

112 Gb/s PM-QPSK transmission systems with reach lengths enabled by optical fibers with ultra-low loss and very large effective area

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ABSTRACT

Steadily increasing data traffic gives rise to increasing capacity requirements in optical communication networks. It is well understood that systems with higher symbol rates and/or multi-level modulation formats generally demand higher optical signal-to-noise ratio (OSNR) at the receiver to achieve acceptable system performance. In terms of the optical fiber medium, higher OSNR can be attained by lowering fiber loss and reducing fiber nonlinearity. We review several recent experimental investigations of 112 Gb/s PM-QPSK transmission with reach-length results enabled by the use of optical fibers with ultra-low loss and very large effective area.

Keywords: Optical fiber, OSNR, ultra-low loss, effective area, fiber nonlinearity.

1. INTRODUCTION

Worldwide data traffic continues to grow at a significant rate, giving rise to ever increasing capacity requirements in optical communication networks. The need for higher capacity generally leads to systems with increased bit rates and higher spectral efficiencies. An example is 100 Gb/s transmission over a single optical channel using polarization multiplexing (PM), coherent detection, and a multi-level modulation format such as quadrature phase shift keying (QPSK). 100 Gb/s PM-QPSK systems have been much researched in recent years and initial commercial deployment has begun. It is well understood that systems with higher symbol rates and/or multi-level modulation formats generally demand higher optical signal-to-noise ratio (OSNR) at the receiver to achieve acceptable system performance. In terms of the optical fiber medium, higher OSNR can be attained by lowering fiber loss and allowing higher channel launch powers through reduced fiber nonlinearity. Therefore, to facilitate new and future systems with very high bit rates and capacities, it is desirable to lower the fiber attenuation as much as possible while making the fiber effective area as large as possible. We review here several recent experimental investigations of 112 Gb/s PM-QPSK transmission over systems with record results enabled by the use of optical fibers with ultra-low loss and very large effective area. The systems discussed include an unrepeated single-span configuration, a system with 100 km spans and EDFA amplification, a system with 200 km spans employing hybrid EDFA/Raman amplification, and an all-Raman amplified system with 100 km spans.

2. OSNR REQUIREMENTS AND FIBER FIGURE OF MERIT

2.1 OSNR requirements

As mentioned above, the move to higher data rates and multi-level modulation formats generally requires higher and higher optical-signal-to-noise ratios (OSNR) to maintain the same system performance in terms of bit error ratio (BER). For the same modulation format and detection scheme, the required OSNR scales directly with bit rate, e.g. 2x bit rate requires 3 dB higher OSNR, 4x bit rate requires 6 dB higher OSNR, etc. However, different modulation formats have different OSNR requirements with multi-level formats generally needing higher OSNR even for the same bit rate, while coherent detection offers a benefit in required OSNR compared to direct detection systems. Table 1 summarizes the relative required OSNR for various bit rates and modulation formats, spanning direct detection and coherent detection systems. The relative OSNR values in Table 1 are adapted from Roberts *et al*¹ and represent theoretical results. The results are referenced to 10 Gb/s ON-OFF keying (OOK) with direct detection. All of the polarization multiplexed formats assume the use of coherent detection. While the relative required OSNR for 40 Gb/s PM-BPSK and PM-QPSK are both only 1.7 dB higher than for 10 Gb/s OOK direct detection, the requirements go up quickly for 100 Gb/s and 200 Gb/s signals, especially for PM-16QAM signals. QAM represents quadrature amplitude modulation, and 16QAM is a

variant that has 16 constellation points. These data for the 100 and 200 Gb/s signals point clearly to the need for systems that enable higher OSNR values at the same reach lengths as are attainable currently with lower bit rate systems. In this paper we examine optical fiber properties that enable higher OSNR for 100 Gb/s systems and beyond.

Table 1. Relative required OSNR for different bit rates and data formats. Shaded cells assume coherent detection.

Modulation format	Bit rate (Gb/s)	Relative required OSNR (dB)
ON-OFF keying, direct detection (OOK-DD)	10	Reference
Differential binary phase shift keying (DBPSK)	40	+3
Differential quadrature phase shift keying (DQPSK)	40	+4.4
Polarization-multiplexed BPSK (PM-BPSK)	40	+1.7
PM-QPSK	40	+1.7
PM-QPSK	100	+5.7
PM-16QAM	100	+9.3
PM-16QAM	200	+12.3

2.2 Fiber figure of merit (FOM)

The main factors that determine the OSNR for a given system link at a given distance are the channel launch power into each span, the noise figure of the optical amplifiers, the loss per span, and the total number of spans in the link. Of these, the factors that are directly related to optical fiber parameters are channel launch power and span loss. The channel launch power is limited by optical nonlinear impairments in the fiber. The two fiber parameters affecting nonlinear tolerance are the fiber effective area (A_{eff}) and n_2 , the nonlinear index of refraction, and in general the fiber nonlinear tolerance (and thus optimal channel launch power) scales as the ratio A_{eff}/n_2 . Of course span loss is directly related to the fiber attenuation coefficient α_{dB} (dB/km), so reducing α_{dB} reduces span loss and leads to increased OSNR. There is also a connection between nonlinear tolerance and fiber attenuation that is defined by the effective length² (L_{eff}), where L_{eff} is defined as

$$L_{\text{eff}} = \frac{(1 - \exp(-\alpha L))}{\alpha} \quad (1)$$

and α is the attenuation in linear units (km^{-1}) and L is the span length. This definition of effective length recognizes that for lower attenuation fiber, the signal power does not drop as quickly with distance and so there is a slight reduction in nonlinear tolerance compared to a fiber with similar A_{eff} and n_2 but higher attenuation.

