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Edition 2.0 2023-01

TECHNICAL REPORT

Optical amplifiers –
Part 6: Distributed Raman amplification

colour inside

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Part 6: Distributed Raman amplification

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OPTICAL AMPLIFIERS –

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FOREWORD

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This second edition cancels and replaces the first edition published in 2010. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) correction of the formula for noise figure;
b) correction of errors in Figure 10.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
86C/1822/DTR	86C/1831/RVDTR

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

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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 document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document 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- withdrawn,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 many advantages that it offers to 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 transmission system in which it is deployed. Thus, a discrete amplifier is a unique and separate element with well-defined input and output ports, allowing rigorous specifications of the amplifier 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 transmission system in which a Raman amplifier is deployed.

This document provides an overview of DRA and its applications. It also provides a detailed discussion of the various performance characteristics related to DRA, as well as some of the methods that can be used to test these characteristics. Information is also provided on 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, relates to distributed Raman amplification (DRA). Its main purpose is to provide background material for future standards related to DRA, such as specifications, test methods and operating procedures. This document 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 new technology, and still rapidly evolving, some of the material in this document can become obsolete or irrelevant in a fairly short period of time. This document will be updated frequently to minimize this possibility.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.2 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

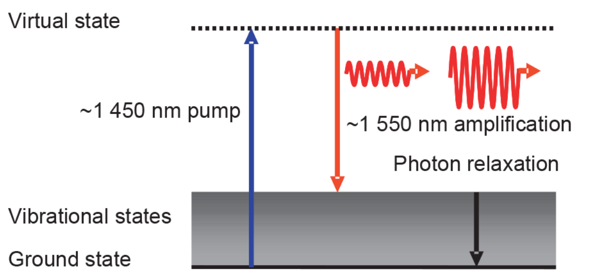
4.1 General

Clause 4 provides a brief introduction to the main concepts of Raman amplification. Further information can be found in IEC TR 61292-3 and ITU-T G.665 as well as in the Bibliography.

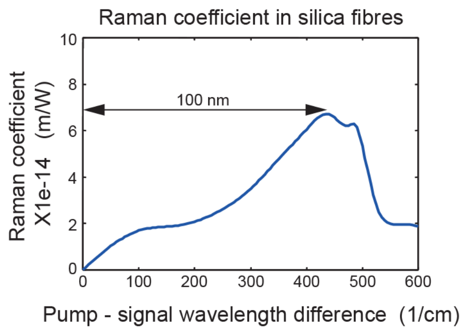
4.2 Raman amplification process

Raman scattering, first discovered by Sir Chandrasekhara Raman in 1928, describes an inelastic scattering process whereby light is scattered by matter molecules and transferred to a longer wavelength (lower energy). In this interaction between light and matter, a 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 longer wavelength.

Stimulated Raman scattering describes a similar process whereby the presence of a longer wavelength photon stimulates the scattering process, namely the absorption of the initial shorter wavelength photon, resulting in the emission of a second longer wavelength photon, thus providing amplification. This process is shown in Figure 1 a) 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 in Figure 1 b).



a) **Stimulated Raman scattering process**



b) **Raman gain spectrum for silica fibres**

Figure 1 – Stimulated Raman scattering process and Raman gain spectrum for silica fibres

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 6.3.2). Neglecting pump power depletion (i.e., small input signal regime), the on-off gain of a Raman amplifier can be approximated by

$$G = 4{,}34\, C_{\mathrm{R}}\, P\, L_{\mathrm{eff}}$$

where

G is the on-off gain (in dB);

C_{R} is the Raman efficiency between pump and signal;

P is the coupled pump power;

L_{eff} is the effective length of the fibre with respect to the Raman process, defined as

$$L_{\mathrm{eff}} \equiv \frac{1 - \mathrm{e}^{-\alpha_{\mathrm{p}} L}}{\alpha_{\mathrm{p}}}$$

where

α_{p} is the fibre attenuation coefficient at the pump wavelength.

