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TECHNICAL REPORT

Optical amplifiers –
Part 6: Distributed Raman amplification

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OPTICAL AMPLIFIERS –

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FOREWORD

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IEC 61292-6, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86C/910/DTR	86C/936/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 61292 series, published under the general title *Optical amplifiers,* can be found on the IEC website.

The committee has decided that the contents of this amendment and the base publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Distributed Raman amplification (DRA) describes the process whereby Raman pump power is introduced into the transmission fibre, leading to signal amplification within the transmission fibre though stimulated Raman scattering. This technology has become increasingly widespread in recent years due to the many advantage that it offers optical system designers, including improved system optical signal-to-noise ratio (OSNR), and the ability to tailor the gain spectrum to cover any or several transmission bands.

A fundamental difference between distributed Raman amplification and amplification using discrete amplifiers, such as erbium-doped fibre amplifiers (EDFAs), is that the latter can be described using a black box approach, while the former is an inherent part of the system in which it is deployed. Thus, a discrete amplifier is a unique and separate element with a well defined input and output ports, allowing rigorous specifications of the amplifiers performance characteristics and the methods used to test these characteristics. On the other hand, a distributed Raman amplifier is basically a pump module, with the actual amplification process taking place along the transmission fibre. This means that many of the performance characteristics of distributed Raman amplification are inherently coupled to the system in which it is deployed.

This technical report provides an overview of DRA and its applications. It also provides a detailed discussion of the various performance characteristics related to DRA, some of the methods that can be used to test these characteristics, and some of the operational issues related to the distributed nature of the amplification process, such as the sensitivity to transmission line quality and eye-safety.

The material provided is intended to provide a basis for future development of specifications and test method standards related to DRA.

OPTICAL AMPLIFIERS –

Part 6: Distributed Raman amplification

1 Scope

This part of IEC 61292, which is a technical report, deals with distributed Raman amplification (DRA). The main purpose of the report is to provide background material for future standards (specifications, test methods and operating procedures) relating to DRA. The report covers the following aspects:

– general overview of Raman amplification;
– applications of DRA;
– performance characteristics and test methods related to DRA;
– operational issues relating to the deployment of DRA.

As DRA is a relatively young technology, and still rapidly evolving, some of the material in this report may become obsolete or irrelevant in a relatively short period. This technical report will be frequently updated in order to minimize this possibility.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60825-2, *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)*

IEC 61290-3, *Optical amplifiers – Test methods – Part 3: Noise figure parameters*

IEC 61290-3-1, *Optical amplifiers – Test methods – Part 3-1: Noise figure parameters – Optical spectrum analyzer method*

IEC 61290-3-2, *Optical amplifiers – Test methods – Part 3-2: Noise figure parameters – Electrical spectrum analyzer method*

IEC 61290-7-1, *Optical amplifiers – Test methods – Part 7-1: Out-of-band insertion losses – Filtered optical power meter method*

IEC 61291-1, *Optical amplifiers – Part 1: Generic specification*

IEC/TR 61292-3, *Optical amplifiers – Part 3: Classification, characteristics and applications*

IEC/TR 61292-4, *Optical amplifiers – Part 4: Maximum permissible optical power for the damage-free and safe use of optical amplifiers, including Raman amplifiers*

ITU-T G.664, *Optical safety procedures and requirements for optical transport systems*

ITU-T G.665, *Generic characteristics of Raman amplifiers and Raman amplified subsystems*

NOTE A list of informative references is given in the Bibliography.

3 Abbreviated terms

For the purposes of this document, the following abbreviated terms apply.

APR	automatic power reduction
DCF	dispersion compensating fibre
DOP	degree of polarization
DRA	distributed Raman amplification
DRB	double Rayleigh backscattering
DWDM	dense wavelength division multiplexing
EDFA	erbium-doped fibre amplifier
ESA	electrical spectrum analyzer
FBG	fibre Bragg grating
FWHM	full width half maximum
GFF	gain flattening filter
LRFA	lumped Raman fibre amplifier
MPI	multi-path interference
NZDSF	non-zero dispersion shifted fibre
OA	optical amplifier
OFA	optical fibre amplifier
OSA	optical spectrum analyzer
OSC	optical supervisory channel
OSNR	optical signal-to-noise ratio
PDG	polarization dependent gain
PMD	polarization mode dispersion
RIN	relative intensity noise
ROADM	reconfigurable optical add drop multiplexer
SMF	single mode fibre

4 Background

4.1 General

This clause provides a brief introduction to the main concepts of Raman amplification. Further information can be found IEC/TR 61292-3, ITU-T G.665, as well as in the bibliography.

4.2 Raman amplification process

Raman scattering, first discovered by Sir Chandrasekhara Raman in 1928, describes an inelastic scattering process whereby light is scattered from matter molecules to a higher wavelength (lower energy). In this interaction between light and matter, a 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 vibration (i.e. acoustic) energy. Due to the vibration energy, the emitted photon has less energy than the incident photon, and therefore a higher wavelength.

Stimulated Raman scattering describes a similar process whereby the presence of a higher wavelength photon stimulates the scattering process, i.e. the absorption of the initial lower wavelength photon, resulting in the emission of a second higher wavelength photon, thus providing amplification. This process is shown in Figure 1 for silica fibres, where a ~1 550 nm signal is amplified through absorption of pump energy at ~1 450 nm. Unlike doped OFAs, such as EDFAs, where the gain spectrum is constant and determined by the dopants, with Raman amplification the gain spectrum depends on the pump wavelength, with maximum gain occurring at a frequency of about 13 THz (for Silica fibres) below that of the pump. This is shown on the right side of Figure 1.

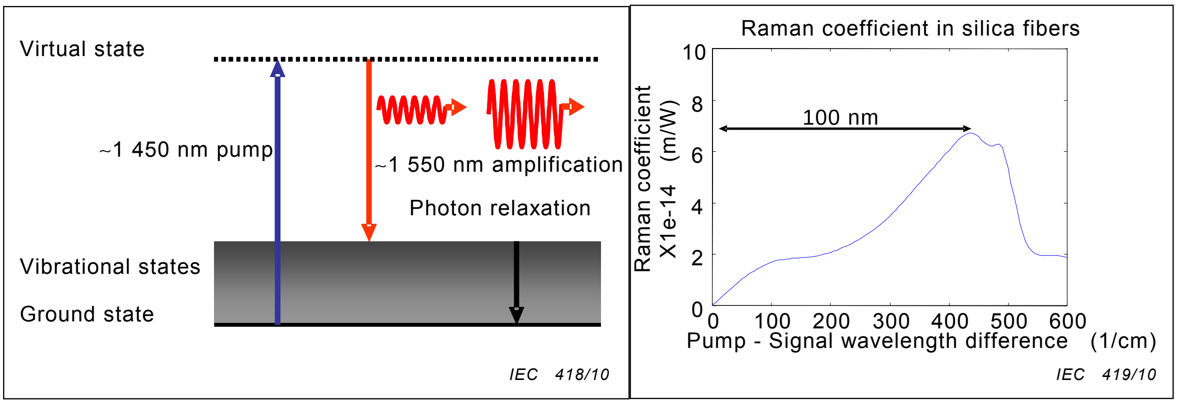


Figure 1 – Stimulated Raman scattering process (left) and Raman gain spectrum for silica fibres (right)

In its most basic form, a Raman amplifier consists of a Raman pump laser, a fibre amplification medium, and a means of coupling the Raman pump and input signal into the fibre. The main performance parameter characterizing the Raman amplifier is the on-off gain, which is defined as the ratio of the output signal (i.e. the signal at the fibre output) when the Raman pumps are on to the output signal when the Raman pumps are off (the on-off gain will be further discussed in 6.2.1), Neglecting pump power depletion (i.e. small input signal regime), the on-off gain of a Raman amplifier can be approximated by

$$G = 4{,}34 C_R P L_{eff}$$

where G is the on-off gain (in dB), C_R the Raman efficiency between pump and signal, P the coupled pump power, and L_{eff} the effective length of the fibre with respect to the Raman process, defined as

$$L_{eff} \equiv \frac{1 - e^{-\alpha_p L}}{\alpha_p}$$

where α_p is the fibre attenuation coefficient at the pump WL.

