Raman Amplification for Ultra-Large Bandwidth and Ultra-High Bit Rate Submarine and Terrestrial Long-Haul WDM Transmission

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Abstract: At a time when Raman amplification is recognized as a key enabler for high-capacity optical networking, this paper reviews recent capacity and reach advances for terrestrial and submarine long-haul optical communications.
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1. Introduction

Insatiable capacity growth and lower cost per transported bit are part of the main challenges any long-haul optical transmission infrastructure needs to cope with. The advent at the beginning of this decade of 100G channel rate, with PM-QPSK modulation format associated with digital coherent detection [1], offered a 10-fold capacity increase compared to networks based on 10G waves. As 100G volume production starts, the cost per long-haul 10G equivalent is becoming lower with 100G waves than 10G waves. Although 100G technology is quite young (for the sake of comparison, 10G technology is about 17-year old and will still be here within the next several years for a lifetime likely to get up to 20-25 years), some players of the optical telecommunication industry are already pushing for higher channel rates that raise new challenges from an optical transmission perspective. Higher channel rate and spectral density inherently require higher OSNR which is the ultimate limit for ultra-long-haul transmission.

EDFA amplification technology limits the [Capacity x Reach] performance in three ways: i) the optical spectrum is limited to a maximum of 38 nm which means that packing more carriers leads to narrower spacing and stronger inter-carrier optical impairments, ii) EDFA noise performance is not optimal, resulting in a significant noise accumulation and OSNR degradation along long optical paths, and iii) EDFAs represent hot spots, boosting the signals power periodically along the optical links and resulting in a power profile that is conducive to nonlinearities within the line fiber. Typical transmission distances with EDFA in field conditions, not in laboratory environments using ultra-low loss and ultra-large core fiber, are 2,000 km for 100G channels and 600 km for 400G channels.

2. Raman Amplification for Terrestrial Networks

Raman amplification is an effective answer to remove these three key limitations. First, Raman amplifiers offer broader spectrum than EDFAs. Raman amplifiers with 100 nm bandwidth were deployed in commercial networks as soon as 2004 [2]. Second, superior noise performance of Raman amplifiers leads to higher OSNR performance than in EDFA-based networks. Lastly, distributed Raman amplification within the line fiber results in a lower peak-to-peak power excursion along the optical path, reducing the amount of nonlinearities. The two dimensions of Raman amplification benefits (longer reach in the longitudinal dimension, broader spectrum in the transversal dimension) were demonstrated in recent field trials using commercial all-distributed Raman transmission equipment.

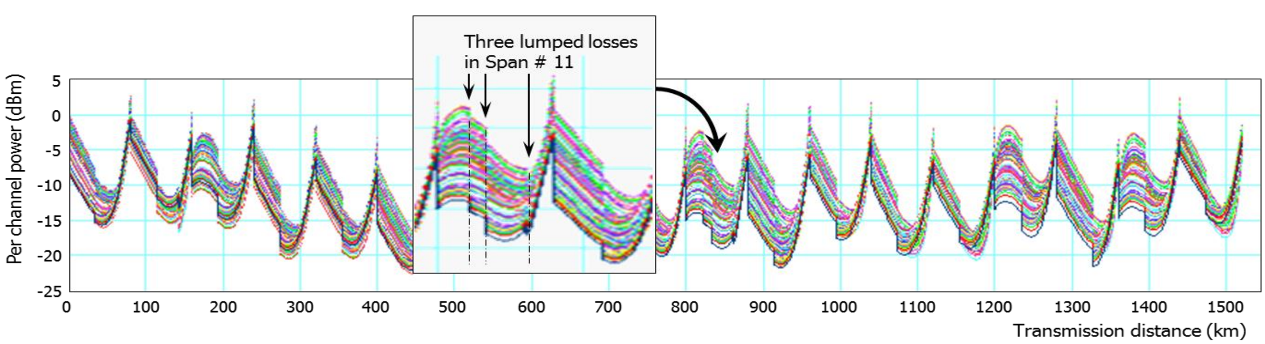

Fig. 1. Simulated per channel power profiles for a 150 x 100G transmission on 1,504 km.

