Transmission of 112 Gb/s PM-QPSK Signals over 7200 km of Optical Fiber with Very Large Effective Area and Ultra-Low Loss in 100 km Spans with EDFAs Only

John D. Downie, Jason Hurley, John Cartledge[1], Scott Bickham, and Snigdharaj Mishra
Corning Incorporated, SP-AR-02-1, Corning, New York, 14831
e-mail: downiejd@corning.com

Abstract: We experimentally investigate transmission of 16×112 Gb/s PM-QPSK signals over an optical fiber with effective area of 134 μm^2 and attenuation of 0.162 dB/km. We demonstrate transmission over 7200 km with 100 km span lengths.

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

1. Introduction

Much attention has recently been focused on the optical fiber attributes necessary for next generation high bit rate optical transmission systems at 100 Gb/s and beyond. It is well understood that moving to higher transmission system bit rates generally requires higher optical signal-to-noise ratio (OSNR) values to achieve acceptable levels of performance. Achieving higher system OSNR can be accomplished by lowering fiber loss, allowing higher channel launch powers through reduced fiber nonlinearity, and lowering optical amplifier noise figures. Therefore, it is desirable to lower the fiber attenuation as much as possible while making the fiber effective area as large as possible [1,2]. Indeed, many recent ultra-long haul distance transmission results at high bit rates have been achieved with fibers that have at least ultra-low loss or very large effective area [3-6].

In this work, we demonstrate ultra-long haul transmission of 112 Gb/s polarization-multiplexed quadrature phase-shift keying (PM-QPSK) signals over a new optical fiber that has the characteristics of both ultra-low loss and very large effective area. The average effective area of the fiber was 134 μm^2 and the average fiber attenuation was 0.162 dB/km. We show 16 channel transmission over 7200 km, with 100 km span lengths and simple single-stage erbium doped fiber amplifiers (EDFAs). To the best of our knowledge, this is the longest distance recorded at this bit rate with 100 km spans and amplification using only single-stage EDFAs.

2. Experimental set-up

The experimental configuration is shown in Fig. 1. At the transmitter, 16 DFB lasers ranging in wavelength from 1547 to 1553 nm were grouped into odd and even channels and combined to form a channel plan with 50 GHz spacing. All lasers were modulated together with a QPSK modulator driven by two de-correlated 2^{15}-1 PRBS patterns with a symbol rate of 28 Gbaud. The output from the QPSK modulator was optically polarization multiplexed to produce the PM-QPSK signals modulated at 112 Gb/s. The channels were launched into the re-circulating loop with a nominally flat spectrum.

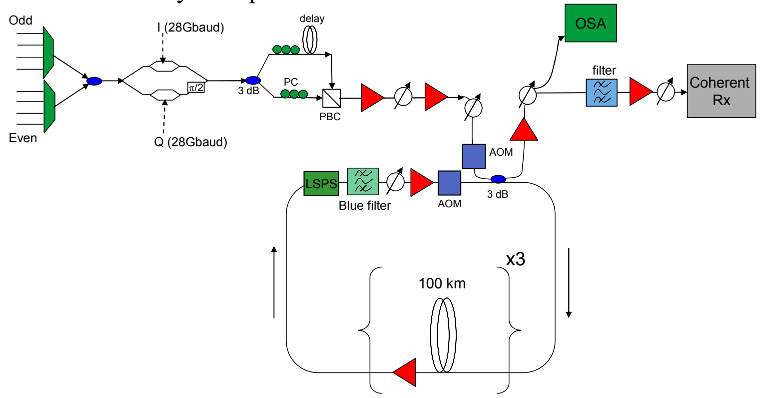

Fig. 1. Experimental set-up of transmission system with re-circulating loop.

The loop was comprised of 3 spans of the optical fiber, each span 100 km in length. The average fiber effective area and attenuation were 134 μm^2 and 0.162 dB/km, respectively. The fiber dispersion at 1550 nm was about 21

---

[1] Also with Queen's University, Kingston, ON, Canada.

ps/nm/km. This fiber is similar to a version with slightly smaller effective area that was previously reported in an unrepeatered span experiment using an effective area-managed configuration [7]. The total average span loss was about 17.0 dB including splices between transmission fiber spools, splices from the transmission fiber to standard single-mode fiber pigtails at the ends of the spans, and connector losses. A single-stage EDFA followed each span and a loop synchronous polarization scrambler (LSPS) was used to mitigate any possible loop polarization artifacts. We used a passive filter after the polarization scrambler at the end of the loop to filter out ASE in the blue end of the spectrum. No optical dispersion compensation was used in the transmission system so all dispersion compensation was applied electronically in the digital coherent receiver.

