Ultra-high Capacity Transmission with Few-mode Silica and Hollow-core Photonic Bandgap Fibers

V.A.J.M. Sleiffer,[1] P. Leoni,[2] Y. Jung,[3] H. Chen,[1] M. Kuschnerov,[4] S.U. Alam,[3] M. Petrovich,[3] F. Poletti,[3] N.V. Wheeler,[3] N. Baddela,[3] J. Hayes,[3] E. Numkam Fokoua,[3] D.J. Richardson,[3] L. Grüner-Nielsen,[5] Y. Sun,[5] and H. de Waardt[1]

[1]*COBRA institute, Eindhoven University of Technology, The Netherlands, e-mail: v.a.j.m.sleiffer@tue.nl*
[2]*Universität der Bundeswehr München, 85577 Neubiberg, Germany*
[3]*Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK*
[4]*Coriant R&D GmbH, St-Martin-Str. 76, Munich, Germany*
[5]*OFS, Priorparken 680, 2605 Brøndby, Denmark*

Abstract: We review the capacity records achieved using mode-division multiplexing in few-mode fiber and hollow-core photonic bandgap fibers. Currently the MDM-capacity record for both fiber types is 73.7 Tb/s, whereas per wavelength 960 Gb/s is achieved.

OCIS codes: (060.1660) Coherent communications, (060.2330) Fiber optics communication, (060.4080) Modulation.

1. Introduction

With the advances in several fields of technology, the amount of data traffic is steadily growing every year [1]. To support this growth, optical networks, which carry most of the traffic, will have to be scaled up in capacity. For the coming years conventional single mode fiber (SMF) will still provide sufficient capacity, but at some point in the future, foreseen to be around 2020, new transmission fiber technology is likely to be required to fulfill the world's wish for "unlimited" connectivity at an acceptable cost per bit.

Research has looked into several physical dimensions in order to exploit the capacity of SMF to the maximum: wavelength-division multiplexing (WDM), polarization-multiplexing and quadrature-amplitude modulation (QAM) [2, 3]. Capacity-distance product results have been achieved in the laboratory at close to what is believed to be the practical limit of SMF technology [4]. Only one dimension remains to be exploited: the spatial domain. Using space-division multiplexing (SDM) multiple parallel, high capacity transmission lanes can be created in a single fiber and this is attracting a lot of recent research attention. Both multi-core [5-8] and multi-mode technology [9-18] are producing a lot of interesting results, paving the way to significant system capacity enhancements, with transmitted capacities larger than 1 Pbit/s demonstrated[7-8] and Exabit/s·km capacity-distance products already demonstrated.

Looking more specifically into multi-mode technology, two main fiber technologies exist: solid-core few-mode fibers (FMFs) [9-16] and hollow-core photonic bandgap fibers (HC-PBGF) [17-25]. In HC-PBGFs light travels mostly in air, thereby offering beneficial properties compared to solid core fibers including: a potential lower loss than solid-core fibers, ultra-low nonlinearity and low latency [25]. In this work we review the highest mode-division multiplexing (MDM) transmission capacities as well as the maximum per channel data rate achieved to date for both fiber types.

2. Experimental setup

The experimental setup used for our MDM experiments using the linear-polarized (LP) LP_{01}, LP_{11a} and LP_{11b} modes of a FMF [12-18], is depicted in Fig. 1. A similar setup is used in [10-11] and can readily be extended to employ more modes, as shown in [9].

At the transmitter side three transmitter setups were employed, creating 48 even, 48 odd and a channel under test (CUT). In total 96 of these 97 channels, running at 50-GHz ITU specified frequencies from 191.35 THz up to 196.1 THz, were multiplexed using a wavelength-selective switch (WSS), sweeping the CUT over all the

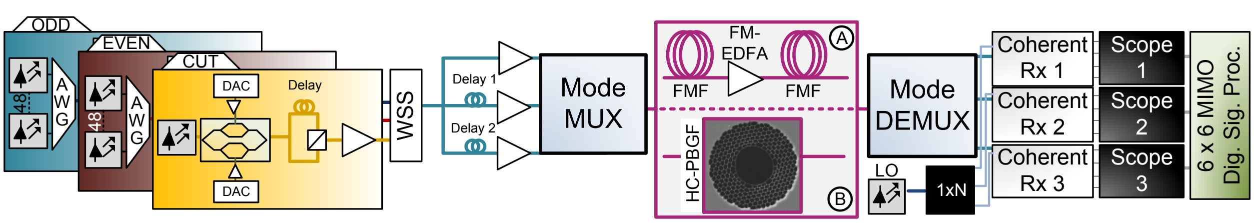


Fig. 1. Transmission setup used for mode-division multiplexing experiments reported in [12-14, 23, 25-26]. The transmission link consists either of A) few-mode fiber spans (FMF) with inline few-mode erbium-doped fiber amplifier (FM-EDFA) [12, 23, 25-26], or of B) hollow-core photonic bandgap fiber (HC-PBGF) [13-14, 18].