Given these relations, we can define a fiber figure of merit (FOM) that effectively relates the relative expected OSNR of any given fiber to a reference fiber. The FOM used here is adapted from closely related definitions^{3,4} and is defined as

$$\text{Fiber FOM(dB)} = 10 \log \left[\frac{A_{\text{eff}} \cdot n_{2,\text{ref}}}{A_{\text{eff},\text{ref}} \cdot n_2} \right] - (\alpha_{\text{dB}} - \alpha_{\text{dB},\text{ref}}) \cdot L - 10 \log \left[\frac{L_{\text{eff}}}{L_{\text{eff},\text{ref}}} \right]. \quad (2)$$

An example of the fiber FOM as a function of effective area A_{eff} and attenuation α_{dB} is shown in Figure 1 for 75 km spans. The reference fiber parameters used here are 0.2 dB/km attenuation and $80 \mu\text{m}^2$ effective area. Although the exact reference fiber parameters are not very important, these parameters are generally representative of the average in round numbers of dispersion managed fiber spans in submarine systems.

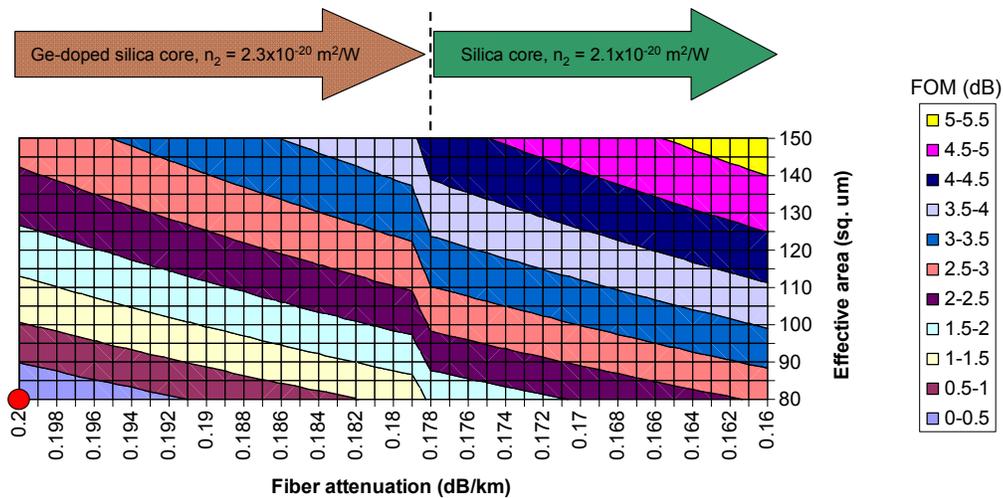


Figure 1: Fiber FOM as a function of attenuation and effective area for 75 km span length. Red circle represents parameters of reference fiber.

The data in Figure 1 clearly show that increasing the fiber FOM can be attained by either increasing the fiber effective area, decreasing the fiber attenuation, or doing both at once. In fact, for this example of 75 km span length, >5 dB increase in FOM can be obtained by moving to an ultra-low loss fiber with attenuation of 0.162 dB/km and an effective area of at least 145 μm^2 . The discontinuity observed in the contour plot in Figure 1 between 0.179 dB/km and 0.178 dB/km is the result of an assumption made here that for attenuation values ≤ 0.178 dB/km, the fiber will have to be a silica core fiber rather than a conventional Germanium-doped fiber. The discontinuity reflects the fact that silica core fibers have an intrinsically smaller nonlinear index⁵ n_2 , which provides a FOM advantage on the order of 0.3-0.4 dB.

The relative effect on fiber FOM of attenuation and effective area is dependent on the system span length, as seen in Eq. 2. We compare the equivalent changes in these two parameters, with respect to the reference fiber, for span lengths of 50, 75, and 100 km in Figure 2. The x-axis represents change in attenuation from the reference fiber's 0.2 dB/km and the y-axis is change in effective area from the reference fiber's 80 μm^2 . The dashed line drawn at the delta attenuation value of -0.35 dB/km compared to the reference fiber represents an actual attenuation of 0.165 dB/km. This attenuation level is equivalent to increasing the effective area by 34, 55, and 83 μm^2 above the reference fiber's 80 μm^2 effective area for 50, 75, and 100 km spans, respectively. While this analysis evaluates the equivalent changes in the two fiber parameters, it is clear from Eq. 2 and Figure 1 that to maximize fiber FOM, one would like to simultaneously push both parameters toward their limits, and thus both minimize attenuation and maximize effective area.

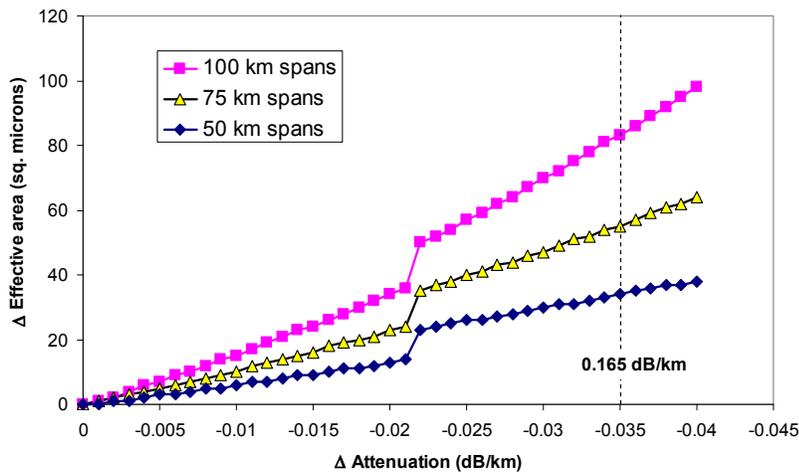


Figure 2: Relative impacts of decreasing fiber attenuation and increasing fiber effective area with respect to the reference fiber, for system span lengths of 50, 75, and 100 km.

