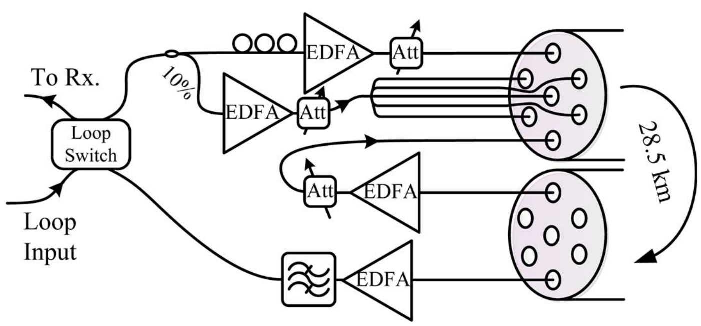
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Experimental Investigation of Crosstalk Penalties in Multicore Fiber Transmission Systems

Volume 7, Number 1, February 2015

Tobias A. Eriksson
Benjamin J. Puttnam
Ruben S. Luís
Magnus Karlsson
Peter A. Andrekson
Yoshinari Awaji
Naoya Wada



DOI: 10.1109/JPHOT.2015.2397275

Experimental Investigation of Crosstalk Penalties in Multicore Fiber Transmission Systems

Tobias A. Eriksson,[1] Benjamin J. Puttnam,[2] Ruben S. Luís,[2] Magnus Karlsson,[1] Peter A. Andrekson,[1] Yoshinari Awaji,[2] and Naoya Wada[2]

[1]Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
[2]Photonic Network Research Institute, National Institute of Information and Communications Technology, Tokyo 184-8795, Japan

DOI: 10.1109/JPHOT.2015.2397275

Manuscript received November 25, 2014; revised January 21, 2015; accepted January 23, 2015. Date of publication February 4, 2015; date of current version February 18, 2015. This work was supported by the Swedish Research Council (VR). The work of T. A. Eriksson was supported by the Sweden–Japan Foundation, by Mitsubishi, and by Ångpanneföreningens Forskningsstiftelse. Corresponding author: T. A. Eriksson (e-mail: tobias.eriksson@chalmers.se).

Abstract: We experimentally study the impact of crosstalk in multicore fibers, using polarization-multiplexed quadrature phase-shift keying signals. Using a 7-core fiber, we perform single-span transmission experiments, where the level of crosstalk to the core under test can be varied. We find the penalty in the required optical signal-to-noise ratio (OSNR), compared to a system with no crosstalk, for different signal-to-crosstalk ratios and at different pre-forward-error-correction target bit-error rates (BERs). We show that, for a 1-dB penalty, a 15.7-dB signal-to-crosstalk ratio can be tolerated at BER $= 1 \times 10^{-3}$. We also perform recirculating loop experiments with varying amount of crosstalk per span to find the impact on the achievable transmission distance.

Index Terms: Multicore fiber, spatial division multiplexing, crosstalk, optical fiber communication.

1. Introduction

Spatial division multiplexed (SDM) optical communications systems employing multimode fibers or multicore fibers (MCF) have been studied intensely in the last few years and are considered key components for increasing the transmission capacity through a single fiber. MCFs have been used in large transmission capacity experiments showing for instance 112 Tb/s in a 7-core fiber [1], 305 Tb/s in a 19-core fiber [2], and 1.02 Pb/s in a 12-core fiber [3]. Further, MCFs have enabled high spectral efficiency distance product experiments using 7-core fibers with quadrature phase shift keying (QPSK) [4] and duo-binary shaped QPSK for super-Nyquist wavelength-division multiplexed transmission [5].

In MCFs, the signal integrity is affected by in-band crosstalk between different cores, which arises due to power coupling between the cores during the fiber propagation. The crosstalk grows with the mode overlap integral and decreases rapidly with the core separation [6]. Further, crosstalk in MCF systems originates not only from the transmission fiber, but other components such as multicore Erbium-doped fiber amplifiers [7], imperfect splices, and the in- and out-coupling to the MCFs [8] can also introduce significant crosstalk between spatial channels. Although in-band crosstalk is more prominent in SDM systems, it should be noted that in single mode fiber transmission systems, in-band crosstalk can arise due to finite extinction ratio in add-and-drop routing systems [9]. However, the crosstalk in the different components are of slightly different nature as the crosstalk in MCFs is distributed throughout the transmission fiber, whilst the crosstalk in the in- and out-coupling as well as for the routing system is localized to a few centimeters.