frequencies and dropping one of the even or odd channels. All channels were optically modulated using digital-to-analog converters (DACs), generating 32 GSymbols/s driving the in-phase and quadrature ports of an IQ-modulator. Polarization-multiplexing was emulated by splitting the signals in to two equally-powered tributaries, delaying one for de-correlation, and combining them again using a polarization beam-combiner. In this way 96 channels carrying 256-Gb/s dual-polarization (DP) 16QAM or 20 WDM 320-Gb/s DP-32QAM modulated signals were generated.

Afterwards three independent signals operating at the same wavelength are emulated by splitting the signal into three tributaries and delaying all of them by a different amount of symbols to ensure signal de-correlation. Next the signals have to be multiplexed into a FMF or HC-PBGF supporting an equal or greater number of LP modes than the number of input signals. The multiplexing can be achieved in a number of ways: a phase-plate based mode multiplexer [10-13, 17-18]; a photonic integrated mode-coupler [14, 26]; a spot-launching multiplexer [15, 27], 3D waveguide [9, 16], or photonic lantern [28]. After mode-multiplexing and travelling through a length of fiber, amplification is obtained by employing a FM-EDFA [10, 29-31], in which modal gain control is important to avoid degradation of the signal due to mode-dependent loss. After transmission the signals are de-multiplexed using one of the methods listed is also used for multiplexing, since all devices are in essence reciprocal.

All three signals have to be received simultaneously using three coherent receivers. Proper time-aligned reception is important to be able to undo the mixing of the modes during transmission. For signal reconstruction 6×6 multiple-input, multiple output digital signal processing (MIMO-DSP) [18, 32-35] is employed as described in [18], since each polarization and LP-mode (ending up with six signals for this case) can couple to each other.

3. Few-mode Fiber Transmission Results

Using three LP-mode supporting FMF [36], phase-plate based mode multiplexing and de-multiplexing, and exploiting all other domains to increase capacity, a transmission experiment with 96 WDM channels × 3 MDM × 256-Gb/s, adding up to a total transmitted gross capacity of 73.7 Tb/s was shown both over 119 km of FMF [12] with a mid-span FM-EDFA [29], and after 84km of FMF. The results after transmission are depicted in Fig. 2A, as well as the received spectrum as received on the LP_{01}-port of the mode de-multiplexer. The forward error correcting code (FEC)-limit was assumed at a pre-FEC bit error rate (BER) of $2.4{\cdot}10^{-2}$ [37]. As observed, the performance of all 96 wavelength channels is relatively flat, confirming the broadband operation of the FM-EDFA which is evident from the received spectrum. The transmission distance was output power limited, caused mainly by the high losses of the phase-plate based mode multiplexing (MMUX) and de-multiplexing. The net data rate per channel, taking into account 20% of FEC and additional overhead, was 600 Gb/s yielding a spectral efficiency (SE) of 12 bits/s/Hz and a net capacity of 57.6 Tb/s: the current record for MDM technology.

To show that MDM technology in combination with MIMO-DSP is a very robust way of transmitting data, the modulation format in follow up experiments was scaled to 32QAM. Generating 32QAM at high baud rates is very challenging due to the resolution and bandwidth limitations of current DACs and this results in a high error-floor for the generated 320-Gb/s DP-32QAM (BER of $2{\cdot}10^{-3}$) [13]. Using MDM, this error-floor increased to $4{\cdot}10^{-3}$. To be able to show post-FEC error-free transmission, pre-generated FEC-symbols were loaded into the DAC. The FEC-scheme used, being a concatenation of soft-decision inner-FEC and hard-decision outer-FEC code [38], resulted in a FEC-limit at a BER of $2{\cdot}10^{-2}$. Fig. 2B shows the transmission results for 20 WDM channels × 3 MDM × 320-Gb/s DP-32QAM over 60 km of three LP-mode supporting FMF with an FM-EDFA after 30km of FMF. This allowed for operation of the FM-EDFA in a high input power regime [29]. As observed all 20 wavelength channels perform the same, with a maximum average BER of $5{\cdot}10^{-3}$, which is well below the FEC-limit, and as such all channels were

