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Multimode communication with programmable photonic integrated mesh

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Abstract

The programmable photonic integrated mesh is arising as a powerful tool to deal with crosstalk in the multimode optical communication link.

Main

As wavelength-division multiplexing (WDM) systems are approaching the ~200 Tb/s capacity limit, research on space-division multiplexing (SDM) systems has become active in the past decades, demonstrating data rate exceeding 10 Pb/s [1]. SDM significantly increases the capacity and efficiency of optical communication systems by encoding information in a fiber either comprises multiple single-mode cores (multi-core fiber, MCF), a multi-mode core carrying multiple orthogonal modes (few-mode fiber, FMF, and multi-mode fiber, MMF), or a combination of the two. Unlike wavelength channels whose crosstalk is slight, modes are less reliable in maintaining orthogonality. They can easily couple with each other in transmission channels, such as FMF/MMF or free space, due to random perturbations in the effective refractive indices experienced by different modes, necessitating the unmixing of signals at the receiver to recover the transmitted information. In traditional SDM systems, the descrambling of mixed signals is implemented through multiple-input multiple-output (MIMO) processing in digital signal processors (DSPs), which involves computationally expensive matrix inversion operations [2–4]. This process imposes heavy overhead in both power consumption and latency on the DSPs, especially when data rate is high and the number of modes is large, thereby impairing the efficiency of the optical communication link. Optical MIMO descrambler offers a promising alternative to DSPs at the receiver end for addressing mode scrambling and polarization rotation directly in the optical domain without priori information about the modulation format and channel mixing status. Given the orthogonality of the input modes, output modes, crosstalk matrix and dispersion matrix, a unitary matrix (preserves orthogonality and is referred to as an orthogonal matrix when all matrix elements are real-valued) is required to descramble the mixed signals. A programmable photonic integrated Mach-Zehnder interferometer (MZI) mesh, which encodes an arbitrary unitary matrix [5], forms the core component of the optical signal

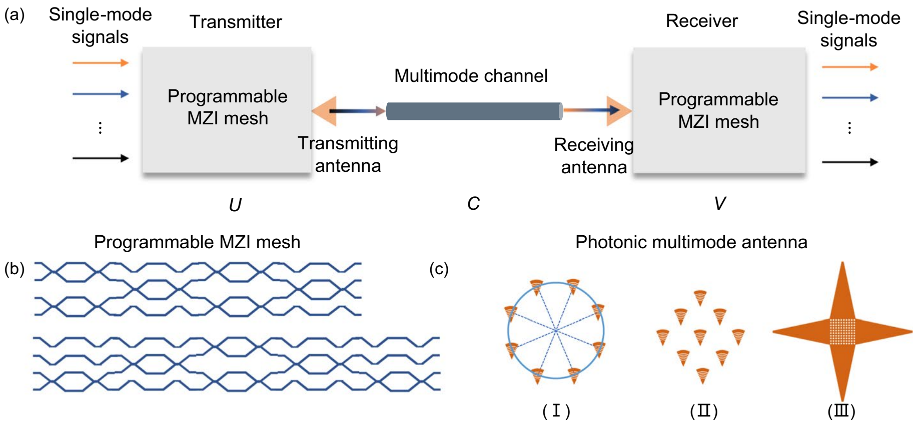

Fig. 1 The schematic of multimode communication using programmable integrated photonic meshes. **a** The overall frame of the multimode communication system. **b** Instances of programmable MZI mesh. **c** Instances of transmitting and receiving optical antennas

processors (OSPs) in SDM systems, as primitively demonstrated by simple signal unmixing in MCF systems [6–8].

Research on multimode communication systems utilizing programmable photonic integrated meshes has been initiated in recent years. Figure 1(a) presents a general diagram of such a system. The transmitter transforms the input single-mode signals into different orthogonal spatial modes via a uniform transformation in the first programmable MZI mesh. The multimode signals propagate through the communication channel (whether in free space, FMFs or MMFs), where they experience power loss and crosstalk among different modes. At the receiver end, the mixed modes are first converted back into multiple single-mode signals, each carrying mixed information bits, and then undergo a reverse uniform transformation in the second programmable MZI mesh to recover the original input signals. The transmitting and receiving antennas, typically consisting of single-mode grating coupler arrays or multi-mode grating couplers, are used to convert between on-chip single-mode signals and off-chip multimode-signals by sampling the complex amplitudes of optical fields or through mode conversion.

