TECHNICAL REPORT

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Second edition
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**Single-mode optical fibres –
Raman gain efficiency measurement
using continuous wave method –
Guidance**

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International Electrotechnical Commission, 3, rue de Varembé, PO Box 131, CH-1211 Geneva 20, Switzerland
Telephone: +41 22 919 02 11 Telefax: +41 22 919 03 00 E-mail: inmail@iec.ch Web: www.iec.ch

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SINGLE-MODE OPTICAL FIBRES – RAMAN GAIN EFFICIENCY MEASUREMENT USING CONTINUOUS WAVE METHOD – GUIDANCE

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

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IEC/TR 62324, which is a technical report, has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition published in 2003. It constitutes a technical revision.

This second edition differs from the first in that in the previous edition, in the paragraph before Figure 2, there was an approximation of the relationship between wavelength and optical frequency that led to some inconsistencies in interlaboratory agreement. This approximation has been removed.

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

Enquiry draft	Report on voting
86A/1058/DTR	86A/1072/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.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result 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.

A bilingual version of this publication may be issued at a later date.

SINGLE-MODE OPTICAL FIBRES – RAMAN GAIN EFFICIENCY MEASUREMENT USING CONTINUOUS WAVE METHOD – GUIDANCE

1 Scope and object

This technical report is applicable to the Raman gain efficiency measurement of a single-mode transmission optical fibre. It is useful in assessing the fibre's performance in Raman amplified transmission systems.

This technical report describes a method that uses two unmodulated continuous waves to measure the Raman gain efficiency of a single-mode transmission optical fibre. This parameter assesses the fibre's efficiency at converting input pump power to information signal power.

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 60793-1-22, *Optical fibres – Part 1-22: Measurement methods and test procedures – Length measurement*

IEC 60793-1-40, *Optical fibres – Part 1-40: Measurement methods and test procedures – Attenuation*

IEC 60825-1, *Safety of laser products – Part 1: Equipment classification, requirements and user's guide*

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

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
effective length
L_{eff}
the fibre's effective length accounts for decreasing nonlinear effects as light attenuates along a fibre's length, and is defined as:

$$L_{\text{eff}} = \frac{1 - e^{-0,23\alpha L}}{0,23\alpha} \qquad (1)$$

where α is the fibre attenuation coefficient in decibels per kilometre (dB/km), and L is the fibre length in kilometres (km).

NOTE 1 When the α in equation (1) is expressed in nepers per kilometre (Np/km), the two occurrences of 0,23 disappear, and the resultant equation is the form that typically appears in the technical literature.

NOTE 2 When 0,23αL >>1, equation (1) simplifies to give $L_{eff} \approx 1/(0{,}23\alpha)$, which is the length at which the power in the fibre has decreased by a factor of $1/e$. As an example, L_{eff} = 17,4 km when α = 0,25 dB/km.

3.2
depolarized light
light whose electric field vector, described in a plane perpendicular to the direction of propagation, is uniformly distributed in all radial directions

NOTE 1 Rotation of a polarizer in a beam of depolarized light reduces its intensity by 50% regardless of the polarizer's angular orientation. This test, however, is not sufficient to assess whether the light is depolarized because circularly polarized light produces the same result. To guard against this possibility, a rotatable quarter wave retarder should be inserted before the polarizer. If the output intensity is constant over all independent rotations of the retarder and the polarizer, the input light can be considered depolarized.

NOTE 2 Depolarized light is also termed unpolarized or randomly polarized.

4 Overview

When a fibre carries high optical intensities, the optical power can be scattered because of interactions with mechanical vibrations in the fibre. For low power levels, the scattered power is a small fraction of the incident power. However, as the incident power increases, the scattered power increases at a faster pace, and is said to be "stimulated". There are two forms of nonlinear stimulated scattering—Brillouin and Raman.

Stimulated Brillouin Scattering (SBS) arises because of an interaction between light and mechanical vibrations that occur in the form of a sound wave travelling along the length of the fibre (an "acoustic phonon"). SBS scatters light in the reverse direction.

