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OPTICAL AMPLIFIERS THAT BUILD BETTER NETWORKS

White Paper

Applications for Distributed Raman Amplification

1 Introduction

Distributed Raman amplification (DRA) has emerged in recent years as a key technology for modern optical networks. Recognizing this, RED-C Optical Networks has invested significant resources in developing and producing a state-of-the-art Raman amplifier with unique features designed to facilitate the adoption of this technology.

However, as with any new technology, it is important to understand the applications which can benefit from it, as well as various issues related to the real-world deployment of the technology. In this white paper we focus on these questions, beginning with a brief introduction to DRA, followed by a detailed discussion on applications, and finishing with deployment issues and how RED-C Raman amplifiers can address these issues.

2 Background

2.1 Raman Amplification

Raman scattering was first discovered by Sir Chandrasekhara Raman in 1928, and describes a process whereby light photons are scattered from matter molecules to a higher wavelength (lower energy). The light photon excites the matter molecules to a high (virtual) energy state, which then relaxes back to the ground state by emitting another photon as well as vibrational (i.e. acoustic) energy. Due to the vibrational energy, the emitted photon has less energy than the incident photon, and therefore a higher wavelength.

Stimulated Raman scattering describes a similar process whereby a higher wavelength photon stimulates the scattering process, i.e. the absorption of the initial photon, resulting in the emission of a second higher wavelength photon, thus providing amplification. This is shown in Figure 1 for silica fibers, where a ~1550nm signal is amplified through absorption of pump energy at ~1450nm.

Unlike Erbium Doped Fiber Amplifiers (EDFA’s), where the gain spectrum is constant and determined by the Erbium atoms, the Raman amplification gain spectrum depends on the pump wavelength, with maximum gain occurring about 100nm higher than the pump wavelength. This is shown on the right side of Figure 1.

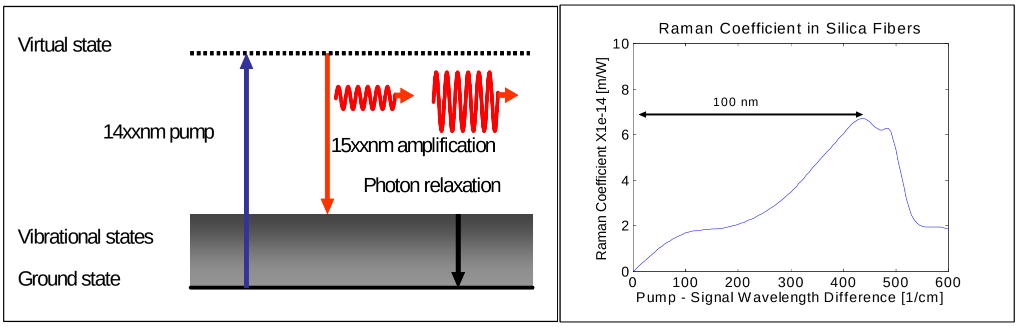

Figure 1: Left – Stimulated Raman Scattering / Right – Raman gain spectrum for Silica fibers

2.2 Distributed Vs. Lumped Amplification

Traditional EDFA's are classified as lumped amplifiers, meaning that amplification occurs in the Erbium Doped Fiber (EDF) located within the closed amplification module. These modules are placed after every ~80km span of the transmission line, so that the transmission signal which is attenuated along the span is amplified back to the required power level at the discrete amplification site at the end of each span. This is shown by the green curve in Figure 2.

While EDFA's need a special EDF to provide amplification, Raman amplification can occur in any fiber, and in particular the transmission fiber itself. This enable Distributed Raman Amplification (DRA), i.e. the process whereby the transmission fiber itself is pumped to provide amplification for the signal propagating along the fiber. The blue curve in Figure 2 shows signal evolution for distributed Raman amplification in counter-propagating ("Backward") configuration, where the Raman pump power is introduced at the end of each span, and propagates counter to the signal. Since gain occurs along the transmission fiber, DRA prevents the signal from being attenuated to very low powers where noise is significant, thus improving the Optical Signal to Noise Ratio (OSNR) of the transmitted signal.

The fact that the net signal attenuation is reduced can also be utilized to launch the signal with less power, which is important when signal non-linearities are an issue. DRA can also be used in co-propagating ("Forward") configuration, where the Raman pump power is introduced at span input and propagates with the signal. This is generally less common than backward pumping, and will not be covered here.