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} can 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 $L_{eff} \approx \alpha_p^{-1} \approx 17$ km, a 500 mW pump provides approximately 15 dB of on-off gain, illustrating the low gain efficiency of the Raman process. The gain efficiency can be increased using highly non-linear fibre (such as DCF); however, a relatively long length of fibre (approximately 10 km) is still needed to achieve reasonably high 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 desired power level at the discrete site at the end of each span. This is illustrated graphically by the green curve in Figure 2. Raman amplifiers can also be used as discrete amplifiers. However, as shown in 4.2, this requires special highly non-linear fibres. Even then the application of such amplifiers is limited due to multi-path interference (to be discussed in 6.3.6), and other issues, and in most cases other lumped amplifiers, such as EDFAs, are preferable.

While most OFAs require a special doped fibre (such as Erbium doped fibre for EDFAs) to provide amplification, Raman amplification can occur in any fibre, and within the transmission fibre itself. This enables distributed Raman amplification (DRA), i.e., the process whereby the transmission fibre itself is pumped 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 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 a co-propagating ("forward") configuration, where the Raman pump power is introduced at the span input and propagates with the signal. The distinction between the two configurations is discussed in more detail in 4.5.

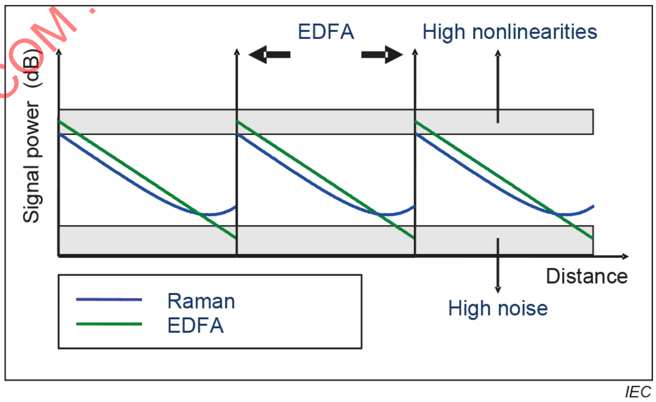


Figure 2 – Distributed vs. lumped amplification

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 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 6.2.4 and 6.3.4. The PDG can be further reduced by using two pumps with the same wavelength but with orthogonal polarization.

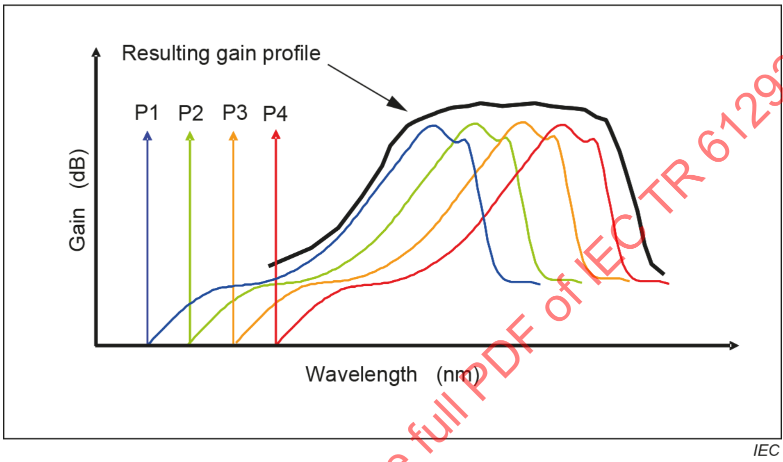
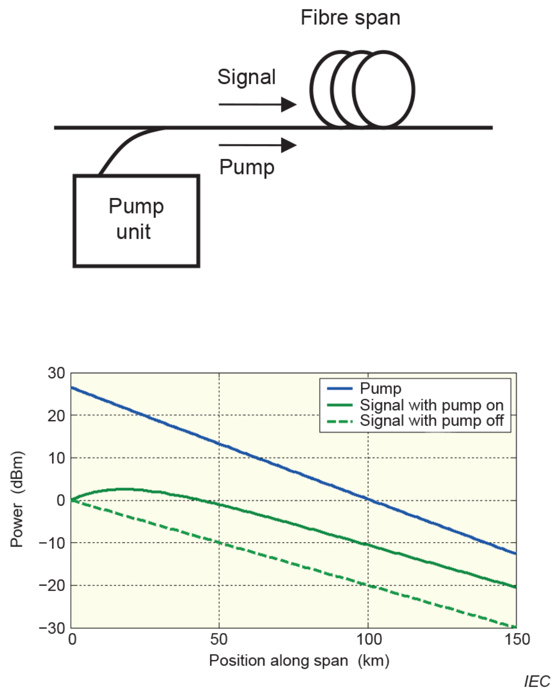