Stimulated Raman Scattering (SRS) is an interaction between light and the fibre's molecular vibrations as adjacent atoms vibrate in opposite directions (an "optical phonon"). Some of the energy in an optical pump wave λ_p is transferred to the molecules, thereby further increasing the amplitude of their vibrations. If the vibrational amplitudes become large, a threshold is reached at which the local index of refraction changes. These local changes then scatter light in all directions—similar to Rayleigh scattering. However, unlike Rayleigh scattering, the wavelength of the Raman scattered light λ_R is shifted to longer wavelengths by an amount that corresponds to the vibrational frequencies of the molecules. The Raman scattered light amplifies information signals λ_s. The magnitude or gain efficiency of this amplification depends on:

- pump wavelength λ_p;
- signal wavelength λ_s;
- fibre effective area A_{eff} (the larger the area, the lower the power density);
- fibre material composition (vibration frequency and amplitude depend on material);
- fibre attenuation coefficient, and
- fibre length.

The Raman gain efficiency of a fibre varies with signal wavelength when measured with a specific pump source. Consequently, Raman gain efficiency $E_R(\lambda_s)$ is measured over a range of signal wavelengths. The peak Raman gain efficiency corresponds to a Stokes downshifted frequency of about 13 THz, which equates to an upshifted wavelength of ~110 nm for a 1 450 nm pump, and ~70 nm for a 1 240 nm pump. The Full Width Half Maximum (FWHM) of the gain profile is about 7 THz (55 nm) at 1 550 nm.

NOTE The notation "C_R" is often used in the technical literature, and is variously referred to as the "Raman gain coefficient"[1], the "Raman efficiency"[2], and the "Raman gain."[3] [1)]

1) Figures in square brackets refer to the Bibliography.

5 Method

5.1 Description

The method described in this technical report for measuring Raman gain efficiency uses unmodulated continuous waves generated by a signal source and a pump source. The signal source can be broadband (such as an LED or amplified spontaneous emission (ASE)) or narrowband (such as one or more tunable lasers). If using a broadband signal source, a tunable filter might be needed at the source's output so that short signal wavelengths do not pump longer signal wavelengths. To minimize the influence of a noisy pump or one whose output power is not completely depolarized, the measurement is made by injecting light from the signal and pump sources so that they propagate in opposite directions (counter propagation) in the fibre under test. The fibre has an effective length L_{eff}.

A pump source having wavelength λ_p injects optical power P_p into the fibre under test so as to induce stimulated Raman scattering. The pump power should be chosen to minimize ASE noise and amplified double Rayleigh backscattered signal power. Subclause 6.2 gives guidance on how to choose the pump power level and spectral width.

The pump-induced SRS in the fibre under test amplifies an input signal having wavelength λ_s, which is launched into the fibre under test in a direction opposite to that of the pump. Subclause 6.2 gives guidance on how to choose the signal power level and spectral width.

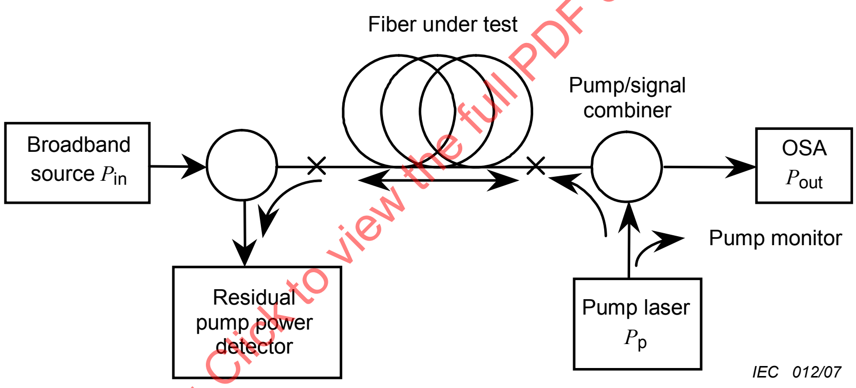

Figure 1 – Typical test set-up for measuring the Raman gain efficiency of a fibre

Figure 1 shows a typical test set-up. The output power P_{out} is measured in three configurations:

- P_1 – signal "on" and pump "off." This indicates the relative magnitude of the launched signal power diminished by the attenuation of the components. P_1 includes double Rayleigh backscattered power from the unamplified signal.
- P_2 – signal "off" and pump "on." This measures the ASE.
- P_3 – signal "on" and pump "on." This measures the Raman amplified signal, ASE, and double Rayleigh backscattered power from the amplified signal.

