Scaling up SDM transmission capacity

Filipe Marques Ferreira
Optical Networks Group
University College London
London, UK
f.ferreira@ucl.ac.uk

Fabio Aparecido Barbosa
Optical Networks Group
University College London
London, UK
fabio.barbosa@ucl.ac.uk

Alfonso Ruocco
Optical Networks Group
University College London
London, UK
a.ruocco@ucl.ac.uk

Mu-Chieh Lo
Optical Networks Group
University College London
London, UK
m.lo@ucl.ac.uk

***Abstract*— We outline our vision to introduce ground-breaking programmable spatial multiplexing in novel transceivers capable of interfacing advanced multi-mode/core fibres with hundreds of spatial pathways and enabling scalability of all data pathways to reduce the cost and energy-consumption per bit.**

***Keywords*— multimode fibres, space-division multiplexing, photonic integrated circuits**

Space-division multiplexing (SDM) has emerged as a solution to overcome the capacity limit of single-mode fibres (SMFs) [1]. Among the possible SDM approaches, multi-mode fibres (MMFs) offer the highest spatial information density followed by coupled-core multi-core fibres (MCFs) – and with bundles of SMFs and uncoupled-core MCFs on the other end. Spatial density will play a critical role in maximising opportunities for opto-electronic integration gains, namely in transceivers, optical amplifiers, wavelength selective switches (WSSs), connectorisation and cable management and cable payload, and fibre-to-chip interface. SDM-specific transceiver integration is key to the overall value proposition of SDM. Spatial super-channels can share one laser for N spatial tributaries (as opposed to combining N lasers through a $1/N$ coupler – for WDM super-channels) and thus share common DSP functions such as laser frequency/phase recovery, beyond what can be achieved with parallel WDM systems. Also, with all crosstalking spatial paths originating and terminating at the same transceiver (as in coupled SDM), crosstalk cancellation techniques such as MIMO-DSP [2, 3] can be used, just as in wireless communications.

Multi-mode SDM offers the unique possibility of amplifying all spatial tributaries in a single Erbium-doped fibre pumped by a single high-power 980nm multimode pump with a wall-plug efficiency as much as 10 times better than that of single-mode version. Also in switching, multimode SDM offers the unique possibility of having all spatial tributaries traversing the same optical elements as in a conventional WSS. This way offering great advantages over uncoupled SDM approaches that require WSS optics to handle many more free-space beams than switching ports [4].

SDM based on multi-mode fibres also presents major challenges. The multitude of spatial modes introduces new linear impairments, namely group delay (GD) spread [5-7] stemming from the interplay between differential mode delay (DMD) and linear mode coupling (LMC), and mode dependent loss (MDL) [3]. The GD spreading can be undone using of MIMO equalisation [2, 3] but with complexity scaling with the total time spread. Therefore, multi-mode SDM fibres are designed with a graded-index cores [8, 9] to reduce the DMD. However, higher the number of modes supported higher will be the minimum DMD achievable. In [10], we took first steps into understanding what would be the characteristics of optical fibres approaching 1000 spatial and polarisation modes with a DMD comparable to that of conventional multimode fibres. And what would be the trade-offs in attempting to do so.

Despite having SDM fibres with much larger fundamental capacity, we need an effective way of extracting it. Ideally, SDM networks should offer a pathway to scale capacity like the one offered by wavelength-division-multiplexing (WDM) in SMF networks – capacity could be increased by lighting more wavelengths using transceivers with more wavelength stable lasers.

One of the main challenges with multi-mode SDM is that conventional MIMO equalization requires all guided modes to be detected for successful equalisation [11] – binding the number of fibre modes with the number of coherent front-ends required at transceivers. This prevents the installation of many-mode ($\gg 1$) fibres since it would not be possible to deploy transceivers with as many optical front ends from day one. And given that new fibre deployments need a major motivation (installations costs are recouped over a long time period ~10years), this tie needs to be breakdown. Motivation such as that offered by MMFs and multiplexers approaching 1000 spatial and polarisation modes [10].