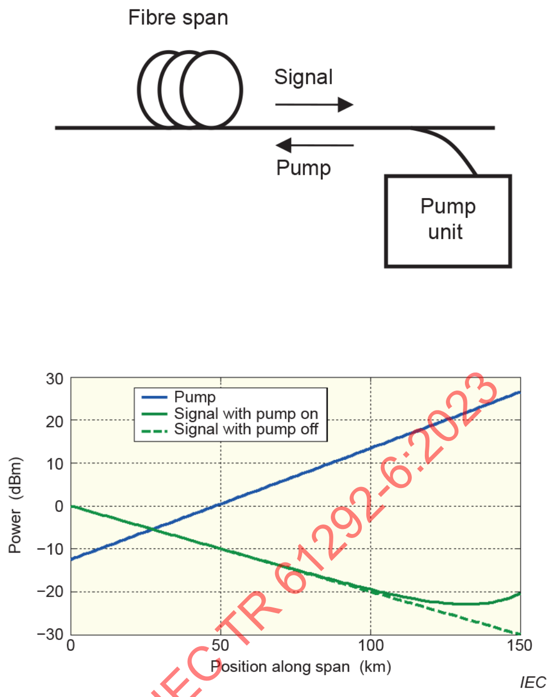
Figure 3 – The use of multiple pump wavelengths to achieve flat broadband gain

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 span input, 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.



a) **Forward pumping configuration**



b) **Backward pumping configuration**

NOTE Two pumps at different wavelengths 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

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 several 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 in 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 6.2.5.
- Pump depletion: As the composite signal input power increases, pump depletion occurs, resulting in the reduction of 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 EDFAs, 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.

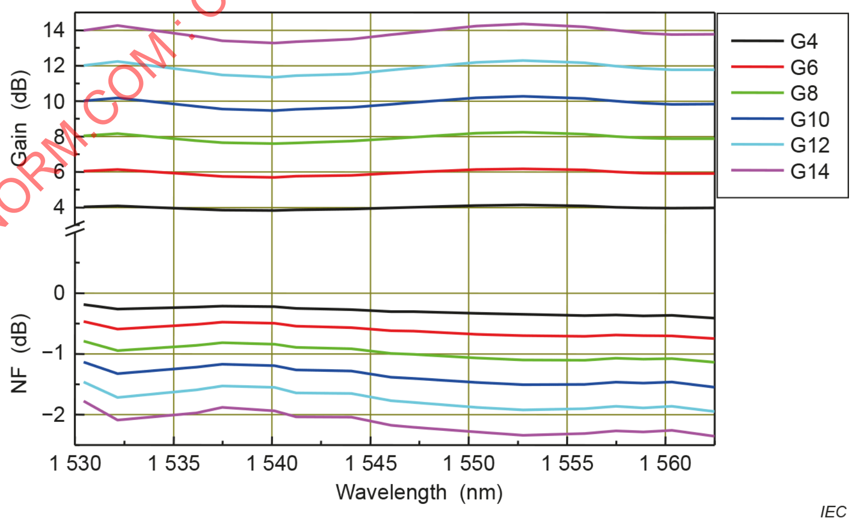
While the backward pumping configuration does not suffer from the above disadvantages, the OSNR improvement is typically more modest since the amplification occurs in the last few tens of km of the fibre span. For example, 10 dB of Raman gain in the backward configuration will typically result in about 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 dB 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 described 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). In this example, a gain of 10 dB is achieved with about 450 mW of composite pump power, and a gain of 14 dB with 650 mW pump power. Figure 5 also shows the equivalent noise figure (NF) 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 6.3.5 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 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 NF of about 5 dB for an EDFA, 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-based system.



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 like EDFAs. One advantage is improved system OSNR and the second is 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 optical pump powers, as well as by 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 Clause 5.

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 EDFAs. 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 for ultra-long haul (> 1 500 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 along the transmission fibre to provide approximately 20 dB of net gain. The 20 dB gain is achieved by 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 sufficient 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 (ROADMs), 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 can lead to increased MPI due to double Rayleigh backscattering (see 6.3.6). 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 limited to ultra-long-haul point-to-point (i.e., non-reconfigurable) optical links.

