconnecting components within the chip area. Sharp bends may cause mode distortions at the bending regions. Various multimode bends have been reported based on vertical multimode waveguide,[37] transformation optics,[38] curved waveguides,[39,40] mode conversion,[41] metamaterial structure,[42] etc. It is viable to engineer the waveguide structure in a bending area to gradually convert the guided mode and minimize the mode distortion.

D. Mode coupling and conversion between fibers and chips

In a fiber/waveguide MDM system, a coupling device between the fiber and the waveguide is indispensable to ensure the mode field matching. Device footprint, coupling loss, and mode crosstalk are of important considerations. To seamlessly interconnect the fiber and the chip, the multimode coupling should be implemented in an integrated form rather than through discrete components. For example, at a receiver end, the conventional approach to fiber-chip interconnection is going through an off-chip de-multiplexing stage through a photonic lantern and then coupling multiple single mode fibers to the chip, which can easily use up the limited chip circumference. Therefore, direct coupling between the fiber and the chip is needed, requiring good mode matching between the two components through a mode converter on chip. Co-design of the waveguide mode converter and the specialty fiber is often considered, providing opportunities in the two fields.

A mode expander capable of converting the incoming LP modes from a conventional FMF to TE/TM modes on a chip.[43] However, the implementation has been quite challenging and the scalability is limited due to the mode profile mismatch between the waveguide modes and the LP modes. Another possible approach is through employing a rectangular core fiber (RCF)[44] that supports TE/TM modes, which are

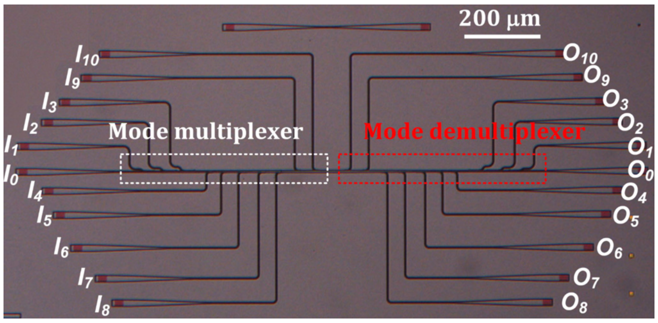

FIG. 2. Microscope image of the 11-channel MDM device.[35] Reproduced with permission from He *et al.*, J. Light. Technol. **36**, 24 (2018). Copyright 2018 IEEE.

naturally compatible with those in a multimode waveguide on chip, as shown in Fig. 3. Such RCFs may show higher losses than that of conventional FMFs, but could enable convenient interconnects between chips in short distance scenarios such as data centers. A critical component to bridge an RCF and a chip is the mode size converter. We first study the electric field distributions of a mode expander assisted by a Si_3N_4 layer and an RCF by simulations, as shown in Fig. 3(b). Here we use TE_{01} mode as an example. It can be noted that the mode profile in the RCF is different from conventional LP modes and more like an eigenmode in a rectangular waveguide. The coupling efficiency is calculated to be 61.7%. Higher efficiency mode coupling can be realized by properly designing the integrated waveguide to achieve better mode field overlap. Encouraging progress has been made by employing multiple layers of Si_3N_4/Si materials.