The previous analysis was directed at repeatered systems with optical amplifiers at the end of each span. We saw that generally, both fiber attenuation and effective area play a significant role in the fiber FOM. We now briefly look at the special case of an unrepeatered submarine system. This is usually a very long single span on the order of 300-400 km with no amplifiers between the transmitter at one end and the receiver at the other end. Figure 3 contains fiber FOM data for a 350 km unrepeatered span. It is obvious that for very long spans such as 350 km, fiber attenuation is the critically important parameter in determining FOM. This data assumes a reference fiber with 0.185 dB/km attenuation and 100 μm^2 effective area. As seen in the figure, for constant attenuation, increasing the effective area from 100 μm^2 effective area to 150 μm^2 produces < 2 dB improvement in the FOM. However, for constant effective area, approximately 8 dB improvement in the FOM is obtained by decreasing the attenuation from 0.185 dB/km to 0.162 dB/km. For a fiber that combines both ultra-low attenuation and large effective area near these values, we can expect up to about 9.5 dB increase in the FOM compared to the reference fiber.

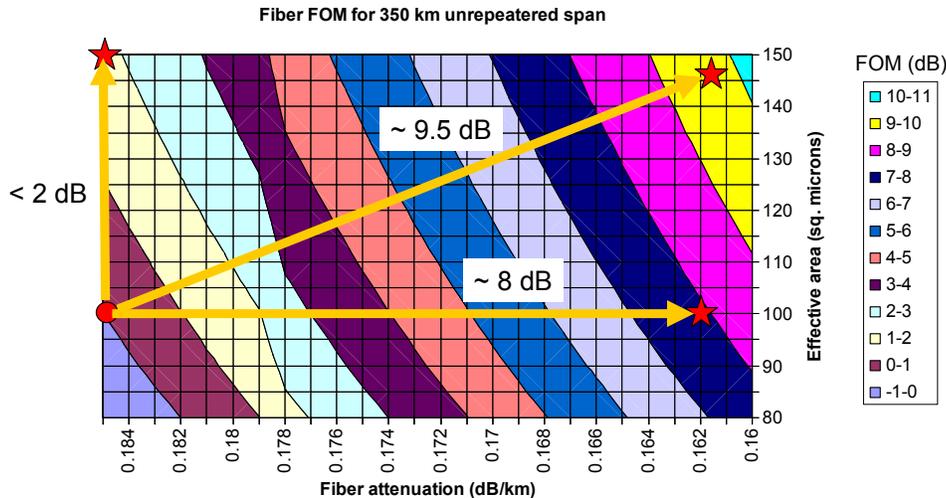


Figure 3: Fiber FOM as a function of attenuation and effective area for an unrepeatered 350 km span system. Red circle represents parameters of reference fiber: 0.185 dB/km attenuation and 100 μm^2 effective area.

3. RECENT EXPERIMENTS WITH ULTRA-LOW LOSS AND LARGE A_{EFF} FIBERS

Having observed the potential benefits of optical fibers with ultra-low loss and large effective area as quantified by the fiber FOM in the previous section, we will now describe several recent 112 Gb/s PM-QPSK transmission experiments using fibers with these characteristics. Some of the fibers used in the experiments are commercially available and some were prototypes of fiber under development. The experiments and results highlight the long reach lengths and good system performance enabled by the fiber attributes.

3.1 Effective area-managed 365 km unrepeatered span

The first transmission system investigated was an unrepeatered system with span length 365 km⁶. We demonstrated transmission of 4 Tb/s with 40 channels modulated at 112 Gb/s with the PM-QPSK modulation format over a 365 km unrepeatered span using an effective area-managed fiber configuration⁷ with EDFA-only amplification at the transmitter and backward-pumped Raman/EDFA amplification at the receiver. The span was comprised of 3 types of ultra-low loss fiber with effective areas ranging from 76 μm^2 to 128 μm^2 in an arrangement designed to maximize nonlinear tolerance and overall effectiveness of the Raman amplifier.

The experimental system set-up is shown in Figure 4. Forty DFB lasers spaced by 50 GHz and ranging from 1542.9 nm to 1558.6 nm were multiplexed together and modulated by a QPSK modulator. The modulator was driven by two 2^{15} -1 PRBS patterns at 28 Gsymbol/s. The output from the QPSK modulator was then polarization multiplexed by splitting the signal, orthogonalizing the polarization states, de-correlating by hundreds of symbols with a relative delay, and combining with a polarization beam combiner to produce the final PM-QPSK signals modulated at 112 Gb/s. The 40

channels were launched into the 365 km span with a nominally flat launch spectrum after de-correlation using a short piece of standard single-mode fiber and amplification with a high-power EDFA.

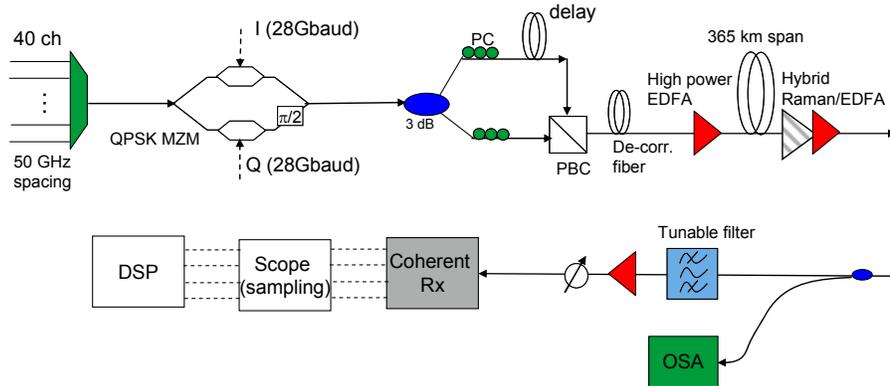


Figure 4: Experimental set-up for 365 km unrepeated span transmission system experiment.

