8x100G Unrepeatered Transmission Over Record 92.7 dB Span (618 km)

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Abstract: We report 8x100G transmission over a 92.7 dB record span loss for this capacity. The experimental span consisted primarily of an ultra-low-loss fiber with an effective area of 150 μm^2 and included both transmit and receive ROPAs pumped by 5-W dual-wavelength ROPA pumps. The 100G and later 800G channels were provided by eight 800G-capable transponders based on 7 nm DSP using 70 or 96 Gbaud 8-dimensional frequency domain hybrid modulation format, operated with optimized feed-forward carrier averaging, subcarrier averaging and nonlinear compensation. The span fiber was then replaced with another ultra-low-loss fiber with an effective area of 125 μm^2 and transmission tests of 8x100G and 1-4x800G were conducted.

1. INTRODUCTION

Unrepeatered links are a cost-effective solution to provide communication from mainland to islands or from island to island and, via festoon links, to connect coastal communities separated by inhospitable terrain. They are also an attractive option for communication links to offshore oil and gas platforms. Considerable efforts have been devoted to increasing the capacity and reach of such links. In recent years, hero experiments [1-6] aimed at pushing the limits of the capacity x reach product have involved new ultra-low-loss, high-effective-area fibers, high-power Raman amplification, enhanced remote optically pumped amplifier (ROPA) assisted link architectures and advanced coherent technologies.

In this paper, we report the transmission of 8x100G over a 92.7 dB span of an ultra-low-loss fiber with an effective area (A_{eff}) of 150 μm^2. This is, to the best of our knowledge, a record span loss for this capacity. We also report 8x100G and up to 4x800G transmission over another ultra-low-loss fiber with a lower A_{eff} of 125 μm^2. The link architecture for the transmission experiments with both fiber types was the same and included both transmit and receive ROPAs pumped by 5-W dual-wavelength ROPA pumps. Although the 8x100G reach with the 125-μm^2 fiber was slightly less (90.8 dB), the lower loss/km for this fiber means that the bridgeable link length is only marginally lower than that achieved with the 150-μm^2 fiber and the smaller A_{eff} is usually preferred in today's submarine cables due to better handleability during the cabling process.

Both the 125- and 150-μm^2 fibers are based on an ultra-low-loss, silica-core design, which is a de-facto industry standard for high-performance large A_{eff} fibers. Both fibers have a maximum cable cut-off wavelength of 1520 nm, although the typical cable cut-off is lower (1440 nm for the 125-μm^2 fiber and 1465 nm for the 150-μm^2 fiber). Both fibers have a very similar chromatic dispersion (20.8 ps/nm/km typical at 1550 nm for the 125-μm^2 fiber, and 20.9 ps/nm/km typical at 1550 nm for the 150-μm^2 fiber). The nonlinear refractive index is the same for both fibers and equals to 2.1 x 10^{-20} m^2/W.

Eight frequency-tuneable, multi-symbol rate 800Gb/s-capable transponders were used to generate 8x100G and up to 4x800G

channels. Each transponder generated two channels of probabilistic shaped (PS) 64-QAM using 8 subcarriers for each channel [7]. The 8x100Gb/s channels were generated with 33% forward error correction (FEC) overhead and 70 Gbaud symbol rate with 2 bps spectral efficiency.
For the 1-4x800G channels, 20% FEC overhead was used with 96 Gbaud symbol rate generating 10.5 bps spectral efficiency.

2. EXPERIMENTAL SETUP

The link architecture used for the transmission measurements with both fiber types is shown in Fig. 1 below.