III. SYSTEMS AND APPLICATIONS BASED ON MDM

A. Quasi-single mode transmission by employing MDM

Fiber imperfections such as inhomogeneities and micro-bending manifest as a perturbation of the index/permittivity from the ideal fiber, which randomly varies in all directions.[45] The variation in the propagation can be decomposed into its Fourier components. Some of these components causes phase-matched coupling between pairs of spatial modes. It turns out that the strength of these Fourier components decays strongly with the spatial frequency owing to the current method of fiber fabrication and cabling. Therefore, modes separated by large difference in their propagation constants, or equivalently effective indices, tend to have weak crosstalk. It has been shown that FMFs with effective index difference $> 1e^{-3}$, sufficient for suppressing mode crosstalk, can be fabricated. The effective areas of these FMFs can be much larger than that of SMFs, and therefore, can be used to suppress fiber nonlinear effects. Transmission systems that utilize only the fundamental modes of the FMFs to break the nonlinear Shannon limit of SMFs are called quasi-single mode (QSM) transmission systems. Here is an experimental demonstration of QSM, photonic lanterns[46] are needed at the transmitter/receiver ends for mode multiplexing and de-multiplexing, respectively. Figure 4 compares the transmission performances of three fiber configurations:[47] all single mode (blue), all FMF (red) and hybrid, FMF followed by SMF (black). The hybrid configuration always performs the best. The all-FMF configuration performed better than the SMF configuration at 2000 km while the reverse is true at 4000 km. The reason is that the benefit of large mode area is offset by mode crosstalk. For QSM, it is multipath interference when the fundamental mode is coupled to the LP_{11} mode and then coupled back into the fundamental mode. Mode crosstalk can also lead the extra losses, if the fundamental mode is eventually coupled to radiation modes. So, for nonlinear applications, the FMF not only needs to have large area but also low crosstalk. The QSM technique has previously been applied in high-power fiber amplifiers and lasers in which the large effective area of the FMF is used to suppress nonlinearity and the selective use of only the fundamental mode leads to high beam quality (small M2). Recently, The QSM technique has been applied to silicon photonics.[48] In waveguides, the fundamental mode is always the best confined. As a result, it experiences less scattering from surface roughness, which cannot be eliminated from the fabrication process. By selective use of the fundamental mode in the few-mode waveguide, record low loss has been achieved. Furthermore, it is expected that the selective use of the fundamental

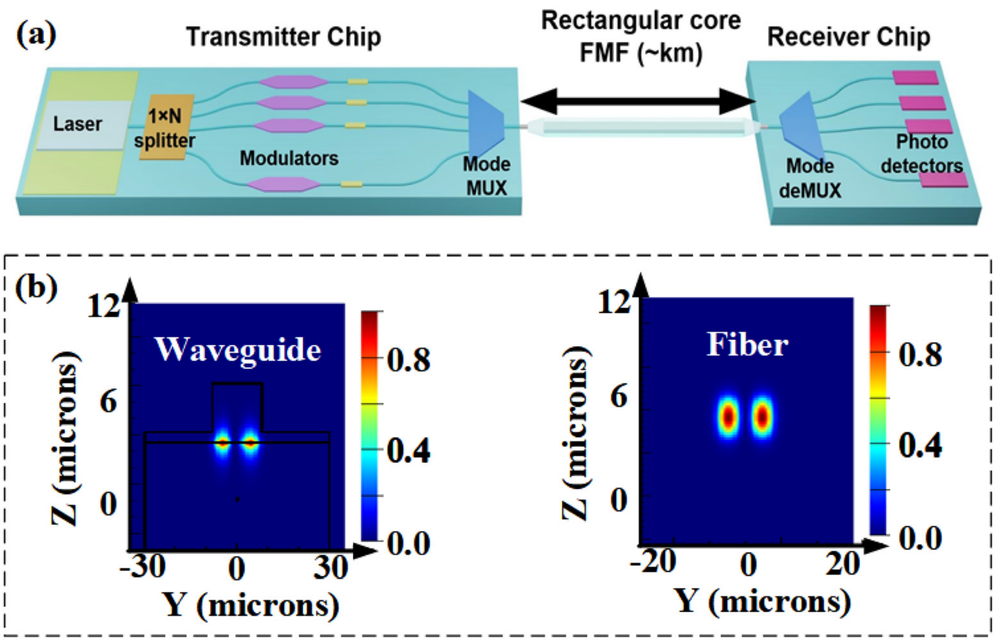

FIG. 3. (a) Schematic configuration of a possible short reach MDM link with fully integrated MUX and deMUX components. (b) Simulated electric field distributions monitored at the edge of an integrated waveguide and an RCF.