The inter-core crosstalk can be reduced by different design techniques in the fabrication of the MCF, such as maximizing the distance between the cores or using cores with different propagation constants [6], [10]. However, the minimum distance is typically reduced when the number of cores per fiber is increased. Another technique is the trench-assisted MCF where the refractive index around the cores is modified to increase the confinement of the optical field [6], [11].

The impact of inter-core crosstalk can also be mitigated using digital signal processing such as multiple-input multiple-output (MIMO) equalization [12]. Assuming optimal equalization, strong coupling between the cores can be tolerated [13]. However, the number of filters needed for optimal MIMO detection scales quadratically with the number of cores which might be impractical for systems with a large number of cores.

It is reasonable to assume that in an MCF transmission system there will always be crosstalk present to some extent, from using either low crosstalk fibers with no crosstalk mitigation in the receiver or using high crosstalk MCFs with non-ideal MIMO detection. The penalty in the required optical signal-to-noise ratio (OSNR) from localized crosstalk has been studied for different quadrature amplitude modulation formats [14]. In MCF transmission, the impact on the required OSNR for QPSK from crosstalk has been evaluated for some different scenarios. In [1], the penalty on the center core of a 7-core fiber has been studied for a varying ratio of power in the outer cores to the inner core. In [3], the OSNR penalty from crosstalk on a 32-ary quadrature amplitude modulation (QAM) signal is measured for one of the cores of a 12-core fiber. The penalty on the required OSNR for QPSK, 16QAM and 64QAM as a function of inter-core crosstalk has been investigated in simulations in [15]. Further, the effect of crosstalk for self-homodyne MCF systems has been investigated in [16].

In this paper, we experimentally investigate the transmission penalties from different amounts of crosstalk on polarization-multiplexed (PM) QPSK signals. We find the penalty in required OSNR for different signal-to-crosstalk ratios through a single span of MCF. We also perform recirculating loop experiments where the level of crosstalk per span can be varied to find the penalty in terms of transmission distance for different amounts of crosstalk. We show that maintaining a low level of crosstalk is crucial and that crosstalk levels as low as -52.7 dBm per span of 28.6 km can reduce the transmission distance by 25%.

2. Pair-Wise Crosstalk-Induced Power Coupling in a Single Span

In this section, we characterize the crosstalk levels in a 28.6 km 7-core MCF with a core distribution as indicated in Fig. 1(a). To measure the pair-wise crosstalk for the 7-core fiber, amplified spontaneous emission (ASE) noise with 5 nm bandwidth was generated by concatenated EDFAs and optical bandpass filters. The center wavelength for the bandpass filters was 1550.6 nm. The ASE could be switched into the different cores of the fiber and the output of each core could be switched to a high sensitivity optical power meter, measuring the full 7×7 coupling matrix of the MCF. In other words, the measured crosstalk is the averaged crosstalk over the 5 nm bandwidth. The measured pair-wise power coupling between the cores of the 7-core fiber is shown in Fig. 1(b). As seen, the crosstalk coefficients from the outer cores to the central core are approximately equal whereas the outer cores mainly have crosstalk from the three neighboring cores.

The total power-crosstalk to each core, i.e., the summation of all pair-wise crosstalk coefficients, is shown in Fig. 1(c). As expected, the center core suffers the highest crosstalk whereas the outer 6 cores have roughly equal crosstalk. The crosstalk in the outer cores ranges by 1.4 dB,

