COMPARISON OF C- AND L-BAND UNREPEATERED RAMAN ENHANCED TRANSMISSION SOLUTIONS WITH ADVANCED MODULATION FORMAT

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Abstract: In this paper, we present modeling and experimental comparison of C- and L-band unrepeatered system reaches (system margins) for equal capacities with co- and counter-Raman amplification. It is shown experimentally that by using 40 channels spaced by 100 GHz in the L-band it is possible to increase the link budget by ~ 2 dB compared to the same capacity in the C-band. The transmission experiments were carried out using standard C- and L-band EDFA boosters and pre-amplifiers as well as 3rd-order counter- and multiplexed laser diode co-pumps for distributed Raman amplification. An innovative proprietary subcarrier-based frequency-domain 8-dimension advanced modulation format, Frequency-Domain Matrix-Enhanced PSK (FD-ME-PSK), was also used for better nonlinear tolerance.

1. INTRODUCTION

Unrepeatered fiber links can provide cost-effective solutions for communication between two sites where it is not desirable, or may not be possible, to add in-line active elements. To extend reach or increase capacity, low-loss fiber, advanced coherent modulations and high-power Raman amplification can all play important roles to benefit unrepeatered transmission.

The C-band is the most common signal band used in fiber telecommunications. For the most part, the L-band has been looked at as a means of increasing overall capacity in an additive fashion by implementing C+L band transmission [1]. The advantage of L-band only transmission vs C-band has really only been promoted in connection with DWDM implementation over links consisting of dispersion shifted G.653 fiber. However, quite apart from dispersion considerations and in today's preferred fiber types, there are several theoretical advantages of placing the channels in the L-band (1570-1610 nm) instead of the C-band. These advantages are especially pronounced in situations where higher-order distributed Raman amplification is used [2,3]. Combined with advanced modulation formats which can better tolerate nonlinearities from transmission, the system performance can be significantly improved.

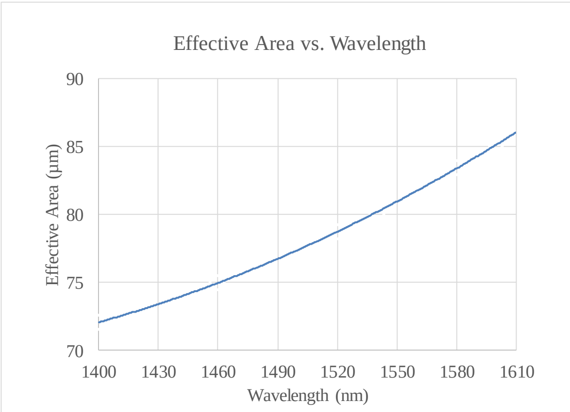

Figure 1: Effective area vs the wavelength of the typical telecom single mode fiber.

Several parameters of standard telecom fibers offer advantages in the L-band as compared to the C-band, such as the Mode Field Diameter (MFD) and average fiber loss. Since MFD, and therefore the effective area, in the fiber is larger in the L-band compared to the C-band, as shown in Figure ***1***, signals in the L-band can be launched at higher powers than C-band signals for equal nonlinear penalty.

Furthermore, the average loss in the L-band (1570-1610 nm) is lower compared to the average loss in the C-band (1530-1565 nm). For example, for a 300 km Corning ULL link, the average loss in the L-band is ~0.7 dB lower than in the C-band. The typical loss dependence is shown in Figure 2.

Additional advantages of L-band transmission become apparent when one considers the Raman interaction between transmitted signals which leads to power transfer from the short wavelength channels to the long wavelength channels.

