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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- withdrawn,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
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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.

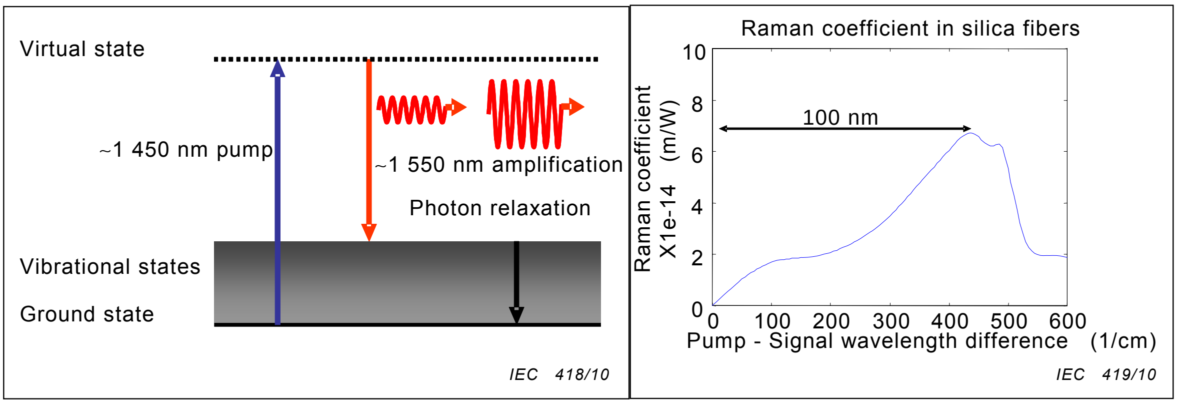

Figure 1 – Stimulated Raman scattering process (left) and Raman gain spectrum for silica fibres (right)

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 $L_{eff} \approx \alpha_p^{-1} \approx 17$ 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.

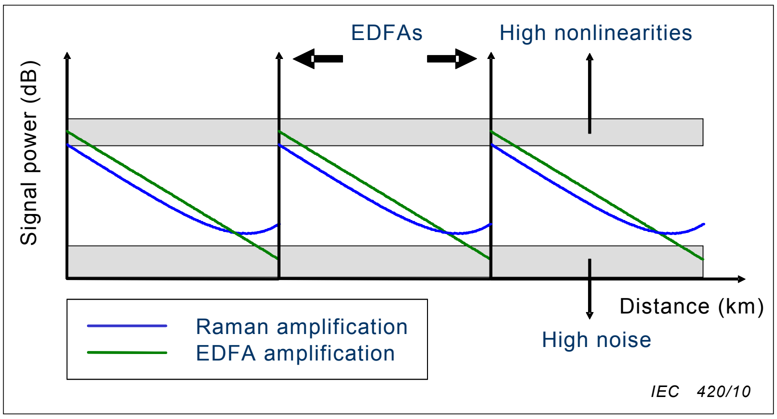

Figure 2 – Distributed vs. lumped amplification

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