The Raman efficiency C_R depends on the separation between the pump and signal wavelengths, as well as their relative polarization. If the pump and signal polarizations are orthogonal, then $C_R = 0$, whereas if they have the same polarization, C_R is maximum. In many cases, the pump is depolarized, and then C_R is approximately half the maximum value. In other cases, the pump and signal relative polarization changes continuously as they propagate along the fibre amplification medium, so that C_R has the same average value as for the depolarized pump case. However, in this case, C_R may have some residual dependence on signal polarization, resulting in PDG.

Taking as an example conventional single mode fibre (SMF) and a depolarized pump with wavelength of 1 450 nm, then C_R for a signal located at 1 550 nm is approximately 0,4 $W^{-1}km^{-1}$. In the limit of a long fibre, where $L_{eff} \approx \alpha_p^{-1} \approx 17\,\text{km}$, a 500 mW pump provides approximately 15 dB of on-off gain, illustrating the relatively low gain efficiency of the Raman process. The gain efficiency can be increase using highly non-linear fibre (such as DCF), however, a relatively long length of fibre (approximately 10 km) is still required to achieve reasonable gain.

4.3 Distributed vs. lumped amplification

Typically OFAs are deployed as lumped (or discrete) amplifiers, meaning that the amplification occurs within a closed amplifier module. These modules are placed at various points along the optical link (discrete amplification sites at the end of each fibre span), so that the transmission signal which is attenuated along the fibre span is amplified back to the required power level at the discrete site at the end of each span. This is shown graphically by the green curve in Figure 2. Raman amplifiers may also be used as discrete amplifiers, however, as shown in 4.2, this requires special highly non-linear fibre. Even then the application of such amplifiers is limited due to multi-path interference (to be discussed in 6.3.5, and other issues, and in most cases other lumped amplifiers, such as EDFA's, are preferable.

While most OFAs require a special doped fibre (such as Erbium doped fibre for EDFA's) to provide amplification, Raman amplification can occur in any fibre, and in particular within the transmission fibre itself. This enable distributed Raman amplification (DRA), i.e. the process whereby the transmission fibre itself is pumped in order to provide amplification for the signal as it travels along the fibre. 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 fibre, 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 attenuation of the signal along the span is reduced can also be utilized to launch the signal into the transmission fibre with less power, which can be important in applications where signal non-linear effects are an issue. DRA can also be used in co-propagating ("forward") configuration, where the Raman pump power is introduced at input to the span and propagates with the signal. The distinction between the two configurations will be discussed in more detail in 4.5.

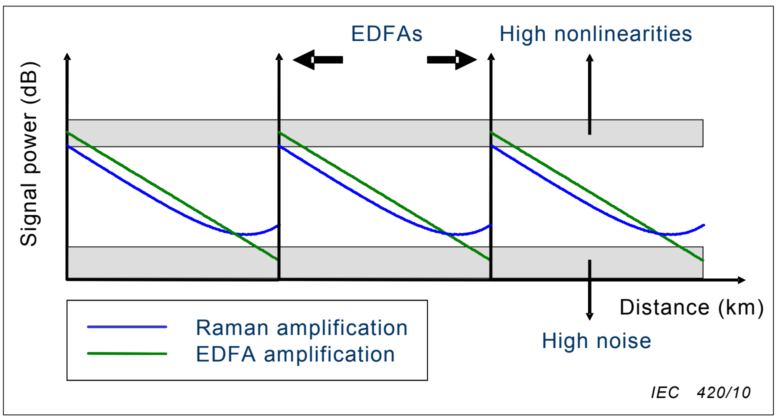


Figure 2 – Distributed vs. lumped amplification

4.4 Tailoring the Raman gain spectrum

As mentioned earlier, the shape of the Raman gain spectrum depends on the pump wavelength, with the maximum gain occurring at a wavelength approximately 100 nm 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 be used in order to achieve flat broadband gain over a large spectral region, as illustrated in Figure 3.

Besides achieving 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 (this will be discussed in more detail in 6.2.3 and 6.3.3. The PDG can be further reduced by using two pumps with the same wavelength but orthogonal polarization.

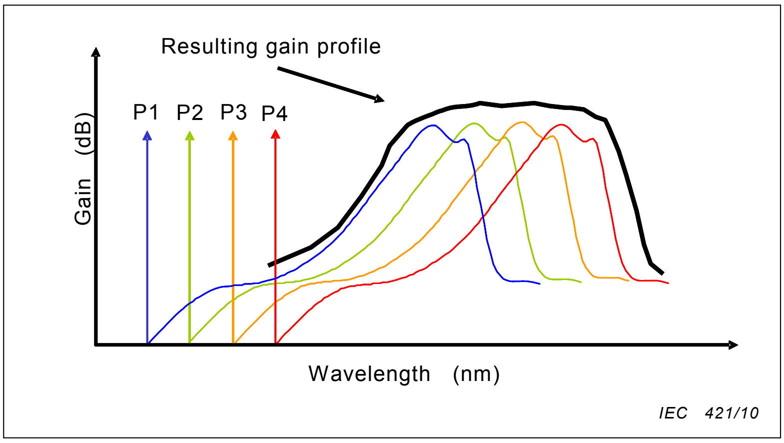
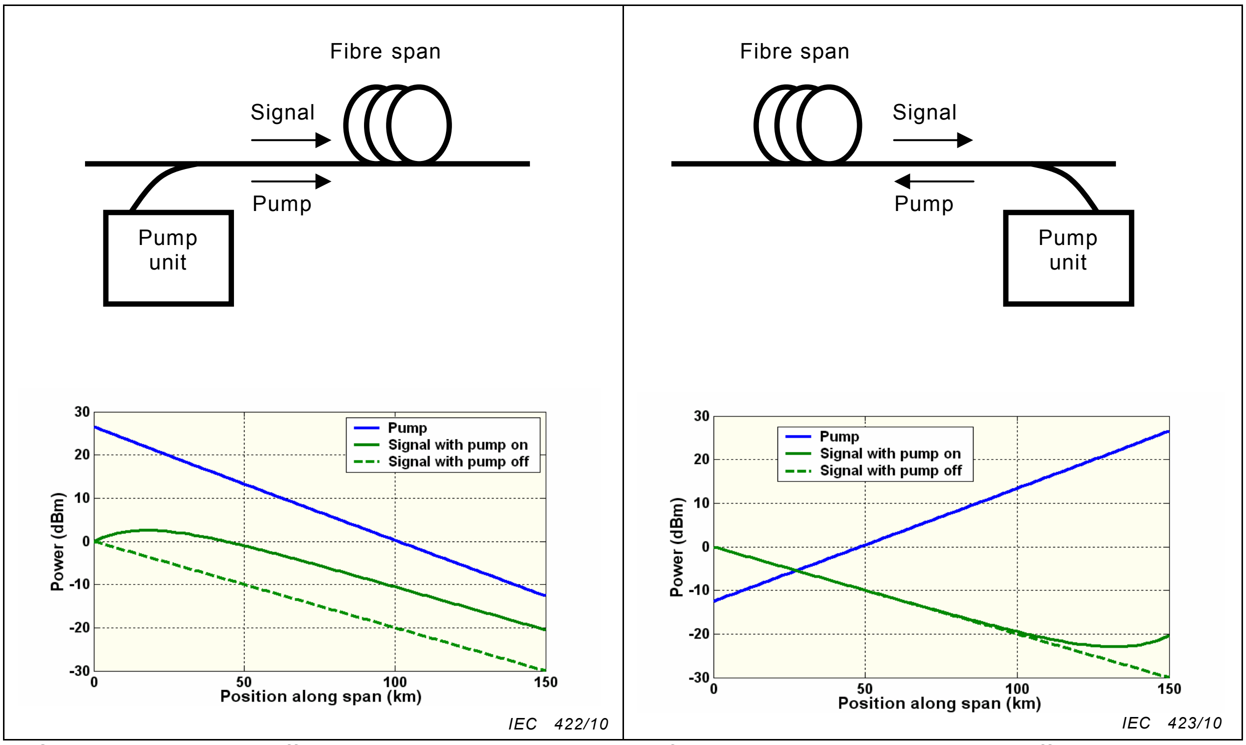


