White Paper

Applications for Distributed Raman Amplification

Updated November 2012

1 Introduction

Distributed Raman amplification (DRA) has emerged in recent years as a key technology for modern optical networks, and especially for coherent transmission. Recognizing this, Finisar has invested significant resources in developing and producing state-of-the-art Raman amplifiers and Hybrid Raman-EDFAs with unique features designed to facilitate the adoption of this technology.

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 Finisar Raman and hybrid amplifiers can address these issues.

2 Background

2.1 Raman Amplification

Raman scattering was first discovered by Sir Chandrasekhar 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 (EDFAs), 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.

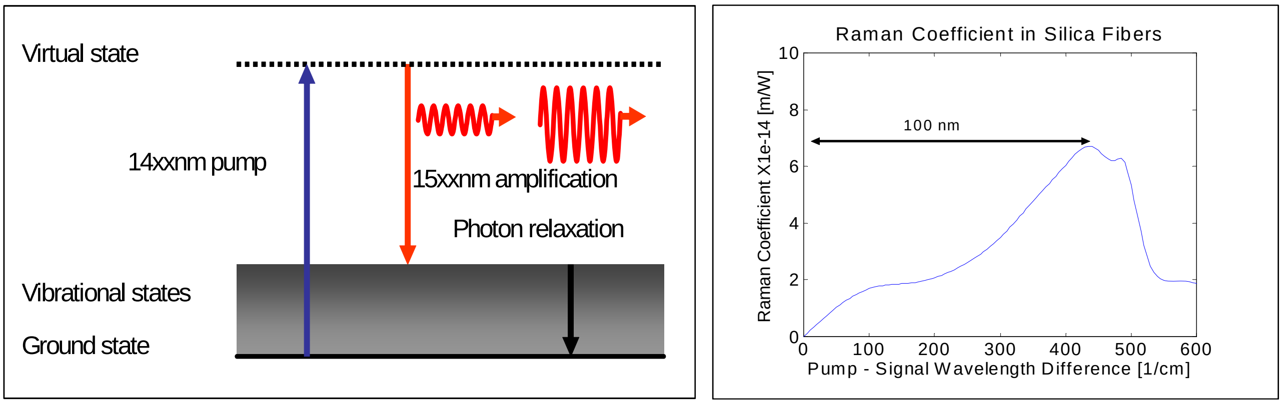

Figure 1: Left – Stimulated Raman scattering / Right – Raman gain spectrum for Silica fibers

2.2 Distributed Vs. Lumped Amplification

Traditional EDFAs 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 EDFAs need a special EDF to provide amplification, Raman amplification can occur in any fiber, and in particular the transmission fiber itself. This enables 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, especially in coherent systems. 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 the backward pumping configuration, and will not be covered here.

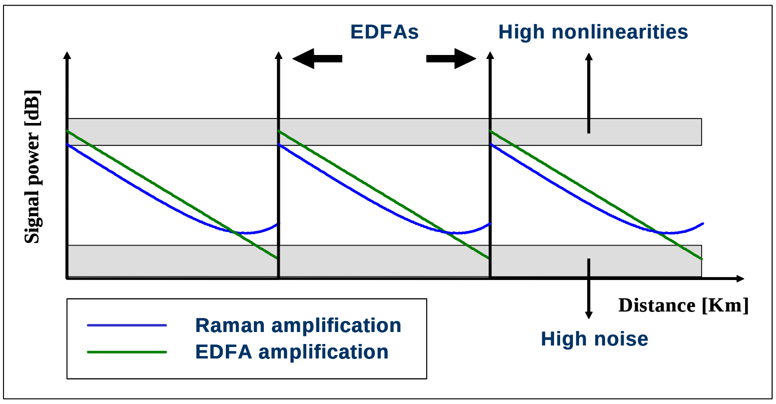

Figure 2: Distributed Vs. Lumped amplification

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, and also by using de-polarization methods when using a single pump per wavelength.

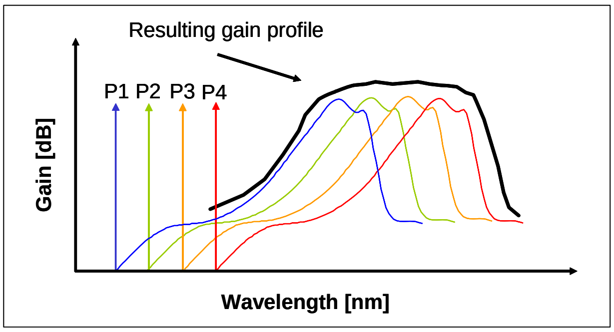

Figure 3: The use of multiple pump wavelengths to achieve flat broadband gain

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 EDFAs, with the Raman pump module serving as a pre-amplifier to the EDFA. In many cases the Raman and EDFA modules are combined into a single hybrid Raman/EDFA module, thus reducing costs, streamlining and optimizing performance, and achieving unified real-time control of both units.