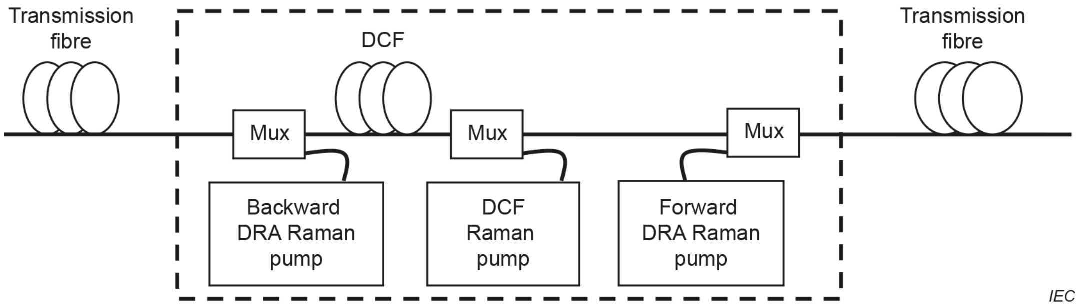


Figure 6 – Typical configuration of an amplification site in an all-Raman system

5.3 Hybrid EDFA Raman systems

5.3.1 General

EDFA based transmission systems are by far the most common optical communication systems in deployment today. EDFA technology is mature and can provide a cost effective and efficient solution for most common applications. However, there are some challenging applications for which EDFA technology is not sufficient. In these cases, DRA, and particularly backward DRA, can be employed to improve the end-to-end system OSNR.

The cost of adding DRA to EDFA based systems can be reduced by tightly integrating the Raman pump module with the EDFA and optimizing the overall design. This is particularly useful for long-haul and ultra-long-haul applications (see 5.3.4), where DRA is used in every span of the link. Integration and optimizing of the design can 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 amplifier (and reducing the number of separate Raman pumps). Due to the pre-amplifier function of the DRA, the GFF can be placed before the EDFA without significantly increasing the composite NF of the hybrid module, thus reducing the EDFA pump power.

In 5.3.2 to 5.3.4, applications for hybrid EDFA Raman systems are discussed.

5.3.2 Long repeaterless links

Long repeaterless links (> 150 km) have many applications, such as connecting islands or oil rigs, traversing hostile or inaccessible terrain, and links where repeater sites can 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 can 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 in addition to backward DRA. Assuming a system with a 20 dBm EDFA booster, for example, the addition of a 700 mW forward DRA pump module will provide ~8,5 dB Raman on-off gain. This corresponds to about 7 dB OSNR improvement (considering 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 OSNR can be increased by up to 13 dB compared to corresponding EDFA only systems.

5.3.3 Long span masking in multi-span links

Most multi-span links are typically constructed in such a way that in-line EDFA repeaters are placed after every 80 km to 100 km fibre span. However, geographical constraints can require individual spans to be longer, or practical considerations can be an incentive to reduce the number of spans and thus increase the length of one or more spans. In both cases, DRA can provide the extra OSNR margins needed 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 standard EDFAs in the system, thus increasing system flexibility and utility.

While repeaterless links, discussed in 5.3.2, tend to be static (i.e., non-reconfigurable) point-to-point links, multi-span links are most often dynamic and provide ROADM functionality. Therefore, by nature, such systems can 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.

5.3.4 High capacity long haul and ultra-long-haul systems

In high capacity systems (with high bit rate and/or dense channel spacing), 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

Clause 6 describes important performance parameters relevant to DRA and considers test 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 that are system dependent can be characterized on average for various types of transmission fibre, so that the expected performance of 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

6.2.1 Basic configuration

A Raman pump module typically consists of several Raman pump lasers together with passive components designed to multiplex the output of these pump lasers with the signal. The module can also contain detectors for monitoring pump power and signal power, as well as 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, which are two polarization multiplexed diodes at wavelength λ_1, and one laser diode at wavelength λ_2.