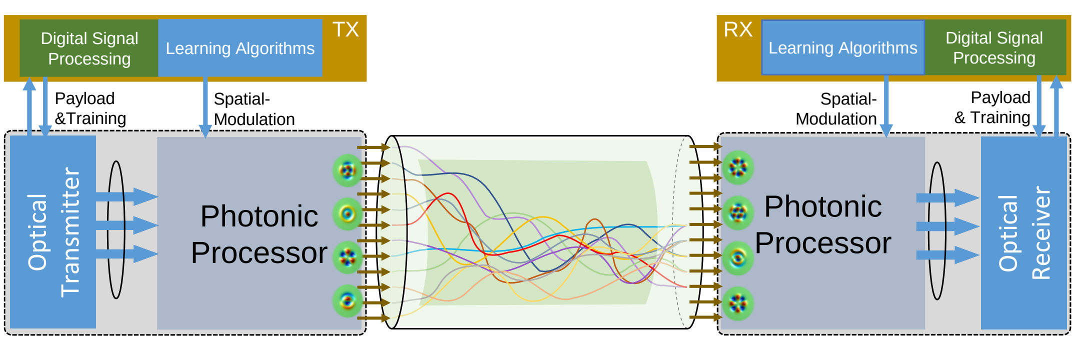

Fig. 1: Schematic view of the UKRI Future Leaders Fellowship Beyond Exabit Optical Communications.

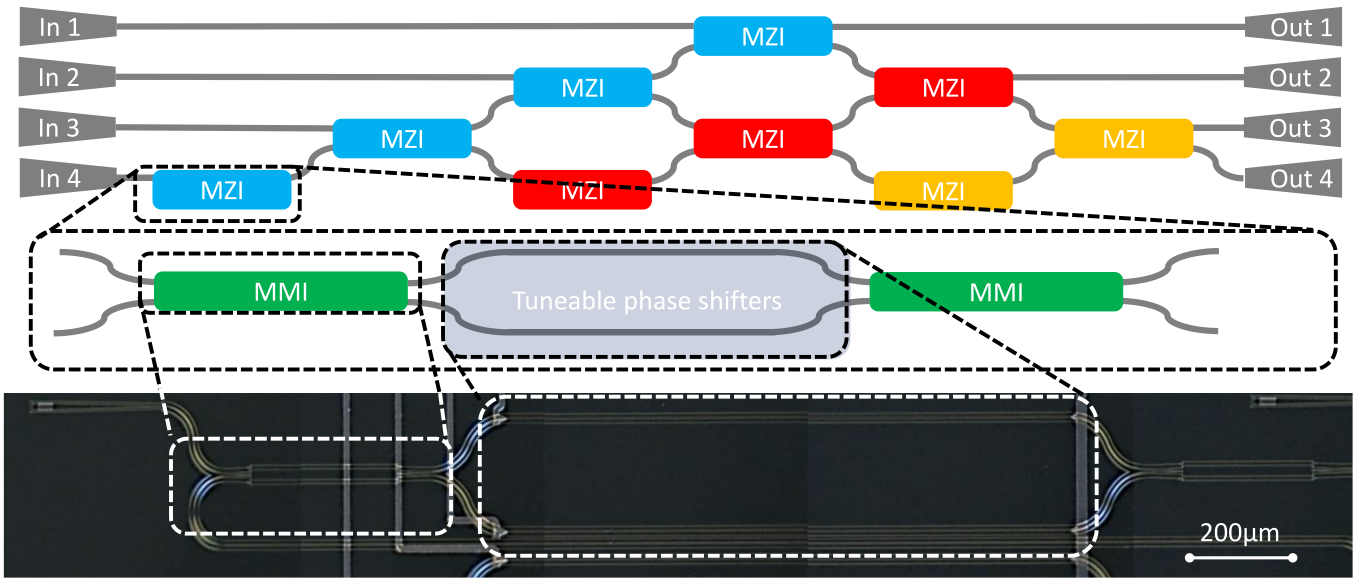

Fig. 2: (a) Schematic of the integrated implementation of the circuit using MZIs. (b) MZI is implemented using standard 2 × 2 multimode interferometers (MMIs) with individual thermo-optical phase tuning on the two arms. (c) Microscope image of the fabricated device.

In our project [12], we aim to develop a new family of scalable transceivers to exploit a growing number of modes over the same fibre infrastructure over several transceiver generations. We are investigating programmable solutions for an optical mapping of spatially independent signals to a desired combination of modes. This vision is encapsulated in the system schematic shown in Fig. 1. This process can be performed using a mesh of Mach–Zehnder interferometers (MZIs) mesh in a photonic integrated chip (PIC) [13]. Fig. 2 shows our first 4 x 4 circuit (fabricated over Cornerstone SiN MPW #2): (a) a schematic of the mesh, (b) the MZI implementation, and a microscope image of the fabricated device. Fig. 2(a) shows a mesh with four waveguides entering a triangular mesh with 'diagonal lines' that can each be configured to implement an arbitrary unitary matrix transformation between inputs and outputs. Our vision is to use PICs for programmable mode (de-)multiplexing allowing to launch and detect arbitrary mode vectors, and by leveraging on the growing capabilities of PICs, to develop a new family of transceivers capable of extracting a progressively larger modal subset of ~1000-mode fibres. Additionally, we are also exploring a spatial light modulator (SLM) and multi-plane light conversion (MPLC) [14, 15].

