IEC TR 61292-6

Edition 2.0 2023-01

TECHNICAL REPORT

colour inside

Optical amplifiers –
Part 6: Distributed Raman amplification

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CONTENTS

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OPTICAL AMPLIFIERS –

Part 6: Distributed Raman amplification

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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- withdrawn,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 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

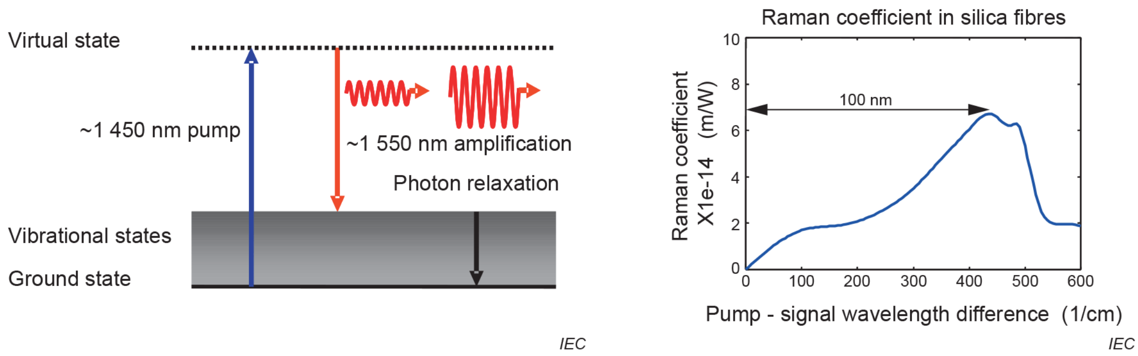
4.1 General

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

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

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

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

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 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.

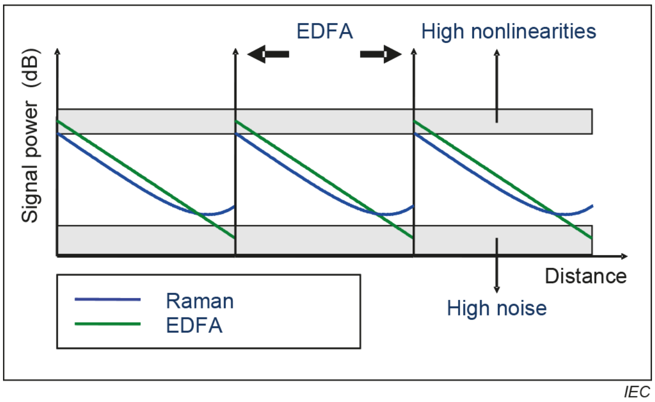


Figure 2 – Distributed vs. lumped amplification