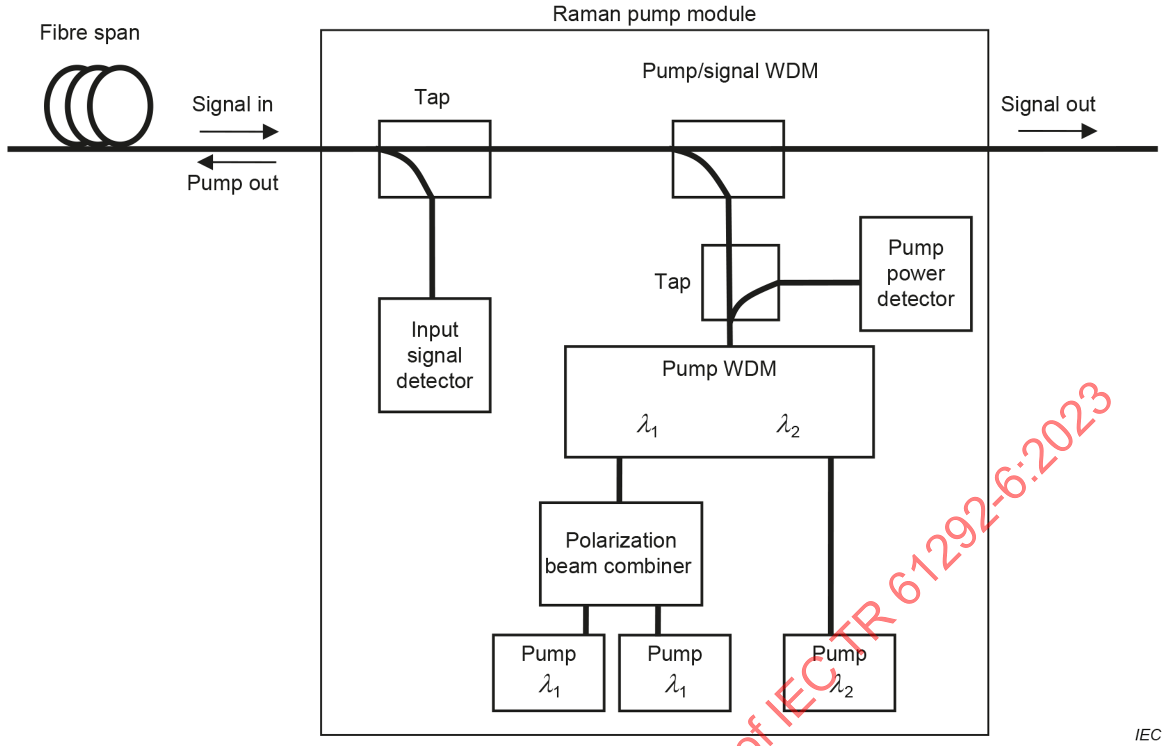


Figure 7 – Typical configuration of a Raman pump module used for counter-propagating DRA

6.2.2 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 can originate from one or more pump sources (as for wavelength λ_2 in the example shown in Figure 7). The pump spectrum 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 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.

6.2.3 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 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.

6.2.4 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 at a given pump wavelength, only the corresponding pumps within the pump module are activated, with the pump output 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 $\left(P_{max} - P_{min}\right)/\left(P_{max} + P_{min}\right)$, usually expressed in %. Thus, a DOP of 100 % corresponds to a fully polarized pump wavelength, and a DOP of 0 % corresponds to a fully depolarized pump signal.

6.2.5 Pump relative intensity noise (RIN)

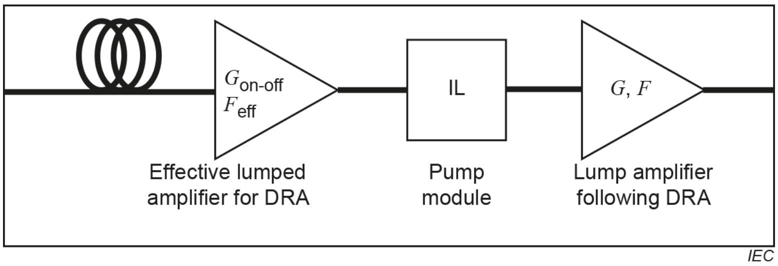
The RIN of a pump laser describes the intensity fluctuations of the laser output and is measured in units of dB/Hz. Thus, within a given bandwidth B, the relative variance σ^2 / P^2 of the intensity fluctuation of the laser power is given by $\sigma^2 / P^2 \equiv N_{RIN} \times B$, where P is the average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

The system effect of the Raman pump RIN depends on the magnitude of the RIN, and on the walk-off between the signal and pump, which determines the bandwidth of the fluctuations 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, so that the effect of pump RIN is negligible. In co-propagating DRAs, the walk-off between signal and pump can be small, depending on the fibre dispersion, so that the system effect of Raman pump RIN is not negligible.