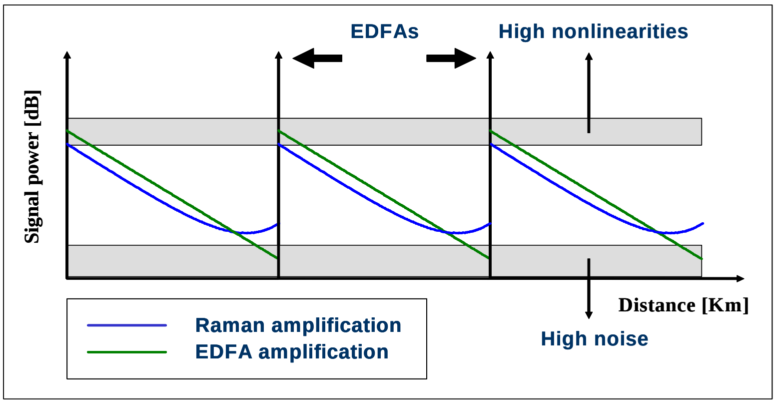

Figure 2: Distributed Vs. Lumped amplification

2.3 Tailoring the Gain Spectrum

As mentioned earlier, the shape of the Raman gain spectrum depends on the pump wavelength, with the maximum gain occurring approximately 100nm higher than the pump wavelength. This unique feature of Raman amplification enables amplification in any wavelength band, just by using the appropriate pump wavelengths. Furthermore, multiple pumps with different wavelengths can achieve flat broadband gain over a large spectral region, as shown in Figure 3.

Besides flat broadband gain, multiple pump wavelengths also help to reduce the Polarization Dependent Gain (PDG) which can be significant when a single pump is used. The PDG can be further reduced by using two pumps with the same wavelength but orthogonal polarization.

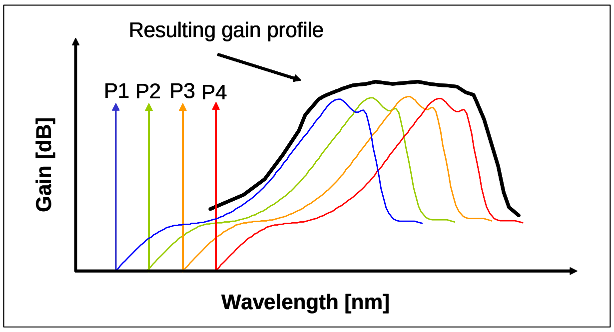

Figure 3: The use of multiple pump wavelengths to achieve flat broadband gain

2.4 Raman Pump Modules for DRA

DRA is implemented using Raman pump modules, as shown in Figure 4 for the counter propagating backward configuration. In this configuration DRA is most often used in conjunction with conventional EDFA amplifiers, with the Raman pump module serving as a pre-amplifier to the EDFA. This is known as hybrid Raman/EDFA amplification.

RED-C Raman amplifiers contain either two or three pump laser diodes. In the two pump model the pumps have different wavelengths chosen for optimized flat gain over the transmission band, providing a maximum combined output power of 490mW, and a typical gain of ~10dB for G652 (SMF) transmission fiber. In the three pump model two of the pumps have the same wavelength but different polarization, thus reducing PDG. This model provides a maximum output power of 690 mW, with a typical gain of ~15dB for G.652 fiber.

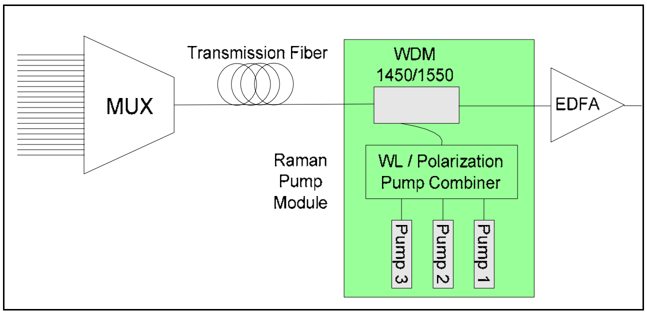

Figure 4: A simplified block diagram of the RED-C Raman amplifier deployed in backward pumping configuration

Figure 5 shows spectral gain and equivalent Noise Figure (NF) for backward DRA using a three pump Raman module (two polarization multiplexed pumps with one wavelength, and another pump with a second wavelength). The figure shows a gain flatness of ~1dB peak to peak over the C-Band for 14 dB gain.

As discussed above, one major advantage of DRA is that it improves the OSNR of the signal. In order to quantify this one can define an equivalent Noise Figure (NF) for DRA, in analogy to the NF commonly used to quantify the noise performance of EDFAs. The data of Figure 5 shows a negative NF for distributed Raman amplifiers as compared to typical NF values of 5-6dB for EDFAs with comparable gain, illustrating the improved noise performance due to DRA.