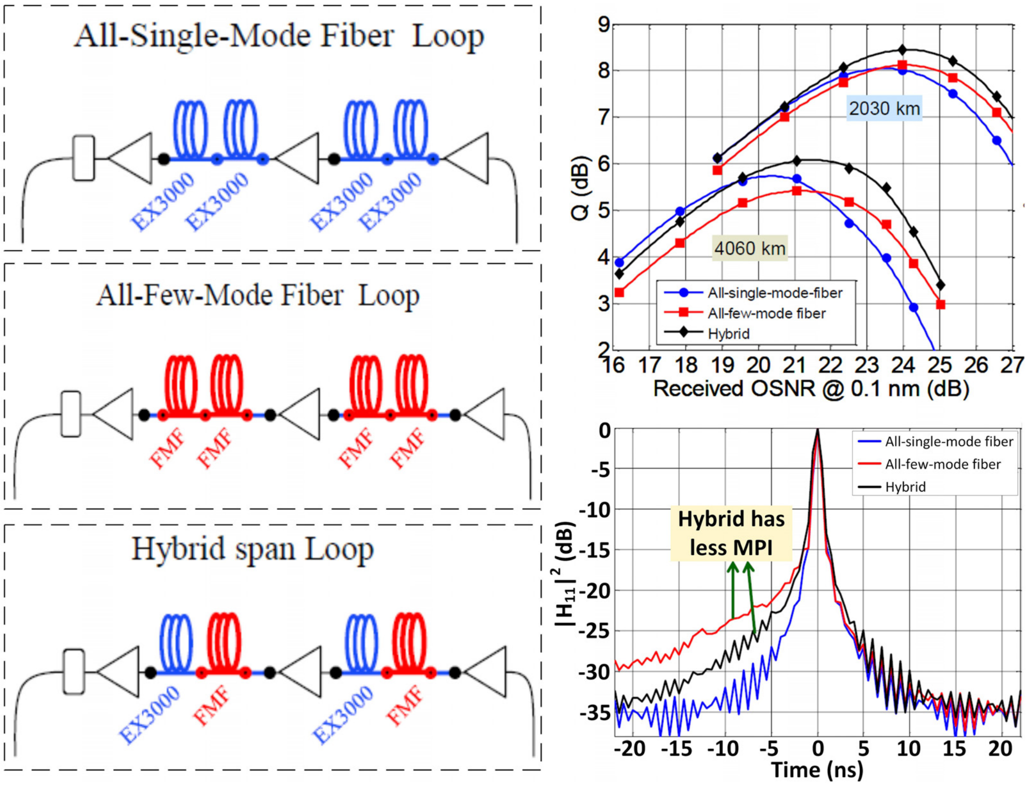

FIG. 4. Experimental demonstration of QSM.[47] Reproduced with permission from Yaman *et al.*, in *Optical Fiber Communication Conference* (2015), p. Th5C.7. Copyright 2015 Optical Society of America.

mode will also make device performance tolerant to fabrication-induced geometrical variations, thus eliminating the need for thermal tuning of many silicon photonic devices.

B. Multi-core and multi-mode optical amplification

Multicore and multimode erbium-doped fiber amplifiers (EDFAs)[49–51] can achieve parallel amplification for independent signals in a compact footprint. Core-pumped uncoupled multicore EDFA[52] employing most conventional components applied in the single-mode EDFAs, such as wavelength-division mutliplexing (WDM) combiner and single-mode pump laser diodes, has the potential to replace an array of single-mode amplifiers. Cladding pumping is more widely implemented on the SDM EDFAs in order to lower the cost per bit and total power consumption due to the availability of uncooled high-power multimode pump laser diodes and efficient edge pumping schemes. In contrast to single-mode laser diodes, multimode pump laser diodes are more efficient in electrical-to-optical power conversion, more tolerant to temperature variations and more cost-effective. In cladding pumping, pump light is distributed over the entire cladding but signals are only guided by the cores, which significantly reduces the overlap between the pump and signals compared to core pumping, and usually causes more than half of the pump light unused at the EDFA output. A multimode pump laser diode with tens of watts output power is usually needed to achieve a high population inversion. Increased core and cladding ratio[51,53] and pump recycling[54] have been applied in enhancing the pump absorption efficiency. To facilitate the deployment of the SDM fibers to sustain future high-capacity optical networks, it will be essential to demonstrate cladding-pumped SDM EDFAs with a comparable pump absorption efficiency to the core-pumped counterparts.