Figure 3 – The use of multiple pump wavelengths to achieve flat broadband gain

4.5 Forward and backward pumping configuration

DRA can be deployed in either forward (co-propagating) configuration, where the pump is introduced together with the signal at the input to the span, or backward (counter-propagating) configuration, where the pump is introduced at the end of the span and propagates counter to the signal. These two pumping configurations are illustrated in Figure 4. Assuming a small input signal and the same pumps, the on-off gain in both configurations is the same, with the difference being the position along the span where the amplification takes place.



NOTE Two pumps at different wavelength provide a total of 500 mW, resulting in 10 dB on-off gain across the C-band.

Figure 4 – Simulation results showing pump and signal propagation along an SMF span in forward (right plot) and backward (left plot) pumping configurations

The main advantage of the forward pumping configuration is that each dB of Raman gain is equivalent to effectively increasing the signal launch power by one dB, thus achieving a dB of OSNR system improvement. However, there are a number of issues that reduce the overall effectiveness of the forward pumping configuration:

- Signal non-linear effects: Since the Raman gain occurs a few tens of km within the fibre, the maximum signal power within the span is less than what would occur if a lumped amplifier with equivalent gain were to be placed at the beginning of the span. While this reduces signal non-linear effects, these can still become an issue when the effective launch power per channel increases, thus placing a practical limit on the amount of forward Raman gain that can be used.
- Pump relative intensity noise (RIN): Typical commercial semi-conductor Raman pump lasers have RIN values of the order of -115 dB/Hz. In forward pumping configuration there is a long walk-off length between signal and pump, which results in significant transference of the pump RIN to the signal, thus resulting in a system penalty which can accumulate along many spans. This is discussed in more detail in 6.2.4.
- Pump depletion: As the composite signal input power increases pump depletion occurs, resulting in reduction of the Raman gain. For example, 650 mW of pump power configured to provide 15 dB flat gain across the C-Band for SMF fibre in the small signal regime, will only provide about 8,5 dB of gain when the composite input signal is 20 dBm. Pump depletion can also lead to large transient effects when the input signal changes abruptly (e.g. due to channel add/drop). Unlike EDFA’s where transient effect can be suppressed using electronic feed-back and feed-forward mechanisms, such effects cannot be fully suppressed in forward DRA due to the fast response time of the Raman effect and the distributed nature of the amplification.

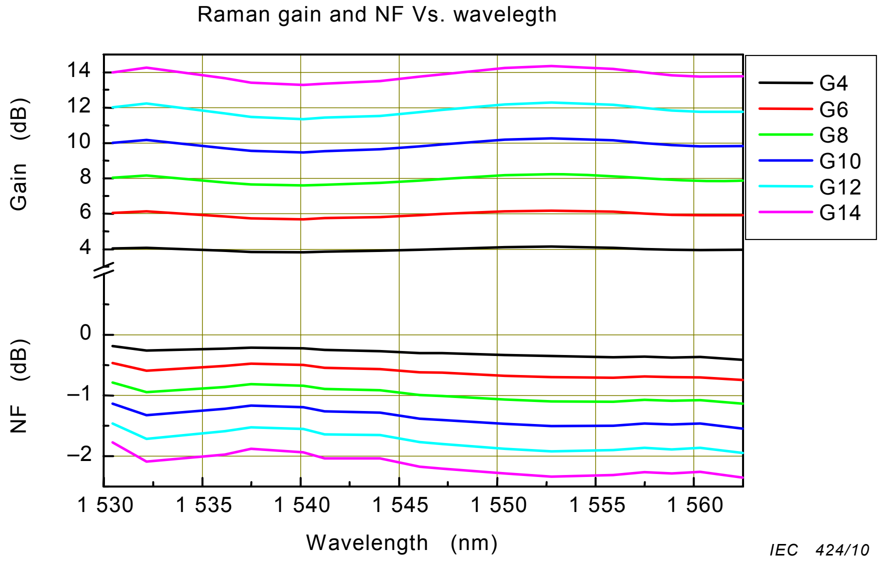
While the backward pumping configuration does not suffer from the above disadvantages, the OSNR improvement is typically more modest since the amplification occurs in the last few tens of km of the fibre span. For example, 10 dB of Raman gain in the backward configuration will typically result in about 5 dB OSNR improvement (relative to a lumped amplifier providing the same gain at the end of the span), while increasing the Raman gain further will only result in an additional 1 dB to 2 dB OSNR improvement. Further OSNR improvement (typically another 1 to 2 dB) can be achieved using complex multi-order Raman pumping schemes, which involve boosting the Raman pump energy in the transmission fibre with additional pumps at even shorter wavelengths. Thus the Raman gain occurs deeper within the span, leading to improved OSNR.

Overall, the backward pumping configuration usually provides better system performance for the same amount of Raman pump power, and is simpler to implement. Thus, in most systems backward pumped DRA is usually deployed first, and then forward pumped DRA only for those spans where backward pump DRA alone cannot supply sufficient OSNR improvement.

4.6 Typical performance of DRA

As we shall see in Clause 5, DRA is most often used to provide moderate (10 dB to 15 dB) flat on-off gain in the C-Band, most often in the backward configuration, and less often in the forward configuration.