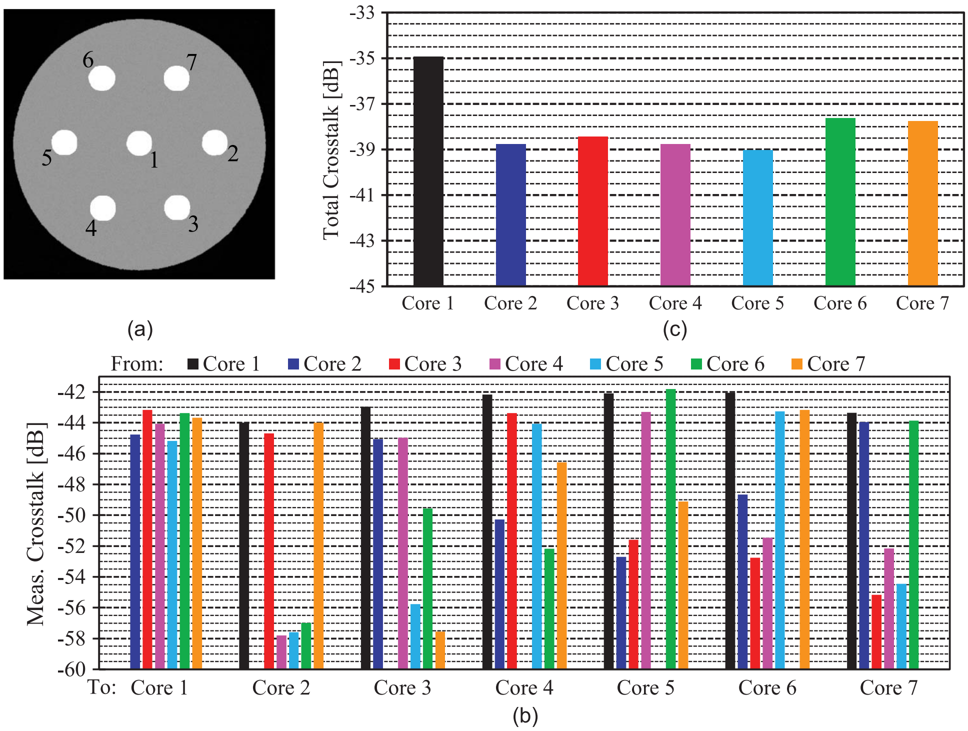


Fig. 1. (a) Core configuration of the 28.6 km 7-core fiber used in this paper. (b) Measured pairwise crosstalk power between cores and (c) the total power-crosstalk per core. (a) Core configuration. (b) Total crosstalk. (c) Pair-wise crosstalk.

and the difference between the center core and the outer core with the lowest crosstalk is 4.1 dB. In this work, we choose a non-trench assisted fiber with relatively high inter-core crosstalk to be able to simulate a large range of crosstalk values, although we note that a number of fibers with superior crosstalk characteristics have been reported [1], [2], [6], [11].

3. Experimental Setup for BER-Measurement

The experimental setup of the transmitter (Tx) and receiver (Rx) used in the BER measurements are both shown in Fig. 2. The transmitter, Fig. 2(a), consisted of an external cavity laser (ECL) with ~500 kHz linewidth followed by one I/Q-modulator per polarization that were driven by 10 Gbaud decorrelated pseudo random binary sequences (PRBS) with length $2^{15} - 1$ to generate 40 Gbit/s PM-QPSK.

The receiver, Fig. 2(b), was based on a polarization diverse 90°-hybrid with a ~100 kHz linewidth laser as local oscillator (LO). The electrical output of the hybrid was digitized using an 80 GS/s real-time oscilloscope with 33 GHz bandwidth. The data was processed off-line using a conventional receiver structure with the constant modulus algorithm (CMA) for polarization demultiplexing and equalization, fast-Fourier transform based frequency estimation and Viterbi-Viterbi based phase-estimation.

4. Influence of Crosstalk in Single-Span Transmission with Noise Loading

To evaluate the influence of crosstalk on the required OSNR for a specific BER, the 10 Gbaud PM-QPSK signal was switched into one of the cores of the MCF as illustrated in Fig. 3. A part of the signal was tapped off, amplified, and launched into the other six cores. The signal into each core was decorrelated using fiber patch cords of different lengths. The core under test was sent to an ASE noise loading stage, based on concatenated EDFAs, bandpass filters with 5 nm bandwidth and an variable optical attenuator (VOA) to control power of the added ASE, before

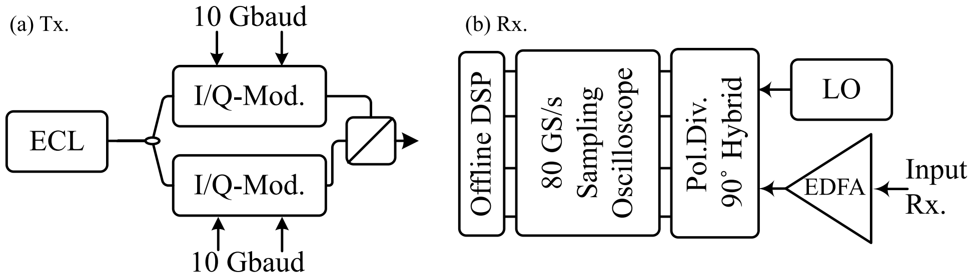


Fig. 2. (a) Transmitter (Tx) to generate 10 Gbaud PM-QPSK. (b) Polarization-diverse coherent receiver (Rx).

