TECHNICAL REPORT

IEC TR 61282-4

First edition
2003-06

Fibre optic communication system design guides –

Part 4: Accommodation and utilization of non-linear effects

Guides de conception des systèmes de communication à fibres optiques –

Partie 4: Adaptation et utilisation des effets non linéaires

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 4: Accommodation and utilization of non-linear effects

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the 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, the IEC publishes International Standards. 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. The 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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Technical reports do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful by the maintenance team.

IEC 61282-4, which is a technical report, has been prepared by subcommittee 86C: Fibre optic subsystems 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/389/DTR	86C/446A/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 2010. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 4: Accommodation and utilization of non-linear effects

1 General

1.1 Scope

This part of IEC 61282, which is a technical report, is intended to describe physically and analytically non-linear effects in fibre optic systems, their impact on system performance, ways of minimizing the effects or using them to advantage, and methods of measuring and quantifying them. It contains some of ITU-T Recommendation G.663 [1][1] with additional material. More details on applications are considered in [2] and networks in [3].

1.2 System trends leading to non-linear effects

The market demand for new advanced telecommunications services has driven the rapid increase of system bandwidth, and, for some applications, longer system distances.

Greater bandwidth has been addressed in two ways. One way is by increasing the channel bit-rate, accomplished with optoelectronic time-division multiplexing (TDM) and various types of signal encoding. Another way is by increasing the number of channels, accomplished with channel multiplexing, such as polarization division multiplexing or (more commonly) by dense wavelength division multiplexing (DWDM). Bandwidth limitations of the optical fibre cable can be overcome with various dispersion management techniques.

Longer distances, defined to be the optical path lengths between 3R regenerators, can be achieved by two methods. One method is by increasing the span length, where a span is defined to be the optical path between optical amplifiers (OAs). A longer span length may be attained with fibre cable of lower attenuation coefficient and with fibre optic passive components having lower loss. The span length may also be increased with increased launched channel power from the output of the OA at the beginning of the span or with lower allowed power at the input of the OA at the end of the span. Another method of increasing the optical path length is to increase the number of spans. This increases the number of OAs, but improvements can be limited by amplifier noise degradation.

There are a number of interactive trade-offs in system design. For example, increasing the bit-rate reduces the span length by requiring higher received power or by requiring lower link dispersion. The latter may be addressed by dispersion compensation, but this introduces losses. Increasing the number of channels in DWDM systems also reduces span length due to optical multiplexing and demultiplexing losses. The loss limitations of a span can be overcome with OAs, but these introduce noise.

1.3 Optical amplifiers and non-linearities

An OA accepts a modulated signal at its input and emits an essentially identically shaped signal at its output. However, the optical power is higher (desired), and there is some additional noise (not desired). This technical report is concerned with the effects of higher power on the fibre and the implications for system design. These non-linear effects are so-called because they are not linearly proportional to launched power into the fibre or to the fibre length in either absolute units or in dB units. They are affected primarily by characteristics of the optical signal (power, optical spectrum, modulation, state of polarization), of the optical fibre (effective area, effective length, gain coefficients, non-linear index, dispersion, dispersion slope, polarization

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[1] Figures in square brackets refer to the bibliography.

mode dispersion), and of system aspects such as distance between regenerators and the number and spacing of channels in DWDM systems. Power levels as low as several mW can induce non-linear effects.

One class of non-linear effects is stimulated scattering of the signal. Stimulated Brillouin scattering limits the power transmitted through the fibre by scattering some light backwards in the fibre. Stimulated Raman scattering mainly causes forward crosstalk in a DWDM system.

Another class of non-linear effects is phase-shifting of the signal. This leads to self-phase modulation and modulation instability that produce distortion even on a single channel, or to cross-phase modulation and four-wave mixing that introduce interference between channels. These interact with chromatic dispersion to degrade or enhance system performance. Soliton formation is another related effect.

1.4 Background and notation

1.4.1 Wavelength and frequency

These simple concepts are essential in discussing advanced optical transmission systems. One can interchangeably talk about the vacuum wavelength λ in nm and optical frequency ν in THz (10^{12} Hz or 1 000 GHz). The optical frequency is not to be confused with the signal modulation frequency f or the signal bit-rate B. By using the speed of light in a vacuum c, one can change between wavelength and frequency through the fundamental relation

$$\lambda(\text{nm}) \times \nu(\text{THz}) = c(\text{nm/ps}) \quad \text{where} \quad c \approx 299{,}792{,}458 \text{ nm/ps} \tag{1}$$

The fundamental mode of a single-mode fibre has a phase (refractive) index n, which is dimensionless, with a value around 1,46 in silica fibre. It decreases as the wavelength of light increases, and details depend upon the refractive index profile of the fibre and the characteristic of the fundamental mode. The wavelength of light in a fibre decreases to $\frac{\lambda}{n}$ and the speed of the light decreases to $\frac{c}{n}$, but the light's frequency ν does not change.