Figure 5 shows the gain for SMF in the C-Band provided by a triple pump backward DRA with pump wavelengths of 1 424 nm (two pumps) and 1 452 nm (one pump). For 10 dB gain about 450 mW of composite pump power is required, whereas for 14 dB gain 650 mW pump power is required. The figure also shows the equivalent NF figure of the backward DRA for different gains, which is defined as the NF of an equivalent lumped amplifier (generating the same gain and same amount of ASE) placed at the end of the span (see 6.3.4 for further detail). In a hybrid EDFA/Raman system (see 5.3) backward DRA is used as a pre-amplifier for a conventional EDFA which provides the remaining gain required to compensate the span loss. Since the DRA has a very low effective NF, and since it acts as a pre-amplifier, it mainly determines the NF of the combined EDFA Raman amplifier. Thus, assuming a typical EDFA NF of about 5 dB, the combined EDFA/Raman amplifier can be shown to have a composite NF of about 0 dB in the case of 10 dB on-off Raman gain, which results in a 5 dB OSNR improvement compared to an equivalent EDFA case.



NOTE The various curves correspond to different composite pump powers.

Figure 5 – On-off gain and equivalent NF for SMF using a dual pump backward DRA with pumps at 1 424 nm and 1 452 nm

5 Applications of distributed Raman amplification

5.1 General

DRA offers two unique advantages compared to conventional amplifiers such as EDFAs: Improved system OSNR; and the ability to provide flat gain for any and multiple transmission bands. These advantages are offset by the high cost of DRA, due to the high pump power required, as well as operational issues which will be further discussed in Clause 7. For this reason, DRA is usually only utilized in those applications where it offers a significant advantage, or there are no other viable alternatives. These applications will be discussed in this clause.

5.2 All-Raman systems

All-Raman systems are systems which utilize only Raman amplification, both DRA and lumped Raman amplifiers. By using only Raman amplification, such systems benefit from the inherent OSNR improvement provided by DRA, and can be operated in wavelength ranges for which it is impossible or impractical to provide amplification with more common technologies such as EDFA's. In particular, all Raman systems can operate in the L-Band, for which EDFA technology is much less efficient compared to the C-Band. Since L-Band systems allow for longer system reach compared to C-Band systems when using Non-zero dispersion shifted transmission fibre (NZDSF), all Raman L-Band systems are particularly well suited to ultra-long haul (>1500 km) optical links.

A typical configuration of an all-Raman amplification site is shown in Figure 6. The configuration comprises three Raman pump modules, one for backward DRA, one for forward DRA and one for providing lumped Raman amplification within the DCF fibre. In a typical system such an amplification site is placed every 80 km, and thus is required to provide approximately 20 dB of net gain. This is achieved by providing about 20 dB gain using forward and backward DRA, and by pumping the DCF so that its net gain is zero (i.e. the on-off Raman gain exactly compensates the DCF insertion loss, typically about 10 dB). Since DCF has a relatively high Raman efficiency (due to its small effective area), a relatively small amount of pump power is required to pump the DCF.

Besides the relatively high cost of all-Raman systems, it is also difficult to upgrade them to support reconfigurable optical add drop multiplexers (ROADM's), which are an integral part of more modern optical networks. The reason for this is two-fold:

- Firstly, additional lumped amplification needs to be provided to compensate for the added insertion loss of the ROADM modules. One option for providing the additional Raman gain is to pump the DCF with higher pump power. However, this may lead to increased MPI due to double Rayleigh backscattering (see 6.3.5). Another option is to use a separate lumped Raman amplifier, which further adds to the overall cost of the system.
- Secondly, the transients resulting from system reconfiguration are difficult to suppress, especially in the case of forward DRA.

For these reasons, the application of all-Raman systems is mainly limited to ultra-long haul point to point (i.e. non-reconfigurable) optical links.

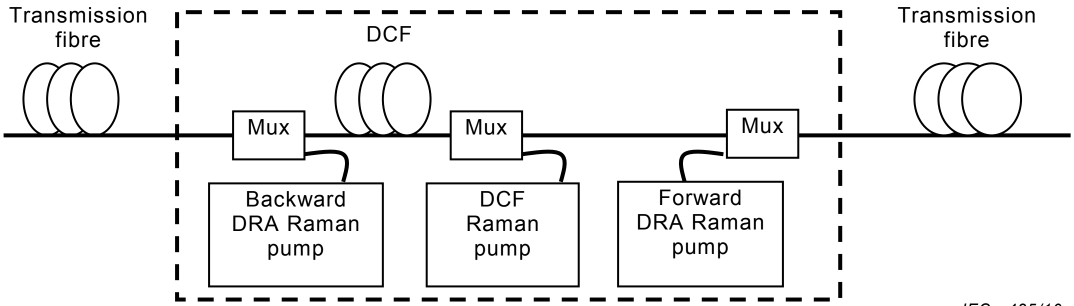


Figure 6 – Typical configuration of an amplification site in an all-Raman system

5.3 Hybrid EDFA Raman systems

EDFA based system are by far the most common optical communication system in deployment today. EDFA technology is mature and well developed, and can provide a cost effective and efficient solution for most common applications. However, there are some more challenging applications for which EDFA technology may not be sufficient, in which case DRA, and particularly backward DRA, is required to improve system OSNR.

The cost of adding DRA to EDFA based systems may be reduced by tightly integrating the Raman pump module with the EDFA, and optimizing the overall design. This is particularly useful for LH and ULH applications (see 5.3.3), where DRA is used in every span of the link. Integration and optimizing of the design may include, for example, mounting the Raman and EDFA pumps in the same physical package, thus reducing package costs and footprint. Additionally, a combined gain flattening filter (GFF) can be designed to take into account the Raman gain spectral shape as well as the EDFA gain spectral shape, thus reducing gain flattening requirements for both the EDFA and the Raman (and possibly reducing the number of separate Raman pumps). Due to the pre-amplifier function of the Raman, the GFF can be placed before the EDFA without significantly increasing the composite NF of the Hybrid module, thus reducing the required EDFA pump power.

In the following subclauses, applications for hybrid EDFA Raman systems are discussed.

5.3.1 Long repeaterless links

Long (>150 km) repeaterless links have many applications, such as connecting islands or oil rigs, traversing hostile or inaccessible terrain, and links where repeater sites may pose a security or logistic challenge.

By utilizing backward DRA, the system OSNR can typically be improved by 5 dB to 7 dB, depending on the pump power. For example, using a 700 mW Raman pump module configured to provide approximately 15 dB of on-off Raman gain across the C-Band, an OSNR improvement of approximately 6 dB may be achieved depending on the transmission fibre type, thus allowing the link reach to be extended by approximately 30 km.

For even longer links, it is possible to use forward DRA as well as backward DRA. For example, assuming a system with a 20 dBm EDFA booster, adding a 700 mW forward DRA pump module will provide ~8,5 dB Raman on-off gain, corresponding to about 7 dB OSNR improvement (taking into account the insertion loss of the Raman pump module).

Thus, using forward and backward DRA with moderate pump power (e.g. up to 700 mW), the system reach for repeaterless links can be increased by up to 13 dB compared to corresponding EDFA only systems.

5.3.2 Long span masking in multi-span links

Most multi-span links are typically constructed such that in-line EDFA repeaters are placed after every 80 km to 100 km span. However, geographical limitation may require individual spans to be longer, or practical considerations may provide an incentive to reduce the number of spans and thus increase the length of one or more span. In both cases, DRA can provide the extra OSNR margins required to support the longer spans. In addition, many systems are designed such that the in-line EDFA can support a limited gain range while still maintaining flat gain. In this case, besides providing improved OSNR, DRA allows longer spans to be supported while still using the standard EDFA used by the system, thus increasing system flexibility and utility.