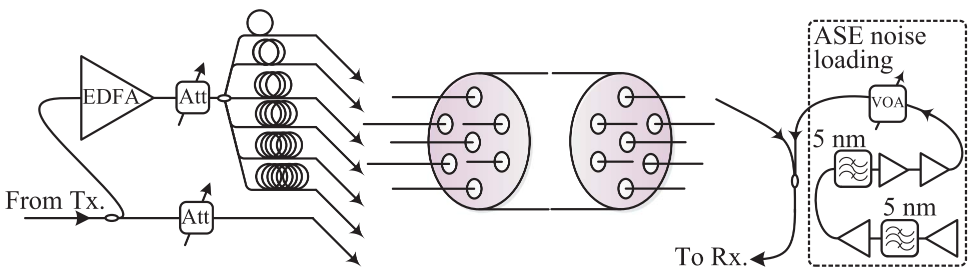


Fig. 3. Experimental setup for the single span experiments.

the signal was sent to the receiver. The remainder of the cores were terminated to avoid reflections. The signal-to-crosstalk ratio (SCR) in core n is defined as

$$\mathrm{SCR}_n = \frac{P_n}{\sum_{k=1}^{N} \alpha_{n,k} P_k} \tag{1}$$

where P_n is the signal power at the input of the core-under-test, and $P_{Xt,n} = \sum_{k=1}^{N} \alpha_{n,k} P_k$ is the total power coupled to the core-under-test from all other cores. P_k is the power into core k, $\alpha_{n,k}$ is the coupling coefficient from core k to core, n and $\alpha_{i,i} = 0$. Note that $\alpha_{n,k}$ for the MCF used in this paper can be found from Fig. 1(b). It should be noted that the statistical behavior of the crosstalk depends on the signal bandwidth, and for narrow bandwidths the crosstalk cannot be considered as additive white Gaussian noise [17].

Fig. 4(a) shows the BER as a function of OSNR (0.1 nm) measured for core 1 (center), 2, 3, and 6. The crosstalk channels are launched with 7 dBm optical power and the signal launch power is adjusted in each case to achieve different signal-to-crosstalk ratios. To assure that no penalty originates from the relative high launch power of the crosstalk channels, we also conducted experiments with 0 dBm launch power for the crosstalk channels (not shown in the figure). We saw no significant difference for the two cases, and the higher launch power was used to enable a wider range of signal-to-crosstalk ratios. The dashed black line shows the theoretical prediction for the additive white Gaussian channel and the open black circles shows the measured performance without any crosstalk present.

As seen in Fig. 4(a), for the same signal-to-crosstalk ratio there is no apparent difference in the OSNR penalty for different cores. In Fig. 4(b), the measured OSNR penalty, defined as the OSNR required for a certain BER with crosstalk compared to the OSNR required for the same BER when no crosstalk sources are present, is plotted. The OSNR penalty is shown for BER = 1×10^{-3} (black circles), 3.8×10^{-3} (blue stars), and 2×10^{-2} (red triangles). Note that the OSNR penalty is achieved from an averaged BER over core 1, 2, 3, and 6 in Fig. 4(a). These results follows the same trend as was found in simulations in [15]. Further, the penalty for BER = 1×10^{-3} agrees fairly well with what was found in [14], which suggests that for this fiber length,