Examples of the wavelength/frequency correspondence from Equation (1) are shown in the two left columns of Table 1 for several significant wavelengths of interest. Note that as the (vacuum) wavelength increases, the frequency decreases.

For DWDM systems it is important to be able to relate wavelength and frequency in terms of differences. These differences describe channel widths and separations. From Equation (1), two wavelengths separated by $\Delta\lambda$ may be related to the frequency separation $\Delta\nu$ by

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta\nu}{\nu} \tag{2}$$

The fractional changes in wavelength and frequency are the same, though of opposite sign (important in later discussions of chirp). This can also be written as

$$-\frac{\Delta\lambda}{\Delta\nu} = \frac{\lambda^2}{c} = \frac{c}{\nu^2} \tag{3}$$

and examples of the correspondence in wavelength and frequency spreads are shown in the two right columns of Table 1. For a communications engineer, dealing in frequency, which is related to information content, is more natural than dealing with wavelength. Note that a constant frequency spread has a larger wavelength spread at longer wavelengths.

It is sometimes convenient to use the notation $\beta(\omega) = \frac{2\pi}{\lambda} n(\omega)$ for the propagation wave number in the material. It depends upon the circular frequency $\omega = 2\pi\nu$, so Equation (1) is

$$\omega n(\omega) = c\beta(\omega) \quad (4)$$

1.4.2 Various velocities

It is important to distinguish between two types of velocities in optical fibre. The phase of an optical wave, as written in $e^{i\phi}$, is

$$\phi = \beta z - \omega t = 2\pi\left(\frac{nz}{\lambda} - \nu t\right) \quad (5)$$

where

z is the distance along the fibre; and

t is time.

For a point of constant phase along the optical wave, $d\phi = 0 = \beta dz - \omega dt$, so ${}^{dz}/_{dt}$ is the phase velocity (actually "speed") given by

$$v_p = \frac{\omega}{\beta(\omega)} = \frac{c}{n(\nu)} \quad (6)$$

Table 1 – Correspondence of wavelength and frequency

Wavelength nm	**Frequency** THz	**1 nm spread** GHz	**100 GHz spread** nm
1 260,000 (nominal lower limit due to cut-off)	237,931	188,8	0,530
1 310,000 (nominal zero dispersion for category B1 fibre)	228,849	174,7	0,572
1 395,000 (nominal water peak)	214,905	154,1	0,649
1 550,000 (nominal zero dispersion for category B2 fibre)	193,414	124,8	0,801
1 552,524 (ITU grid reference)	193,100	124,4	0,804
1 625,000 (nominal upper limit due to attenuation)	184,448	113,5	0,881

Although the optical subcarrier travels at the phase velocity, this is not the primary interest of a communications engineer. The subcarrier is modulated to produce an analogue or digital signal. The more slowly varying signal envelope and its associated energy travel at the group velocity.

$$v_g = \left(\frac{d\beta}{d\omega}\right)^{-1} = \frac{c}{N} \quad (7)$$

is the group velocity. Here

$$N = n - \lambda \frac{\mathrm{d}n}{\mathrm{d}\lambda} = n + \upsilon \frac{\mathrm{d}n}{\mathrm{d}\upsilon} \tag{8}$$

is the group index. (For silica fibre in the wavelength regions of interest, this is slightly larger than the phase index because the wavelength derivative is positive.) These "group" quantities describe the speed at which energy and information (such as pulses) travel down the fibre. Also, this index is the appropriate one for the pulses generated by an optical time-domain reflectometer (OTDR). The group index can easily be measured as the time delay of a pulse or the phase shift of an RF modulation, both for a known physical length of fibre.

1.4.3 Chromatic dispersion

The chromatic dispersion coefficient is defined as the wavelength variation of the group delay per unit fibre length:

$$D(\lambda) = \frac{\mathrm{d}v_g^{-1}}{\mathrm{d}\lambda} = \frac{1}{c}\frac{\mathrm{d}N}{\mathrm{d}\lambda} = -\frac{\lambda \mathrm{d}^2 n}{c\,\mathrm{d}\lambda^2} - \frac{2\pi c}{\lambda^2}\frac{\mathrm{d}^2\beta}{\mathrm{d}\omega^2} \tag{9}$$

