10 x 112Gb/s PDM-QPSK transmission over 5032 km in few-mode fibers

Fatih Yaman[1,*], Neng Bai[2], Y. K. Huang[1], M. F. Huang[1], B. Zhu[3], Ting Wang[1] and Guifang Li[2]

[1]NEC Laboratories America, Inc. 4 Independence Way, Suite 200 Princeton, NJ 0854, USA
[2]College of Optics & Photonics/CREOL & FPCE, University of Central Florida,
4000 Central Florida Blvd. Orlando FL, 32816-2700, USA
[3]OFS Labs 19 Schoolhouse Rd Somerset, NJ 08873, USA
*fyaman@nec-labs.com

Abstract: Few-mode fibers (FMFs) are used for the first time to transmit over 5000 km. Ten WDM channels with 50GHz channel spacing at 112 Gb/s per channel using PDM-QPSK are launched into the fundamental mode of the FMFs by splicing single-mode fibers directly to the FMFs. Even though few-mode fibers can support an additional spatial mode LP_{11} at 1550 nm, the signal remains in the fundamental mode and does not experience mode coupling throughout fiber transmission. After each span the signal is collected by a second single-mode fiber which is also spliced to the FMF. Span loss is compensated by single-mode EDFAs before it is launched to the next FMF span. The lack of mode coupling ensures that the signal does not suffer any impairments that may result from differential mode delay or excess loss. Therefore the FMFs used in this "single-mode operation" have the same bandwidth as single-mode fibers. Experimental results verified that FMFs have the significant advantage of large core size which reduces the nonlinear impairments suffered by the signal. It is shown that FMFs with an effective area of 130 μm^2, have an optimum launch power 2 dB higher compared to standard single-mode fibers and as a result a 1.1 dB improvement in the Q-factor is obtained after 3000 km.

©2010 Optical Society of America

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications; (060.4370) Nonlinear optics, fibers; (190.4370) Nonlinear optics, fibers

---

References and links

1. A. R. Chraplyvy, "Limitations on Lightwave Communications Imposed by Optical-Fiber Nonlinearities," J. Lightwave Technol. **8**(10), 1548–1557 (1990).
2. R.-J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, "Capacity limits of optical fiber networks," J. Lightwave Technol. **28**(4), 662–701 (2010).
3. A. R. Chraplyvy, A. H. Gnauck, R. W. Tkach, and R. M. Derosier, "8 x 10 Gb/s Transmission Through 280 km of Dispersion-Managed Fiber," IEEE Photon. Technol. Lett. **5**(10), 1233–1235 (1993).
4. A. H. Gnauck, G. Raybon, S. Chandrasekhar, J. Leuthold, C. Doerr, L. Stulz, A. Agarwal, S. Banerjee, D. Grosz, S. Hunsche, A. Kung, A. Marhelyuk, D. Maywar, M. Movassaghi, X. Liu, C. Xu, X. Wei, and D. M. Gill, "2.5 tb/s (64x42.7 Gb/s) transmission over 40x100 km NZDSF using RZ-DPSK format and all-raman-amplified spans," presented at the OFC 2002, PD-FC2.
5. G. Charlet, N. Maaref, J. Renaudier, H. Mardoyan, P. Tran, and S. Bigo, "Transmission of 40Gb/s QPSK with coherent detection over ultra-long distance improved by nonlinearity mitigation," Proc. Eur. Conf. Opt. Commun. 2006.
6. F. Yaman, and G. Li, "Nonlinear Impairment Compensation for Polarization-Division Multiplexed WDM Transmission Using Digital Backward Propagation," IEEE Photon. J. **1**(2), 144–152 (2009).
7. P. Nouchi, P. Sansonetti, and S. Landais, G. Barre, C. Brehni, J. Y. Boniort, B. Perrin, J. J. Girard, and J. Auge, "Low-loss single-mode fiber with high nonlinear effective area," OFC 1995 ThH2.
8. H. T. Hattori, and A. Safaai-Jazi, "Fiber designs with significantly reduced nonlinearity for very long distance transmission," Appl. Opt. **37**(15), 3190–3197 (1998).

9. X. Zhou, J. Yu, M. Huang, Y. Shao, T. Wang, L. Nelson, P. Magill, M. Birk, P. I. Borel, D. W. Peckham, and R. Lingle, "64-Tb/s (640x107-Gb/s) PDM-36QAM transmission over 320 km using both pre- and post-transmission digital equalization," OFC 2010 PDPB9.