These three powers are measured over a range of signal wavelengths $\lambda_s > \lambda_p$. The "on/off" gain $G_{on/off}$ (λ_s) is then computed at each signal wavelength using:

$$G_{on/off}(\lambda_s) = \frac{P_3 - P_2}{P_1} \qquad (2)$$

where the Ps are in linear units, such as watts (W) or milliwatts (mW). The dimensionless quantity $G_{on/off}$ (λ_s) is used to compute the fibre's Raman gain efficiency for depolarized light:

$$E_R(\lambda_s) = \frac{\ln[G_{on/off}(\lambda_s)]}{P_p L_{eff}} \quad (3)$$

where P_p is the pump power launched into the fibre under test and expressed in watts. L_{eff} is the fibre effective length in kilometres computed at the pump wavelength. $E_R(\lambda_s)$ has the units of 1/(W·km).

Because $E_R(\lambda_s)$ is obtained for a range of signal wavelengths, $E_R(\lambda_s)$ can be plotted versus $\delta\lambda = \lambda_s - \lambda_p$, or alternatively, versus $\delta f = f_p - f_s$ where f_p and f_s are the optical frequencies of the pump and signal waves, respectively (see Figure 2).

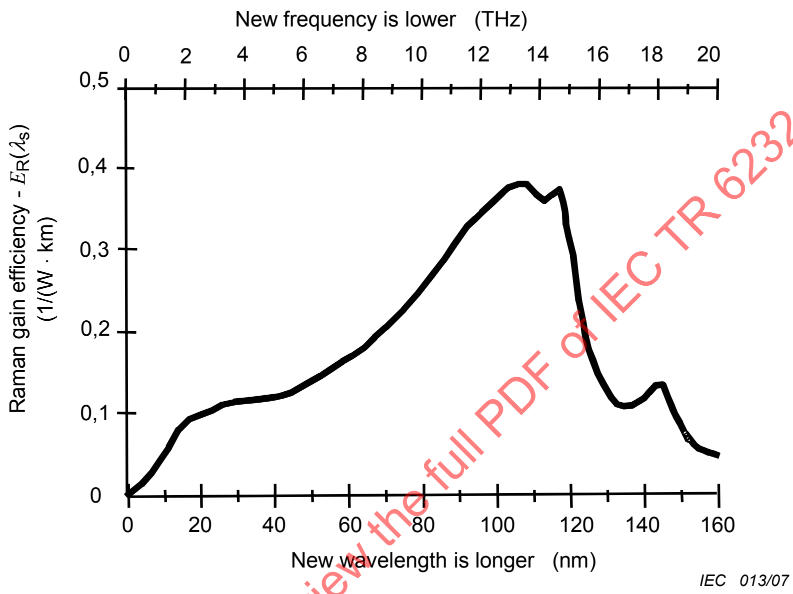

Figure 2 – Raman gain efficiency of depolarized light for a dispersion-unshifted fibre pumped at 1 486 nm [4]

5.2 Laser safety

The safety procedures in IEC 60825-1 and IEC 60825-2 shall be observed when using high optical powers.

6 Apparatus

Figure 1 shows a schematic diagram of a typical test apparatus.

6.1 Optical pump source

Because the measured Raman efficiency can vary by at least a factor of two depending on the orientation of the pump polarization relative to the signal polarization, the optical pump source P_p is a depolarized laser with a degree of polarization (DOP) less than 10 %. Such lasers are readily available commercially. Its wavelength λ_p remains fixed during the measurement. If the pump contains several narrow spectral lines, the pump wavelength is defined as the centroid, which is a weighted average of the power.

The pump power at which SBS occurs increases with the pump's spectral width. The pump's spectral width should be wide enough (about 1 nm) to suppress SBS, but not wider than what is normally achieved with a wavelength locking filter used with the pump. Although multiple pump lasers, each at a different wavelength, are typically combined and used when constructing Raman amplifiers, multiple pumps at different wavelengths should not be used when measuring the Raman efficiency of a fibre. Such a configuration can substantially alter the measurement results. The Raman efficiency obtained using a single pump can be used with a model of various physical processes (such as, pump-to-pump power transfer, signal-to-signal power transfer, pump depletion, and double Rayleigh scattering) to design practical discrete and distributed Raman amplifiers. [5]

The pump laser should be able to launch enough power (typically 200 mW to 300 mW) [6] into the fibre under test so as to induce SRS while at the same time minimizing ASE noise and amplified double Rayleigh backscattered signal power. ASE noise is too high if P_2 is close to the magnitude of P_1. This condition produces large errors when subtracting the two powers in Equation (2). A method for assessing when double Rayleigh backscattered power becomes a problem is under study. [7]

The optical power levels associated with the pump are high enough to damage connectors and other optical components, such as circulators. The potential for damage can be reduced by keeping the connectors clean, and by not making or breaking connections while they are carrying high optical powers.