The dispersion-slope coefficient is the derivative

$$S(\lambda) = \frac{\mathrm{d}D}{\mathrm{d}\lambda} = \frac{4\pi c}{\lambda^3}\frac{\mathrm{d}^2\beta}{\mathrm{d}\omega^2} + \left(\frac{2\pi c}{\lambda^2}\right)^2 \frac{\mathrm{d}^3\beta}{\mathrm{d}\omega^3} \tag{10}$$

1.4.4 Fibre types

The various types of category B single-mode fibre according to IEC 60793-1 and IEC 60793-2 have nominally similar attenuation coefficients. They differ primarily in their dispersion coefficients and mode-field diameters (or effective areas, as applied to non-linear effects). In the 1 550 nm region, category B1 (dispersion-non-shifted) fibre has a positive dispersion coefficient that averages at about 17 ps/nm-km. Category B2 (dispersion-shifted) fibre has a zero dispersion point in this region, whereas category B4 (non-zero-dispersion) fibre has a small positive or negative dispersion in this region. The dispersion slope of these fibres may be important for DWDM applications. The effective area of category B1 fibre is generally larger than for the other two types.

1.5 General optical non-linearities

These effects have been studied since the 1970s in fibres and were induced in the laboratory by injecting the light from high-power lasers into the fibre. Now they are of practical importance to communications engineers since such powers are found in systems at the output of OAs, both optical fibre amplifiers (OFAs) and semiconductor optical amplifiers (SOAs).

Consider two lightwaves of the same polarization co-propagating along the fibre. The electric field E_1 of one wave is affected by the "pump" optical power $|E_2|^2$ of the other wave. After an incremental length dL of propagation, the first wave grows approximately as

$$E_1(z + \mathrm{d}z, \mathrm{d}t) = E_1(z,t)\exp\left\{i(\beta\,\mathrm{d}z - \omega\,\mathrm{d}t) + \frac{1}{2}\left[-\alpha + \frac{\gamma}{A_{\mathrm{eff}}}|E_2(L)|^2\right]\mathrm{d}z\right\} \tag{11}$$

Compared to the phase of Equation (5), attenuation and gain are included. The second signal E_2 loses power by being converted to another wavelength and by attenuation. Here

- α is the attenuation coefficient in Np/km appropriate to the exponential notation. Relating this to $\log_{10}$ notation, 1 Np is about 4 343 dB.

- A_{eff} is the effective area of the fibre cross-section over which the integrated non-linear interaction takes place. It can be slightly different (usually larger) than the area calculated using the mode-field diameter (MFD) [4] because the field intensities are weighted differently in the two calculations. The effective area ranges from above 85 μm^2 for IEC category B1 fibre, to about 60 μm^2 for category B2 fibre, to below 25 μm^2 for dispersion compensating fibre (DCF). Smaller effective areas generally lead to larger non-linear effects.
- $L_{\text{eff}} = \dfrac{1-e^{-\alpha L}}{\alpha}$ is the effective length of fibre over which the integrated non-linear interaction takes place. It equals the fibre length only for short fibre lengths over which no significant attenuation has taken place, but is less than the full fibre length because of the reduced non-linear power levels with distance. For long lengths this approaches $1/\alpha$, which is approximately 12,4 km at 1 310 nm (for 0,35 dB/km) and 19,7 km at 1 550 nm (for 0,22 dB/km). These are the maximum distances over which non-linear effects occur; beyond these, the power levels causing them are low and have diminishing effect.
- y is the non-linear coefficient. If it is real and positive, it corresponds to a gain, or to a loss if it is negative, and it is due to scattering of photons with phonons (mechanical vibrations in the silica), producing heat. If it is imaginary, it is effectively a change in the phase index, the Kerr effect. Both are discussed in some detail below.

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 (all parts), *Optical fibres – Part 1: Measurement methods and test procedures*

IEC 60793-2 (all parts), *Optical fibres – Part 2: Product specifications*

IEC 61292-3, *Optical amplifier technical reports – Part 3: Classification, characteristics and applications of optical amplifiers*[1]

3 Optical non-linearities based on scattering

3.1 General description of scattering

In modern low-loss silica fibre, the spectral attenuation coefficient is “linear” in the sense of dB/km. Intrinsic absorption occurs mainly in the ultraviolet region below 500 nm, and in the infrared region above 1 650 nm. The only significant “impurity” absorption that may exist in some fibres is due to some “water” content that results in an absorption band beginning at a wavelength as low as 1 360 nm, peaking at about 1 385 nm, and extending as high as 1 430 nm, depending upon the level of OH^- ion in the fibre.

Otherwise, the dominant attenuation mechanism is Rayleigh scattering in which photons change direction due to interacting with molecular density fluctuations in the silica. (Those that scatter in other than the forward direction are “lost”. However, captured backward scattering is the useful principle behind OTDRs.) In this elastic scattering, there is a change in the photon momentum direction, but no energy transfer to other photon or to phonons, so the frequencies (and wavelengths) of the input and output light are not changed.