While the repeaterless links discussed in the previous clause tend to be static (i.e. non-reconfigurable) point-to-point links, multi-span links are most often dynamic, and thus required to provide ROADM functionality. Therefore, by nature such system may generate transient events, which are problematic to suppress when forward DRA is used. This is one reason why forward DRA is not often used in such applications, and backward DRA is much more common.

5.3.3 High capacity long haul and ultra-long haul systems

In high capacity (high bit rate and/or dense channel spacing) systems OSNR quickly becomes a critical issue as the number of spans increases. By utilizing backward DRA in every span in the system, the OSNR can be increased significantly, thus allowing the system to support more spans and/or higher capacity. For example, by providing 10 dB of backward DRA in each span (approximately 500 mW pump power), the system OSNR can be improved by about 5 dB compared to an equivalent EDFA only system, allowing a 3-fold increase in the reach of the system.

6 Performance characteristics and test methods

6.1 General

This clause describes important performance parameters relevant to DRA, and considers tests methods for these parameters. As discussed previously, a fundamental difference between DRA and lumped amplifiers is that the performance of DRA depends on the transmission fibre, so that a full characterization of the amplifier performance can only be performed on a system level, rather than on a device level. However, there are some performance parameters that are specific to the Raman pump module, which can be specified and measured independently of the system in which the module is installed. Furthermore, those parameters which are system dependent can be characterized on average for various types of transmission fibre, so that the expected performance is a system can be predicted. In what follows, we first discuss these device level characteristics, and then proceed to system level performance.

6.2 Performance of the Raman pump module

A Raman pump module typically consists of a number of Raman pump lasers together with passive components designed to multiplex the output of these lasers with the signal. The module may also contain detectors for monitoring pump power and signal power, as well circuits and software for controlling the amplifier. A possible construction of a Raman pump module used for counter-propagating DRA is shown in Figure 7. In this example, the pump module contains three pumps laser diodes, two polarization multiplexed diodes at wavelength λ1, and one laser diode at wavelength λ2.

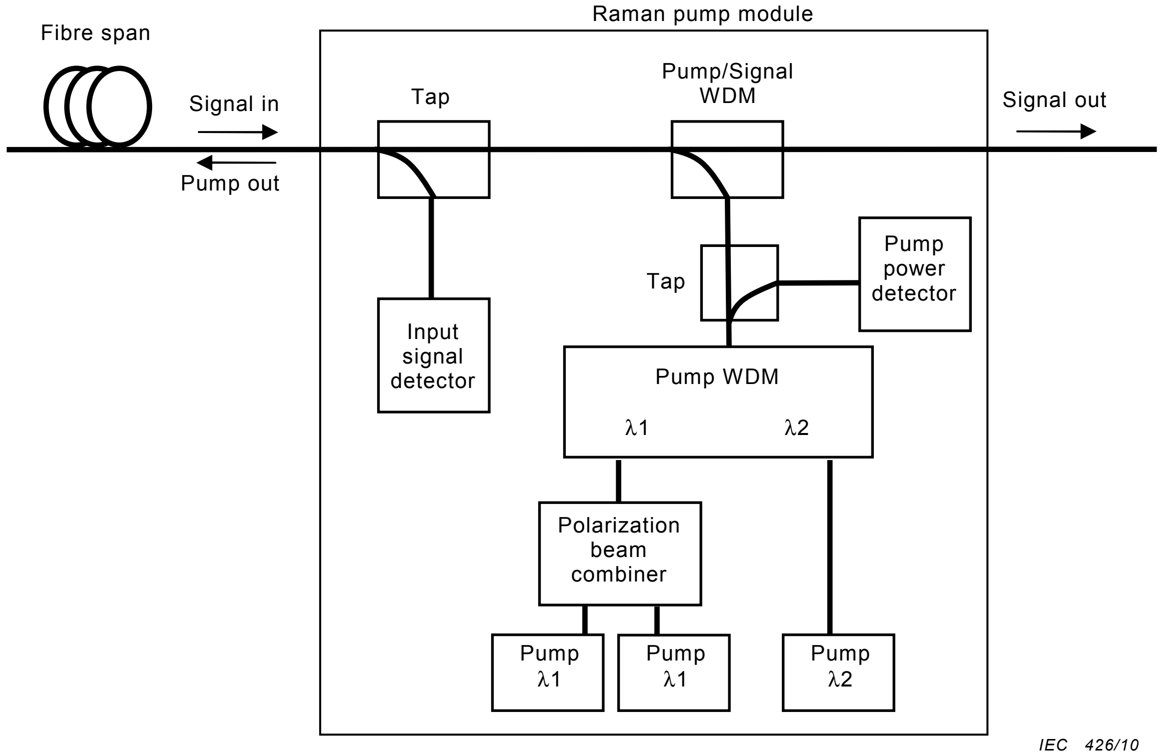


Figure 7 – Typical configuration of a Raman pump module used for counter-propagating DRA

6.2.1 Pump wavelengths

The spectrum of the pump power exiting the pump out port of the Raman pump module is critical in determining the on-off Raman gain spectrum of the signals propagating in the fibre span connected to the module. The pump power spectrum typically consists of a number of discrete wavelengths, each of which may originate from one or more pump sources (as for wavelength λ2 in the example shown in Figure 7). The pump spectrum may be measured by connecting the pump output port to an OSA (usually via an attenuator due to the high pump power), resulting in a list of wavelengths corresponding to the peaks that comprise the spectrum. Another relevant parameter that can be measured by the OSA is the width of each peak, measured for example as FWHM. For most 14xx nm FBG stabilized pump laser diodes on the market today, the FWHM is of the order of 1 nm to 2 nm.

6.2.2 Pump output power

The pump power exiting the Raman pump module for each of the pump wavelengths is another critical parameter that determines the on-off Raman gain spectrum. In most Raman pump modules, the pump power of individual pumps can be controlled so as to change the total pump power exiting the module, as well as the division of the pump power between the different wavelengths. The pump output power spectrum for a given operating condition of the pump module can be measured by connecting the pump output port to an OSA (usually via an attenuator due to the high pump power), resulting in a list of pump powers associated with each pump wavelength. The total pump output power of all the wavelengths together can also be measured, for example by connecting a high power optical detector to the pump output port of the pump module.

6.2.3 Pump degree-of-polarization (DOP)

The DOP of each pump wavelength can affect the PDG of the DRA, as discussed in 4.2 The exact effect of the DOP of any given pump wavelength depends on the type of DRA (counter- or co-propagating), the type and condition of the transmission fibre, as well as the relative power and DOP of other pump wavelengths.

To measure the DOP of a given pump wavelength, only the corresponding pumps within the pump module should be activated, with the Pump out port of the module connected to a rotating polarization analyzer. The maximum and minimum power ($P_{\max}$ and $P_{\min}$) at the output of the analyzer is then measured, and the DOP Is defined as $DOP \equiv 100\left(P_{\max} - P_{\min}\right)/\left(P_{\max} + P_{\min}\right)$. Thus, a DOP of 100 % corresponds to a fully polarization pump wavelength, and a DOP of 0 % corresponds to a fully depolarized pump signal.