C. Few-mode fiber sensing

The fiber optical sensing technology has been studied extensively over the last few decades and widely used in the fields ranging from oil and gas industry,[55] structural stability monitoring,[56] and biomedical science.[57] Compared with SMFs or MMFs, FMFs support limited guided modes and each mode in an FMF can be detected independently and does not introduce severe inter-modal crosstalk. The operation principle of the FMF-based sensors is based on the different effective refractive index n_{eff} values of the spatial modes.[58] Various LP modes in FMFs respond differently when subjected to environment parameter deviations, such as temperature, pressure, etc. It is viable to monitor the different responses of the modes and thus enable full characterization through the enlarged parameter space. Therefore, FMFs are advantageous in sensing applications.[59–61] Most FMF sensors are based on interferometric structures,[60,62] Bragg gratings,[63] or fiber tapers.[64]

IV. FUTURE PERSPECTIVE AND TECHNOLOGY DEVELOPMENT TREND

MDM has the potential to significantly scale the transmission capacity, while several factors are limiting its applications in practical systems. Here we discuss the challenges, technology developments, and perspectives for MDM systems. Applications based on the optical properties of high order modes are also introduced, extending to the non-telecom fields.

A. Towards MIMO-free mode-multiplexed transmission

MMF is usually treated as a coupled-SDM solution since it experiences strong coupling between the degenerate modes within the same mode group and weak mixing between the mode group. MIMO-based DSP can be applied to undo the coupling after transmission and recover transmitted signals. System performance is mainly determined by system mode-dependent loss, optical signal-to-noise ratio, and independent of mode coupling strength. However, MIMO processing is computationally complex and needs full-field information offered by coherent detection. High receiver complexity limits MDM applications in cost-sensitive short and medium-reach optical networks requiring low-cost and low-power consumption receiver schemes like direct detection. With respect to receiver-side MIMO, MIMO processing can also be operated at the transmitter to permit simple receivers. The operation uses the knowledge of the coupling matrix of the MMF and predistorts the mode-multiplexed signal by multiplying the signal with the inverse of the coupling matrix to mitigate crosstalk after transmission. Transmitter-side MIMO can be applied in the optical networks with a point-to-multipoint topology such as PON where the cost of the central office can be shared by a group of end users to achieve MIMO-free MDM transmission.[65] Modal crosstalk can also be mitigated employing optical signal processing such as low-coherence matched detection[66] which uses the short coherence length property of amplified spontaneous emission noise to decoherence the modes and suppresses coherent interference through matched detection at the cost of spectral efficiency.

From the fiber design perspective, an all-solid heterogeneous MCF with non-identical fiber cores was proposed[67] and experimentally demonstrated.[68] Crosstalk between any pair of cores can be sufficiently suppressed due to the phase mismatch. Measured crosstalk between neighboring cores can reach −70 dB,[69] which is applicable for MIMO-free transmission. In an MMF, a step-index core profile is more desired for MIMO-free MDM transmission compared to a grade-index core MMF.[70] The effective index differences between the modes need to be large enough ($>1 \times 10^{-3}$) to suppress mode coupling. Effective index differences between the modes can be further enlarged through optimizing fiber's reflective index profile. One example is to sectionally tailor the step-index core profile along the radial direction to fine-tune the effective indices for certain modes.[71] Breaking the rotational symmetry of the fiber core, e.g., using an elliptical core, can decouple the modes which normally degenerate in a circular fiber core, therefore increasing the number of weakly coupled spatial modes applicable for MIMO-free transmission.[72,73]