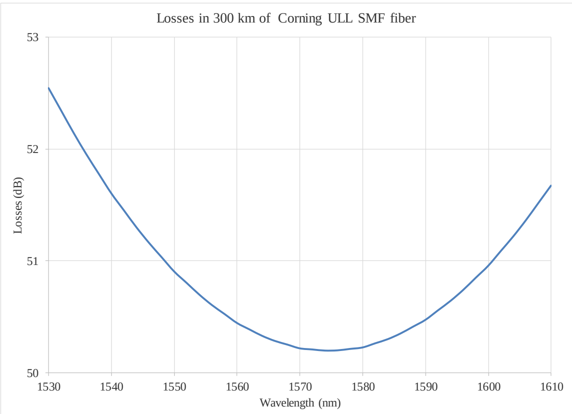

Figure 2: Losses of a 300 km link of Corning ULL SMF fiber

In the C-band, shorter wavelength channels have higher fiber losses and suffer from power transfer to the longer wavelength channels, while longer wavelengths experience smaller fiber losses. Having both the Raman power transfer and fiber loss acting in an additive manner to favor the long wavelength channels makes it more difficult to achieve equal transmission performance across the whole C-band. On the other hand, in the L-band, the two effects act to offset each other.

There is another significant advantage when applying distributed Raman amplification for signals in the L-band compared to the C-band case, both in co- and counter-pumping regimes. The optimal wavelengths for L-band Raman pumping are longer and thus the pumps suffer smaller fiber losses and penetrate farther into the link. As a result, in the counter pumping case, the incoming signals begin to be amplified "earlier" and, in the co-pumping case, the outgoing signals are amplified further out into the span.

A comparison of the modelled OSNR values for received C- and L-band signals with 3rd -order Raman counter pumping shows an OSNR advantage of ~2 dB for the L-band channels, see Figure 3.

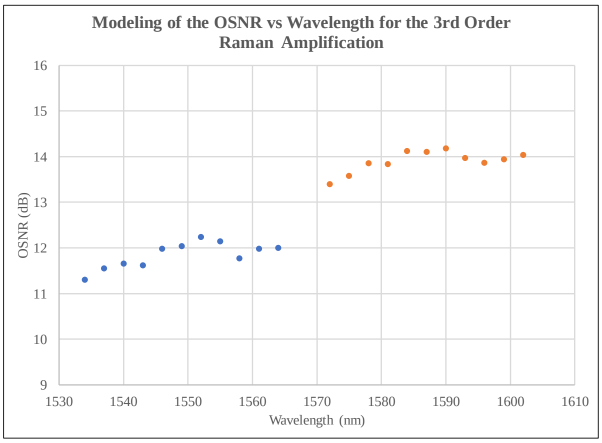

Figure 3: 3rd-order Raman counter pumping modeling – comparing C- and L-band OSNR in the 300 km PSCF link.

Figure 3 shows a comparison of counter-pumping Raman amplification of 11 channels in the C-band and 11 channels in the L-Band. The composite signal launch power into the 300 km span is 110 mW with pre-emphasis of 2.4 dB for the C-band and virtually no pre-emphasis for the L-band. A simulation of co-pumping amplification using a single pump at 1450 nm for a 1550 nm signal and one at 1485 nm for a signal at 1585 nm is illustrated in Figure 4. In both cases, the pump power is 600 mW and the launched signal power is adjusted to have equal Normalized Nonlinear Path Integrals $NI = \int P(z)dz/(\int P(z)dz)_{MAX}$.

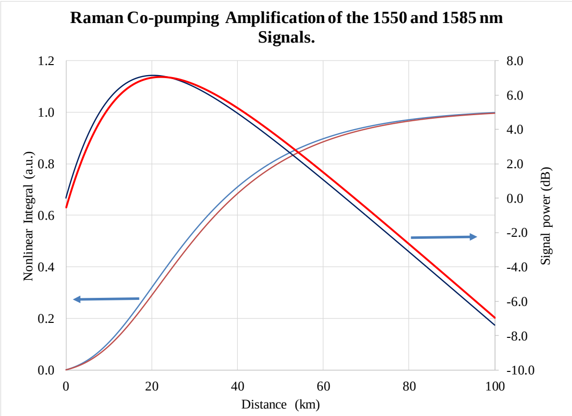

Figure 4: Comparison of co-pumping Raman amplification of single C-band (1550 nm) and L-band (1585 nm) signals by a single 600-mW pump at 1450 or 1485 nm, respectively.

The simulation shows that downstream of the amplification region the L-band signal power is 0.4 dB higher than that of the C-band signal. It should be noted that, in this simulation which is intended to show the L-band advantage arising solely from the lower fiber losses experienced by L-band pumps, the increased MFD for the L-band signal was not taken into account.

