Focus Issue: Space Multiplexed Optical Transmission

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Introduction

Optical fiber communication is the backbone for the telecommunications infrastructure that supports the internet. Fueled by emerging bandwidth-hungry applications and increase in computer processing power that follows the Moore's Law, internet traffic has sustained exponential growth and this trend is expected to continue for the foreseeable future. It is well known that the capacity of a communication channel is constrained by the Shannon limit, $W\log_2(1+S/N)$, where W is the spectral bandwidth and S/N is the signal-to-noise ratio (SNR). In optical fiber communication, fiber nonlinearity imposes an additional limit in the high power or high SNR regime. Digital coherent detection increases optical signal tolerance to linear noise such as amplified spontaneous emission noise, and sometimes nonlinear phase noise. However, the single-channel capacity increase scales logarithmically with the increase in SNR. This logarithmical single-channel capacity scaling ultimately will not be able to support exponential traffic growth. While it might be impossible to provide exponential single-channel capacity growth in optical communication, multiplicative growth in optical communication capacity has satisfied traffic demand in the past, especially when dense wavelength-division multiplexing (DWDM) with a multiplicative factor on the order of 100 was invented. As today's DWDM coherent optical communication technology has already taken advantage of all degrees of freedom of a lightwave in a single-mode fiber, namely frequency, polarization, amplitude, and phase, further multiplicative growth has to explore new degrees of freedom. Mode-division multiplexing (MDM) using few-mode fibers (FMF) and space-division multiplexing (SDM) using multi-core fibers (MCF) have emerged as promising candidates for the next multiplicative capacity growth for optical communication.

This Optics Express Focus Issue features the state-of-the-art research activities in MDM and SDM aimed at order-of-magnitude capacity growth in future optical communication systems.

This Focus Issue starts with two record-setting high-capacity transmission demonstrations using SDM in MCF. The first paper by B. Zhu *et al.* from OFS Labs and Bell Labs reports a transmission capacity of 112 Tb/s over a distance of 76.8-km using SDM in a 7-core fiber using SDM and DWDM in the C and L bands. Each of the 7 cores carried 160 polarization-division multiplexed quadrature phase-shift keying (PDM-QPSK) channels at 107-Gb/s on a 50-GHz grid, resulting in an aggregate spectral efficiency of 14 b/s/Hz. The impact of the inter-core crosstalk was experimentally investigated and the system implications of core-to-core crosstalk on long-haul transmission were discussed. The second paper by T. Hayashi *et al.* from Sumitomo Electric Industries reports an ultra-low-crosstalk MCF that is suitable for ultra-long-haul transmission. A remarkably low inter-core crosstalk level of below −60 dB was achieved in a 16.8-km 7-core fiber, by using a trench-assisted index profile. A transmission capacity of 109 Tb/s was demonstrated by using SDM and DWDM.

Following the two MCF transmission demonstrations are three papers on MDM-based transmission in FMF. C. Koebele *et al.* from Bell Labs, Kylia, Draka, and Irisa/Inria report the transmission of two 112-Gb/s PDM-QPSK signals over two orthogonal LP_{11} modes of a 40-km FMF, using liquid crystal on silicon (LCOS) based mode multiplexer and demultiplexer. 4 × 4 multiple-input multiple-output (MIMO) processing was used in an offline digital coherent receiver to achieve mode separation. A. Li *et al.* from The University of Melbourne reports successful transmission of two 17.65-Gb/s coherent optical orthogonal frequency-division multiplexing (CO-OFDM) signals over two orthogonal LP_{11} modes of a 26-km two-mode fibers using all-fiber mode converters and 4 × 4 MIMO-OFDM processing. S. Randel *et al.* from Bell Labs and OFS labs present the transmission of three 112-Gb/s PDM-QPSK signals over the fundamental mode (LP_{01}) and two orthogonal LP_{11} modes of a 33-km FMF. 6 × 6 MIMO processing was used to achieve the separation of the 3 spatial modes and the 2 polarizations of the transmitted signals. These experiments show the feasibility of scaling capacity using MDM in FMF in combination with

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MIMO signal processing. Practical implementation tasks such as power-efficient optical amplification for FMF and hardware-efficient MIMO processing remain to be important for future research.

The practical realizations of MDM and SDM call for enabling optical components such as multi-mode or multi-core optical fiber amplifiers, multi-mode processors, and novel multi-mode or multi-core optical fibers. K. S. Abedin et al. from OFS Labs have demonstrated a multicore erbium-doped fiber (MC-EDF) amplifier for simultaneous amplification in the 7-cores. The pump and signal were coupled to individual cores of the MC-EDF using two tapered fiber bundled (TFB) couplers. The average gain achieved in the MC-EDF fiber was 30 dB, and noise figure was less than 4dB. N. Bai *et al.* from of Central Florida and NEC Laboratories America propose a method for controlling modal gain in a multimode Erbium-doped fiber amplifier (MM-EDFA) by tuning the mode content of a multimode pump. By adjusting the powers and orientation of input pump modes, modal dependent gain can be tuned over a large dynamic range. The MM-EDFA may potentially be a key element for long haul mode-division multiplexed transmission. P. Krummrich from Technische Universitaet Dortmund presents optical amplification and optical filter based signal processing concepts for low-cost and energy efficient spatial multiplexing. Deployment of multimode Erbium-doped fiber amplifier (MM-EDFA) was shown to bring cost and energy efficiency advantages over MCF-based EDFA. Signal processing based on adaptive passive optical filters was suggested as an alternative approach for the separation of channels at the receiver which have experienced mode coupling along the link. This approach may also bring additional benefits in capacity and energy efficiency as compared to pure electronic signal processing. C. Xia *et al.* from University of Central Florida and AT&T Labs introduces the of supermode transmission, in which strong coupling between the cores of a MCF is allowed in order to achieve a larger mode effective area and higher mode density than those achievable by a low-crosstalk MCF. Compared to FMF, the coupled MCF was numerically shown to offer lower mode-dependent loss, mode coupling, and differential modal group delay.

The emergence of MDM and SDM as potential breakthrough technologies for future optical networks also calls for fundamental study on the ultimate capacity limit and energy consumption. This Focus Issue concludes with three papers that theoretically address these important fundamental questions. P. Winzer and G. J. Foschini of Bell Labs study MIMO capacities and outage probabilities in spatially multiplexed optical transport systems. They found that in order to achieve the low-outage standards required for optical transport networks, SDM transponders should be capable of individually addressing, and preferably MIMO processing all modes supported by the optical SDM waveguide. The impact of mode-dependent loss (MDL) on system capacity and system outage was also investigated. K.-P. Ko and J. M. Kahn from Silicon Image and Stanford University investigate the fundamental performance limitations on MDM due to MDL. Information-theoretic channel capacities of mode-division-multiplexed systems in the presence of MDL were studied, including average and outage capacities, with and without channel state information. Finally, I. Djordjevic of University of Arizona discusses energy-efficient spatial-domain-based hybrid multi-dimensional coded-modulations for multi-Tb/s optical transport. Orbital angular momentum (OAM) was used as an additional dimension to further improve the overall optical channel capacity. Promising multi-dimensional signal constellations were suggested to maximize the information capacity, while taking the energy efficiency into consideration.

It is our hope that this Focus Issue on MDM and SDM has provided a comprehensive survey of the state-of-the-art research activities in MDM and SDM and it will stimulate future research on this subject to address the remaining fundamental and practical challenges, potentially enabling dramatic capacity growth in future optical communication systems.

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