6.2.4 Pump relative intensity noise (RIN)

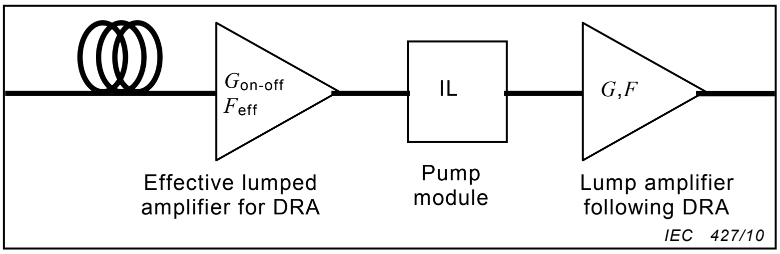
The RIN of a pump laser describes the intensity fluctuations of the laser output, and is measured in units of dB/Hz. Thus, within a given bandwidth B, the relative variance of the intensity fluctuation of the laser power is given by $\sigma^2 / P^2 \equiv RIN \times B$. Since the Raman gain is proportional to the pump intensity (see 4.2), fluctuation in the intensity can be transferred to the signal.

The system effect of the Raman pump RIN depends on the magnitude of the RIN, and also the walk-off between the signal and pump, which determines the bandwidth of the fluctuation transferred from the pump to the signal. For typical 14xx nm pump laser diodes on the market today, the RIN value is approximately –115 dB/Hz. Regarding walk-off, if the relative group velocity between signal and pump is Δv then the bandwidth of the transferred RIN fluctuations is given by $B \sim c^2 / L_{eff} \Delta v$, where L_{eff} is the Raman effective length and c the velocity of light. In counter-propagating DRA the walk-off is very fast, i.e. $\Delta v \sim c$, and therefore B is very small and the effect of pump RIN is negligible. In co-propagating DRA the walk-off between signal and pump can be small, depending on the fibre dispersion, and the system effect of Raman pump RIN may not be negligible.

The RIN of any pump laser within a Raman pump module may be measured by activating only that laser, and connecting the pump output port of the module to a fast detector (bandwidth >= 100 MHz), and then to an ESA.

6.2.5 Insertion loss

Since DRA takes place within the transmission fibre, and not within the Raman pump module, the Raman pump module itself can be considered as a passive module with respect to the signal propagating from the signal in to the signal out ports of the module. Thus, an important performance characteristic of the module is the insertion loss experienced by the signal. For counter propagating DRA, the signal insertion loss can be modelled as shown in Figure 8, and contributes to the overall noise performance of the DRA. For co-propagating DRA the Raman pump module is typically placed directly following a booster amplifier, and thus the module insertion loss directly reduces the signal launch power into the fibre span.



NOTE $G_{\text{on-off}}$ and F_{eff} are the on-off gain and effective noise figure of the DRA, and G, F are the gain and NF of a lumped amplifier that would typically follow the Raman pump module.

Figure 8 – Model for signal insertion loss (IL) of a Raman pump module used for counter-propagating DRA

A related parameter to signal insertion loss is the out-of-band insertion loss, describing insertion loss of wavelengths which lie outside the designated system transmission band. For example, the system may include an optical supervisory channel (OSC), often located at 1 510 nm, which is added and dropped at each repeater location. Thus, the insertion loss experienced by the OSC within the Raman pump module directly impacts the OSC link budget. Note that in some cases the OSC may be dropped or added within the Raman pump module itself, and thus the OSC insertion loss (or other relevant out of band insertion losses), should be measured between the relevant ports of the pump module, and not necessarily between the signal-in and signal-out ports of the module.

The insertion loss of the Raman pump module may be measured in the same manner as for other types of OAs, as described in IEC 61290-7-1.

6.2.6 Other passive characteristics

As noted in the previous clause, the Raman pump module can be considered as a passive module with respect to signals propagating between the various input and output ports of the module. Thus, various performance characteristics of passive module should also be considered, such as PMD and reflectance. Some of these characteristics are defined in IEC 61291-1, together with the relevant test methods.

6.3 System level performance

In this clause, we consider the main system level performance parameters associated with DRA. By nature, these parameters can only be fully specified and measured in relation to the actual system within which the DRA is deployed. However, in many cases it is possible to characterise the typical performance expected from a Raman pump module under certain system condition, such as type of transmission fibre, and appropriate system independent tests can be defined.

6.3.1 On-off signal gain

The main performance parameter of a Raman pump module is the expected on-off signal gain under different operating conditions, such as pumps power output level and the type of transmission fibre. On-off signal gain is defined as follows: first measure the signal level S_{off} at the output of the transmission fibre within which DRA takes place when the Raman pump module is powered off. Then, measure the signal level S_{on} at the same point when the Raman pump module is powered on at the desired operating conditions (i.e. pumps power level). The on-off gain is then defined as $G_{on-off}(dB) = S_{on}(dB) - S_{off}(dB)$.

A typical configuration used for measuring the on-off gain is shown in Figure 9 (a) in case of co-propagating DRA and Figure 9 (b) in the case of counter-propagating DRA. The signal source can provide either a single wavelength, or multiple multiplexed wavelengths. The use of an OSA to measure the signal powers (S_{on} and S_{off}) at each wavelength allows simultaneous measurement of on-off gain at different wavelength in the case of a multi-wavelength signal source. Additionally, the OSA allows the separation of the signal power from the continuous ASE spectrum generated by the DRA, thus measuring only the actual signal gain (If S_{on} is very weak, it may also be necessary to subtract the ASE within the signal wavelength itself, which can be measured for example by interpolating the ASE level on either side of the signal).

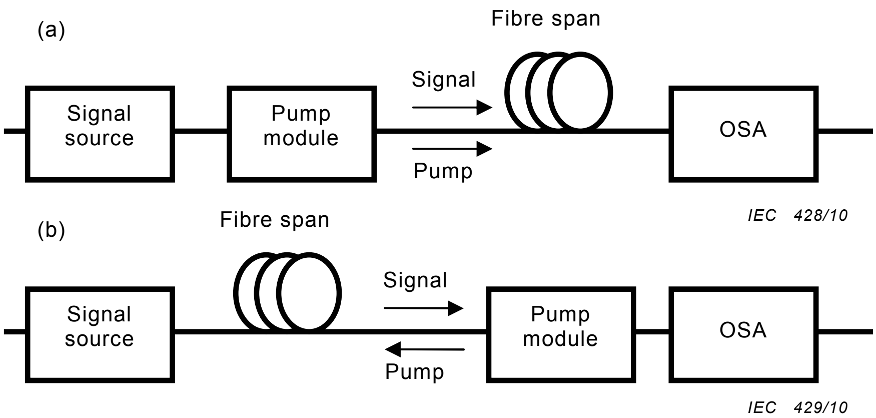


Figure 9 – Typical configuration used to measure on of gain (a) for co-propagating DRA and (b) for counter-propagating DRA

A number of issues should be considered when measuring on-off gain:

- Often the aim of an on-off gain measurement is to characterize the achievable gain for a specific type of transmission fibre. In this case, it is desirable to measure the on-off gain in the limit where the fibre length is much longer than the Raman effective length. For typical transmission fibres on the market today, a length of >75 km is usually sufficient to emulate the infinite fibre limit.
- The on-off gain is significantly impacted by any excess loss between the pump module and the fibre span, which reduces the available pump power into the span, and thus the gain. When measuring the typical on-off gain for a given fibre type, care should be taken to reduce this excess loss to a minimum. When comparing such typical results to actual measured on-off gain in the field, any excess loss should be taken into account accordingly.
- In the case of counter-propagating DRA the signal power is typically weak at the end of the span, so that the on-off gain is usually considered as small signal gain, and does not depend strongly on the signal level itself. Thus, the signal source at the input to the fibre span should not be too strong as to cause pump depletion. As a general rule, the signal source strength should be such that the total signal output power with the Raman pumps on, $\sum_{WL's} S_{on}$, should be at least 20 dB less than the Raman pump power at the output of the pump module.
- In the case of co-propagating DRA, the signal levels at the input of the span are often sufficiently high to cause pump depletion. Thus, the on-off gain for any given wavelength depends on the total signal input power (for all wavelengths), and should be characterized accordingly.