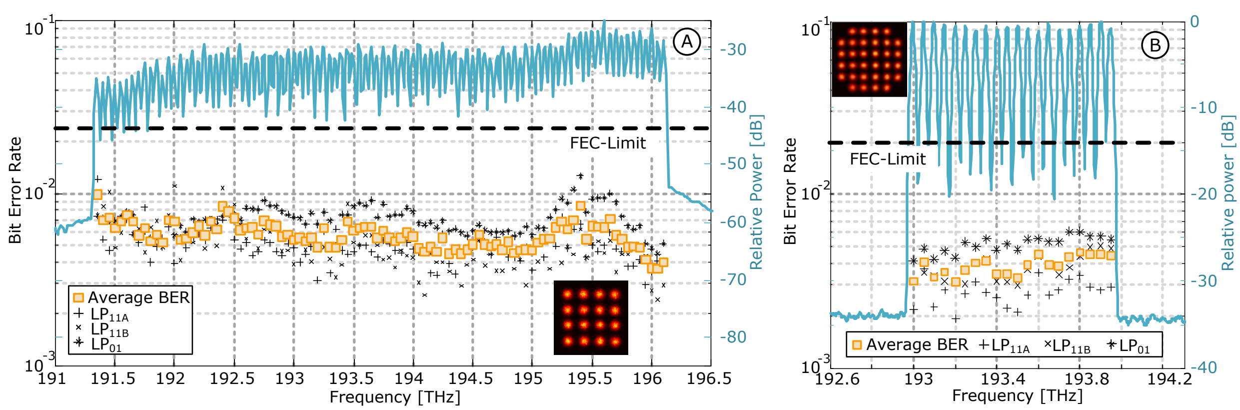
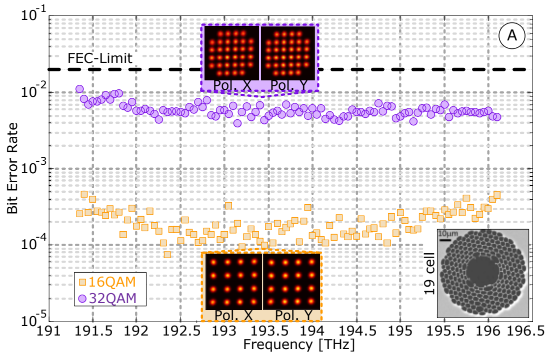


Fig. 2. A) 96 WDM × 3 MDM × 256-Gb/s DP-16QAM transmission results after 119km of FMF with inline FM-EDFA [12]. B) 20 WDM × 3 MDM × 320-Gb/s DP-32QAM transmission results after 60km of FMF [13]



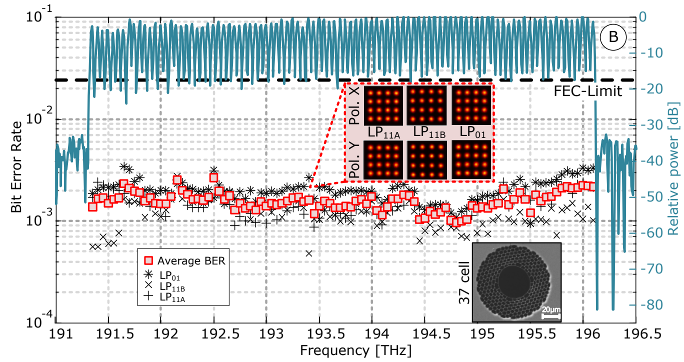


Fig. 3. A) Single-mode 96 WDM × 256-Gb/s DP-16QAM and 320-Gb/s DP-32QAM transmission results over 230m of 19-cell HC-PBGF [22]. B) 96 WDM × 3 MDM × 256-Gb/s DP-16QAM transmission results over 310m of 37-cell HC-PBGF [17-18].

successfully decoded to ensure zero post-FEC errors. Hereby 960-Gb/s per wavelength was successfully transmitted, corresponding to 750-Gb/s per wavelength transmission taking into account all overheads. It should be noted that in [9] the same data rate per wavelength was achieved using 6 LP-modes and 16QAM modulation, achieving a higher SE, but with lower symbol rates and without a FM-EDFA.

4. Hollow-core Photonic Bandgap Fiber Transmission Results

HC-PBGFs offer a number of beneficial properties compared to solid-core fibers, obtained since the light travels mostly in air rather than glass [25]. Low-loss HC-PBGFs will probably be inherently multi-mode, since an as low as possible overlap with the glass has to be achieved dictating a large core size (19 cells or above). The ultimate lowest loss is also at wavelengths around 2μm, at which the first experiments have now been reported [23-24].

