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Ultrahigh Capacity Optical Communications beyond Pb/s

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Abstract: Recent progress in ultrahigh capacity optical communication technologies based on space-division multiplexing is described including one Pb/s transmission in a newly developed multi-core fiber with future perspectives for more capacity.

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems

1. Introduction

The global data traffic is continuing to increase driven by the ever-increasing computing powers, memory capacity as well as large user applications, and rapidly-increasing wired/wireless access speeds. As we look back on the last three decades since 80's, we have enjoyed various great inventions as shown in Fig. 1, achieving a capacity increase of as much as 60 dB from 100 Mb/s up to 100 Tb/s (2dB/year), and we will probably need a similar scalability for the next three decades. Recent experimental and theoretical studies, however, strongly suggest that we are approaching a fundamental capacity limit in single-mode fibers due to fiber nonlinearities, optical amplifier bandwidth, and fiber fuse [1-3]. Space-division multiplexing (SDM) to utilize the last degree of freedom of "space", initially proposed more than three decades ago [4-5], has revived and has been intensively studied recently as a means to substantially increase the transmission capacity per fiber [6-7] in a cost-effective and energy-efficient way.

Fig. 1. Evolution of optical transmission technologies.

2. Recent progress in ultrahigh capacity optical communications technologies based on SDM

Two SDM schemes based on multi-core fibers (MCFs) [8-10] and multi-mode (few-mode) fibers (MMFs or FMFs) [11-12] have been proposed. When multiple independent modes are used as an independent channel, the multiplexing scheme is also called mode-division multiplexing (MDM). Recently, few-mode multi-core fibers (FM-MCFs) have also been proposed combining the two fibers to further increase the transmission capacity. As shown in Fig. 2, new components for SDM are space-multiplexer (SDM-MUX) to couple light from different cores or different modes into SDM fibers, SDM fibers, SDM optical amplifiers to amplify SDM signals, space-demultiplexer (SDM-DEMUX), optical connectors, mode exciters (generators) in the case of MDM, and MIMO processing. Major important characteristics of the passive components are low insertion loss, low core/mode dependent loss, low crosstalk among modes/cores and wide bandwidth to support WDM/SDM signals. SDM optical amplifiers are also a challenge where low core/mode/wavelength dependent, wide bandwidth amplification characteristics with high gain and low noise figures (NFs) are desirable in a energy efficient manner. Much progress has been made in MDM transmission, employing well designed FMFs or coupled MCFs either with or without multiple-input multiple-output (MIMO) processing, in which a transmission distance up to 4,200 km [13] or 57.6 Tb/s net capacity over 119 km [14] have been reported. MDM experiment based on orbital angular momentum (OAM) modes has also been demonstrated where 400 Gb/s QPSK data was transmitted recently over 1.1 km [15].

Fig. 2. Basic components of SDM systems.

SDM transmission utilizing low crosstalk MCFs has also seen many experimental demonstrations with capacity over 100 Tb/s, 300 Tb/s up to 1 Pb/s, employing uncoupled 7-core, 19-core, and 12-core MCFs [16], respectively or over 1,000 km. Multi-mode (MM) or multi-core (MC) optical amplifiers are strongly required for long-haul systems and should be major enablers to make SDM systems cost-effective and energy-efficient compared to present systems. MM or MC amplifiers, either EDFA-based or Raman-based, have been proposed and used in the transmission experiments. Nonlinearity in these new fibers has also begun to be studied [17]. Recently, one Pb/s transmission (12 SDM x 222 WDM x 456 Gb/s) over 52 km with an aggregate spectral efficiency of 91.4 b/s/Hz has been demonstrated employing a low crosstalk, a one-ring structured 12-core MCF and PDM-32 QAM modulation where the MCF has a core pitch of 37 μm , a cladding diameter of 225 μm , and the effective core area (A_{eff}) at 1550 nm and 1625 nm are 80.7 μm^2 and 84.7 μm^2 on average, respectively [16]. Attenuation at 1550 nm and 1625 nm are 0.199 dB/km and 0.207 dB/km, respectively.