1 To be published.

By contrast, there is inelastic scattering in which a "pump" light photon of the incident signal interacts with a vibrational phonon in the fibre, with an energy transfer. One result is a new phonon to preserve the overall energy and momentum. Another result is a new signal photon, either a Stokes photon downshifted in energy (and frequency) by the Stokes frequency, or a new anti-Stokes photon upshifted in frequency for photons in some directions. This additional photon may be an undesired second "signal". Thermal equilibrium and momentum conservation dictate that Stokes (rather than anti-Stokes) photons predominate, bound in either the forward or backward directions of the fibre.

Below a low-input pump power threshold, the output optical power is proportional to the input, and the process is "linear". At higher incident powers above threshold, however, the Stokes and anti-Stokes powers grow more rapidly than the incident power. This "stimulated" scattering is non-linear.

To understand the physical process involved, it is useful to write down a couple of equations. Use the notation I for light intensity (power divided by effective area), g for the gain coefficient, and α for the attenuation coefficient; all these quantities are a function of the frequency ν. The number of photons in the beam is proportional to the intensity divided by the energy per photon or proportional to I/ν. In the equations, subscripts P, S denote parameters for the pump (signal) and Stokes waves, respectively.

Along the distance z of the fibre, the generated longer wavelength Stokes light increases due to gain from the pump and it decreases due to attenuation. The net fractional increase of Stokes light per length is expressed by

$$\frac{dI_s}{I_s\,dz} = gI_P - \alpha_S \qquad (12)$$

In the same way the incident shorter wavelength pump light decreases due to fibre attenuation and decreases also due to conversion into Stokes light as expressed by the fractional decrease per length

$$\frac{dI_P}{I_P\,dz} = \frac{\nu_P}{\nu_S} gI_S - \alpha_P \qquad (13)$$

The frequency ratio in front of the gain coefficient g arises from a careful photon count. The term represents an additional pump attenuation due to the Stokes gain.

The spectral shape of the gain is characteristic of the fibre materials and the type of phonons involved, and it varies with the pump wavelength. It can be roughly described in terms of a peak strength value g, a peak Stokes frequency by which the Stokes photon is downshifted from the signal pump frequency, and a full width at half-maximum (FWHM) $\Delta\nu$ in frequency related to the phonon attenuation and lifetime. The efficiency of the gain process depends on the overlap of the transmitter source pump spectrum with the gain spectrum.

The solution of these coupled equations needs to be integrated over the gain frequency spectrum, and the result is not simple, especially when time-dependent pulses are included. It shows that the "stimulated" aspect occurs when the incident pump light intensity exceeds a threshold high enough to increase the phonon population and the probability of scattering into the "non-linear" regime. This leads to exponential growth of the Stokes light along the fibre length, and is a form of optical amplification. The source-fibre gain is defined as ratio $I_S(L)/I_S(0)$ of output over input Stokes intensities. At very high pump intensities more pump depletion occurs, and this gain saturates to a near-constant value.

Now consider the two types of phonons involved in photon interactions that lead to non-linear effects. These result in two basic types of non-linear stimulated scattering.

3.2 Stimulated Brillouin scattering (SBS)

3.2.1 Phenomenon

Here a signal pump photon interacts with a longitudinal (acoustic) phonon. This interaction of light and sound waves produces density variations in the refractive index and hence causes light scattering. The gain FWHM $\Delta\nu_B$ ranges from 20 MHz to 50 MHz (only about 3×10^{-4} nm) depending upon the fibre details. The strength g_B of the gain peak is about $4{,}5 \times 10^{-17}$ km/mW, and it occurs at a frequency offset

$$\nu_B = \frac{2nV_S}{\lambda} \tag{14}$$

where V_S is the speed of sound in the fibre. This corresponds to a rather small Stokes downshifting of about 11 GHz (0,088 nm upshifting) at 1 550 nm, or 13 GHz (0,104 nm) at 1 310 nm. (This means that the attenuation coefficients and frequencies for both photons in Equations (12) and (13) are nearly equal to each other.) There is no consequence here for crosstalk of current DWDM systems, so the effect is independent of the number of wavelength channels. Compared with the incident photons, the scattered photons are guided in the backward direction.

3.2.2 Effects

The practical effects of SBS are as follows.