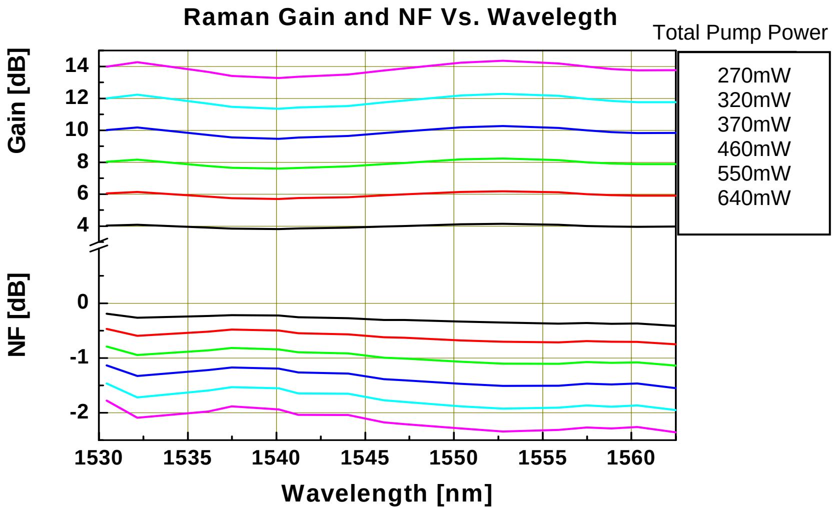

Figure 5: Gain and NF as a function of wavelength for different Raman pump powers

3 Applications

Erbium Doped Fiber Amplifiers (EDFAs) have been deployed in optical networks for over a decade, and are based on mature, robust and cost effective technology. While DRA can complement EDFA's in many applications, various deployment challenges need to be considered:

- Laser safety, due to the introduction of high pump power into the transmission line.
- The need for clean connectors along the transmission line to avoid connector damage
- The sensitivity of Raman gain to the transmission fiber characteristics, as well as to various loss points along the transmission line
- The additional CapEx and OpEx associated with the deployment.

Thus, it's critical to identify those applications where DRA provides significant advantage, as opposed to other applications where EDFA's are sufficient. Broadly speaking, these applications can be classified as follows:

- Enabling remote long distance links (typically >160km) where intermediate amplification station are impractical (e.g. between islands)
- Enabling transmission over longer spans or spans with high loss in regional, long haul (LH) and Ultra-Long Haul (ULH) systems
- Enabling higher capacity or longer distance transmission in ULH systems

3.1 Long Distance Single Span Links

Often it's necessary to provision an optical communication link connecting two remote locations between which it's difficult or impractical to deploy conventional amplification sites. Examples are:

- Undersea links between islands, remote coastal locations, oil rigs, etc. (so called “island hopping”)
- Locations separated by mountain ranges or desert, or other large unpopulated areas
- Applications where commercial, legal, or security constraints render amplification sites between terminal equipment impractical.

If the link is shorter than about 160km, then it can be handled using conventional EDFA technology at the terminal sites. However, longer links require the use of DRA.

To illustrate this Figure 6 shows the calculated OSNR as a function of link loss for different Raman gains. The launch power is taken as +8dBm per channel, and an EDFA pre-amplifier with NF of 5dB is assumed at the end of the link. Since the system is assumed to be low capacity (relatively few DWDM channels), no penalty for dispersion or non-linear effects is accounted for. The figure shows that using DRA with 10dB Raman gain, an extra link loss of ~5dB, corresponding to ~25km fiber, can be tolerated for the same OSNR. DRA with 14dB Raman gain allows up to ~6.3dB extra link loss. Using Forward Error Correction (FEC) and assuming 10Gb/s channels, error free transmission can be achieved over link losses of about 52 dB, or up to ~250km of fiber.