To extend the reach further, advanced modulation formats utilizing QPSK symbol set and multidimensional coding [4,5] have been used. In this study, Frequency-Domain Matrix-Enhanced PSK, an innovative frequency domain 8-dimensional modulation scheme with digital subcarrier multiplexing, has been applied. The FD-ME-PSK scheme ensures that the polarizations of adjacent subcarriers are orthogonal which significantly reduces the non-linear penalties due to cross phase modulation (XPM) and cross polarization modulation (XPolM) [6] and thereby improves the system performance.

2. EXPERIMENT SETUP

The experimental setup, which is similar for both C- and L-band tests, is illustrated in Figure 5. The representative unrepeatered link consisted of 310 km of Pure Silica Core Fiber (PSCF) in two sections, 115 km and 195 km. A VOA was placed between the two sections to vary the total link loss.

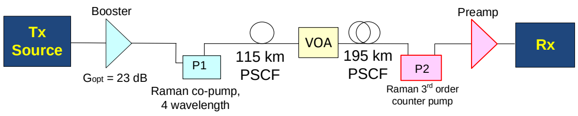

Figure 5: Experimental set-up. Booster: C-band or L-band EDFA with output power up to 30 dBm, P1: C-band or L-band co-directional Raman pump based on multiplexed laser diodes, VOA: variable optical attenuator, P2: counter directional third-order Raman pump, Preamp: C-band or L-band preamplifier

All losses in the fiber span were measured using a broad-band ASE source with an output spectrum spanning from 1525 to 1610 nm and calibrated at 1550 nm. A fiber loss measurement of the 310 km PSCF with a middle span VOA attenuation set to zero is shown in the Figure 6. In this fiber span the measured average loss in the L-band is about 0.4 dB lower than in the C-band.

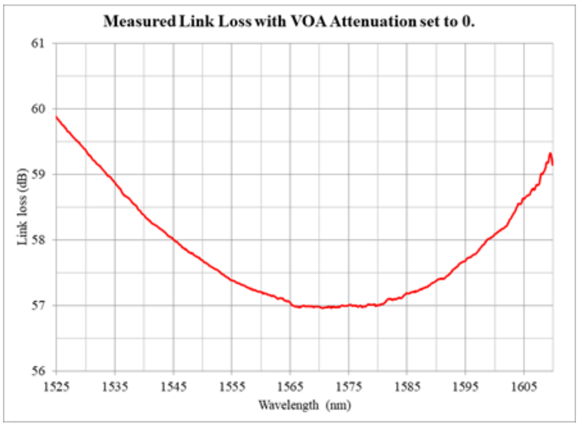

Figure 6: Measured losses in the 310 km of the PSCF used in the experiments when middle-stage VOA was set to 0.

The transmitter source is illustrated in Figure *7*. A bank of lasers provide the 40, 100-GHz spaced channels in either C- or L- band in order to compare cross-band performance. In the C-band, the channel wavelengths extend from 1534.25 to 1565.5 nm (191.5 to 195.4 THz) while in the L-band the channel plan covers 1571.24 to 1604.03 nm (186.9 to 190.8 THz). The 40 channels are combined in a polarization-maintaining multiplexer and then routed to a dual-polarization 32 GHz IQ modulator, with a linear driver driven by a high-speed digital-to-analog convertor (DAC), where the dual 50 Gb/s FD-ME-BPSK signals plus overhead are applied. The signals are then amplified to compensate for the modulator insertion losses and pass through a C- or L-band wavelength selective switch (WSS) where the proper filtering and pre-emphasis are applied to optimize performance. Following the WSS, an additional optical amplifier is used to provide a suitable input power level for the main booster amplifier. Both C- and L-band booster amplifiers are gain-flattened EDFAs with adjustable gain tilt for pre-emphasis and a composite output power up to 30 dBm. The co-pump consists of multiplexed laser diodes providing a maximum total output of 2 W with the diode wavelengths between 1400 and 1454 nm for the C-band unit and between 1400 and 1485 nm for the L-band case.