6.2 Optical signal source

The optical signal may be either a broadband source (as shown in Figure 1) or several tunable lasers. The use of laser diodes can introduce interference effects because of their coherence.

The signal source should emit wavelengths over a range beginning approximately at the pump wavelength λ_p (f_p) and extending to at least λ_p + 160 nm (f_p–20 THz).

Because the intent is to measure the small-signal Raman gain of the fibre under test, the power of the input signal P_s is chosen as a compromise. The maximum signal power should be low enough so that it does not saturate the Raman amplifying ability (produce pump depletion) of the fibre under test, nor generate stimulated Brillouin scattering. Saturation can be determined by measuring P_3 for several input signal power levels P_s. Saturation exists if P_3 does not appreciably change when varying P_s. Alternatively, pump depletion is insignificant if the residual pump power (observed when monitoring it as shown in Figure 1) remains constant as the signal source is turned on and off.

The minimum signal power should be high enough that the amplified signal can be precisely measured at the output in the presence of background ASE. A typical signal power might be 0,2 mW at the signal wavelength.

SBS is usually not a problem when using a broadband signal source. For a fibre whose length is longer than its effective length (~22 km at 1 550 nm), the Brillouin threshold is given by: [8],[9]

$$P_B \approx \frac{42 A_{eff}}{g_B L_{eff}} \left(1 + \frac{\Delta \nu_s}{\Delta \nu_B} \right) \tag{4}$$

where:

P_B = Brillouin threshold power;

g_B = peak value of the Brillouin gain coefficient (~4×10^{-9} cm/W);

A_{eff} = effective area;

L_{eff} = effective length;

$\Delta\nu_s$ = spectral width of the input signal source;

$\Delta\nu_B$ = spectral width of the Brillouin gain coefficient (~40 MHz).

6.3 Optical signal conditioning

Various combiners, such as couplers, WDM devices, and circulators can be used to couple the output of the pump and signal sources into the fibre under test. Figure 1 shows one possible implementation. The devices should be capable of operating over the wavelength range of interest.

6.4 Power meter

If the signal source consists of one or more tunable lasers, P_{out} (Figure 1) can be measured with a power meter instead of an optical spectrum analyzer. In this case, when measuring P_2 and P_3, the power meter detects all the ASE power instead of only the ASE in the spectral band near the signal wavelength. This will not pose a problem for small ASE.

6.5 Optical spectrum analyzer

If the signal source is broadband, P_{out} can be measured with an optical spectrum analyzer (OSA). The OSA's resolution should be sufficient to clearly resolve the fibre's SRS gain peak (see Figure 2).

6.6 Examples

The various measurement tradeoffs allow many combinations of parameters that meet the criteria set forth in this test method. Table 1 illustrates some examples that have been successfully used to measure the SRS gain efficiency in C-Band (1 530 nm to 1 565 nm).

Table 1 – Examples of parameters for measuring Raman efficiency

Example number	Pump wavelength λ_p nm	Pump power in fibre under test mW	Single-mode fibre category	Fibre Length km	Effective area µm²	Peak efficiency E_R 1/W·km
1 [6]	1 455	–	B1.1	13,2	80	0,38
2 [2]	1 400	250	B1.1	23,3	83	0,45

7 Sampling and specimens

7.1 Specimen endfaces

Prepare flat endfaces at the input and output ends of the specimen. If power levels are sufficiently high to damage the endfaces, fusion splicing may be necessary.

7.2 Specimen length

The length of the fibre specimen shall be measured according to IEC 60793-1-22 or a suitable equivalent test method.

7.3 Length selection

The upper limit and lower limits on the length of the test fibre are set by the ability to obtain reliable on/off gain measurements.

7.4 Specimen attenuation coefficient

The attenuation coefficient of the fibre specimen shall be measured according to IEC 60793-1-40 or a suitable equivalent test method.