3. Future perspectives

A capacity-distance product of 1 Eb/s-km (1 Pb/s x 1,000 km, for example) will be the next mile stone in SDM transmission technologies. For a new SDM fiber to be considered for installation by network operators in the future, an SDM gain in capacity of more than 100, corresponding to 10 Pb/s per fiber should be necessary. This could be realized by a combination of > 20 cores per fiber and > 5 modes per polarization per core. Fiber nonlinearity and attenuation loss of new fibers, NFs/bandwidth of optical amplifiers will limit the WDM/SDM capacity and transmission distance. Lower nonlinearity and lower attenuation loss with a new wavelength window are what hollow core photonic bandgap fibers (PBGFs) are seeking and further progress will be expected. New node/switching architectures will also be important research subjects to fully utilize the vast capacity in future networks.

4. References

- [1] R.-J. Essiambre et al., "Capacity limits of optical fiber networks," J. Lightwave Technol., Vol. 28, No. 4, pp. 662–701, (2010).
- [2] A. D. Ellis et al., "Approaching the non-linear Shannon limit," J. Lightwave Tech., Vol. 28, No. 4, pp. 423–433 (2010).
- [3] T. Morioka, "New generation optical infrastructure technologies: "EXAT initiative: towards 2020 and beyond," OECC 2009, FT4 (2009).
- [4] S. Inao et al., "Multicore optical fiber," OFC79, WB1 (1979).
- [5] S. Berdague et al., "Mode division multiplexing in optical fibers," Appl. Opt., Vol. 21, No. 11, pp.1950–55 (1982).
- [6] T. Morioka et al., "Enhancing optical communications with brand new fibers," IEEE Commun. Mag., Vol. 50, No. 2, pp. s31-s42, (2012).
- [7] M. Nakazawa, "Extremely advanced transmission with 3m technologies (multi-level modulation, multi-core & multi-mode)," OFC/NFOEC 2012, OTu1D.1 (2012).
- [8] K. Imamura et al., "Multi-core holey fibers for ultra large capacity wide-band transmission," ECOC 2008, P.1.17 (2008).
- [9] Y. Kokubun et al., "Novel multi-core fibers for mode division multiplexing: proposal and design principle," IEICE Electron. Exp., Vol. 6, No. 8, pp. 522–528, (2009).
- [10] M. Koshiha et al., "Heterogeneous multi-core fibers: proposal and design principle," IEICE Electron. Express, Vol. 6, No. 2, pp. 98–103 (2009).
- [11] C. Koebele et al., "40 km transmission of five mode division multiplexed data streams at 100 Gb/s with low MIMO-DSP complexity," ECOC 2011, Th.13.C.3 (2011).
- [12] E. Ip et al., "88x3x112-Gb/s WDM Transmission over 50-km of Three-Mode Fiber with Inline Multimode Fiber Amplifier," ECOC 2011, Th.13.C.2 (2011).
- [13] R. Ryf, et al., "Space-division multiplexed transmission over 4200 km 3-core microstructured fiber," OFC/NFOEC 2012, PDP5C.2 (2012).
- [14] V. Sleiffer et al., "73.7 Tb/s (96X3x256-Gb/s) mode-division-multiplexed DP-16QAM transmission with inline MM-EDFA," ECOC 2012, PDP Th.3.C.4 (2012).
- [15] N. Bozinovic et al., "Orbital angular momentum (OAM) based mode division multiplexing (MDM) over a Km-length fiber," ECOC 2012, PDP Th.3.C.6 (2012).
- [16] H. Takara et al., "1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) crosstalk-managed transmission with 91.4-b/s/Hz aggregate spectral efficiency," ECOC 2012, PDP Th.3.C.1 (2012).
- [17] S. Mumtaz et al., "Nonlinear Propagation in Multimode and Multicore Fibers: Generalization of the Manakov Equations," IEEE J. Lightwave Technol., Vol. 31, Issue 3, pp. 398-406 (2013).