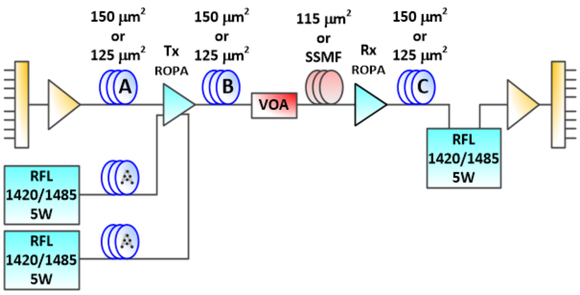

Fig. 1: Transmission Link Architecture

In each case, the large A_{eff} fiber was used for the fiber segments where the channel powers entering the link segments were approaching the nonlinear limit for the signal format in the particular fiber type and for the segments where the A_{eff} and loss spectrum of the fiber play a significant role in determining the 1485-nm pump power that can be delivered to the ROPAs by the dual-wavelength ROPA pumps. The segment B following the Tx ROPA was in each case long enough to ensure that the channel powers exiting this segment were well below the level at which any nonlinear impairments could be generated. The choice of fiber for the segment between the VOA and the Rx ROPA was not critical since the channel powers were low and this segment was not involved in the pump delivery to the Rx ROPA. In the first series of experiments, this segment consisted of fiber with an A_{eff} of 115 µm^2 while, in the second series, standard single-mode fiber (SSMF) with an A_{eff} of 80 µm^2 was used.
The output of the dual-wavelength ROPA pump consists of relatively weak, depolarized 1485-nm seed power from a laser diode along with high power at 1420 nm from a Raman fiber laser (RFL). As the 1485-nm seed power propagates along the fiber, it experiences Raman amplification due to the co-propagating high 1420-nm power. Fig. 2 shows the simulated evolution of the 1420- and 1485-nm powers along an ultra-low-loss fiber with an A_{eff} of 150 µm^2. Also shown for comparison is the evolution of the 1485-nm power when it alone is launched from a high-power 1485-nm RFL. In each case, the maximum power that can be delivered to a ROPA at a given location along the span is limited by the maximum tolerable launch power, which is the power (or, in the case of the dual-wavelength pump, the combination of main and seed powers) that would result in peak Raman gains greater than ~ 40 dB which in turn would lead to lasing instabilities in the span and the conversion of the desired 1485-nm power to useless power in the 1600-nm region. The calculated Raman gain spectra for the two cases and for the launch powers of Fig. 2 are shown in Fig.3. The peak gains in the 1590–1600 nm region show that the launch powers of Fig. 2 are at their maximum. The gain for the region occupied by the signal channels is in the range from 28 to 29 dB. Comparing the dual-wavelength ROPA pump to direct 1485-nm pumping, one can see that, with 1420/1485 pumping, 1.5 dB more 1485-nm power can be delivered at a given distance or the same power can be delivered 9 km further out.

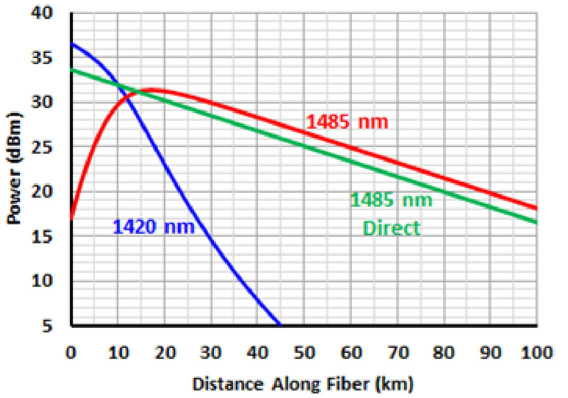

Fig. 2: Simulated evolution of the 1420 and 1485 nm powers from a dual-wavelength ROPA pump and the power from a 1485-nm RFL along an ultra-low-loss fiber with a 150-µm² A_{eff}

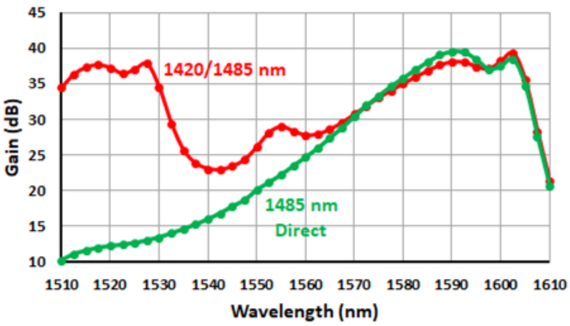

Fig. 3: Calculated Raman ON/OFF gain spectra in ultra-low-loss fiber with 150-µm² A_{eff} for dual-wavelength and direct 1485-nm ROPA pumping with launch powers as shown in Fig. 2.