6.3.2 Gain flatness

Gain flatness characterizes the variation of the on-off signal gain over a relevant transmission band, such as the C-Band (1 529 nm to 1 564 nm). It is defined as the difference between the maximum and minimum on-off gain at different signal wavelength within the band, measured as described in the previous clause.

The gain flatness is impacted by the configuration of pump wavelengths and power at each wavelength. Many Raman pump modules support preset configurations of pump powers so to provide optimized gain flatness for different types of transmission fibre.

6.3.3 Polarization dependant gain (PDG)

PDG characterizes the variation of the on-off signal gain at a given wavelength as a function of signal input polarization, and is defined as the difference between the maximum and minimum on-off gain over all possible signal polarization states. The PDG can be measured using the setup shown in Figure 9 by including a polarization controller in the signal source, and by measuring the difference between the maximum and minimum value of S_{on} over all configurations of the polarization controller.

The PDG is impacted by the configuration of pump wavelengths, the DOP of each wavelength, and the polarization characteristics of the transmission fibre. The more wavelengths there are, the lower the PDG even if one or more of the wavelength are not depolarized.

Since the PDG also depends on the transmission fibre, a PDG measurement should ideally be taken over a long period of time (e.g. 24 h), to account for the effect of environmental changes on the fibre.

6.3.4 Equivalent noise figure

The equivalent noise figure is an important performance characteristic relevant only to counter-propagating DRA, which quantifies the noise performance of the DRA. The equivalent noise figure refers in fact only to the signal-spontaneous noise factor, as defined for example in IEC 61290-3. It is defined in relation to a model lumped amplifier, as shown in Figure 8, which has the same on-off gain as the DRA, and generates the same amount of ASE as the DRA generates at the output of the fibre span (i.e. the input to the Raman pump module).

Defining the Raman ASE power density for a single polarization at the signal wavelength, ρ_{ASE}, at the output of the model lumped amplifier, i.e. at the input to the Raman pump module, the equivalent noise figure is then given by (see IEC 61290-3) $F_{eq} = 2\rho_{ASE} / (G_{on-off} h\nu)$, where h is Planck's constant and $\nu = c/\lambda$ is the signal frequency.

To measure ρ_{ASE}, one can utilize an OSA as described in IEC 61290-3-1. In practice, the OSA can be placed following the Raman pump module, as in Figure 9, in which case the insertion loss of the pump module has to be accounted for in the measurement (since the ρ_{ASE} is defined as the ASE power density at the input to the pump module). Another possibility is to tap a portion of the power at the input to pump module, and feed this to an OSA, using an appropriate calibration factor for the tap.

As shown in Figure 5, the typical equivalent noise figure of a counter-propagating DRA with on-off gain of 10 dB is about –1 dB, as compared to a typical value of approximately 5 dB for an EDFA. To translate this into OSNR system improvement, it is necessary to account for addition supplementary lumped amplification which may be required, as shown in Figure 8 (see also 4.6).

6.3.5 Multi-path interference (MPI)

MPI in DRA is caused by double Rayleigh backscattering (DRB) which is amplified due to Raman gain. DRB describes the process whereby a fraction of the signal is Rayleigh backscattered, propagates back towards the signal source, and is then Rayleigh backscattered a second time, thus creating a replica of the signal propagating in the same direction as the signal, resulting in MPI.

In a typical transmission fibre without DRA, the level of DRB is very low (<–60 dB), and has a negligible system effect. However, in the presence of Raman gain the double backscattered signal replica is amplified in both propagation directions, which can result in significant enhancement of the MPI. The level of MPI depends on the Rayleigh scattering coefficient of the transmission fibre, the Raman effective length, and the Raman on-off gain. For example, for 15 dB on-off gain in SMF, the level of MPI is about –45 dB.

Measurement of MPI in DRA can be performed using an ESA placed at the output of the fibre span, as described in IEC 61290-3-2.

7 Operational issues

7.1 General

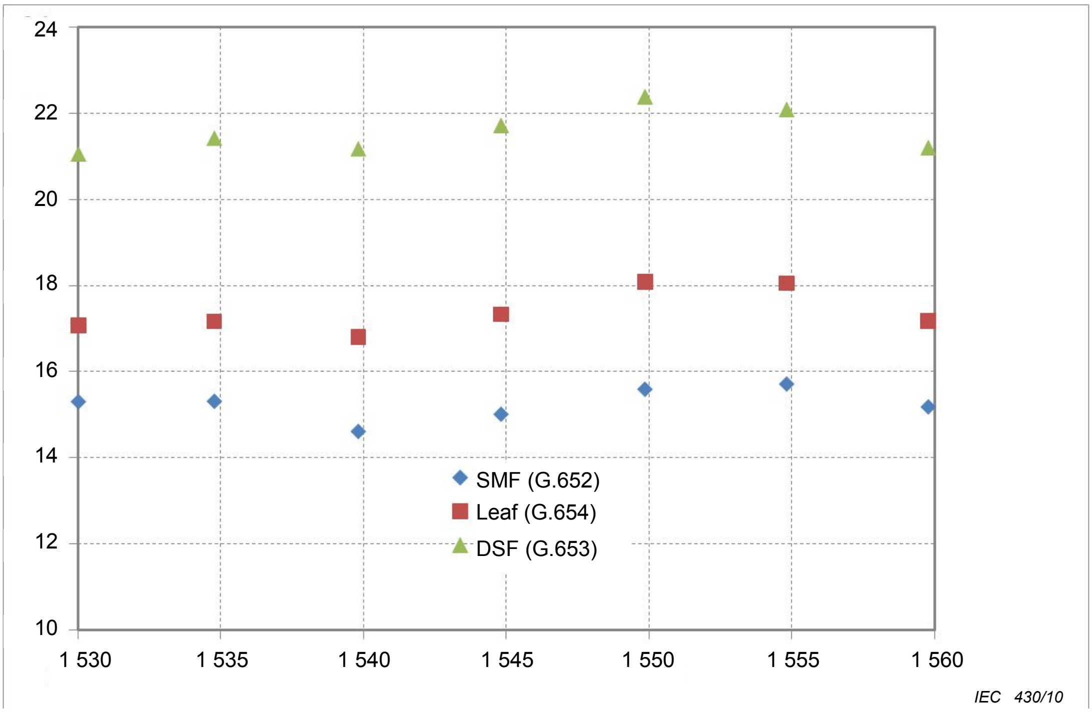
As discussed in Clause 5, DRA can provide significant OSNR improvement for challenging applications. However, there are a number of operational issues unique to DRA that need to be addressed before taking advantage of the technology. These issues are related to the high Raman pump power injected into the transmission line, and the distributed and uncontrolled nature of the amplification.