The fiber span was comprised of 3 types of ultra-low loss fibers with different effective areas. The fibers used were Corning® Vascade® EX1000 fiber with $76 \mu\text{m}^2$ effective area, Vascade® EX2000 fiber with about $112 \mu\text{m}^2$ effective area, and a first generation developmental fiber for Vascade® EX3000 fiber with an effective area of $128 \mu\text{m}^2$. The average attenuation values of the 3 fiber types used in this experiment were 0.162 dB/km, 0.162 dB/km, and 0.164 dB/km, respectively. The total fiber span loss including splices was about 59.6 dB, giving an average span attenuation of 0.163 dB/km. The span configuration is shown in Figure 5 and consisted of about 40 km of the $128 \mu\text{m}^2$ effective area fiber, followed by 155 km of Vascade® EX2000, 160 km of Vascade® EX1000, and then another 10 km of Vascade® EX2000 fiber at the end of the span. The length of the largest A_{eff} fiber at the beginning was chosen to balance nonlinear tolerance and OSNR. The Raman gain primarily occurred in the $76 \mu\text{m}^2$ effective area fiber, while the addition of 10 km of the fiber with $112 \mu\text{m}^2$ A_{eff} at the end of the span was predicted by modeling to maximize the overall system OSNR at the receiver while minimizing nonlinear penalties.

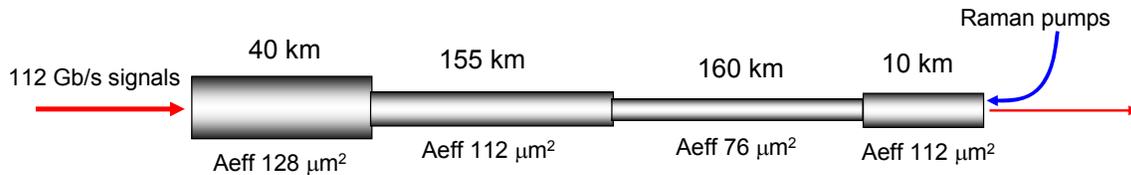


Figure 5: Configuration of the effective area-managed span.

The Raman amplifier had 3 pump wavelengths at 1427 nm, 1443 nm, and 1462 nm. The aggregate output power of the pumps was approximately 1 W which produced a total Raman gain of about 25 dB. Immediately following the Raman amplifier was an EDFA. A tunable optical filter with 0.4 nm bandwidth was then used to select a channel for measurement. The receiver was a standard coherent receiver employing standard digital signal processing algorithms described in reference 6.

Experimental results from transmission tests are shown in Figure 6. In Figure 6a, the measured BER value for the central channel at 1550.92 nm is given as a function of channel launch power for two cases: 40 channels with 50 GHz spacing and 16 channels with 100 GHz spacing. The relatively small difference between the two cases suggests that the primary nonlinear penalty is single channel in nature, i.e. self-phase modulation. From this data, the optimal launch power for the 40 channel 50 GHz spaced system was found to be 13.5 dBm. We then measured the BER and OSNR values of all 40 channels, based on 1,000,000 samples for each of the four tributary signals. The calculated Q values based on the measured BER data and OSNR data are shown in Fig. 6b. All 40 channels were determined to have Q values above the enhanced FEC (EFEC) threshold of 8.5 dB. The average Q value was 9.6 dB and the average OSNR value was 14.7 dB. The total capacity-distance product demonstrated in these experiments was 1460 Tb/s-km, a result enabled by the effective area-managed span configuration using 3 ultra-low loss optical fibers.

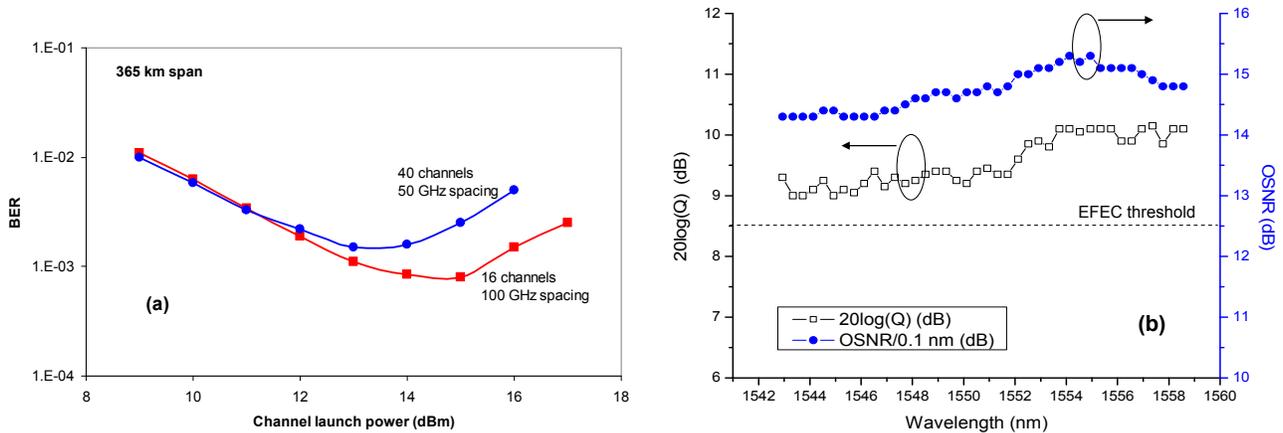


Figure 6: (a) BER vs. channel launch power for 40 channel, 50 GHz system, and 16 channel, 100 GHz system. (b) OSNR (0.1 nm noise bandwidth) and $20\log(Q)$ values of all 40 channels after transmission over 365 km unrepeated span.

3.2 System with 100 km spans and EDFA-only amplification

In the next system studied, we investigated ultra-long haul transmission of 112 Gb/s PM-QPSK signals over a second generation of the developmental prototype Vascade[®] EX3000 optical fiber with characteristics of both ultra-low loss and very large effective area⁸. The average effective area of the fiber used here was $134 \mu\text{m}^2$ and the average fiber attenuation was 0.162 dB/km. The fiber dispersion was about 21 ps/nm/km at 1550 nm. 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.