This new family of transceivers will use programmable mode multiplexers to interface mode-vectors whose characteristics are compatible with dynamic demand (e.g. throughput, distance). For instance, in multi-mode fibres [10]: (a) high-order groups, characterised by higher-degeneracy (number of paths), smaller nonlinearity and higher walk-off between paths, are ideal for high throughput over shorter inter-datacentre distances (much larger than exabit/s×km); (b) intermediate-order groups, with a more balanced level of nonlinearities and walk-off, can be used for long-haul transmission (at exabit/s×km); (c) the fundamental-order group, with high nonlinearity but very low walk-off, can be used to a carry a supervisory channel. To fully exploit this heterogeneous domain, we are exploring new end-to-end signalling approaches [16] and developing new machine learning techniques that will have to deal with the complexity and processing delays associated with dynamic operation and fibre characteristics drifting.

Acknowledgment

This work was supported by the UKRI Future Leaders Fellowship MR/T041218/1.

References

[1] D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," *Nature Photonics*, 7, p. 354, 2013.
[2] B. Inan *et al.*, "DSP complexity of mode-division multiplexed receivers," *Opt. Express*, 20(10), p. 10859, 2012.
[3] A. Lobato *et al.*, "Impact of mode coupling on the mode-dependent loss tolerance in few-mode fiber transmission," *Opt. Express*, 20(28), p. 29776, 2012.
[4] D. M. Marom *et al.*, "Wavelength-selective switch with direct few mode fiber integration," *Opt. Express*, 23(5), p. 5723, 2015.
[5] F. Ferreira, P. Monteiro, and H. Silva, "Semi-analytical model for linear modal coupling in few-mode fiber transmission," in *Proc. ICTON*, 2012, p. Th.A1.5,.
[6] K.-P. Ho and J. M. Kahn, "Linear Propagation Effects in Mode-Division Multiplexing Systems," *J. Light. Technol.*, vol. 32, no. 4, pp. 614-628, 2014,.
[7] A. Mecozzi, C. Antonelli, and M. Shtaif, "Intensity impulse response of SDM links," *Opt. Express*, vol. 23, no. 5, pp. 5738-43, 2015.
[8] F. Ferreira, D. Fonseca, and H. Silva, "Design of few-mode fibers with M-modes and low differential mode delay," *J. Light. Technol.*, 32(3), p. 353, 2014.
[9] F. Ferreira, D. Fonseca, and H. Silva, "Design of few-mode fibers with arbitrary and flattened differential mode delay," *IEEE Photon. Technol. Lett.*, 25(5), p. 438, 2013.
[10] F. M. Ferreira and F. A. Barbosa, "Towards 1000-mode Optical Fibres," *submitted to ECOC* [available on arXiv], 2022.
[11] P. J. Winzer and G. Foschini, "MIMO capacities and outage probabilities in spatially multiplexed optical transport systems," *Opt. Express*, 19(17), p. 16680, 2011.
[12] "Beyond exabit optical communications: From new devices, via new dimensions to new systems," ed: UKRI Future Leaders Fellowship MR/T041218/1, 2020.
[13] A. Ribeiro, A. Ruocco, L. Vanacker, and W. Bogaerts, "Demonstration of a 4x4-port universal linear circuit," *Optica*, 3(12), p. 1348, 2016.
[14] N. K. Fontaine *et al.*, "Programmable Vector Mode Multiplexer," in *ECOC*, p. Th.PDP.C.6, 2017.
[15] D. Pohle, S. Rothe, F. Barbosa, F. M. Ferreira, N. Kouk-ourakis, and J. W. Czarske, "Intelligent self calibration tool for adaptive mode multiplexers using multiplane light conversion," to be presented at the 25th Congress of the International Commission for Optics, 2022.
[16] F. A. Barbosa "On a Scalable Path for Multimode MIMO-DSP," *submitted to ECOC* [available on arXiv], 2022.