At the receiver end, a tunable optical filter selected a channel for measurement. The measurement channel was amplified and detected in a polarization- and phase-diverse digital coherent receiver that used a free-running local oscillator laser with nominal linewidth of 100 kHz. The four signals from the balanced photodetectors were digitized by analog-to-digital converters operating at 50 Gsamples/s using a real-time oscilloscope with 20 GHz electrical bandwidth. The sampled waveforms were processed off-line in a computer, with the digital signal processing steps including (i) quadrature imbalance compensation, (ii) up-sampling to 56 Gsamples/s and chromatic dispersion compensation using a frequency-domain equalizer, (iii) digital square and filter clock recovery, (iv) polarization recovery and equalization using an adaptive butterfly structure with filter coefficients determined using the constant modulus algorithm, (v) carrier frequency using a spectral domain algorithm, (vi) phase recovery using a pre-decision algorithm, and (vii) bit decisions. The bit error rate (BER) was measured for each of the 28 Gb/s tributary signals by direct error counting.

3. Experimental results

We first investigated the nonlinear tolerance of the system by varying the launch power per channel and measuring the BER of the central channel at 1550.92 nm. This was done at three different distances and the results are shown in Fig. 2a. The results show that the optimal channel launch power is around 2-3 dBm for a wide range of distances from 4500 km to 7500 km. To investigate the nature of the limiting nonlinearity, we then modified the channel plan by removing 8 channels including the 6 closest channels to the central measurement channel. In this configuration, the closest channels were 200 GHz away from the measurement channel. The results obtained at 7200 km transmission in this configuration are shown in Fig. 2b and compared to the original 50 GHz, 16 channel system. There is only a small difference in the nonlinear tolerance between the 2 systems, with the 200 GHz spaced system having < 1 dB higher optimal launch power. The difference in Q values corresponding to the minimum BER values for each system is about 0.6 dB, partly due to a slightly higher OSNR for the 200 GHz system. This suggests that the dominant nonlinear effect is single-channel in nature and cross-channel effects are small in comparison.

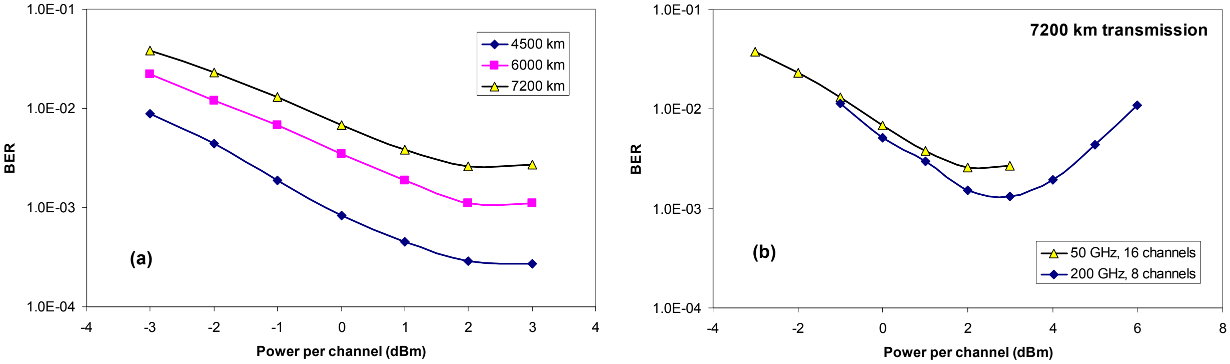

Fig. 2. (a) BER of measurement channel at 1550.92 nm vs. channel launch power at different distances. (b) BER of measurement channel at 7200 km for 50 GHz and 200 GHz systems.

For the central 1550.92 nm channel in the 16 channel 50 GHz system, we next measured the signal Q value (calculated from the BER measurements via the relationship $Q(dB) = 20\log\left(\sqrt{2}erfc^{-1}\left(2BER\right)\right)$) and OSNR (with 0.1 nm noise bandwidth) as functions of distance; these are shown in Fig. 3. The launch power per channel was 2 dBm at all distances. We observe that transmission for this channel is possible out to at least 7200 km with Q values above the enhanced forward error correction (FEC) threshold at 8.5 dB. All 16 optical channels were then measured at the distance of 7200 km. The Q and OSNR results obtained at this distance are shown in Fig. 4a and typical PM-QPSK constellation diagrams obtained for the central channel are shown in Fig. 4b. We see that all 16 channels meet or exceed the FEC threshold at this distance. The launched and received spectra after 7200 km transmission for the 16 channel system are shown in Fig. 5. The spread in received power levels was about 3 dB.

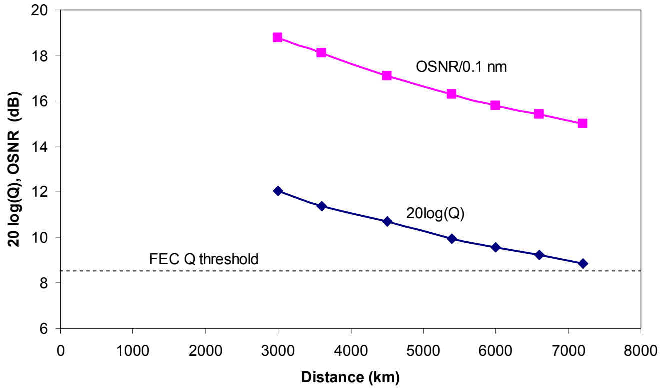

Fig. 3. Q and OSNR as functions of distance for the central channel at 1550.92 nm.