Finisar Raman amplifiers can contain up to six pump laser diodes, providing up to 2W Raman pump power. In the most common application a two or three pump module provides up to 850mW Raman pump power and up to ~18dB Raman on-off gain for G.652 fiber. For special applications requiring higher pump power, a six pump standalone unit with removable hot-swappable pump laser drawers is available.

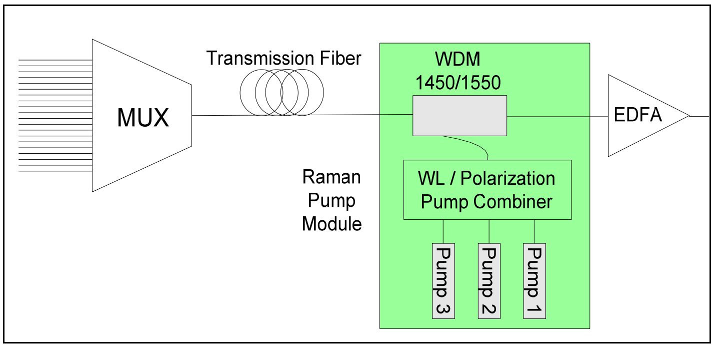

Figure 4: A simplified block diagram of the Finisar Raman amplifier deployed in backward pumping configuration

Figure 5 shows spectral Raman on-off gain and equivalent Noise Figure (NF) achieved using a dual wavelength Raman pump module. The peak-peak gain flatness for 15 dB gain is better than 1dB. 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.

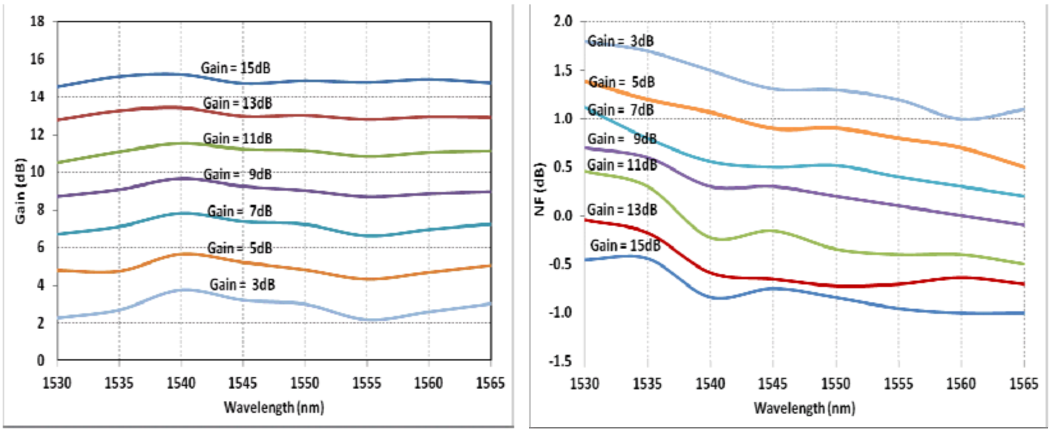

Figure 5: Gain (left) and NF (right) as a function of wavelength for different Raman pump powers

3 Applications

Broadly speaking, the system applications where DRA provides significant advantage 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. In particular, enabling so called “hut skipping” where the distance between repeater stations can be increased, thus reducing operational complexity and cost.
- Enabling higher capacity or longer distance transmission in LH and ULH systems, as well as mesh networks. This is particularly relevant to systems using coherent 40Gb/s and 100Gb/s transmission.

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. (known as “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 with and without DRA. The launch power is taken as +8dBm per channel, and an EDFA pre-amplifier with NF of 6dB 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 14dB Raman gain, an extra link loss of ~6dB, corresponding to ~30km fiber, can be tolerated for the same OSNR. Thus, for a 10Gb/s channel with forward error correction (FEC), the maximum link budget using DRA increases to about 52dB, corresponding to about 250km of G652 fiber (SMF).