- Light is backscattered toward the transmitter as occurs with ordinary Rayleigh scattering, but with a higher intensity since SBS is a stimulated process. This can cause instabilities in the optical source. A high-speed Tx typically has a built-in isolator that serves to block light back into the source, thereby eliminating the problem.
- Light is backscattered from every fibre span in an amplifier in a chain. However, SBS does not accumulate in the reverse direction along such a link because isolators are usually built into every OA.
- The backward light can be reflected by a point discontinuity back into the forward direction and added as noise to the received signal. In practice, this is not a problem if reflectances along a link are kept small.
- In bidirectional transmission over one fibre, the backward scattering will interfere with the “forward” direction of the other channel. Again, OA isolators help here, or two-wavelength transmission can be used.
- Associated with the scattered power is intensity noise. This is particularly serious with AM-VSB.
- Finally, the backscattered light depletes the signal power and limits the amount transmitted in the forward direction.

Some primary effects of SBS are shown in Figure 3 for a particular fibre; other fibre types will have qualitatively similar behaviour, but with quantitatively different power levels. Very low levels of Stokes backscatter power occur at even very low levels of input signal pump power. Above about 8 dBm (5 mW) of input power for this fibre, the scattered power is about –20 dBm, and the forward transmitted power is noticeably no longer proportional to the input. The forward and backward power cross over at the input threshold pump power of about 10 dBm, and at a high input power of about 20 dBm the transmitter power saturates at about 10 dBm. The rest of the power is backscattered, wasted and sometimes troublesome as discussed above.

The threshold signal pump power depends upon source and fibre parameters as

$$P_B \approx \frac{21K}{g_B} \frac{A_{eff}}{L_{eff}} \left(1 + \frac{\Delta \upsilon_S}{\Delta \upsilon_B}\right) \quad (15)$$

where $\Delta \nu_S$ is the frequency bandwidth of the modulated source spectrum. The polarization factor K has a value between 1 and 2. The threshold has its minimum value when the source spectral width is much less than that of the narrow-width SBS gain. This threshold ranges from about 7 dBm for an externally modulated laser, to about 15 dBm for a directly modulated laser, though these values depend on fibre type.

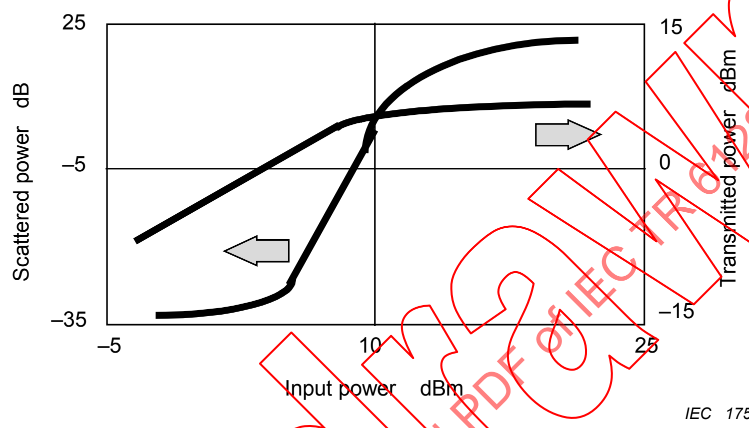

Figure 1 – Power effects of stimulated Brillouin scattering for a narrow-band source

3.2.3 Mitigation

The threshold can be raised by several means.

- The ratio of source-to-Brillouin bandwidths is made large. However, care needs to be taken that the increased source spectral spread does not cause increased chromatic dispersion of the link. In practice, the source bandwidth is modified by laser chirping (which may also help dispersion) or by dithering the source modulation at a low frequency (which may hinder dispersion). The dithering frequency should correspond roughly to the reciprocal of the group delay along the effective length, c/L_{eff}, or about 0,14 MHz at 1 550 nm. The threshold increase due to modulation is related to the increase in effective linewidth. The source spectral width could also be increased to enable higher input powers (see Figure 1).
- The polarization factor in Equation (15) can be increased up to a value of 2 by assuring polarization scrambling. Modulation formats can also give the threshold a boost from a factor 2 to 5. These techniques correspond to allowing the input power to increase by 2 dB to 7 dB.
- Modifications in fibre design have been appearing, such as to raise the effective area. Others include tailoring the silica doping profile, but this is not commonly done since current fibre designs are already optimized with respect to a number of other parameters.

A beneficial aspect of SBS is that it is broadened by fibre strain. This has allowed development of instrumentation to probe fibre strain as a function of length, and this can identify points of high stress along a cable that can potentially lower fibre reliability.

3.2.4 Measurement

Under consideration.