Fig. 1 shows the simulated per channel power profiles for 150 x 100G waves along a 1,504 km, 19-span link with an average attenuation of 0.275 dB/km [3]. The zoomed window shows details of signal power profiles within Span # 11 where the three power step decreases are caused by lumped losses (up to 1.9 dB) present in this span. In addition to achieve 15 Tbit/s line capacity over a 1,504 km fiber plant with a Q factor margin of 5 dB, this field trial demonstrates that properly-designed Raman amplifiers can be deployed in presence of lossy fibers, numerous optical connectors (114 in this field trial) and lumped losses.

The results show that all-distributed Raman systems can provide wide spectrum (61 nm here, accommodating 150 wavelengths at 100G each, spaced 50 GHz apart) over long reach with excellent transmission performance even over a non-ideal fiber plant in field conditions. Given the linear nature of the optical propagation (enabled by Raman distributed amplification), the high Q factor margin demonstrates that 150 x 100G channels can be transmitted on up to 4,500 km in real network environment.

While 100G PM-QPSK has become the standard long-haul transmission modulation format for backbone applications, PM-16QAM modulation format (used to build 400G or 1T channels by the combination of multiple 200G PM-16QAM carriers) has been considered so far only for practical metro and regional networks because of the much higher OSNR requirement and larger sensitivity to fiber nonlinearities for 16QAM signals compared with QPSK signals. The transmission distance of one of the latest reported terrestrial field trial of PM-16QAM with an EDFA-based commercial system is 412 km, which covers only regional distances [4]. Combining an all-distributed Raman amplification system and high coding gain FEC, 400G channels with dual PM-16QAM carrier implementation were transmitted with margin over the same aged 1,504 km fiber plant as described above [5]. This field trial demonstrates that 200G/400G/1T channels built with 16QAM modulation format can be transmitted on more than 2,000 km using Raman amplifiers in real network environment.

3. Raman Amplification for Unrepeatered Link

Raman amplification is an effective technology to bridge long spans in single- (e.g. in subsea networks) or multi-span (in terrestrial networks) links. For the sake of simplicity, recent single-span 100G transmission results are reported here, exploring the two dimensions (capacity and reach) offered by Raman amplifiers.

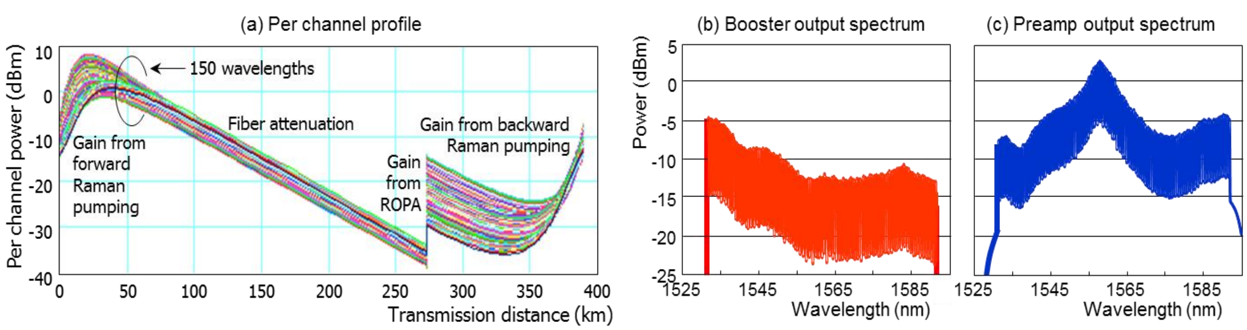

Fig. 2. Simulated per channel power profiles for a 150 x 100G unrepeatered transmission on 390 km (a), 150 channel optical spectrum at the output of the booster amplifier (b), and 50 channel optical spectrum at the input of the preamplifier (b).

As illustrated in Fig. 2, an ultra-high capacity of 15 Tbit/s was demonstrated on 390 km of Corning's SMF-28® ULL optical fiber. The 64.3 dB link attenuation was bridged with the help of a Remote Optically Pumped Amplifier (ROPA) [6]. Reach wise, a record unrepeatered 100G transmission distance of 557 km was bridged using Corning's Vascade EX2000 fiber (with a total attenuation of 90.2 dB) and an innovative ROPA configuration based on residual pump sharing between forward and backward ROPAs [7].