10. J.-X. Cai, Y. Cai, C. R. Davidson, D. G. Foursa, A. Lucero, O. Sinkin, W. Patterson, A. Philipetskii, and N. S. And, Bergano, "Transmission of 96x100G pre-filtered PDM-RZ-QPSK channels with 300% spectral efficiency over 10,608 km and 400% spectral efficiency over 4,368 km," OFC 2010 PDPB10.

11. M.-J. Li, X. Chen, A. Liu, S. Gray, J. Wang, D. T. Walton, and L. A. Zenteno, "Limit of effective area for single-mode operation in step-index large mode area laser fibers," J. Lightwave Technol. **27**(15), 3010–3016 (2009).

12. F. Yaman, N. Bai, B. Zhu, T. Wang, and G. Li, "Long distance transmission in few-mode fibers," Opt. Express **18**(12), 13250–13257 (2010).

13. R. Olshansky, "Mode Coupling Effects in Graded-index Optical Fibers," Appl. Opt. **14**(4), 935–945 (1975).

14. D. Donlagic, "A low bending loss multimode fiber transmission system," Opt. Express **17**(24), 22081–22095 (2009).

1. Introduction

Fiber nonlinearity is a major limitation to fiber transmission capacity [1,2]. Fiber capacity can be increased by using higher modulation formats. However, this requires larger OSNR and therefore higher signal power which leads to higher nonlinearity. Reducing the fiber nonlinearity has a direct impact on the transmission capacity. Several methods have been proposed to reduce the nonlinear impairments indirectly such as using strong dispersion maps, using nonlinearity tolerant modulation formats and using distributed amplification [3,4]. More direct methods of reducing the fiber nonlinearity include removing the nonlinear impairments by digital signal processing [5,6] and increasing the fiber core size [7,8]. Using digital signal processing for nonlinearity impairment compensation requires significant amount of computation and it is limited ultimately by nondeterministic noise processes. Increasing the fiber core size reduces the optical intensity for a given signal power and therefore reduces fiber nonlinearity directly without adding any complexity or energy consumption.

Significance of increasing the fiber core diameter is clear from the fact that almost all of the recent record breaking experiments used fibers with core areas larger than the core area of standard single-mode fibers (SSMF) [9,10]. The major limitation to using even larger core diameter and therefore reducing the fiber nonlinearity further is the single-mode condition. As the fiber core diameter increases either the fiber bending loss becomes prohibitive or the fiber becomes multimode [11]. Using a multimode fiber with a large core diameter would reduce the fiber nonlinearity but its bandwidth could drop dramatically because of differential mode delay (DMD) if the random coupling between the supported modes cannot be avoided. However if the mode-coupling can be avoided, each mode of the multimode fiber would have the same bandwidth as single-mode fiber with the added benefit of reduced nonlinearity. It was shown in a recent experiment that mode coupling can indeed be avoided when fibers that support only a few modes are used [12]. It was shown that after 1000 km no mode coupling was observed. The experiment was performed at 1310 nm using a fiber that is dual mode at 1310 nm but still single mode at 1550 nm.

In this work three significant results are reported. First, it is shown that mode-coupling is not observed even after 5032 km of transmission in a few-mode fiber (FMF) that is dual-mode at 1550 nm. Second, signal suffers less nonlinear penalty in comparison and therefore outperforms SSMF because the dual-mode fiber has larger effective area. And third, using multimode fibers for transmitting the signal in a single mode of the fiber does not require any sophisticated components, i.e., all the components in the transmission system except for the dual-mode fiber remain single mode.

Since multimode fibers support multiple spatial modes, they have a larger maximum capacity compared to single-mode fibers. In principle it is possible to send different signals on different modes using mode multiplexing. However, even if mode coupling is not present, mode multiplexing requires efficient ways to multiplex and demultiplex different spatial channels. It also requires an overhaul of the entire transmission system since all of the intermediary components such as amplifiers, filters, routing equipment etc. must be able to accommodate the same spatial modes. Here mode multiplexing is not used. Signal is

transmitted only in the fundamental mode of the multimode fiber which is also called the single-mode operation. Because mode multiplexing is not used the bandwidth is the same as a single-mode fiber. The advantage of using multimode fiber over single-mode fiber is the large effective area of the multimode fiber.