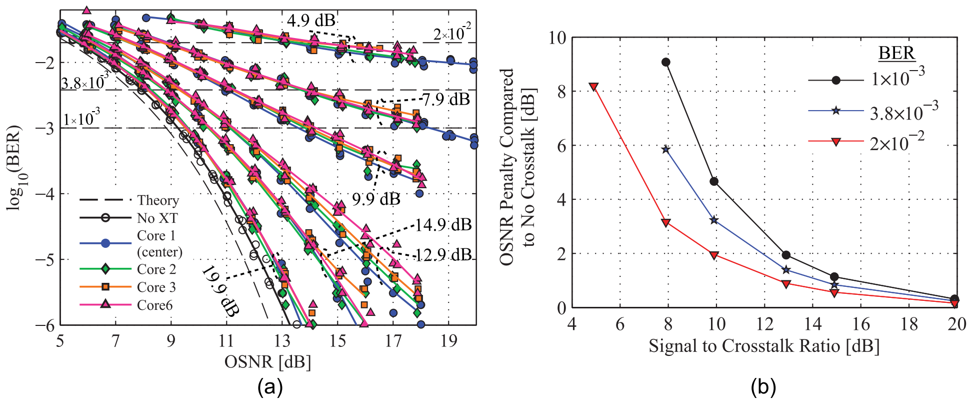


Fig. 4. (a) BER as a function of OSNR for signal-to-crosstalk ratio varying from 19.9 dB to 4.9 dB measured for Core 1 (center) (blue circles), Core 2 (green diamonds), Core 3 (orange squares), and Core 6 (purple triangles). (b) OSNR penalty compared to the case with no crosstalk as a function of signal-to-crosstalk ratio averaged over core 1, 2, 3, and 6 measured at BER $= 1 \times 10^{-3}$ (black circles), 3.8×10^{-3} (blue stars), and 2×10^{-2} (red triangles).

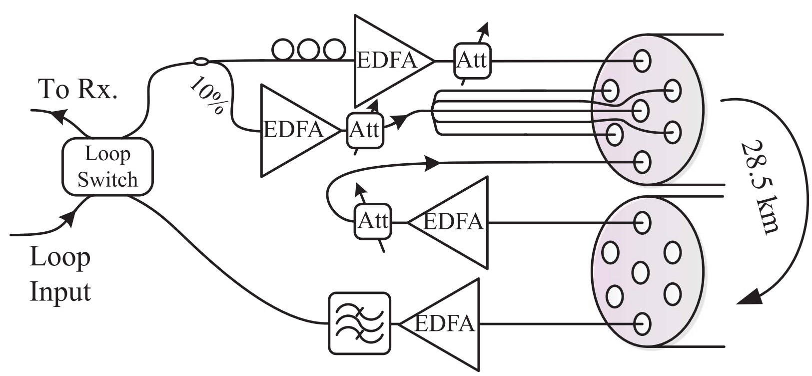


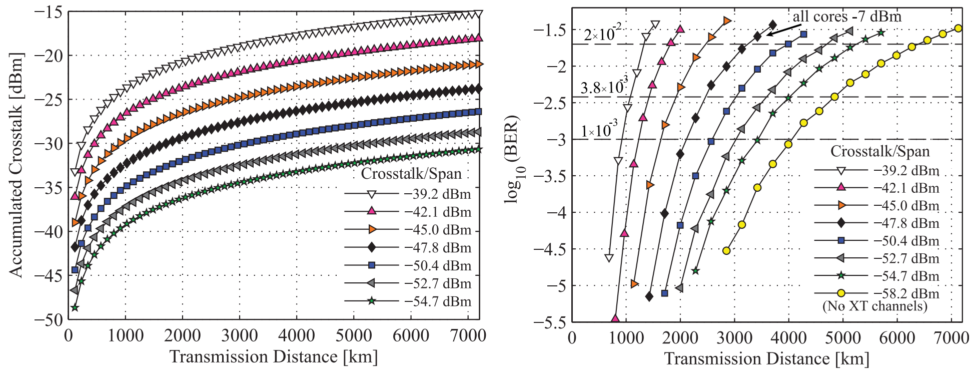
Fig. 5. Experimental setup for the loop experiments.

there is no apparent difference in OSNR penalty from having the crosstalk distributed along the fiber (as in this paper) or localized (as in [14]). This observation is not obvious, since in the localized case the crosstalk is from a single source and the coupling occurs in a single point. In the MCF, the crosstalk is from six sources and distributed through the fiber with randomized phase and polarization on the signals in the six cores. For a 1 dB OSNR penalty, we measure a tolerable signal-to-crosstalk ratio of 15.8 dB, 14.3 dB, and 12.6 dB for pre-FEC targets of BER $= 1 \times 10^{-3}$, 3.8×10^{-3}, and 2×10^{-2}, respectively.