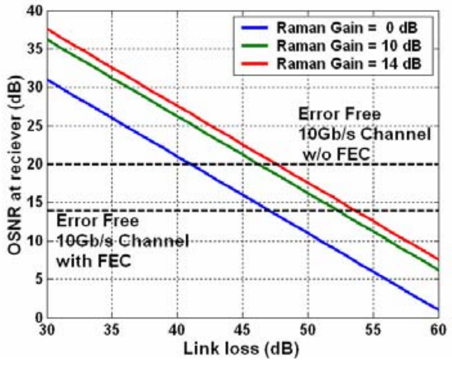

Figure 6: OSNR as a function of link loss for different Raman gains (assumptions: launch power = +8dBm, EDFA NF = 5dB)

3.2 Long Spans within Multi-Span Links

Another important application for DRA is Multi-Span links where one or more of the spans are longer (or have higher loss) than the others. In this respect, it is estimated that about 20% of the spans in regional, LH, and ULH systems can benefit from DRA. In order to illustrate this benefit, consider a ten span system, of which two spans are longer than the others and require DRA. We assume that the normal span loss is about 20dB, and that variable gain EDFA's with NF of 6dB are used throughout the system. Also, since LH and ULH system typically have high capacity, we assume launch power per channel is limited to +3dBm, and that there is a 5dB OSNR penalty resulting from dispersion, non-linear effects, gain flatness, aging, and other issues.

Figure 7 shows the OSNR at the end of the ten span link, as a function of the loss of the longer spans. The figure shows that using DRA provides an extra 2dB of OSNR at high span loss (~40dB), thus allowing error free transmission using FEC for this particular application. Besides improving OSNR, DRA also allows the use of standard unmodified in-line EDFA's for the long spans. Using the assumptions above, a typically variable gain EDFA would have a dynamic gain range of, for example, 14-26 dB. Thus, using a 14dB Raman amplifier enables the EDFA to be operated at 26dB, within the dynamic gain range, providing a total of 40dB gain for the long spans.

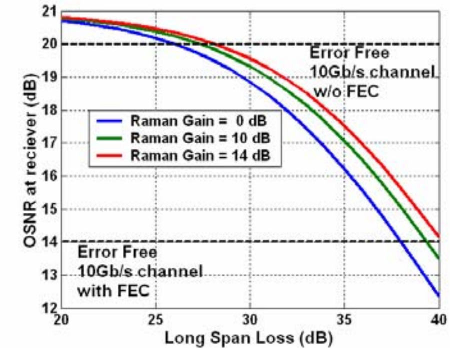

Figure 7: OSNR as a function of the long span loss, with and without DRA

3.3 High Capacity Long Distance ULH Systems

While only a few ULH (>1000km) systems have been deployed in recent years due to the burst of the telecom bubble, there are strong indications that this market segment is recovering, and is expected to contribute a significant portion of DWDM revenues in the coming years. The major driver behind the renewed interest in ULH systems is the migration to dynamic reconfigurable all-optical networks, where the use of Reconfigurable Optical Add Drop Modules (ROADMs) and Optical Cross Connects (OXCs) mean that all channel should be able to traverse long distances over the network. Figure 8a shows the calculated OSNR as a function of the number of spans in the system with and without DRA. The launch power per channel is assumed to be +3dBm, and the span loss 18dB, corresponding to the typical ~80km spans of ULH systems. The EDFA's are assumed to be optimized for ULH systems, with NF of 5dB, and mid-stage access for ROADMs, OXCs, DCMs, etc. Furthermore, an overall OSNR penalty of 10dB resulting from gain flatness, dispersion, non-linearity, aging, and other issues is assumed.

The figure shows that DRA significantly increases the reach of ULH system, allowing for systems of 4000km (=~50 spans) and longer. The improved OSNR provided by DRA (5-7 dB) can also be used to increase system capacity by increasing the number of channels. For example, increasing the channel count from 40 to 80 channels within the C-Band typically required decreasing the launch power per channel by at least 3 dB. Using DRA, this can easily be achieved due to the improved OSNR.

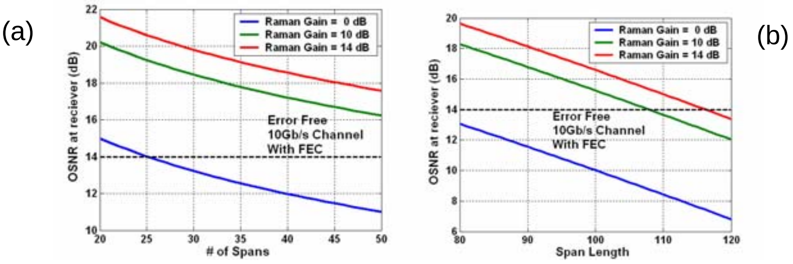

Figure 8: (a) OSNR as a function of # of spans in ULH systems, with and without DRA.
(b) OSNR as a function of span length for a 2500km ULH system, with and without DRA

The above results show how DRA can increase the reach or capacity of ULH systems. However, the improved OSNR provided by DRA can also be used to reduce system costs by increasing the span length, and thus reducing the total number of amplification sites. Figure 8b shows the calculated OSNR as a function of span length for a 2500km system. The same assumptions as before were used, and the span loss was calculated on a basis of 0.2dB/km fiber, with an additional 2dB overhead per span.