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

6.2.6 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 into the signal out ports of the module. Thus, an important performance characteristic of the module is the insertion loss experienced by the signal, because it contributes to the overall noise performance of the DRA. For counter propagating DRA, the signal insertion loss can be modelled as shown in Figure 8. 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_{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 that lie outside the designated system transmission band. For example, the system can include an optical supervisory channel (OSC), often located at a wavelength of 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 is dropped or added within the Raman pump module itself; thus, the OSC insertion loss (or other relevant out of band insertion losses) needs to be measured between the relevant ports of the pump module, not necessarily between the signal-in and signal-out ports of the module.

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

6.2.7 Other passive characteristics

As noted in 6.2.6, 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 modules need to 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

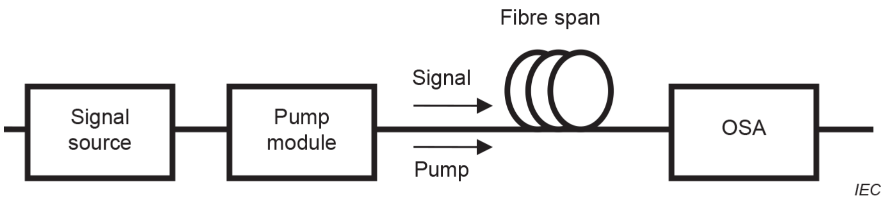
6.3.1 General

In 6.3, 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 conditions, such as type of transmission fibre, and appropriate system independent tests can be defined.

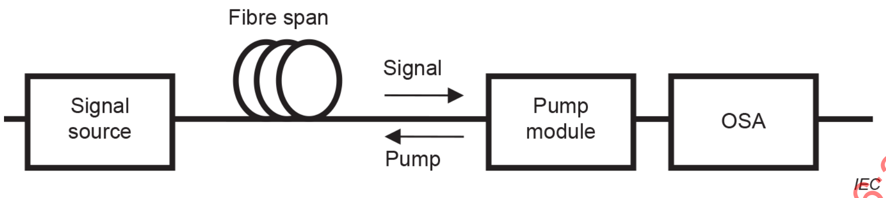
6.3.2 On-off signal gain

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 $G_{\text{on-off}} = S_{\text{on}} - S_{\text{off}}$, where $G_{\text{on-off}}$, S_{on} and S_{off} are expressed in dB.

A typical configuration used for measuring the on-off gain is shown in Figure 9 (a) for the case of co-propagating DRA and in Figure 9 (b) for 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 wavelengths 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 could 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).



a) **Co-propagating DRA**



b) **Counter-propagating DRA**

Figure 9 – Typical configuration used to measure on-off gain of DRA

A number of issues need 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, hence the gain. When measuring the typical on-off gain for a given fibre type, it is advantageous 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 needs to 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 cannot be too strong, to cause pump depletion. As a general rule, the signal source power is adjusted so that the total signal output power with the Raman pumps on, $\sum_{\lambda\text{'s}} S_{\text{on}}$, is 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. The on-off gain for any given wavelength therefore depends on the total signal input power (for all wavelengths), and needs to be characterized accordingly.

6.3.3 Gain flatness

Gain flatness characterizes the variation of the on-off signal gain over a relevant transmission band, like the C-Band (ranging from 1 529 nm to 1 564 nm). It is defined as the difference between the maximum and minimum on-off gain at different signal wavelengths within the band, measured as described in 6.3.2.

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

6.3.4 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 wavelengths are not depolarized.

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

6.3.5 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 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 $NF_{eq} = 10\log_{10}(2\rho_{ASE} / (G_{on\text{-}off}h\nu))$, where h is Planck's constant and $\nu = c / \lambda$ is the signal frequency (see IEC 61290-3).

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 needs to be accounted for in the measurement (since 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 a conventional EDFA. To translate this into OSNR system improvement, it is important to account for additional supplementary lumped amplification in the transmission system, as shown in Figure 8 (see 4.6).

6.3.6 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 extent, 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 various 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 allows fine tuning of the Raman pump powers to achieve a flat gain spectrum.

However, even if the transmission fibre type is known, variations approaching 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 considered in the link design or neutralized via an accurate gain measurement performed during deployment on the installed fibre.