The signal is less sensitive to crosstalk at high BERs, hence, these results show that the use of advanced FEC codes that can operate at high BER could be beneficial in a system with high amount of crosstalk. At 4.9 dB signal-to-crosstalk ratio, the slope of the curve in Fig. 4(a) is extremely flat and does not reach BER $= 3.8 \times 10^{-3}$ within the range of our measurement system.

5. Penalties on Transmission Reach from Crosstalk in Recirculating Loop Experiments

To evaluate the influence of crosstalk in a long haul transmission system, we propagated the PM-QPSK signal over a recirculating loop. Due to the switching time of the loop components, the loop had to be constructed using two cores of the 7-core fiber, see Fig. 5. In other words, the span length was 28.5 km before amplification and the loop length was 2×28.5 km. The loop-switch were based on pairs of dual acousto-optic modulators (AOMs) to achieve zero



(a) (b)

Fig. 6. (a) Evolution of crosstalk in the link. (b) BER as a function of transmission distance for crosstalk per span ranging from −58.2 dBm/span (yellow circles) to −39.2 dBm/span (white downwards triangles).

frequency shift. The switching time was ∼1 us and the extinction ratio of the AOMs was greater than 35 dB. The two opposite cores, i.e., 3 and 6, were selected for the recirculating transmission, whereas the other five cores were loaded with a signal that was tapped of from the loop, amplified and decorrelated. Thus, the interfering crosstalk channels have been transmitted the same distance and been affected by ASE, dispersion and crosstalk in the same way as the recirculating channel. The launch power of the signal under test was optimized with respect to transmission distance at $\text{BER} = 1 \times 10^{-3}$ without any crosstalk present and was found to be −7 dBm. This launch power was used throughout the experiments. The crosstalk per span, defined as the total power coupled to the core under test per fiber span, was controlled with a variable optical attenuator to change the launch power of the crosstalk channels. The crosstalk in the loop evolves as shown in Fig. 6(a) for different amount of crosstalk per span. These plots are obtained using the measured pair-wise coupling powers shown in Fig. 1(c) and the knowledge of the launched power in each core. Note that we cannot achieve transmission without crosstalk since we are using two cores for transmission in the recirculating loop.

The measured BER as a function of transmission distance for various amount of crosstalk per span is shown in Fig. 6(b). Without the crosstalk channels present, i.e. only the two cores that form the loop are present, the crosstalk per span is −58.2 dB (yellow circles) and the achievable transmission distance is 4050 km at $\text{BER} = 10^{-3}$ and at $\text{BER} = 2 \times 10^{-2}$ it is 6400 km. For −52.7 dB crosstalk per span (gray triangles), the transmission distance is reduced by 25% to 3020 km (10-3) and by 26% to 4700 km (2×10^{-2}). With this fiber, launching all cores with −7 dBm corresponds to −47.8 dB of crosstalk per span (black diamonds) and with this amount of crosstalk the transmission distance is reduced by 48% to 2110 km (10^{-3}) and 49% to 3250 km (2×10^{-2}). With −39.2 dB crosstalk per span (white triangles), the transmission distance is severely penalized and the achievable distances are 920 km (10-3) and 1330 km (2×10^{-2}).

6. Conclusion

We have experimentally evaluated the impact of crosstalk on PM-QPSK signals in MCFs at different pre-FEC BER targets, both through a single span with noise loading and through recirculating loop experiments. We believe that the results found in this study can be generalized to any type of MCF since the crosstalk is normalized to the signal-to-crosstalk ratio in the single span experiments and to crosstalk per span in the loop experiments. For 1 dB penalty in the required OSNR, signal-to-crosstalk ratios of 15.7 dB, 14.3 dB, or 12.6 dB for pre-FEC targets of $\text{BER} = 1 \times 10^{-3}$, 3.8×10^{-3}, and 2×10^{-2} can be tolerated. Recirculating loop measurements showed that −52.7 dB crosstalk per 28.6 km span reduced the transmission distance by 25%, showing that crosstalk can have a huge impact on the transmission distance achievable with MCFs and should be addressed to optimize the performance of MCF based communication systems.