To achieve the single-mode operation, the signal must be efficiently coupled to only one of the modes, typically the fundamental mode of the multimode fiber. Signal must also remain only in that spatial mode all along the fiber and at the end it should be efficiently collected back to a standard single mode fiber. Otherwise the signal will be shared by different modes leading to DMD or excess loss if the unwanted modes are filtered out.

Even though critical to maintaining single-mode operation, coupling the signal to and from only one mode of the multimode fiber, particularly the fundamental mode, is easy to achieve. The more essential requirement for single-mode operation is avoiding mode coupling in the fiber. In a perfectly straight and imperfection free multimode fiber, all supported modes travel independent from the others with a different phase velocity. However perturbations caused by fiber imperfections and bending can cause coupling between the modes. The coupling strength between the modes depends on the degree of phase matching between the modes produced by the perturbation. Since the fiber imperfections are typically generated during the fabrication process, the power spectrum of the perturbations decay quickly at higher frequencies. As a result coupling strength between any two given modes decays quickly as the difference between the phase velocities or effective indices of the modes increases [13,14].

For a given fiber the degree of mode-coupling depends on the fiber quality as well as the difference in the effective indices of the modes. Modern transmission fibers are fabricated with extremely high quality with very small imperfection. The important question is, whether the quality of the transmission fibers is high enough to avoid mode coupling. One way to estimate the magnitude of these imperfections is to consider the case of single-mode fibers. If the imperfections are large enough, they will cause excess loss even in single-mode fibers through mode coupling to leaky modes. Compared to multimode fibers, single-mode fibers suffer less from mode coupling mainly because for a given NA, single-mode fibers have smaller core diameters, and index difference between the modes increases when the core diameter is reduced. Conversely, as the core diameter of the fiber is increased and the fiber becomes more and more multimode, the difference in the effective indices of neighboring modes become smaller and smaller until the difference becomes so small that it cannot prevent mode coupling due to fiber imperfections. Our transmission results confirm that it is possible to increase the fiber core diameter into the dual mode regime while avoiding mode coupling.
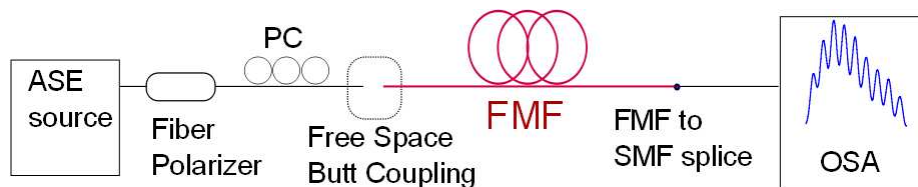
2. Experiment

Fig. 1. Setup used for measuring the phase delay between the two spatial modes supported by the few-mode fiber. PC: polarization controller, OSA: optical spectrum analyzer.

The FMFs used in the transmission experiment support two spatial modes at 1550 nm. The fibers are referred to as few-mode fibers (FMF) rather than dual-mode fibers to emphasize that they support more than one spatial mode however much fewer modes compared to standard multimode fibers. The cutoff wavelengths of the fiber spans are beyond 1650 nm. The effective area of the fibers is 130 μm^2 and the loss coefficient is 0.2 dB/km. To verify that the fibers support two modes at 1550 nm, the setup shown in Fig. 1 is used to measure the

difference between the effective indices of the fundamental mode and the LP_{11} mode. Output of an ASE source with a single-mode pigtail is polarized and then coupled to the input of a 10 m long FMF. To verify the presence of all the modes, it is important to excite all possible spatial modes. This is achieved using free space butt coupling between the single-mode fiber and the FMF. The end of the FMF is spliced to another single-mode fiber and the splice is intentionally misaligned as much as possible to be able to collect all spatial modes at the same time. The output spectrum from the single-mode fiber was measured with an OSA.

Figure 2 shows the input (red) and output (blue) optical spectra of the FMF measured by the OSA. The same optical spectrum is launched in two spatial modes at the FMF. The two spatial modes travel at different phase velocities determined by their effective indices. At the end of the fiber both modes are partially coupled to the fundamental mode of the single-mode fiber at which point the spectral components carried by each mode beat coherently. The beating period observed at the OSA is inversely proportional to the delay between the two modes which is 3.77 ps. Considering the fiber length of 10 m, this delay corresponds to an effective index difference of $1.1x10^{-4}$ which is comparable to the birefringence of polarization–maintaining fibers. The periodic beating in the spectrum shows that the fiber indeed supports more than one spatial mode. Since the beating period is constant, it can be deduced that only two modes are supported by the FMF as expected from the cutoff wavelength. The fact that the beating is induced by spatial modes is verified by changing the position of the single-mode fiber with respect to the FMF fiber at the free space coupling. When the two fibers are aligned, the beating disappears since in this case only the fundamental mode of the FMF is excited. This is also the case when the single-mode fiber at the back end is spliced with a good alignment. In this case, even though both modes may be excited in the fiber only the fundamental mode is coupled into the SMF.