Due to the fact that only one 5-W dual-wavelength ROPA pump was available for the experiments, before installing it at the receive end to pump the Rx ROPA, it was spliced to one end of the large A_{eff} fiber segment that would ultimately be used for segment A between the booster and the Tx ROPA. The 1485-nm power delivered to the other end was then measured as a function the 1420-nm main and 1485-nm seed powers to determine the maximum 1485-nm pump power that could be delivered over this length of the large A_{eff} fiber, which would be the same length as the dedicated Tx ROPA pump delivery fibers in an actual system. Then, during the experimental measurements, individual 1-W 1485-nm Raman fiber laser (RFL) pump sources were connected to the Tx ROPA pump input ports to pump the Tx ROPA at levels up to the maximum delivered pump power determined previously with the 5-W ROPA pump and the large A_{eff} fiber segment. Before the receive fiber segment C was connected to the Rx ROPA, the 5-W ROPA pump was spliced to one end and the 1485-nm pump power delivered to the far end was measured as a function the 1420-nm main and 1485-nm seed powers to determine the 1485-nm pump power that could be delivered over this length of the large A_{eff} fiber.

3. TRANSMISSION TESTS WITH THE 150-µm² A_{eff} FIBER

For the first series of experiments with the 150-µm² A_{eff} fiber, the fiber segment lengths and losses at 1550 nm are given in Table 1 below.

Fiber Segment	Length (km)	Loss at 1550 nm (dB)
A (150 µm²)	50.41	7.9
B (150 µm²)	99.88	15.6
115 µm²	193.96	30.2
C (150 µm²)	151.87	23.7

Table 1: Span Segment Lengths and Losses

The 1485-nm pump power applied to each pump input port of the Tx ROPA was 450 mW and the 1485-nm pump power delivered to the Rx ROPA was 8.4 mW with the 1420-nm main and 1485-nm seed powers of the 5-W ROPA pump set at 4550 and 50 mW, respectively.

The goal of this first set of experiments was to determine the maximum achievable reach for the transmission of 8x100G channels over an unrepeatered link of this 150-µm² A_{eff} fiber. The signal channel wavelengths (with a 100 GHz channel spacing) ranged from 1560.835 to 1566.493 nm. This wavelength range was chosen to take advantage of the lower Noise Figure (5.0 dB) of the Rx ROPA at longer wavelengths. The 8 channels were launched into the link with a composite signal power of 16.2 dBm and an approximately linear +1.7 dB pre-emphasis from the shortest to longest wavelength channel. The composite signal power at the output of the Tx ROPA was 27.5 dBm. The gain of the Rx ROPA varied in a straight-line fashion from 23 dB at 1560.835 nm to 20.5 dB at 1566.493 nm. With the VOA attenuation increased to the point where the total loss of the mid-span section (between the Tx and Rx ROPAs) was 61.1 dB and therefore the total link loss (at 1550 nm) was 92.7 dB, the Q of the received channels ranged from 4.637 to 4.687 dB, close to the Q threshold of 4.63 dB.

Given the typical attenuation of 0.150 dB/km (at 1550 nm) for the 150-µm^2 fiber, the 92.7 dB reach corresponds to a link length of 618 km.

4. TRANSMISSION TESTS WITH THE 125-µm^2 A_{eff} FIBER

For the second set of experiments, with the 125-µm^2 fiber, the fiber segment lengths and losses at 1550 nm are given in Table 2 for the 8x100G transmission tests.

Fiber Segment	Length (km)	Loss at 1550 nm (dB)
A (125 µm^2)	46.15	7.9
B (125 µm^2)	100.86	15.5
SSMF	80.0	15.9
C (125 µm^2)	151.79	23.4

Table 2: Span Segment Lengths and Losses

In this case, the 1485-nm pump power applied to each pump input port of the Tx ROPA was 389 mW and the 1485-nm pump power delivered to the Rx ROPA was 6.8 mW with the 1420-nm main and 1485-nm seed powers of the 5-W ROPA pump set at 3500 and 30 mW, respectively. The 8 channels were launched into the link with a composite signal power of 16.2 dBm and an approximately linear +1.0 dB pre-emphasis from the shortest to longest wavelength channel. The composite signal power at the output of the Tx ROPA was 26.95 dBm. The Noise Figure (NF) of the Rx ROPA was 5.1 dB and the gain varied in a straight-line fashion from 18 dB at 1560.835 nm to 16 dB at 1566.493 nm. With the VOA attenuation increased to the point where the total loss of the mid-span section (between the Tx and Rx ROPAs) was 59.5 dB and therefore the total link loss (at 1550 nm) was 90.8 dB, the Q of the received channels ranged from 4.64 to 4.73 dB (threshold Q = 4.63 dB).