References

[1] B. Zhu *et al.*, "112-Tb/s space-division multiplexed DWDM transmission with 14-b/s/Hz aggregate spectral efficiency over a 76.8-km seven-core fiber," *Opt. Exp.*, vol. 19, no. 17, pp. 16 665–16 671, Aug. 2011.

[2] J. Sakaguchi *et al.*, "19-core fiber transmission of 19x100x172-Gb/s SDM-WDM-PDM-QPSK signals at 305Tb/s," in *Proc. OFC/NFOEC*, Los Angeles, CA, USA, 2012, pp. 1–3, PDP5C.1.

[3] 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," presented at the Eur. Conf. Exh. Opt. Commun., Amsterdam, The Netherlands, 2012, Th.3.C.1.

[4] S. Chandrasekhar *et al.*, "WDM/SDM transmission of 10 × 128-Gb/s PDM-QPSK over 2688-km 7-core fiber with a per-fiber net aggregate spectral-efficiency distance product of 40,320 km.b/s/Hz," *Opt. Exp.*, vol. 20, no. 2, pp. 706–711, Jan. 2012.

[5] K. Igarashi *et al.*, "Super-Nyquist-WDM transmission over 7,326-km seven-core fiber with capacity-distance product of 1.03 Exabit/s · km," *Opt. Exp.*, vol. 22, no. 2, pp. 1220–1228, Jan. 2014.

[6] T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber," *Opt. Exp.*, vol. 19, no. 17, pp. 16 576–16 592, Aug. 2011.

[7] K. S. Abedin *et al.*, "Amplification and noise properties of an erbium-doped multicore fiber amplifier," *Opt. Exp.*, vol. 19, no. 17, pp. 16 715–16 721, Aug. 2011.

[8] Y. Tottori, T. Kobayashi, and M. Watanabe, "Low loss optical connection module for seven-core multicore fiber and seven single-mode fibers," *IEEE Photon. Technol. Lett.*, vol. 24, no. 21, pp. 1926–1928, Nov. 2012.

[9] H. Takahashi, K. Oda, and H. Toba, "Impact of crosstalk in an arrayed-waveguide multiplexer on N × N optical interconnection," *J. Lightw. Technol.*, vol. 14, no. 6, pp. 1097–1105, Jun. 1996.

[10] J. M. Fini, B. Zhu, T. Taunay, M. Yan, and K. Abedin, "Crosstalk in multi-core optical fibres," in *Proc. ECOC*, Geneva, Switzerland, 2011, pp. 1–3, Mo.1.LeCervin.4.

[11] K. Takenaga *et al.*, "Reduction of crosstalk by trench-assisted multi-core fiber," in *Proc. OFC/NFOEC*, Los Angeles, CA, USA, 2011, pp. 1–3, OWJ4.

[12] R. Ryf *et al.*, "MIMO-based crosstalk suppression in spatially multiplexed 3 × 56-Gb/s PDM-QPSK signals for strongly coupled three-core fiber," *IEEE Photon. Technol. Lett.*, vol. 23, no. 20, pp. 1469–1471, Oct. 2011.

[13] C. Xia *et al.*, "Supermodes in strongly-coupled multi-core fibers," in *Proc. OFC/NFOEC*, Anaheim, CA, USA, 2013, pp. 1–3, OTh3K.5.

[14] P. Winzer, A. Gnauck, A. Konczykowska, F. Jorge, and J.-Y. Dupuy, "Penalties from in-band crosstalk for advanced optical modulation formats," in *Proc. ECOC*, Geneva, Switzerland, 2011, pp. 1–3, Tu.5.B.7.

[15] J. H. Chang, H. G. Choi, and Y. C. Chung, "Impacts of increased effective area on the capacity of multi-core fiber system," in *Proc. OECC*, Kyoto, Japan, 2013, pp. 1–2, MR2-4.

[16] B. J. Puttnam *et al.*, "Investigating self-homodyne coherent detection in a 19 channel space-division-multiplexed transmission link," *Opt. Exp.*, vol. 21, no. 2, pp. 1561–1566, Jan. 2013.

[17] T. Hayashi, S. Takashi, and E. Sasaoka, "Behavior of inter-core crosstalk as a noise and its effect on q-factor in multi-core fiber," *IEICE Trans. Commun.*, vol. E97-B, no. 5, pp. 936–944, 2014.