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.
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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.

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 an 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].
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