Given the typical attenuation of 0.148 dB/km (at 1550 nm) for the 125-µm^2 fiber, the 90.8 dB reach corresponds to a link length of 614 km which is only marginally less than the maximum link length obtained with the 150-µm^2 fiber. For a similar transmission distance, the use of fiber with an A_{eff} of 125 µm^2 may be preferred due to better cabling experience and better tolerance to both macro and micro bends. Another advantage is density – the 150-µm^2 fiber used in this work has a coated diameter of 250 µm, while the coated diameter of the 125-µm^2 fiber is 242 µm (both uncolored). We also expect that a 125-µm^2 fiber can be manufactured in a 200-µm form factor (which is a desired feature in emerging SDM systems), while it is unlikely that the same form factor can be achieved for a 150-µm^2 fiber.

Attention then turned to transmission tests of 800G channels over this same fiber. Tests were conducted with channel counts ranging from 1 to 4. The fiber segment lengths and losses at 1550 nm are given in Table 3. When the channel count was increased beyond 2, the length of Segment A (and therefore the length of the dedicated Tx ROPA pump delivery fibers) had to be reduced to allow for a necessary increase in the 1485-nm pump power delivered to the Tx ROPA to increase its saturated output power in the face of the increased number of channels. For the 1 and 2 channel cases, the 1485-nm pump power delivered to each pump input port of the Tx ROPA was 27 mW while, for the 3 and 4 channel cases, it was 33 mW. The pump power delivered to the Rx ROPA was 6.4 mW with the 1420-nm main and 1485-nm seed powers of the 5-W ROPA pump set at 3100 and 50 mW, respectively.

Fiber Segment	Length (km)	Loss at 1550 nm (dB)
A (125 μm^2) 1-2x800G 3-4x800G	114.2 109.1	17.8 17.1
B (125 μm^2)	100.86	15.5
SSMF	80.0	15.9
C (125 μm^2)	151.79	23.4

Table 3: Span Segment Lengths and Losses

The channel wavelengths for each of the 800G channel count transmission tests are shown in Table 4.

No. of Channels	Channel Wavelengths (nm)
1	1564.73
2	1564.73, 1565.61
3	1564.73, 1565.61, 1566.48
4	1563.82, 1564.73, 1565.61, 1566.48

Table 4: 800G Channel Wavelengths

At these wavelengths, the gain of the Rx ROPA varied from 18.3 dB at 1563.82 nm to 17.3 dB at 1566.48 nm and the Noise Figure was 5.0 dB.
The composite launch powers of the 800G channels and the approximate tilt of the launch spectrum (with the longer wavelength channels launched at slightly higher power than the shorter ones) is given in Table 5.

No. of Channels	Composite Launch Power (dBm)	Approximate +ve Pre-emphasis (dB)
1	2.0	-
2	7.5	0.6
3	10.0	1.9
4	13.0	4.0

Table 5: nx800G Launch Powers

In each channel count case, the mid-span VOA attenuation was increased until the minimum Q of the received channels reached 5.65 dB, close to the Q threshold of 5.63 dB. Adding the resultant mid-span loss to the losses of Segments A and C gives the maximum reach values in dB and km shown in Table 6.

No. of 800G Channels	Maximum Reach (dB)	Maximum Reach (km)
1	78.1	528
2	77.2	522
3	75.5	510
4	74.8	505

Table 6: Maximum Reach for 800G Channels

5. CONCLUSIONS

We have demonstrated the unrepeatered transmission of 8x100G over a span loss of 92.7 dB which, to the best of our knowledge, constitutes a record span loss for this capacity. This result was achieved by combining the use of ultra-low-loss large A_{eff} fiber (150 μm^2), transmit and receive ROPAs with enhanced pumping and four dual-carrier coherent transponders with advanced modulation format and DSP. Switching to an ulta-low-loss fiber with a smaller A_{eff} (125 μm^2), we were able to demonstrate a reach of 90.8 dB and, given the lower loss/km for this latter fiber, 90.8 dB corresponds to a link length of 614 km which is comparable to the 618 km achieved with the 150-μm^2 A_{eff} fiber. Continuing with the 125-μm^2 fiber, we also demonstrated up to 4x800G over span losses corresponding to link lengths in excess of 500 km. This work suggests that a 125-μm^2 fiber may be preferred to a 150-μm^2 fiber given its comparable transmission performance but better cabling experience due to improved bend tolerance and lower outer diameter.

6. REFERENCES

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