3.3 Stimulated Raman scattering (SRS)

3.3.1 Phenomenon

Here a signal pump photon interacts with a transverse (optical) phonon. This interaction of light and molecular vibrations produces light scattering. The gain FWHM is about 15 THz (120 nm) at 1 550 nm, quite broad because of the interaction with this phonon type in amorphous silica material. The gain coefficient peak g_R is only about 1×10^{-19} km/mW, and it occurs at a frequency offset ν_R, which corresponds to a considerable Stokes downshifting of about 13 THz (105 nm upshifting at 1 550 nm, 75 nm at 1 310 nm). Compared with the incident photons, the scattered photons are guided mainly in the forward direction. This large shift and forward directivity is of consequence for crosstalk in DWDM systems, though fortunately the gain is small.

The threshold power depends upon source and fibre parameters as

$$P_R \approx \frac{(16 \text{ or } 20)A_{eff}}{g_R\, L_{eff}} \tag{16}$$

where the coefficients 16 or 20 apply to forward and backward scattering, respectively. The frequency bandwidths of the Raman gain and the modulated source spectrum do not appear in Equation (16) because the gain is much broader than the source spectrum so that all of the source spectrum is utilized. Compared with Equation (15) for the Brillouin threshold, the SRS threshold for forward scattering is a factor of about 170 higher, so the threshold ranges from about 30 dBm to 35 dBm (1 W and higher) depending on the fibre type. For backward scattering, the SRS threshold is about another 1 dB higher.

3.3.2 Effects

The practical effects of SRS are as follows.

- There is little effect on single-channel systems since the threshold is so high. The signal power is depleted, and the generation of other wavelengths is of little consequence and they can be filtered out if necessary.
- Crosstalk can occur in DWDM systems. This is because a signal at a particular channel can act as a pump to amplify the signals at longer wavelength channels. Hence, lower frequency channel strengths grow at the expense of higher frequency channel strengths. This effect increases approximately linearly with wavelength separation up until the maximum upshifting of about 105 nm.

Without OAs, the power penalty exceeds 1 dB due to crosstalk if the total power P_t in all DWDM channels and the total DWDM spectral bandwidth $\Delta\lambda_t$ satisfies

$$P_t(W) > \frac{40}{\Delta\lambda_t(\text{nm}) L_{eff}(\text{km})} \tag{17}$$

For example, for a DWDM system extending over a 20 nm spectral width at the EDFA wavelengths, the crosstalk threshold is only about 100 mW. In amplified systems the SRS is somewhat filtered by the OAs, so the threshold decreases only slightly with the number of amplifiers.

3.3.3 Mitigation

These high threshold values are currently not a practical limitation in DWDM systems, and they do not need to be raised as in SBS. In fact, there are beneficial aspects to SRS so that one may wish to lower the threshold. As before, this can be done with modifications of the fibre design, so as to decrease the effective area. The pumped fibre may be used as an optical amplifier or as a laser/amplifier combination.

Figure 2 shows the latter as a Fabry-Perot cavity of 35 km of category B1 fibre between mirrors M and lenses L. In this example a 1 535 nm pump at 24 dBm produced an 8 dB gain for a signal above 1 600 nm. The power of Raman pumps has increased to the 1-W region so that Raman lasers and amplifiers are now be practical with standard-doped silica fibre.

Various types of OAs are discussed in IEC 61292-3.

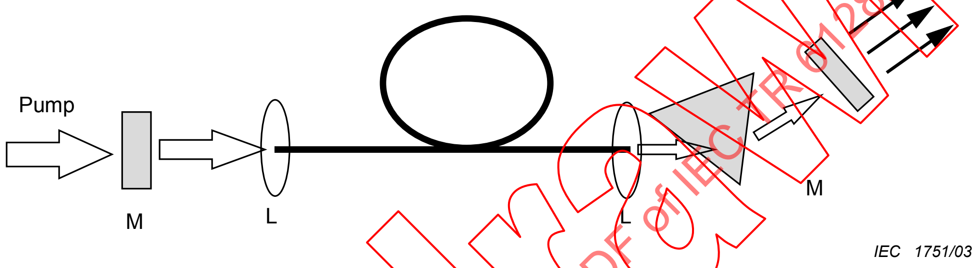

Figure 2 – Schematic of a fibre Raman laser

3.3.4 Measurement

Under consideration

4 Optical non-linearities based on index effects

4.1 General description of induced non-linear phase

Through the Kerr effect, the light wave interacts with bound electrons of the atoms constituting the silica molecules. The anharmonic motion of these electrons responding to the electromagnetic field leads to an increase in the silica refractive index. As a result, there are changes in the phase index of the fibre propagation mode with the time-varying intensity as

$$n(t) = n_0 + n_2 \frac{P(t)}{A_{\text{eff}}} \qquad (18)$$

(The intensity is the optical power divided by the fibre effective area.) Here n_0 is the usual phase/refractive index previously discussed, and n_2 is the non-linear index term that equals about 2.8×10^{-29} km^2 / mW. Using Equation (11) and integrating over the effective length of the fibre leads to a build-up of non-linear phase shift equal to