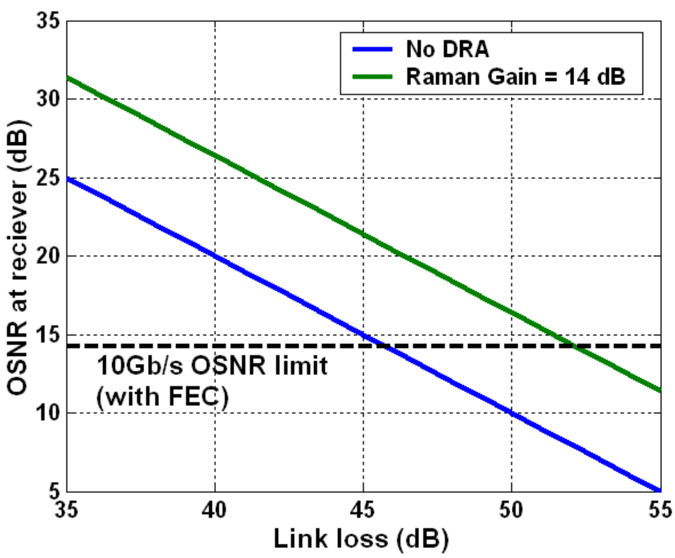

Figure 6: OSNR as a function of link loss for with and without DRA (assumptions: launch power = +8dBm, EDFA NF = 6dB)

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. Besides providing better NF for the longer spans, DRA also provides up to significant signal gain, thus allowing a conventional EDFA with a normal gain range to be used at the end of the link. For example, if a system typically uses a variable gain (VG) EDFA with 14-26dB gain range, then together with DRA the same VG EDFA can be used in spans having more than 40dB loss.

A particular interesting case in this class of applications is so called “hut skipping” where spans are intentionally made longer in order to skip repeater huts and thus reduces both capital expenditure and operation costs of the system. To illustrate this case, consider an eight span system, with 100Gb/s channels launched at 0 dBm/ch into each span. Each span includes an EDFA with NF of 6dB, and we allow a 3dB OSNR penalty resulting from non-linear effects, gain flatness, aging, and other issues.

Figure 7 shows the OSNR at the end of the link, as a function of the span loss. The figure shows that using DRA allows for spans with up to 32dB loss, corresponding to ~160km G652 fiber. Since the link has eight spans, this corresponds to a total link length of >1200km. A conventional link without hut-skipping (i.e. using typical 80km spans) would require 16 repeater stations along the link, which would significantly increase the cost and complexity of the link.

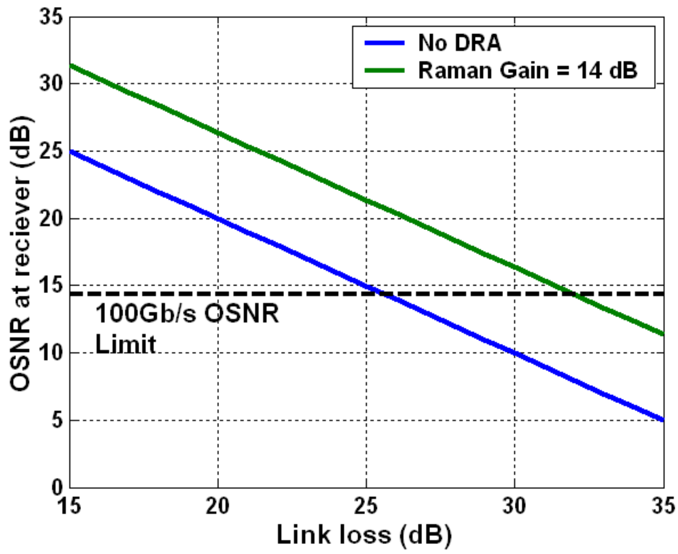

Figure 7: OSNR as a function of the span loss in an 8 span link.

3.3 High Capacity Long Distance Systems

With the increasing deployment of mesh optical networks with optical cross connects (OXC’s) based on wavelength selective switches (WSS’s), signals are being transmitted along much longer distances before being regenerated. DRA proves to be a critical factor in allowing such long transmission distances to be achieved, especially in system using coherent 40Gb/s and/or 100Gb/s transmission. Figure 8 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 +0dBm, and the span loss 18dB, corresponding to the typical ~80km spans of most systems. The EDFAs are assumed to have NF of 6dB, including mid-stage access for WSS’s and other devices required for mesh networks. Furthermore, an overall OSNR penalty of 10dB resulting from gain flatness, non-linearity, aging, and other issues is assumed.

The figure shows that DRA significantly increases the reach of the system, allowing for transmission distances > 3000km (=~40 spans of 80km each). 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, coherent 100Gb/s channels are typically very sensitive to non-linear effects, which increase as the number of channels increases. The use of DRA allows the channel launch power to be decreased, which then reduces the penalty due to non-linear effects in high capacity systems.