For integrated circuits, the effective refractive indices of the waveguide modes are highly dependent on the waveguide dimensions. Thus, the waveguide width deviations caused by inevitable fabrication inaccuracies affect the performance of the mode (de)multiplexers. In addition, due to the small effective refractive index differences between the waveguide modes, there is always a mode mixing during the demultiplexing process, which results in significant inter-mode crosstalk and degrades the performance of the MDM systems. With the scaling of the mode counts, the complexity of the DSP required by the MIMO processing would increase significantly. Currently, for a 15-channel MDM system based on optical fibers, the MIMO complexity has reached 30×30, which requires significant computation power.[74]

To achieve a MIMO-free MDM transmission on-chip, a densely packed waveguide array (DPWA) may be a promising candidate. By employing single mode waveguides with different lateral dimensions, multichannel MDM with low crosstalk values of –20 dB can be obtained.[3] DPWA structures based on bent waveguides with different radius[75] and multimode waveguides[76] have also been proposed to scale the MDM channel counts. Anisotropic dielectric perturbations[77] can be further introduced in the spacing between DPWA waveguides to suppress the coupling between channels, thus realizing a MIMO-free transmission.

B. Economics of SDM against parallel SMF systems

From a transmission capacity perspective, modal channels in a FMF are logically the same as multiple single modes in a single-mode fiber bundle. Whether SDM or fiber bundle wins out will be determined by the cost per bit for transmission. Therefore, SDM must produce enough cost savings elsewhere to offset the additional cost of DSP. In this regard, SDM may reduce cabling cost. To maintain robustness and deployability, each optical fiber cable will be limited in the number of fiber strands, especially for undersea systems. When the transmission capacity requirement exceeds that can be provided by a single-mode fiber bundle in one cable, SDM fibers will cost less for cabling in terms of materials, fabrication, and deployment. The degree of cost saving in cabling will be proportional to the factor over which the transmission capacity requirement exceeds a single-mode fiber cable. Using SDM, transmission capacity increases linearly with power consumption while transmission capacity using higher-order modulation formats in the limited number of fibers increases logarithmic with power consumption. Reduce power consumption not only reduces the electrical part of the cabling costs but also may lend SDM as the only solution due to power delivery considerations in the undersea environment. In addition, in SDM, multiple mode channels can be amplified in a single few-mode EDFA.

C. Quantum information processing

Coupling spatial modes with other degrees of freedom (time, frequency, polarization, etc.) provides a different route to encoding and processing quantum information in higher dimensions,[78] which leads to more efficient logic gates and noise resilient communications. It would be fair to say that the development of MDM technology makes quantum systems more scalable and practical, and the reason for this statement is twofold. First, multimode waveguides, such as few-mode fibers, hollow-core fibers, and integrable waveguide circuits, function as quantum channels for constructing quantum network and distributing spatially entangled states with improved scalability.[79–81] Second, the Kerr nonlinearity in low-loss waveguides can be used to generate and manipulate spatially multimode quantum states.[82–86] The all-fiber (or on-chip waveguide) quantum devices, including the sources of spatial entanglement, hyperentanglement of spatial and polarization modes, and spatial-mode-selective quantum frequency converter etc., will pave the way for generation and manipulation of massively multimode qubits or qudits for future quantum computing and information processing systems.

Currently, the workhorse source of a quantum state in higher-order spatial modes is generated from $\chi^{(2)}$ nonlinear crystals.[78,87] Such a source, however, is not compatible with MDM transmission links. When the quantum states are launched into the low-loss transmission fibers, there exists large coupling losses. This severely degrades the performance of quantum information processing, because the rate of quantum communication depends quadratically on the coupling efficiency. Therefore, it is desirable if a quantum light source could be realized by using the Kerr nonlinearity of FMF itself. By doing so, the source can be seamlessly combined with an MDM transmission system.