$$\phi(t) = 2\pi \Gamma P(t), \quad \text{where } \Gamma = \frac{n_2 L_{\text{eff}}}{\lambda A_{\text{eff}}} \qquad (19)$$

is a non-linear coefficient containing the relevant fibre properties. (A more commonly defined non-linear coefficient is n_2/λ.) This means that the optical intensity of the signal modulates its own phase. Here $\Gamma \approx 4{,}5 \text{ or } 6{,}3\, W^{-1}$ for category B2 fibre or category B1 fibre, respectively, depending upon detailed fibre design.

The non-linear phase effect, often combined with chromatic dispersion, leads to several effects important in amplified systems.

4.2 Self-phase modulation (SPM)

4.2.1 Effect

If the signal power is changing with time, for example, due to modulation, Equations (19) and (5) lead to an optical phase shift

$$\Delta\nu_{SPM} = -\frac{\mathrm{d}\phi}{2\pi\,\mathrm{d}t} = -\Gamma\frac{\mathrm{d}P}{\mathrm{d}t} \qquad (20)$$

This is negative chirp in which the rising leading edge of the pulse shifts to lower frequencies, known as a “red chirp” towards longer wavelengths. The falling trailing edge shifts to higher frequencies as a “blue chirp” towards shorter wavelengths. This is schematically shown in Figure 3.

Hence, the phase of the signal changes due to its own modulation, and this is more pronounced with the smaller rise times and fall times at higher bit-rates. The signal's frequency spectrum is broadened, leading to more pulse distortion due to chromatic dispersion. Moreover, these phase shifts can interfere to cause oscillations in the pulse amplitude, thereby distorting the pulse and raising the system power penalty. This is a single-channel effect, and independent of the number of DWDM channels, though it is closely related to cross-phase modulation as discussed below. For a detailed description of a particular signal, the phenomenon requires a more complex analysis.

Power thresholds are 10 mW or more. However, SPM can have beneficial effects. Consider the positive (“anomalous”) dispersion region of the fibre above the zero-dispersion wavelength for category B1 fibre, category B2 fibre, and some types of category B4 fibre. There the longer wavelengths have a longer delay. This means that the pulse leading edge is delayed relative to the trailing edge that has a higher speed. Therefore, some pulse compression (negative power penalty) occurs; at a longer length, ordinary chromatic dispersion that increases with length overcomes the effect. This is an example of a useful non-linear effect that can be used to reduce dispersive effects, and thereby allow increases in the bit-rate and/or unregenerated distance. In the extreme it can lead to soliton formation, though higher order solitons are detrimental since they lead to pulse break-up. In the negative dispersion region, non-linear pulse spreading adds to the linear dispersion, and a small magnitude of the chromatic dispersion coefficient is desirable.

SPM can be used to reduce the effects of chromatic dispersion, along with passive dispersion compensators. Then the design considerations are quite complex.

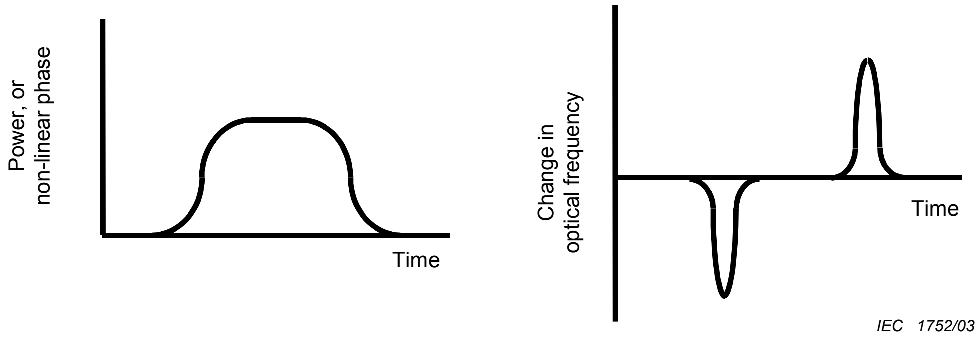

Figure 3 – SPM: Non-linear phase shift and frequency change during pulse modulation

4.2.2 Measurement

Under consideration.

