IEC TR 61292-6

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REDLINE VERSION

TECHNICAL REPORT

colour inside

Optical amplifiers –
Part 6: Distributed Raman amplification

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FOREWORD

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

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- withdrawn,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 ~~it~~ 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 ~~may~~ 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

~~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.~~

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

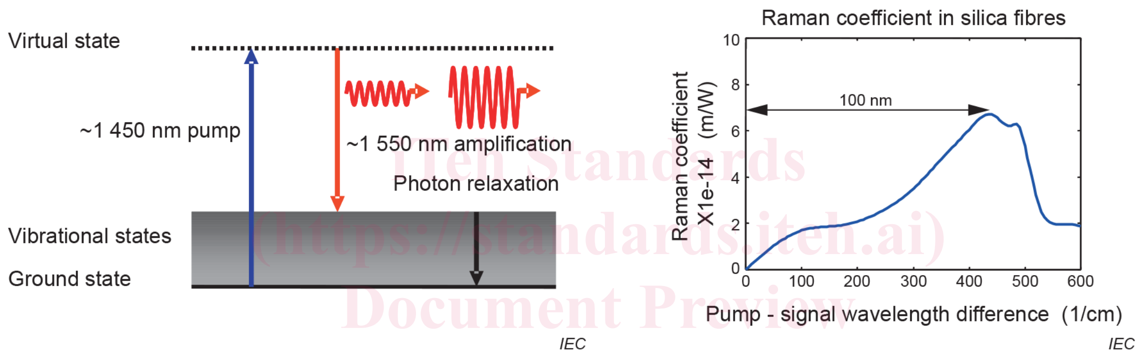
4.1 General

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 ~~higher~~ longer 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~~ longer wavelength.

Stimulated Raman scattering describes a similar process whereby the presence of a ~~higher~~ longer wavelength photon stimulates the scattering process, namely the absorption of the initial ~~lower~~ shorter wavelength photon, resulting in the emission of a second ~~higher~~ 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

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

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 ~~may~~ 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 $L_{\text{eff}} \approx \alpha_p^{-1} \approx 17$ 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 increased using highly non-linear fibre (such as DCF); however, a relatively long length of fibre (approximately 10 km) is still ~~required~~ needed to achieve ~~reasonable~~ 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 ~~required~~ 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 ~~may~~ 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 ~~in particular~~ 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 ~~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 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.

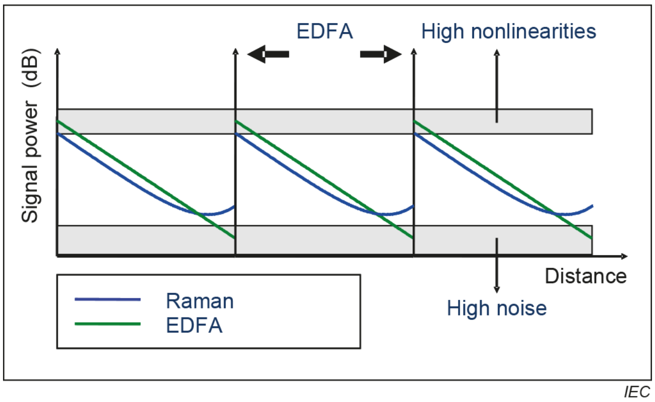


Figure 2 – Distributed vs. lumped amplification

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.

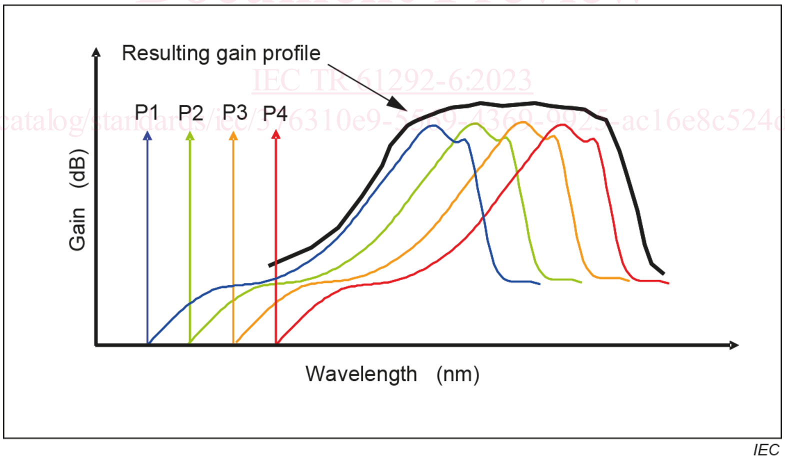
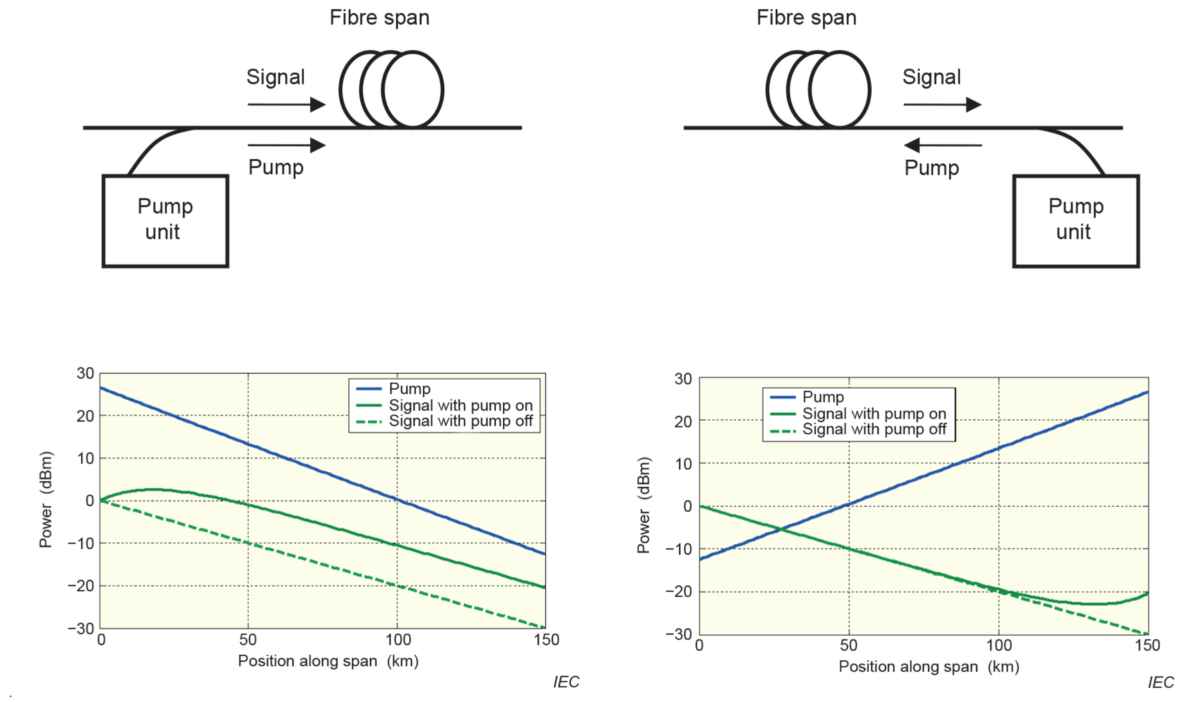


Figure 3 – The use of multiple pump wavelengths to achieve flat broadband gain

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.