The experimental configuration is shown in Figure 7. At the transmitter, 16 DFB lasers ranging from 1547 to 1553 nm were combined to form a channel plan with 50 GHz spacing. The transmitter configuration was as described earlier. The channels were launched into the re-circulating loop with a nominally flat spectrum. The loop was comprised of 3 spans of the optical fiber, each span 100 km in length. 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 pigtailed 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 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.

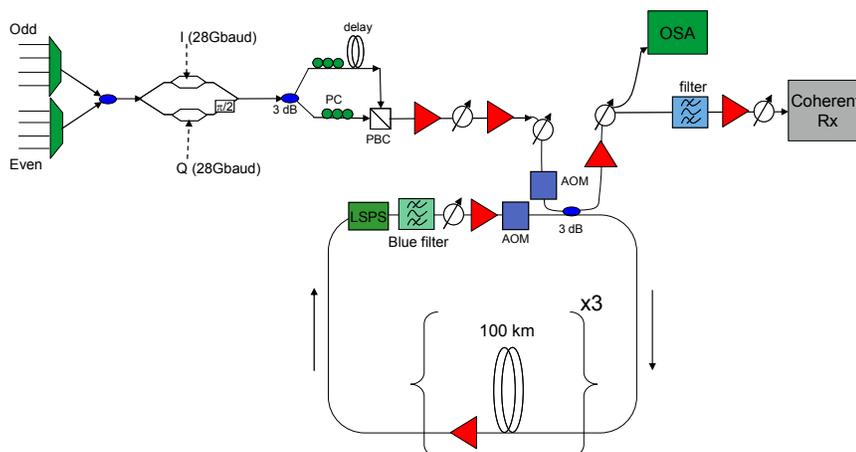


Figure 7: Experimental set-up for 16 channel, 100 km span, EDFA-only, re-circulating loop experiments.

As before, 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 Figure 8a. 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. A typical constellation diagram of the PM-QPSK signal after 7200 km transmission is shown in Figure 8b.

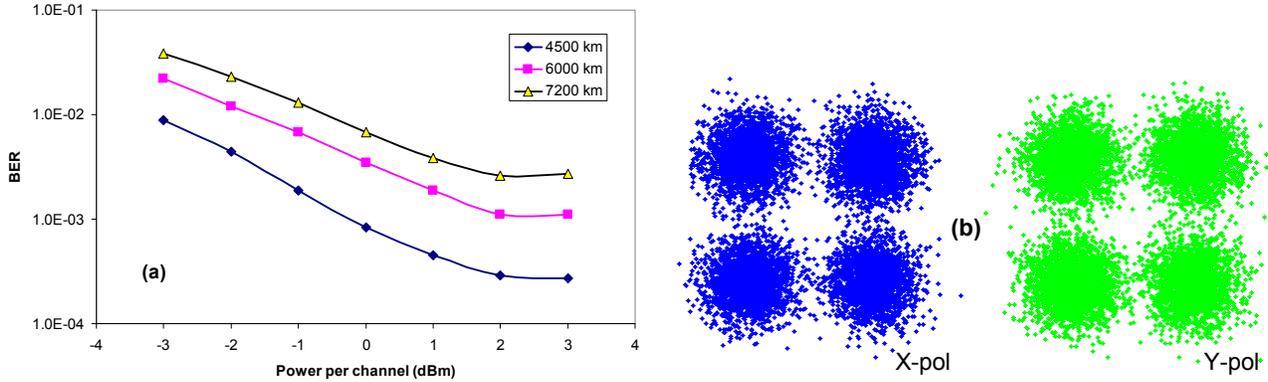


Figure 8: (a) BER vs. channel power for 1550.92 nm channel at 3 different transmission distances. (b) Typical PM-QPSK constellation diagram after 7200 km transmission.

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) and OSNR (with 0.1 nm noise bandwidth) as functions of distance; these are shown in Fig. 9a. 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. 9b. All 16 channels exceed the FEC threshold at this distance. The results demonstrate transmission at 112 Gb/s over submarine scale distances with a very simple system configuration with 100 km spans and EDFA-only amplification. This was primarily enabled by the fiber characteristics of ultra-low attenuation and very large effective area. We also note that the EDFAs used for this transmission experiment were not optimized for the relatively small gain of 17 dB required for each span and thus had noise figures higher than could be achieved with optimization for this gain level. Longer transmission could be attained with the use of amplifiers optimized for the system.

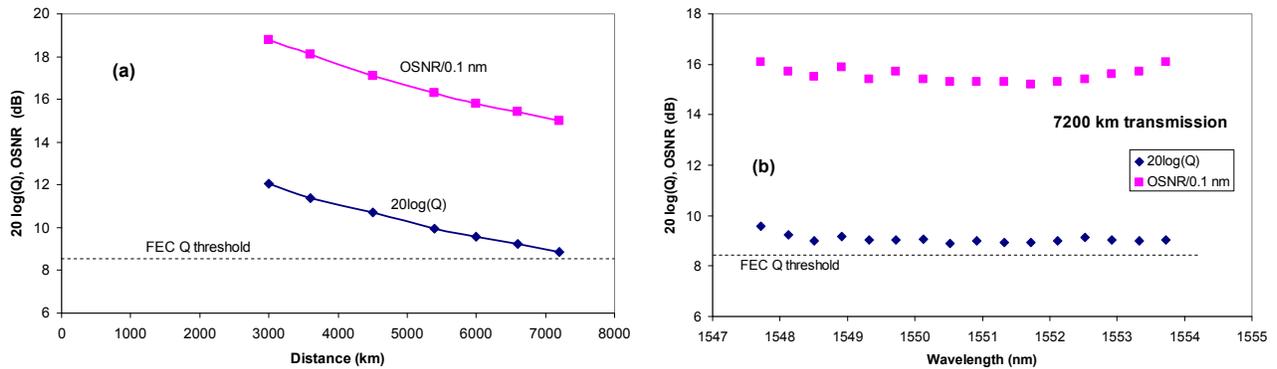


Figure 9: (a) BER and OSNR vs. transmission distance for 1550.92 nm channel. (b) OSNR and Q values for all 16 channels after 7200 km transmission.