A mathematical model of the multi-mode communication system is introduced below to illustrate the entire process. The transmitter, channel (including the transmitting and receiving antennas), and receiver can be represented by transmission matrices $\boldsymbol{U}$, $\boldsymbol{C}$, and $\boldsymbol{V}$, respectively. An ideal loss-free and crosstalk-free link satisfies $\boldsymbol{VCU}=\boldsymbol{I}$, where $\boldsymbol{I}$ is the identity matrix, ensuring that the output modes are exactly the same as the original orthogonal input modes, i.e., $\boldsymbol{y}_r=\boldsymbol{VCUx}_t=\boldsymbol{x}_t$. In practice, the communication channel suffers from nonidealities such as propagation loss, mode crosstalk and mode dispersion, which are reflected in the channel matrix, $\boldsymbol{C}$. Any channel matrix can be represented by its singular value decomposition (SVD) as: $\boldsymbol{C}=\boldsymbol{P\Sigma Q}^{\boldsymbol{H}}$, where $\boldsymbol{P}$, $\boldsymbol{Q}$ are two unitary matrices and $\boldsymbol{\Sigma}$ is a diagonal matrix with singular values on its diagonals. To descramble the mixed modes, the two programmable MZI meshes are pre-trained to satisfy: $\boldsymbol{V}=\boldsymbol{P}^{\boldsymbol{H}}$, and $\boldsymbol{U}=\boldsymbol{Q}$, such that the output modes become: $\boldsymbol{y}_r=\boldsymbol{VCUx}_t=\boldsymbol{P}^{\boldsymbol{H}}\boldsymbol{P\Sigma Q}^{\boldsymbol{H}}\boldsymbol{Qx}_t=\boldsymbol{\Sigma x}_t$. The singular values on the diagonals of $\boldsymbol{\Sigma}$ directly determine the transmission rates of the corresponding modes, with larger singular values being selected as the actual communication channels. The two MZI meshes need to be re-trained when the channels experience environmental disruptions or when the mode bases are changed. In long-haul systems where the mode dispersion becomes significant, additional optical delay lines are needed to compensate for time differences.

Several works employing this architecture have been reported recently, with slightly different configurations of the programmable MZI mesh and the transmitting and receiving optical antennas. In Oct. 2023, Bo Wu and his colleagues from Huazhong University of Science and Technology demonstrated a universal mode processor for chip-to-chip multimode communications [9]. They adopt a rectangular MZI mesh structure (top of Fig. 1(b)) and an optical antenna configuration with grating couplers arranged in a circle (Fig. 1(cI)). They set up a chip-to-chip 4*f* system and demonstrated a four-mode communication system with a 25 Gb/s bit rate and a mode crosstalk of below − 18 dB with different mode bases, including both the orthogonal linearly polarized (LP) mode and orbital angular momentum (OAM) modes. In Nov. 2023, Francesco Morichetti et al. from Politecnico di Milano brought new insights into finding optimized communication channels in free space [10]. The methodology can be applied to arbitrary and scattering optical systems, providing a guideline for spatial multimode communication. They utilized a simplified triangular MZI mesh structure (bottom of Fig. 1(b)) and an optical antenna configuration with grating couplers arranged in a square mesh (Fig. 1(cII)). A crosstalk of below − 30 dB between the two optimized channels in the presence of distorting masks and partial obstructions is experimentally demonstrated. Very recently, Kaihang Lu et al. from The Hong Kong University of Science and Technology proposed a high-dimensional optical fiber communication system with programmable photonic meshes [11]. In addition to the spatial mode crosstalk, they also address the polarization crosstalk. They devised a multimode grating coupler (Fig. 1(cIII)) as a multimode antenna, capable of emitting four LP modes with two polarizations. An 8×8 triangular MZI mesh (bottom of Fig. 1(b)) is adopted to perform mode descrambling. They set up a chip-FMF-chip communication system with a bit rate of 32 Gb/s and achieve a crosstalk of below − 15.2 dB for all modes.

Although recent advancements in multimode communication using programmable integrated photonic meshes have shown their huge potential, there are some crucial challenges. First, the coupling efficiency of the proposed multimode antennas in Fig. 1(cI) and (cII) is quite low due to the small effective area of the grating couplers, while the multimode antenna Fig. 1(cIII) shows satisfying efficiency based on chirped grating designs and optimization algorithms. A high-efficiency and scalable multimode antenna is an indispensable component of the chip-to-chip multimode communication system and deserves more investigation. Possible solutions include increasing the coupling efficiency of a single grating coupler [12, 13], improving the fill factor of the grating coupler array, using off-chip focusing/collimating optics to match the size of the MMF and the grating couplers [10], and replacing grating couplers with higher-efficiency edge couplers [14]. Second, mode dispersion should be taken into account along with mode crosstalk in long-distance multimode communication, which introduces extra temporal inconsistency. Although an integrated scheme for a temporal crosstalk descrambler has been proposed for emulated MCF systems [8], the actual performance in practical MMF systems still needs to be examined. Third, real-time reconfiguration of the programmable photonic mesh to accommodate a complex and dynamic environment is crucial and necessitates further research. When fast adaptation is necessary, faster training algorithms, electro-optic phase tuning, high-bandwidth power monitoring, and high-speed control electronics are required.

The research on multimode communication with programmable photonic integrated meshes represents a significant leap forward in optical communication technology [9–11]. As traditional WDM systems reach their capacity limits, SDM systems utilizing these innovative optical signal processors offer a promising alternative. By processing signals directly in the optical domain, these systems bypass the heavy overhead associated with digital signal processing, thus enhancing efficiency, reducing latency, and cutting power consumption of the optical communication links. It can be anticipated that the programmable integrated photonic mesh holds great promise to transform the current optical communication paradigm, making it more efficient, timely, and intelligent.

Abbreviations

WDM	Wavelength-division multiplexing
SDM	Space-division multiplexing
DSP	Digital signal processor
OSP	Optical signal processor
MIMO	Multiple-input multiple-output
MZI	Mazh-Zehnder interferormeter
SVD	Singular value decomposition
LP	Linearly polarized
OAM	Orbital angular momentum
MCF	Multi-core fiber
FMF	Few-mode fiber
MMF	Multi-mode fiber

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Declarations

Ethics approval and consent to participate

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Consent for publication

Not applicable.

Competing interests

Authors declare that they have no competing interests.

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