In order to estimate whether the measured refractive index difference is large enough to prevent mode coupling between the two supported modes, it can be compared to another well-known mode preserving fiber: the polarization-maintaining fiber (PMF). PMFs typically have an index difference between the two polarization modes in the range between 10^{-4} to 10^{-3}. Note that PMFs are designed to keep the two nearly degenerate modes of "single-mode fiber", the two polarization modes, from coupling to one another by increasing the difference in the effective indices of the two polarization modes, Therefore it is reasonable to expect that the FMF used in our experiments prevent mode coupling between the two supported modes based on the measured index difference of $1.1x10^{-4}$.
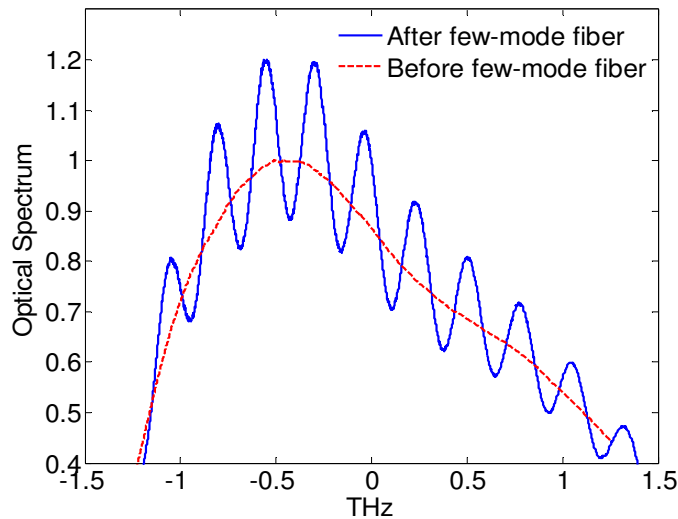
Fig. 2. Optical spectra of the ASE source before the FMF fiber (red, dashed) and after passing through the FMF (blue, solid).

Figure 3 shows the experimental setup used for transmitting 10 polarization division multiplexed WDM channels at 28 Gbaud with QPSK modulation over the FMF. The total bit rate per wavelength is 112 Gb/s. In the transmitter, 10 DFB lasers with a channel spacing of 50 GHz are sparated into 5 even and odd channels. The even and odd channels are modulated individually at 28 Gbaud with an I/Q modulator. Both even and odd channels are polarization multiplexed by separating the same signal into two orthogonal pollarizations, delaying one arm and recombining them. The data in the I and Q channels and the two polarizations are obtained by delaying the same data pattern which is obtained by multiplexing four 7 Gb/s tributaries, each of which carries a PRBS pattern of length $2^{11} - 1$. The odd and even channels are combined with a 50-GHz interleaver at the output of the transmitter.