3.3 Hybrid fiber system with 200 km spans and hybrid Raman/EDFA amplification

A third system demonstration using optical fibers with ultra-low attenuation and large effective area to achieve record reach lengths had 200 km spans comprised of a hybrid fiber configuration⁹. System designs that can take advantage of longer amplifier spans may offer cost savings through reduced numbers of amplifiers and amplifier huts out in the field. However, in order to maintain this cost advantage it is necessary to still attain sufficient reach lengths such that more

frequent signal regeneration is not necessary compared to conventional 80-100 km span systems. One approach that has been shown to enable longer span lengths by increasing the optical signal-to-noise ratio (OSNR) is the use of hybrid Raman/EDFA amplification^{10,11}. Another approach, as we have seen, is to employ optical fibers with lower loss and higher nonlinear tolerance. In this work, we combined both approaches to demonstrate 112 Gb/s PM-QPSK transmission up to 6000 km with a system having 200 km spans.

The basic experimental configuration is shown in Figure 10. Experiments were performed first with 8 channels and then with 32 channels, with both systems on a 50 GHz grid. The channels were launched into a re-circulating loop with a nominally flat spectrum. An EDFA at the beginning of the loop in power control mode determined the launch power in the first span. The loop was comprised of 3 spans of length 200 km. Each span was constructed from 100 km of the developmental prototype Vascade[®] EX3000 ultra-low loss very large effective area fiber spliced to 100 km of SMF-28[®] ULL, an ultra-low loss G.652-compliant fiber, as illustrated at the bottom of Figure 10. The average effective area of the first fiber was 134 μm^2 , allowing higher channel launch power, while that of the second fiber was 85 μm^2 . The total loss of each 200 km fiber span including splices and connectors was 33 dB (0.165 dB/km). The span loss was compensated with backward pumped Raman and single-stage Erbium doped amplifiers. The maximum possible total launch power into each span was 19 dBm, as limited by the EDFAs. A loop synchronous polarization scrambler (LSPS) was used to mitigate possible loop polarization artifacts. For the 8 channel system, we placed a 6 nm wide bandpass filter centered around the channels after the polarization scrambler at the end of the loop to filter ASE and flatten the channel spectrum. For the 32 channel experiments, the bandpass filter was replaced with a dynamic gain equalizer (DGE). All chromatic dispersion was compensated electronically in the digital coherent receiver.

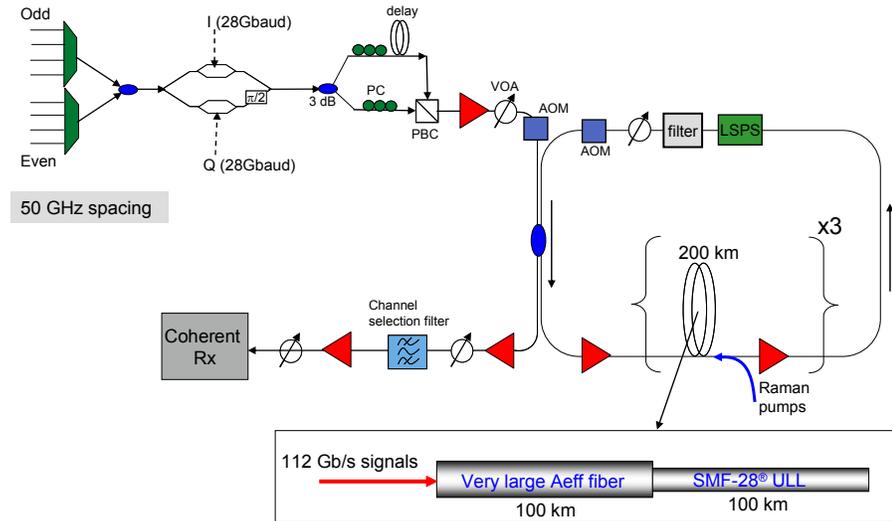


Figure 10: Experimental set-up for re-circulating loop experiments with 200 km fiber spans.

For the initial 8 channel system experiments, 2 counter-propagating Raman pump wavelengths at 1443 nm and 1461 nm were used. The average total pump power for 4 pump lasers (2 orthogonally polarized pumps for each wavelength) was 728 mW which produced an average Raman ON/OFF gain at the center of the 8 channel plan at 1548.51 nm of 20.8 dB. We first determined the optimal channel launch power by varying the total power into each span at 2 different transmission distances: 3000 km and 3600 km. The results given in Figure 11a show that the optimal launch power was about 4.5 dBm per channel. We then set the total power launched into each span at 13.5 dBm to correspond to 4.5 dBm per channel and measured the BER and OSNR of the central 1548.51 nm channel as a function of distance. The results are shown in Figure 11b where the measured BER has been converted into $20\log(Q)$ values. The 8 channel system had a maximum reach of 6000 km defined by the assumed FEC threshold of 8.5 dBQ. All 8 channels demonstrated measured Q performance above the FEC threshold at the 6000 km distance.