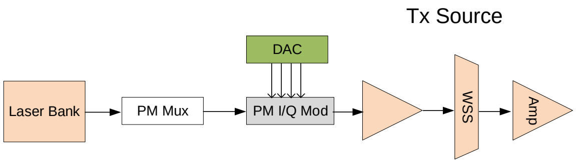

Figure 7: Transmitter source details

At the receiving end, both C- and L-band counter pumps are third-order Raman pumps with a primary output power up to 4 W (sufficient to provide an ON/OFF Raman gain of >28 dB in PSCF). The amplification bands of the third-order Raman pumps are 1530 – 1568 nm for the C-Band unit and 1570 -1610 nm for the L-band unit. The signals then pass through a pre-amp and on to the receiver. In the receiver, as shown in Figure 8, a C- or L-band WSS is used to select channels for testing with the coherent receiver which consists of a typical coherent mixer with a tunable local oscillator and four balanced detectors. The resulting electrical waveforms were digitized by a 100 Gsample/s real-time scope with a 23 GHz bandwidth for off-line signal processing.

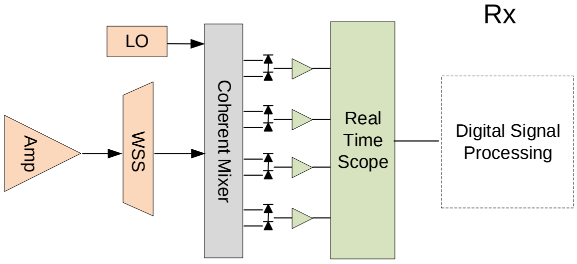

Figure 8: Receiver details

3. EXPERIMENT RESULTS

Two configurations, with co-pumps and without co-pumps, are tested in both C- and L-bands. The testing procedure for both bands are similar. First, optimal counter pumping conditions providing an average On/Off gain of 27 dB with a gain ripple of +/- 0.5 dB are established. It is found that the required primary pump power [2] for the optimal gain is 2.8 W for the C-band and 3.8 W for the L-band. Next, the signal power and pre-emphasis are optimized for the longest reach. Then, the Qs are measured for different link losses without Raman co-pumping. Finally, the optimal pre-emphasis, as well as total signal power and Raman co-pump settings are established while keeping the Raman counter pump settings constant.

For the C-band, the transmit and receive spectra, with both co- and counter Raman pumps, are shown in Figure 9.

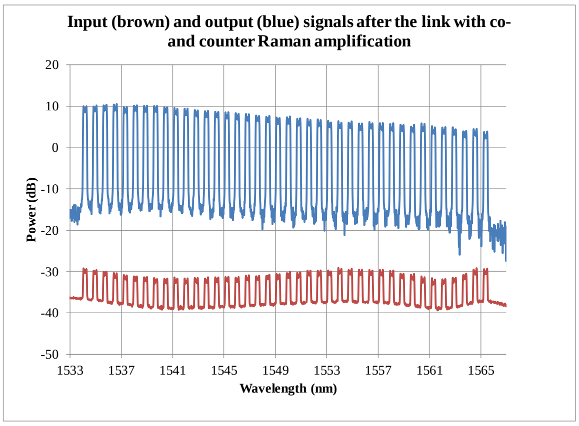

Figure 9: Spectrum of signals at input and output of the C-band link

It is observed that with a Raman co-pumping power of 1.8 W, the optimal composite signal launch power is 16 dBm. When the co-pumping is not used, it is found that optimal composite signal launch power is 23.5 dBm.

For the L-band, the transmit and receive spectra, with both co- and counter Raman pumps, are shown in Figure 10. It is observed that with the optimal co-pump power of 1.5 W, the optimal composite signal launch power is 20 dBm. When the co-pumping is not used, it is found that the optimal composite signal launch power was 25.5 dBm, 2 dB higher than in the corresponding C-band case because of bigger MFD and lower nonlinear interactions in the L-band.