7.2 Dependence of Raman gain on transmission fibre

As discussed in 4.2, the Raman efficiency C_R, and to a lesser extend the effective length L_{eff}, depend on the type of transmission fibre. This means that the magnitude and shape of the Raman on-off gain spectrum is different for different types of transmission fibres, even for the same operating conditions, as illustrated in Figure 10.

Thus, it is important to have prior knowledge of the type of transmission fibre before deploying DRA. This allows more accurate link design taking into account the expected achievable Raman gain for a given transmission fibre type, and also allows fine tuning of the Raman pump powers to achieve a flat gain spectrum.

However, even if the transmission fibre type is known, variations of as much as 10 % in the Raman gain can occur between different spools of the same type of fibre. This means that it is not possible to accurately predict the Raman gain before deployment on an installed fibre. This uncertainty needs to be either taken into account in the link design, or neutralized via an accurate gain measurement performed during deployment on the installed fibre.



NOTE In each case, 75 km of transmission fibre was used, and the Raman pump were configured as: 290 mW at 1 424 nm, 410 mW at 1 452 nm.

Figure 10 – Variations of Raman on-off gain for different transmission fibres

7.3 Fibre line quality

Another important factor to consider in the deployment of DRA is the quality of the fibre line, and especially the quality of connection points and splices in the vicinity of the Raman pump module. High loss between the Raman pump module and the transmission fibre can result in significant reduction of the achievable Raman on-off gain. For example, a total loss of 1 dB between the pump module and the transmission fibre will result in a ~20 % reduction in the on-off gain (measured in dB).

Besides loss, it is also important to minimize back-reflection from the fibre line, especially from faulty or dirty connectors close to the pump units. High back reflection can cause a fraction of the Raman pump power to be redirected back to the Raman pump from which it originated, which can potentially degrade the pumps operation. In general, the total back-reflection from the fibre line should not exceed about –23 dB.

To minimize the adverse effects of both back-reflection and loss it is advantageous to minimize the number of patch cords connecting the Raman pump module to the fibre line, and to ensure that those connectors that remain are as clean as possible and well connected. In some case, especially when the Raman pump power is higher than about 800 mW, connectors should be avoided altogether, and instead the Raman pump module should be directly spliced to the fibre line.

7.4 High pump power issues

In most applications of DRA, the total Raman pump power injected into the fibre line is above 400 mW, and in some applications can reach 1,2 W and above. Such high pump power has implications both with respect to laser safety, as well as possible damage to the fibre line.

7.4.1 Laser safety

Laser safety is a key issue in optical transmission systems, which are typically required to comply with class 1M hazard level requirements according to IEC 60825-2. To comply with a class 1M hazard level, it is necessary to keep power levels within the system below about 120 mW, or alternatively to provide automatic power reduction (APR) mechanisms that reduce power to below 120 mW, within a set time, in the case of an accidental connector opening or a fibre break. Further information and guidelines regarding the implementation of APR in optical communication systems can be found in ITU-T G.664.

Systems deploying DRA differ from conventional EDFA systems in two critical respects:

1) High pump power, almost always above the class 1M limit, is injected directly into the transmission line, thus mandating the use of APR mechanisms (In contrast, in EDFA's and other lumped amplifiers the high pump power remains enclosed within the amplifier and does not exit into the transmission line);

2) DRA generate ASE along the transmission line, meaning that even in the case of a fibre break, ASE power within the transmission band can still propagate along the system. This is especially problematic in the more common case of counter-propagating DRA, and can disrupts the conventional APR method based on loss of input signal commonly used in EDFA based systems.

One option to achieve APR in systems deploying DRA is to detect the presence of a modulated signal, such as an OSC, transmitted along the fibre link together with the data channels, or alternatively to detect a dedicated tone superimposed on one or more of the channels. In either case disappearance of the tone or modulation signifies a break in the fibre link, triggering APR. Another option is to use the level of ASE itself, typically outside the transmission band, as an indicator of a possible break in the fibre link.

7.4.2 Damage to the fibre line

Besides safety hazards due to human exposure to high laser power, another potential issue related to high pump power is damage to the fibre line itself, discussed in detail in IEC/TR 61292-4.

One potential source of damage is fibre fuse, which describes the propagation of a fibre ignition along the fibre in the presence of high optical power. It is shown that fibre fuse can occur in typical single mode transmission fibres if the optical power is above about 1,2 W, however, such high power in itself is not sufficient to ignite the fuse. The fuse itself can be ignited either due to an external source of heat, or due to high optical power propagating through a high loss point in the fibre line, such as a defective connector or sharp fibre bend. To avoid fibre fuse altogether it is common to limit optical power in normal installations below 1,2 W, which also applies to Raman pump power. Higher power is sometimes utilized In specialized highly controlled and regulated installation such as submarine fibre links.

A more commonly occurring source of damage is due to dirt or contamination on connector end-faces, which can cause permanent damage to a connector when high optical power is transmitted though it. In some cases optical power as low as 200 mW can damage a contaminated connector, which makes this source of damage particularly relevant to DRA. To reduce to a minimum the risk of connector damage, all connectors should be thoroughly cleaned and inspected when using DRA, and care should be taken to ensure that all connectors are correctly connected to adaptors. Under no circumstances should a connector be opened while high optical power is propagating through it.

8 Conclusions

In this technical report, we have reviewed DRA and its applications, and discussed performance parameters, possible test methods, and operational issues. The distributed nature and system dependence of the amplification in DRA means that commonly used OA performance parameters, test methods and operating procedures cannot be automatically applied to DRA. Thus, the overview provided in this technical report may form the base of future standards relating to the specifications, testing, and operation of DRA.

Bibliography

1) *Nonlinear Fibre Optics* G. Agrawal, Academic Press

2) *Raman Amplifiers for Telecommunications*, edited by M.N. Islam, Springer series in optical sciences

3) *Raman Amplification for Fibre Communications Systems*, Jake Bromage, J. of Lightwave Technology, Vol. 22, p. 79 (2004)

4) *Raman gain measurement in optical fibres*, S. Gray, in Symp. Optical Fibre Measurements, G.W. Day,D. L. Franzen, and P. A.Williams, Eds., 2000, NIST Special Publication 953, p. 151 (2000)

5) *An analysis of the improvements in OSNR from distributed Raman amplifiers using modern transmission fibres* Chris Fludger, Andrew Maroney, Nigel Jolley, and Robert Mears, Optical Fibre Communication Conference OFC 2000, paper FF2 (2000)

6) *Full characterization of modern transmission fibres for Raman amplified-based communication systems*, Shifeng Jiang, Bruno Bristiel, Yves Jaouën, Philippe Gallion, Erwan Pincemin and Sylvain Capouilliet, Optics Express, Vol. 15, p. 4883 (2007)

7) *Double Rayleigh Scattering Noise in Lumped and Distributed Raman Amplifiers,* Paola Parolari, Lucia Marazzi, Lorenzo Bernardini, and Mario Martinelli, J. of Lightwave Tech. Vol. 21, p. 2224 (2003)

8) *Experimental Determination of Variation of the Raman Gain Efficiency Coefficient with Fibre Mode Field Diameter and Effect on Raman Gain*, S.G. Farwell and C.R.S. Fludger, European Conference on Optical Communications, ECOC 2002, Vol. 2, p. 1-2 (2002)

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