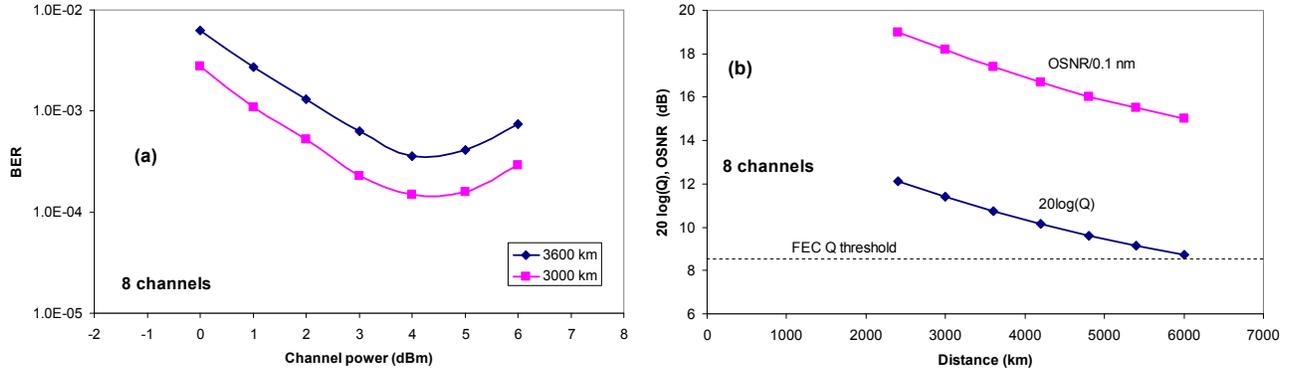


Figure 11: 8 channel transmission data for 1548.51 nm channel. (a) BER vs. channel power, (b) Q and OSNR vs. distance.

For 32 channel transmission we substituted the DGE into the loop for the passive filter. We also used 3 Raman pump wavelengths to broaden the gain spectrum, adding pumps at 1427 nm. The average total pump power was 870 mW and the average ON/OFF gain across the channel plan and for all 3 spans was 21.6 dB. The Raman gain ripple across the channel plan was just less than 1 dB. Given the maximum total EDFA output power level of 19 dBm, this permitted a maximum channel power of 4 dBm into each span, which was just slightly lower than the optimal power. At 4 dBm/channel, we measured the Q value of the central channel as a function of distance. The results are shown in Figure 12a along with the 8 channel results. The small difference between 32 and 8 channel results is likely largely due to the 0.5 dBm lower channel power for the 32 channel system. Finally, all 32 channels were measured at the maximum reach of 5400 km. The Q and OSNR results are given in Figure 12b showing all 32 channels had Q performance above the FEC threshold.

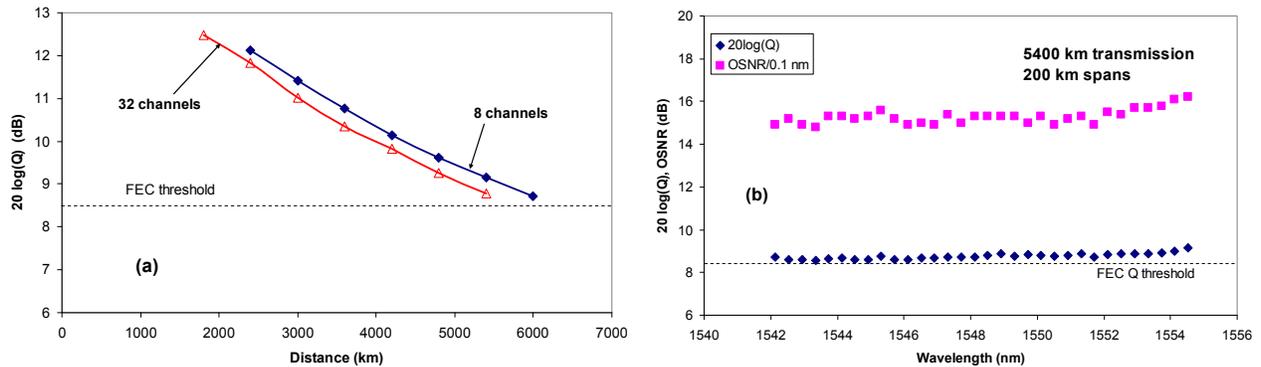


Figure 12: (a) BER vs. channel power and 8 and 32 channel systems, (b) Q and OSNR vs. distance for all channels in 32 channel system.

3.4 Trans-oceanic length transmission with 100 km spans and all-Raman amplification

The previous systems studied have either used EDFAs only or hybrid Raman/EDFA amplification to compensate for span loss. In this last experiment, we used all-Raman amplification to maximize the system reach length. The experimental system configuration is shown in Figure 13. The system studied was a 40 channel system with 50 GHz channel spacing. The 112 Gb/s PM-QPSK channels were launched into a re-circulating loop comprised of three 100 km spans of Corning® Vascade® EX2000 optical fiber. The fiber attenuation was 0.162 dB/km and the effective area was about $112 \mu\text{m}^2$. The channels were amplified within each span by backward propagating Raman pumps at 1427, 1443, and 1461 nm. The ON/OFF Raman gain for each span was set to equal the span loss plus the loss of the Raman amplifiers themselves. The total Raman pump power averaged about 935 mW in each span. A loop synchronous polarization scrambler was placed at the end of the loop along with a dynamic gain equalizer that was used to flatten the gain spectrum. An EDFA was used at the input side of the loop to control the total launch power into the first span and a

second EDFA was placed at the end of the loop to compensate for the loss of the polarization scrambler, DGE, and loop components.