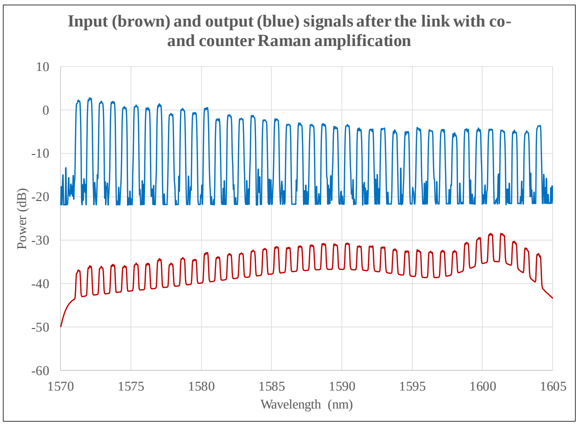

Figure 10: Spectrum of signals at input and output of the L-band link

Figure 11 provides a comparison of the Q margin measurement results for the C- and L-band signals with only Raman counter-pumping. The average margin in the C- band is 2.9 dB for a link attenuation of 63.6 dB and, in the L-band, the average margin is 3 dB for a link attenuation of 65.6 dB. Assuming the ratio of link budget to Q margin is close to 1, the results indicate a link budget in the L-band that is ~2.1 dB higher than in the C-band.

Figure 12 shows a comparison of the C- and L-band signal transmission results when both co- and counter pumping were present. The average Q margin in the C-band is 2.2 dB for a link attenuation of 68.6 dB and, in the L-band, the average margin is 2.8 dB for a link attenuation of 69.6 dB. With similar assumption of ratio between link budget and Q margin, the link budget in the L-band is ~1.6 dB higher than in the C-band.

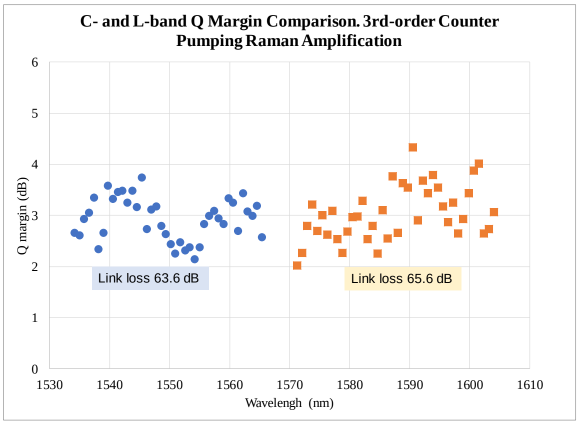

Figure 11: Measured Q margin values for the optimal counter Raman pumping conditions.

It is important to note that by comparing data in Figure 11 and Figure 12, it can also be seen that optimal co-pumping provides a budget increase of ~ 4 to 5 dB.

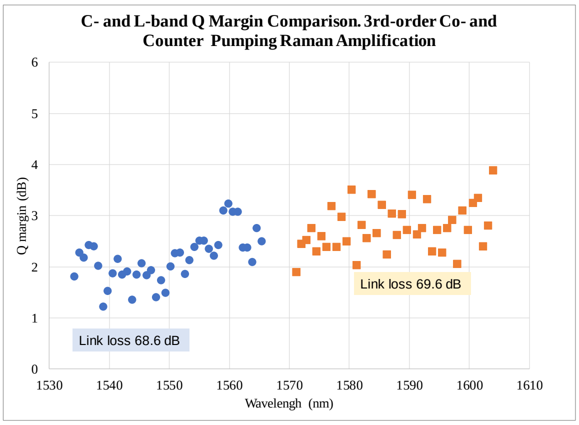

Figure 12: Measured Q values for the optimal co- and counter pumping conditions.

4. CONCLUSION

We demonstrate that using L-band in repeaterless spans offers substantial improvements in system reach (system margin) versus using C-band. Both modeling and experimental comparison of C- and L-band unrepeatered system reaches (system margins) for equal capacities with co- and counter Raman amplification using subcarrier-based FD-ME-PSK are shown. Using 40 channels with 100 GHz spacing in the L-band it is possible to increase the link budget by ~ 2 dB compared to the same capacity in the C-band. The transmission experiments are carried out using standard C- and L- band EDFA boosters and pre-amplifiers as well as 3rd-order counter- and multiplexed laser diode co-pumps for distributed Raman amplification

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