Moreover, it is worth noting that the nonlinearities in FMFs exhibit many phenomena owing to FMF's wide options for mode- and dispersion-engineering, leading to the development of various quantum devices for information processing. Since the quantum device often involves the manipulation of photons via four wave mixing (FWM) processes,[84–86] the existence of Raman scattering (RS) degrades the performance of these quantum devices. Therefore, the RS accompanying FWMs in FMFs needs to be suppressed. Fortunately, this shortcoming can be overcome by properly designing the structures of an FMF and on-chip waveguide. As a result, the toolset realized on an FMF based nonlinear-optical platform will be able to efficiently generate, process, and analyze spatially multimode quantum states, which can greatly increase the capacity of quantum communications (e.g., quantum key distribution) and provide the interface between the high-capacity SDM quantum communication links and quantum memories.

D. Emerging applications

Most on-chip MDM devices do not show resonance or interference effects, offering wide operation bandwidths to combine with WDM technique and, thus, effectively scale up the capacity. Various approaches have been proposed to realize WDM-MDM hybrid multiplexing by combining mode (de)multiplexers with micro-ring resonators[88] or arrayed waveguide gratings.[89,90] For multimode/few-mode fibers, their transparency windows normally cover the communication bandwidths. WDM-MDM schemes based on FMFs,[91] MMFs,[92,93] and ring-core fibers[94] have been reported as viable approaches to achieve high-capacity transmission.

The applications we have discussed in this Perspective are communications centric. By leveraging the optical properties of high order orthogonal modes in MDM, there are many potential applications beyond telecom that may emerge in the near future. For example, through dispersion engineering of high-order waveguide modes,[95] the phase matching condition in the visible regime for four-wave mixing can be satisfied, thus opening an interesting wavelength window for nonlinear applications. Alternatively, a multimode waveguide can support the propagation of a fundamental mode with reduced surface scattering and therefore a very low transmission loss, enabling a broadband frequency comb generation.[48]

An MMF with a large number of spatial modes offers diffraction-limited spatial resolution, which makes the MMFs a strong candidate in ultra-thin optical fiber-based endoscopy for minimally invasive *in vivo* imaging.[96–98] 50 μm field of view can be realized employing an MMF with a diameter of 60 μm in deep brain *in vivo* imaging.[99] To use the MMF as an imaging system, pre-calibration measuring mode coupling[97] is needed through either phase-shifting interferometry or off-axis interferometry at the distal end, sharing a similarity to the coherent detection used in telecommunications. However, the fiber needs to keep rigid during the whole imaging process. Any perturbation, which changes mode coupling, will result in a fiber re-calibration, making current MMF-based endoscopy experience limited flexibility and less reliable compared to the implementation in telecommunications where adaptive equalizers are capable of fast tracking of mode coupling changes.[100] Single-ended full or partial coupling matrix estimation demonstrations employing partial reflector,[101] spatial pilots,[65] and guide-star[102] show the potential to realize a perturbation-insensitive MMF-based endoscopy capable of continuous fiber coupling matrix monitoring without access to the distal end of the fiber.

V. CONCLUSION

We reviewed the current status of MDM techniques implemented with multimode fibers, coupled core fibers, and silicon photonic chips. We then discussed typical systems based on MDM: quasi-single-mode transmission, multicore few-mode amplifier, and FMF sensing. Future development trends and perspective are also brainstormed, including MIMO-free MDM transmission, economics of MDM, and quantum information processing. While most of the discussion is communications centric, we introduced some non-telecom applications by leveraging the optical properties of high order modes, e.g., nonlinear optics in the visible regime, broadband frequency comb generation, and super resolution endoscopy. The optical mode provides an interesting degree of freedom in physics, because the mode manipulation takes into account waveguide design, offering a rich space to explore in scientific research and technology development. Many breakthrough techniques and applications of MDM can be envisioned in the near future.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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