4.3 Cross-phase modulation (XPM or CPM)

4.3.1 Effect

This can occur in DWDM systems where each signal channel experiences an index modulation due to both SPM and the presence of the other channels. The non-linear phase change similar to Equation (18) for signal 1 is

$$\phi_1(t) = 2\pi\left[\Gamma_1 P_1(t) + 2\Gamma_2 P_2(t)\right] \tag{21}$$

where the second term is due to XPM with signal 2. Note that this term is twice as large as the SPM term. (The differences in the Γ-values at the two nearby frequencies are small.) Analogous to Equation (20), the frequency shift due to XPM is

$$\Delta\nu_{1XPM} = -2\Gamma_2 \frac{\mathrm{d}P_2}{\mathrm{d}t} \tag{22}$$

With more wavelengths the cumulative phase changes will be complicated, and strong signals can have a considerable effect on weaker ones. However, chromatic dispersion lessens the effect of XPM since pulses from an interfering channel will separate with distance along the fibre. This means that adjacent channels have a stronger contribution to a particular signal channel, since the interfering pulses of more-distant channels will “walk off” more quickly from the signal. The so-called walk-off length is given by

$$L_W = (B\,D\,\Delta\lambda)^{-1} \tag{23}$$

which decreases with increasing bit-rate, chromatic dispersion coefficient, and wavelength channel spacing (and increasing attenuation when that is taken into account). Some calculations have shown that with 7 dBm (5 mW) input power per channel, a channel separation of 100 GHz is sufficient to effectively eliminate the effects of XPM. This may not be sufficient, however, for some DWDM systems with closer spacings.

4.3.2 Measurement

Under consideration.

4.4 Modulation instability (MI)

4.4.1 Effect

MI can occur with both modulated and unmodulated CW signals This manifests itself as a series of side-lobes, resulting in an increase in the spectral width of the signal. Physically, two signal pump photons of frequency ν_S are converted into a "probe" photon at ν_0 and an "idler" photon at $2\nu_S - \nu_0$. Energy (and frequency) is conserved, and no phonon is required. This is a four-wave mixing process with phase matching by SPM. MI requires positive dispersion (wavelengths above λ_0) where it can be shown that the steady-state condition is unstable to small perturbations in the intensity. This generates two primary side-lobes in frequency as schematically shown in Figure 4, corresponding to the probe and idler. Pulses were used to avoid SBS, so the modulation is quasi-CW with respect to the MI period.

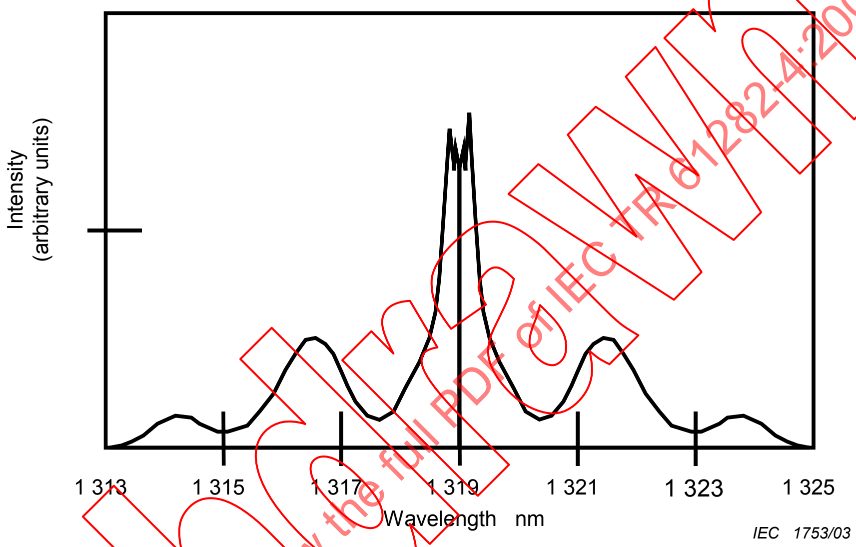

Figure 4 – MI: Spectral side-lobes 100 ps wide, 7 W peak pulse in 1 km fibre

In the time domain, the increased frequency content due to MI increases pulse broadening. As with some other non-linear phenomena, however, operation at positive dispersion can be used to reduce the system power penalty.

The peak gain at each lobe is (note the definition of Equation (19)) given by

$$g_{max} = \frac{4\pi\Gamma}{L_{eff}} P = \frac{4\pi n_2}{\lambda A_{eff}} P \tag{24}$$

For category B1 fibre, this is only about 0,3 /km for an input power of 10 dBm, increasing to about 2,6 /km for 1 W (30 dBm). The frequency shift at these peaks is

$$\pm \Delta\nu = \frac{1}{\lambda}\left(\frac{2\pi c\, g_{max}}{D}\right)^{1/2} \tag{25}$$

For the above powers, this shift can be typically 20 GHz to 60 GHz. The signal degradation due to MI occurs at high gain (input power) and for a frequency shift close to the signal bandwidth.

4.4.2 Measurement

Under consideration.