The loop consists of two spans of FMFs with total lengths of 76 km and 72 km. The first span is obtained by splicing two spools of FMFs directly with lengths of 39 km and 37 km. The second span is obtained by splicing two spools of FMFs with lengths 50 km and 22 km. Each spools is wound on a standard size reel with a 25 cm flange diameter. The loss coefficient, dispersion and effective are of the fibers are 0.2 dB/km, 20 ps/km/nm, and 130 μm^2. Each end of the spans are spliced directly to standard single-mode fibers using fusion splicers in the standard mode which is used to splice standard-single-mode fibers. The splice loss is measured using bidirectional OTDR and it is found to be approximately 0.2 dB per splice. After the two spans are spliced at both ends the loss is measured. The losses for the 76-km long span and the 72-km-long spans are found to be 15.7 dB and 15 dB, respectively, including the splice and connector losses. Therefore, any excess loss that may have resulted from mode coupling is insignificant. Moreover, the measured fiber losses are stable over time and no fluctuation in the output power is observed. Two single-stage EDFAs are used to compensate the span losses and another EDFA is used to compensate the loops control losses. A wavelength selective switch (WSS) is inserted in the loop to equalize the EDFA gain, and to remove the ASE noise outside of the WDM channels.
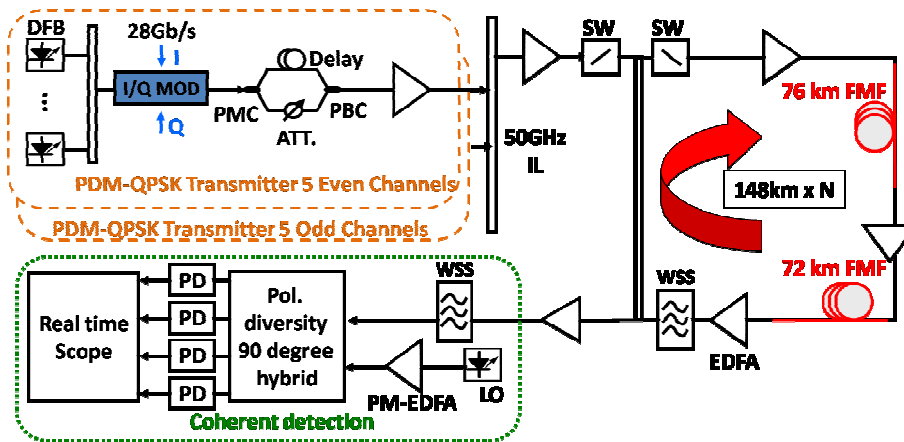
Fig. 3. Setup for 10x112 Gb/s PDM-QPSK-WDM transmission experiment. DFB: distributed feedback laser, PMC: polarization maintaining coupler, PBC: polarization beam combiner, IL: interleaver, SW: optical switch, FMF: few-mode fiber, WSS: wavelength selective switch, PM-EDFA: polarization maintaining erbium doped fiber amplifier, LO: local oscillator, PD: photodiode.

A coherent polarization diversity receiver is used to receive the signal. The signal channel to be received is filtered by a second WSS and mixed with a local oscillator at the polarization diversity balanced hybrid. The output of the balanced photodiodes are collected with a real-time oscilloscope with a 16 GHz analog bandwidth at 40 Gsa/s. The received data is processed off line to estimate the Q value of the received signal. The offline processing consists of digital dispersion compensation, frequency offset estimation, phase noise estimation and 15 tap time-domain equalization based on constant-modulus algorithm which adaptively removes the polarization rotation, compensates for polarization-mode dispersion and any residual dispersion. In the post processing no attempt is made to compensate or mitigate any impairment that may result from DMD.

3. Results and Discussion

Figure 4 shows the Q values of the even channels measured after 34 loops corersponding to 5032 km after averaging over 4 million received bits. The Q values of all channels for both polarizations remain above 10 dB. The constellation diagrams for two points are also shown in the inset which are obtained from 50 000 symbols. It is clear that in the presence of DMD it would not be posible to transmit channels at 28 Gbaud/s over 5000 km. Therefore it is safe to conclude that mode coupling was not present in the FMF.
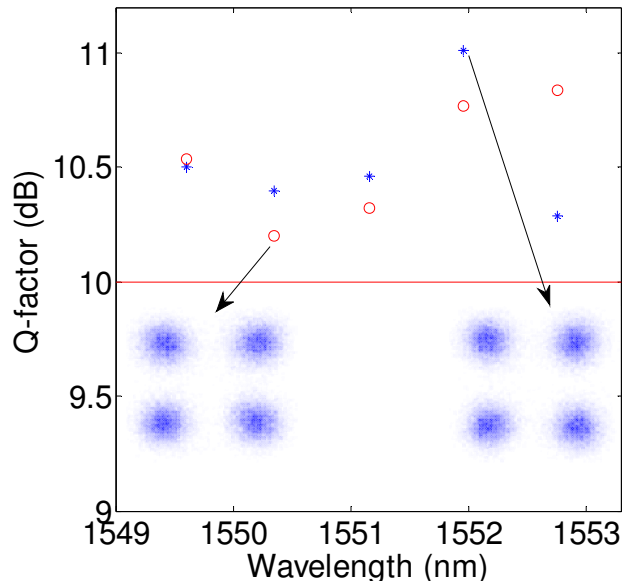
Fig. 4. The Q values of the 5 even channels are plotted for both X (stars) and Y polarizations (circles) after 5032 km transmission. The Q values remain above 10 dB for all channels. The constellation diagrams for two Q values are shown in the inset.