4. Raman Amplification for Submarine Networks

At a time when international traffic shifts from point-to-point connectivity between cable landing stations to meshed datacenter-to-datacenter patterns, it is of the upmost importance that no capacity bottleneck is found between terrestrial and submarine networks and prevents unified network designs.

As far as new builds of submarine cable systems are concerned, no significant technology progress had been made for at least 10 years at the wet plant level. To unleash the potential of new terminal technologies and access the wide spectrum offered by silica line fiber, one had to significantly improve the wet plant in order to enable more sophisticated transmission technologies (like 16QAM format) and offer higher capacity per fiber pair.

The major innovation in the wet plant in the past years is the introduction of Raman amplification under water [8]. Similarly to the terrestrial market segment, the key differentiators offered by using Raman amplification in a subsea repeater include i) creating distributed optical gain along the line fiber, thus mitigating fiber nonlinearities and attaining a noise figure that is inherently lower than that of a traditional EDFA repeater ii) building optical gain outside the fixed window provided by classical EDFA amplifiers, and iii) enabling a dynamic gain spectral shaping and gain tilt equalization. The first differentiator opens the gate to increasing the inter-repeater spans for some specific low-capacity applications, while the second one can widen the useable optical spectrum in high-capacity systems.

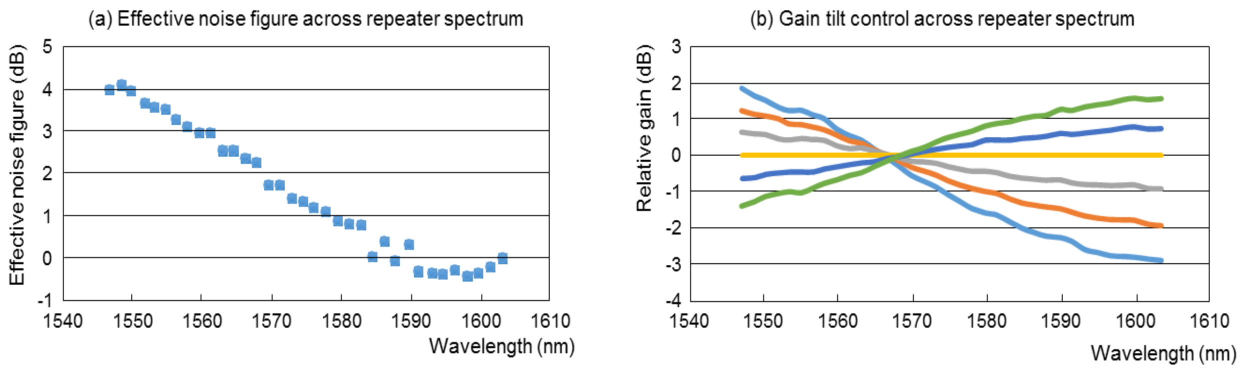

Fig. 3. Effective noise figure (a), and gain tilt control (b) across the spectrum of a Raman-based repeater.

Fig. 3a illustrates the outstanding noise performance of a Raman-based subsea repeater across an optical spectrum exceeding 50 nm. Fig. 3b represents another key benefit offered by Raman amplification: the dynamic control of the gain tilt, avoiding the need for submerged gain equalizers.

5. Conclusion

With 100 nm amplifiers in commercial operation since 2004 and validation of long-haul transport capabilities for 16QAM signals over aged, lossy fiber plants, Raman technology is today a key enabling technology to respond to the sustained need for higher capacity in terrestrial backbone networks. More recently, Raman-based optical repeaters have been developed to bring these capacity benefits under water and facilitate PoP-to-PoP or datacenter-to-datacenter connectivity with no capacity bottleneck between the dry and wet parts of the long-haul optical transmission infrastructure. Raman amplification can offer further broader spectrum with the opening of new spectral windows, like the S band [9]. In the midterm, expansion of the optical spectrum to tap into more of the optical fiber reservoir – as enabled by Raman amplification – is challenging the recent views on Space Division Multiplexing (SDM) and is an evolutionary, safe and efficient solution to meet both short- and midterm capacity needs in backbone networks with no need to deploy a new type of fiber.

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