The results show that DRA allows an increase of up to 50% in span length, corresponding to a reduction of up to 35% in the number of spans. Note however that the OSNR deteriorates rapidly with span length, even with the aid of relatively high gain DRA. Thus, for LH and ULH systems, we believe that the maximum practical span length is in the range of 100-120 km.

4 Deployment Issues

The applications described above show that DRA can provide significant benefit to some classes of optical networks. However, as already mentioned, there are many technical issues related to the actual deployment of DRA that need to be addressed before these benefits can be realized. RED-C Raman amplifiers include unique and powerful features designed to address these issues.

4.1 Laser Safety

Laser safety is a key issue in optical transmission systems, which are typically required to comply with class 1M hazard requirements according to IEC standard 60825 part 2. This means that in the case of an accidental connector opening or a fiber break, all lasers and transmitters along the system are required to reduce power to a safe level, in many cases within 1s of the occurrence of the hazardous event. Additional information on laser safety in system deploying DRA can be found in ITU-T standard G.664.

Systems deploying DRA differ from conventional EDFA systems in two critical respects: (1) The output power of Raman pump modules is much higher than typical power levels in EDFA based systems, and in all cases is well above the designated safe level of radiation; (2) DRA generate Amplified Spontaneous Emission (ASE) along the transmission line. This means that even in the case of a fiber break, ASE power within the C-Band can still propagate along the system. This disrupts the conventional shut-down method based on Loss of Input Signal, which is commonly used to shut down EDFA’s in a system.

In order to address this issue, RED-C Raman amplifiers support additional independent mechanisms for detecting a fiber break or open connector, allowing automatic shut-down of the Raman pump module. These include detection of an optical supervisory channel signal, detection of pump back-reflection energy, and detection of ASE outside the transmission band.

These mechanisms can also provide important diagnostic information and alarms regarding the integrity of the transmission line, and the efficiency of the Raman amplification.

4.2 Dependence of Raman Gain on the Transmission Fiber

The achievable Raman gain for a given pump power, as well as the shape of the gain spectrum, depend on the type of transmission fiber. Thus, to achieve a desired flat gain for any type of transmission fiber, one needs to be able to control the output power of each individual pump laser diode within the Raman pump module. RED-C Raman amplifiers contain pre-set information regarding the required pump powers for any given transmission fiber type and gain setting.

However, even if the type of transmission fiber is known, the achievable Raman gain can still vary from one fiber spool to another due to small manufacturing variations (e.g. in the fiber mode field diameter). This can significantly complicate system planning before deployment, since the maximum achievable Raman gain is not accurately known. To overcome this problem RED-C Raman amplifiers allow off-line measurement of the Raman gain before actual system deployment. This is achieved by measuring the level of ASE generated by the Raman pump energy, and using this measurement to estimate the achievable signal gain of the transmission fiber.

4.3 Network Integration

As with any new technology, integrating DRA into existing system architectures can be a time consuming and costly task. To address this RED-C has developed the Network Interfaced Raman (NIR) unit, which includes the Raman module within a ready to install 1RU Pizza-Box configuration. This fully qualified unit supports SNMP and TL1 communications via a standard Ethernet connection, allowing the NIR to be configured and managed as a separate Network Element (NE). In addition, the NIR includes a simple and intuitive GUI which can be installed on any computer connected via a LAN or WAN to the NIR.

5 Summary

The use of DRA significantly increases the design options for optical networks, often enabling applications which are not feasible or practical with conventional EDFA technology. Such applications include very long single span links, long spans within multiple span links, and increasing the distance and/or capacity of ultra-long haul systems.

However, the added operational complexity associated with DRA, as well as the addition CapEx, means that it is important to identify those applications where DRA really provides a significant advantage. For these cases RED-C Raman amplifiers provide unique and powerful features that facilitate the deployment of this important technology.

6 Further Reading

1. “Nonlinear Fiber Optics”, G. Agrawal, Academic Press
2. “Raman Amplifiers for Telecommunications”, Edited by M.N. Islam, Springer series in optical sciences.
3. “Safety of laser products – part 2 – Safety of optical fiber transmission systems”, IEC International Standard 60825-2
4. “Optical safety procedures and requirements for optical transport systems” ITU-T International Standard G.664
5. “Raman amplification yields system gains”, Lightwave, December 2004, P. 20.