Using a 230m long 19-cell HC-PBGF with a transmission window at the regular C-band, single-mode transmission of 96 WDM × 256-Gb/s DP-16QAM and 320-Gb/s DP-32QAM, adding up to data rates of 19.2 and 24 Tb/s, respectively, have been successfully shown [22], with the results depicted in Fig. 3A. As before, for 320-Gb/s DP-32QAM modulation FEC-symbols were transmitted and all channels were verified to be error-free post FEC. This is an interesting result in itself for low-latency single mode transmission applications.

Exploiting the multi-modedness of a 37-cell HC-PBGF, using phase-plate based mode multiplexing and de-multiplexing exciting only the LP_{01} and LP_{11} modegroups, the same MDM capacity record was set for this fiber type by transmitting 96 WDM channels × 3 MDM × 256-Gb/s DP-16QAM (73.7 Tb/s). Fig. 3B shows the transmission results obtained in this experiment. It should be noted that the high losses associated with the MMUX again compromised the results, however performance well below the FEC-limit was achieved for all 96 channels.

5. Conclusion

We have revisited MDM transmission records over FMF and HC-PBGF, both in terms of total transmitted capacity (73.7 Tb/s) as well as total data rate per wavelength (960 Gb/s).

This work was supported by the EU FP7-ICT MODE GAP project under grant agreement 258033.

6. References

[1] IEEE 802.3 Ethernet Working Group, "IEEE 802.3™ Industry Connections Ethernet Bandwidth Assessment," July 2012
[2] D. G. Foursa et al., proc. ECOC '13, PD3.E.1
[3] M. Salsi et al., proc. ECOC '13, PD3.E.2
[4] R.-J. Essiambre et al., IEEE JLT **28**, pp. 662-701 (2010).
[5] K. Igarashi et al., proc. ECOC '13, PD3.E.3
[6] T. Kobayashi et al., proc. ECOC '13, PD3.E.4
[7] H. Takara et al., proc. ECOC '12, Th.3.C.1
[8] D.Qian et al., proc. FiO '12, FW6C.3
[9] R. Ryf et al., proc. OFC '13, PDP5A.1
[10] E. Ip et al., proc. OFC '13, PDP5A.2
[11] R. Ryf et al., IEEE JLT **30**, 521-531 (2012)
[12] V.A.J.M. Sleiffer et al., Optics Express **20,** B428-B438 (2012)
[13] V.A.J.M. Sleiffer et al., proc. ECOC '13, We.2.D.2
[14] H. Chen et al., proc. OECC '13, PD2-5
[15] H. Chen et al., proc. OECC '13, PD3-6
[16] V.A.J.M. Sleiffer, proc. IPC '13, PD6
[17] Y. Jung et al., proc. OFC '13, PDP5A.3
[18] V.A.J.M. Sleiffer et al., 10.1109/JLT.2013.2274194
[19] J. Xu et al., Optics Express **20**, pp. 12449-12456 (2012)
[20] J. Carpenter et al., proc. OFC '12, JW2A.41
[21] R. Slavik et al., Proc. ECOC'12, Mo.2.F.2
[22] V.A.J.M. Sleiffer et al., Proc. OFC'13, OW1I.5
[23] M. Petrovich et al., Proc. ECOC'12, Th.3.A.5
[24] N. Mac Suibhne et al., Proc. OFC'13, OW1I.6
[25] F. Poletti et al., Nature Photonics **7**, 279-284 (2013).
[26] C. R. Doerr et al., proc. ECOC '11, Th.13.A.3
[27] R. Ryf et al., IEEE PTL **24**, pp. 1973-1976 (2012)
[28] N. Fontaine et al., Optics Express **20**, 27123-27132 (2013)
[29] Y. Jung et al., Optics Express **21**, 10383-10392 (2013)
[30] M. Salsi et al., proc. ECOC '12, Th.3.A.6
[31] Y. Jung et al., proc. ECOC '13, We.4.A.2
[32] S. Randel et al., Optics Express **19**, 16697-16707 (2011)
[33] R.G.H. van Uden et al., proc. ECOC '13, Th.2.C.2
[34] R.G.H. van Uden et al., proc. Sum. Top. '13, WC4.2
[35] V.A.J.M. Sleiffer et al., IEEE PTL **25**, 2137-2140 (2013)
[36] L. Grüner-Nielsen et al., IEEE JLT **30**, 3693-3698 (2012)
[37] D.A. Morero et. al, Globecom (2011)
[38] P. Leoni et al., proc. OFC '13, OW1E.6