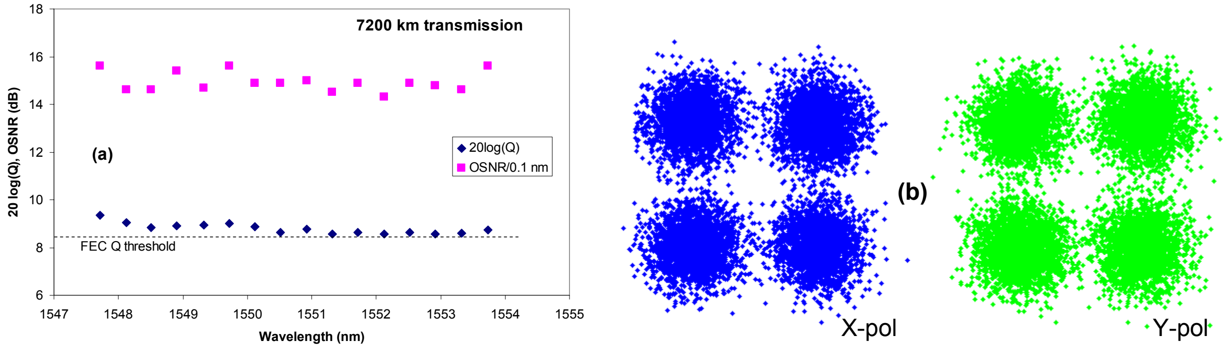

Fig. 4. a) Q and OSNR for 16 channel system after 7200 km transmission. b) Received PM-QPSK constellation diagrams.

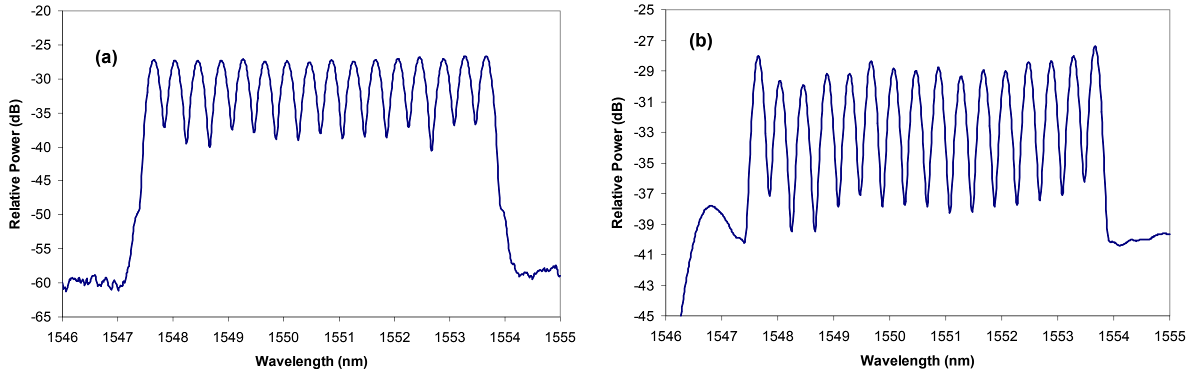

Fig. 5. a) Launched spectrum. (b) Received spectrum after 7200 km transmission.

4. Conclusions

We have experimentally investigated 112 Gb/s PM-QPSK transmission over a new optical fiber with very large effective area and ultra-low loss. This fiber enabled 16 channel transmission over 7200 km with 100 km span lengths and single-stage EDFAs only.

References

1. Y. Yamamoto *et al*, "OSNR-Enhancing Pure-Silica-Core Fiber with Large Effective Area and Low Attenuation," OFC 2010, paper OTuI2 (2010).
2. R. Chen *et al*, "Next Generation Transmission Fiber for Coherent Systems," OFC 2010, paper OTuI1 (2010).
3. G. Charlet *et al*, "72x100Gb/s transmission over transoceanic distance, using large effective area fiber, hybrid Raman-Erbium amplification and coherent detection," OFC 2009, paper PDPB6 (2009).
4. J.-X. Cai *et al*, "112x112 Gb/s Transmission over 9360 km with Channel Spacing Set to the Baud Rate (360% Spectral Efficiency), ECOC 2010, paper PD2.1 (2010).
5. M. Salsi *et al*, "80x100-Gbit/s Transmission over 9000 km using Erbium-Doped Fibre Repeaters only," ECOC 2010, paper We.7.C.3 (2010).
6. S. Chandrasekhar *et al*, "Transmission of a 1.2-Tb/s 24-Carrier No-Guard-Interval Coherent OFDM Superchannel over 7200-km of Ultra-Large-Area Fiber," ECOC 2009, paper PD2.6 (2009).
7. J. D. Downie *et al*, "40 x 112 Gb/s Transmission over an Unrepeatered 365 km Effective Area-Managed Span Comprised of Ultra-Low Loss Optical Fiber," ECOC 2010, paper We.7.C.5 (2010).