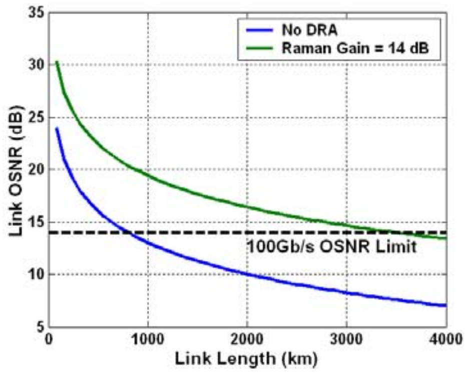

Figure 8: OSNR as a function of link length in a multi-span system, with and without DRA.

4 Deployment Issues

The applications described above show that DRA can provide significant benefit to various classes of optical networks. However, there are technical issues related to the actual deployment of DRA that need to be addressed before these benefits can be fully realized. Finisar Raman amplifiers and Hybrid Raman-EDFAs 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 systems 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 EDFAs in a system.

In order to address this issue, Finisar Raman amplifiers support additional and 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 amplified spontaneous emission (ASE) noise outside the transmission band.

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

4.2 Gain measurement

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 and the quality of the fiber line (e.g. splice and connector quality). 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).

Thus, an important element of any Raman amplifier or hybrid Raman EDFA is the ability to accurately measure the Raman gain in real time, and adjust the pump powers to achieve the desired average gain and gain shape (e.g. either flat gain or tilted). Finisar has developed and patented multiple physical mechanisms and accompanying software algorithms which allow the Raman gain to be measured with a typical accuracy of +/-0.5dB, and the pumps to be adjusted to set the gain and gain tilt. This allows Raman and hybrid amplifiers to be operated in seamless automatic gain control (AGC) mode, in a similar manner to regular EDFAs.

4.3 System Integration

As with any new technology, integrating DRA into existing system architectures can be a time consuming and costly task. To address this Finisar has developed two complementary solutions for different application scenarios.

4.3.1 Hybrid Raman EDFA modules

For applications where DRA is required extensively and in large volumes, such as coherent long haul and mesh networks, Finisar has developed a range of Hybrid Raman EDFA modules. Besides the physical integration of all components in a single cost saving module, these hybrid amplifiers seamlessly integrate the control loops and operating logic of a DRA pre-amplifier followed by a VG EDFA, so that to a large degree the hybrid amplifier can be treated as a conventional EDFA operating in AGC mode. This significantly reduces the amount of R&D effort required by system vendors to adapt DRA within their systems.

Furthermore, the tight integration of the Raman and EDFA modules allows optimization of module parameters for combined operation. For example, the required total gain and gain tilt can be distributed between the Raman and EDFA parts of the module in a manner such that the overall noise figure is minimized. Additionally, enhanced gain flatness can be achieved due to the integration process.

4.3.2 Stand-alone Raman amplifiers

For applications which are relatively infrequent and require a small amount of units, Finisar offers two stand alone network managed Raman amplifiers. Both units include dual redundant 48V power supplies and cooling fans, SNMP communications over Ethernet, a web based GUI for convenient and easy operation, and automated installation and management tools. The units are designed so that they can extend existing systems' capability to include DRA, without the need for full integration within the system.

The first unit, provided in a 1RU package, supports up to three Raman pumps emitting a maximum of 850mW Raman pump power. The second unit, provided in a 3RU package, supports up to six Raman pumps emitting up to 2W Raman pump power. The pumps in this latter unit are located in hot-swappable drawers, which allow them to be replaced during system operation. The unit can also provide full pump redundancy, such that it can continue to operate as specified even after failure of any single pump. Thus, this unit is especially well suited to applications requiring very high reliability, such as submarine terminal application and deployment in remote and inaccessible terrestrial locations.

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 and hut-skipping within multiple span links, and increasing the distance and/or capacity of ultra-long haul and mesh systems, especially systems using coherent transmission.

In order to realize the full potential of DRA, Finisar has addressed various deployment and operational issues to ease the adaption of DRA in system designs. These include laser safety, accurate gain measurement and seamless AGC operation, and a range of Hybrid Raman EDFA modules and stand-alone Raman amplifiers suited for various applications.

6 Further Reading

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2. "Raman Amplifiers for Telecommunications", Edited by M.N. Islam, Springer series in optical sciences.
3. "Raman Amplification for Fiber Communication Systems", Jake Bromage, J. Lightwave Technology Vol. 22 p.79 (2004).
4. "Safety of laser products – part 2 – Safety of optical fiber transmission systems", IEC International Standard 60825-2
5. "Optical safety procedures and requirements for optical transport systems" ITU-T International Standard G.664
6. "Technical Report – Optical Amplifiers - Part 6: Distributed Raman amplification", IEC/TR 61292-6 Ed 1, 2010-02.

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