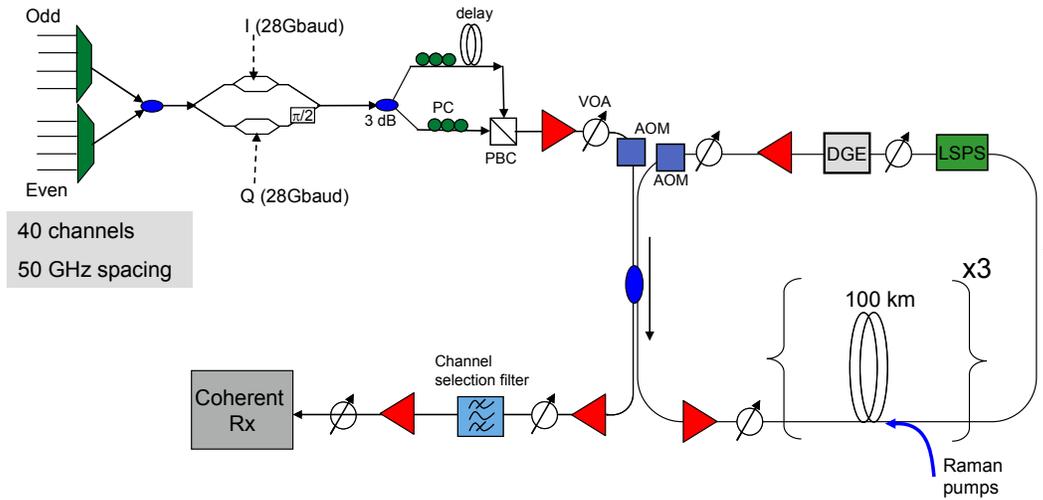


Figure 13: Experimental configuration for 40 channel all-Raman amplified transmission system.

The optimal launch power per channel was first determined for the system and found to be -4 dBm per channel. Using this channel power, we measured the BER as a function of transmission distance of the central measurement channel at 1550.92 nm. The Q results as calculated from the BER data are shown in Figure 14 and show that for this channel, transmission beyond 11,400 km is possible with the Q value remaining above the FEC threshold of 8.5 dB.

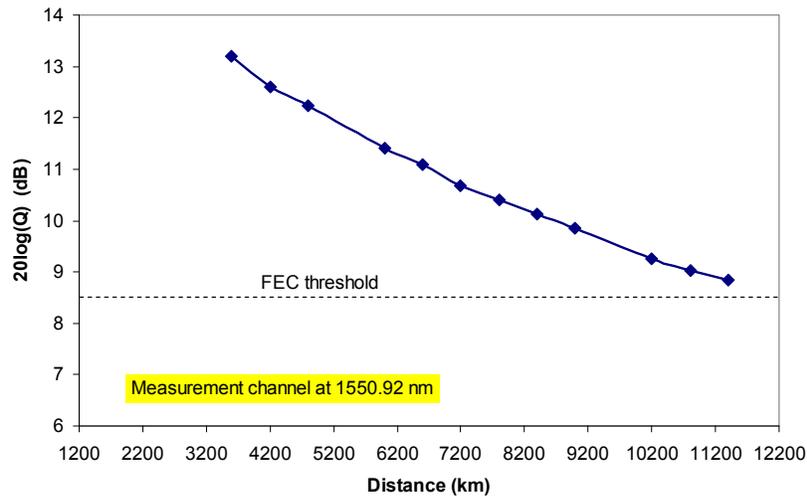


Figure 14: $20\log(Q)$ vs. transmission distance for 1550.92 nm channel in all-Raman amplified system using Vascade[®] EX2000 optical fiber.

All 40 channels were then measured at the distance of 10,200 km. The results for $20\log(Q)$ and OSNR are shown in Figure 15a, with all channels having a Q value above the FEC threshold. The received spectrum is shown in Figure 15b. We note that this fiber has been used in a previous experiment demonstrating 9000 km transmission of 80 x 112 Gb/s channels using 50 km spans and EDFA-only amplification¹².

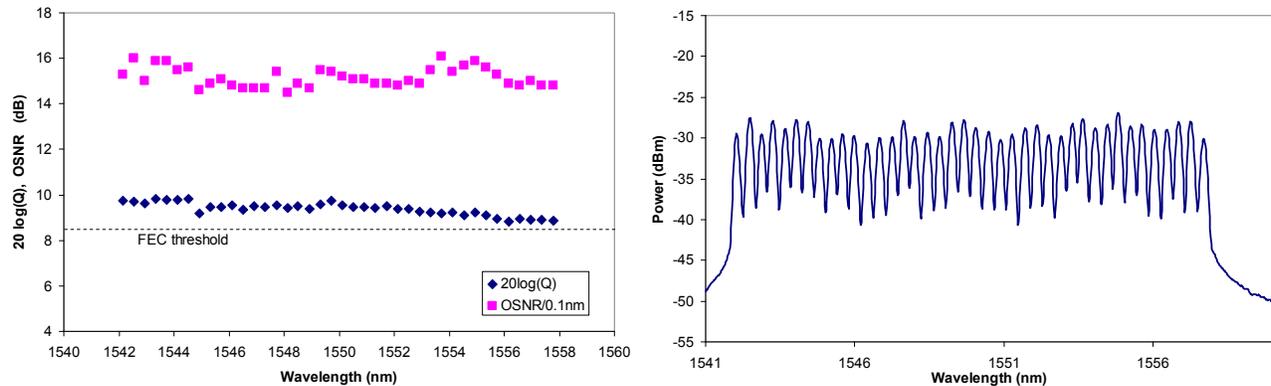


Figure 15: (a) $20 \log(Q)$ and OSNR/0.1nm for all 40 channels at 10,200 km distance. (b) Optical spectrum at 10,200 km.

4. CONCLUSIONS

We have investigated the benefits of optical fiber with ultra-low attenuation and large effective area. This combination of characteristics can be employed to increase system OSNR compared to standard single-mode fiber and thus allow long system reach lengths for high data rate systems at 100 Gb/s and beyond. We then reviewed four recent transmission experiments using both commercial and developmental optical fiber to demonstrate long reach lengths for 112 Gb/s PM-QPSK systems in different configurations that were largely enabled by the advanced optical fiber properties. These experiments included an unrepeated submarine system, a system with 100 km spans and EDFA-only amplification, a system with 200 km spans and hybrid Raman/EDFA amplification, and an all-Raman amplified system with 100 km spans. Given the higher OSNR requirements for data rates beyond 100 Gb/s, the use of optical fibers with both ultra-low loss and very large effective area will become ever more important in future system designs.

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