The main advantage of using few-mode fibers in the single-mode operation instead of single-mode fibers is that FMFs can have much larger core are. It is critical that FMFs induce not only smaller nonlinear impairments due to the larger core area but also no additional impairments due to DMD. To verify this, the transmission experiment is repeated by replacing the two FMF spans by SSMF spans of 80 km length each. The fibers have loss coefficient, dispersion parameter and effective area of 0.2 dB/km, 17 ps/km.nm, and 80 μm^2. To compare the nonlinearity performance of the two cases the the received Q value is plotted as a function of launch power after 3100 km in the case of FMFs (21 loops) and after 3040 km in the case of single-mode fibers (19 loops). The comparison is made at 3000 km so that the Q value remains above 10 dB even when SSMFs are used. The results are shown in Fig. 5 where the red and the blue line shows the average of the Q values in both polarizations in the central channel for the single-mode fiber and FMF transmission. At low powers both cases are limited by OSNR and perform similarly since the loop loss for both cases are similar. As the launch power is increased nonlinear impairments become the dominant source of degradation. Since FMFs have 1.6 times larger effective area, the optimum operating power for FMFs is approximately 1.6 times larger compared to single-mode fibers. As a consequence, the maximum Q value achievable at this distance is 1.1 dB larger in the case of FMFs.
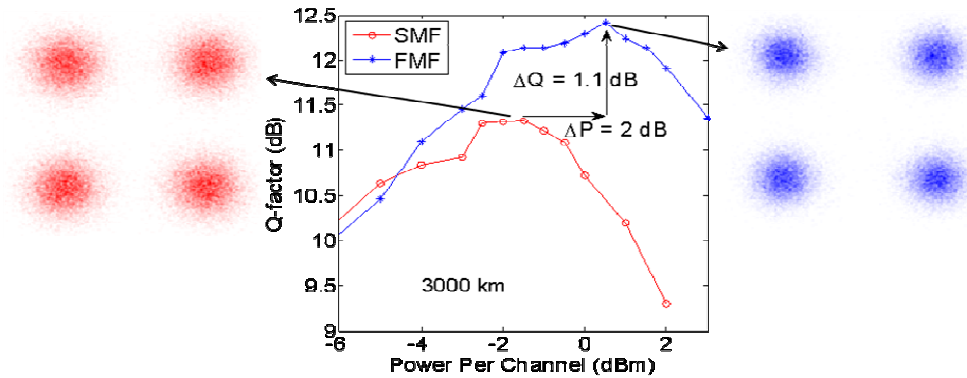
Fig. 5. Q-factor for the center channel as a function of launch power per channel after 3100 km (21 loops) for FMFs (blue, stars) and after 3040 km (19 loops) for single-mode fibers (red, circles). The constellation diagrams for the X-polarization at the optimal power for each case are also shown in the insets.

Even though the tolerance of the single-mode operation is not rigorously tested by inducing varying degrees of mechanical stress to the fibers, it is found that no special handling is necessary to maintain single-mode operation. The FMF spans are spooled on standard diameter spools with 25-cm wide flanges, which shows that the fundamental mode is well contained in the fiber core and do not suffer from excess macro- as well as micro-bending loss which is expected to be large for a spool with moderate tension. Moreover no deterioration in the performance is observed after the experiment is left to run over the span of several days, except for compensating for the drift in the bias points of the I-Q modulators in the transmitter.

4. Conclusion

In conclusion, FMFs can be used in long distance transmission systems (thousands of kilometers) to transmit high data rates in the standard channel spacings and modulation formats. This can be achieved by using the FMFs in the single-mode operation where the signal always remain in the same mode of the fiber. Single-mode operation is possible over long distances since the mode coupling is very low or nonexistent in few-mode fibers. It is also shown that using FMFs has the advantage of lower nonlinear impairments compared to single-mode fibers because of their larger effective area. At the same time they do not induce additional impairments such as differential mode dispersion, or excess loss. Even though the FMFs used in our experiments have a considerably larger effective area of 130 μm^2, compared to SSMFs, fibers with still larger effective area have been reported [10]. However, since FMFs do not have the limitation of the single-mode condition, they can always have larger effective areas compared to single-mode fibers for a given degree of confinement in the fiber core.