

I n t e r n a t i o n a l T e l e c o m m u n i c a t i o n U n i o n

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

Series G
Supplement 47
(10/2009)

SERIES G: TRANSMISSION SYSTEMS AND MEDIA,
DIGITAL SYSTEMS AND NETWORKS

General aspects of optical fibre and cable

ITU-T G-series Recommendations – Supplement 47



ITU-T G-SERIES RECOMMENDATIONS
TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

INTERNATIONAL TELEPHONE CONNECTIONS AND CIRCUITS	G.100–G.199
GENERAL CHARACTERISTICS COMMON TO ALL ANALOGUE CARRIER-TRANSMISSION SYSTEMS	G.200–G.299
INDIVIDUAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON METALLIC LINES	G.300–G.399
GENERAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON RADIO-RELAY OR SATELLITE LINKS AND INTERCONNECTION WITH METALLIC LINES	G.400–G.449
COORDINATION OF RADIOTELEPHONY AND LINE TELEPHONY	G.450–G.499
TRANSMISSION MEDIA AND OPTICAL SYSTEMS CHARACTERISTICS	G.600–G.699
DIGITAL TERMINAL EQUIPMENTS	G.700–G.799
DIGITAL NETWORKS	G.800–G.899
DIGITAL SECTIONS AND DIGITAL LINE SYSTEM	G.900–G.999
MULTIMEDIA QUALITY OF SERVICE AND PERFORMANCE – GENERIC AND USER-RELATED ASPECTS	G.1000–G.1999
TRANSMISSION MEDIA CHARACTERISTICS	G.6000–G.6999
DATA OVER TRANSPORT – GENERIC ASPECTS	G.7000–G.7999
PACKET OVER TRANSPORT ASPECTS	G.8000–G.8999
ACCESS NETWORKS	G.9000–G.9999

For further details, please refer to the list of ITU-T Recommendations.

Supplement 47 to ITU-T G-series Recommendations

General aspects of optical fibre and cable

Summary

Supplement 47 to ITU-T G-series Recommendations provides information on the general transmission characteristics of single-mode optical fibres and cables specified in the ITU-T G.65x-series Recommendations related to the practical use condition. It covers the environmental and length related characteristic of ITU-T G.65x-series optical fibre and cable. The fibre material related characteristics are also described in Appendix I.

Source

Supplement 47 to ITU-T G-series Recommendations was agreed on 9 October 2009 by ITU-T Study Group 15 (2009-2012).

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs). The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this publication, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Compliance with this publication is voluntary. However, the publication may contain certain mandatory provisions (to ensure e.g. interoperability or applicability) and compliance with the publication is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the publication is required of any party.

INTELLECTUAL PROPERTY RIGHTS

ITU draws attention to the possibility that the practice or implementation of this publication may involve the use of a claimed Intellectual Property Right. ITU takes no position concerning the evidence, validity or applicability of claimed Intellectual Property Rights, whether asserted by ITU members or others outside of the publication development process.

As of the date of approval of this publication, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this publication. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at <http://www.itu.int/ITU-T/ipr/>.

© ITU 2010

All rights reserved. No part of this publication may be reproduced, by any means whatsoever, without the prior written permission of ITU.

CONTENTS

	Page
1 Scope	1
2 References.....	1
3 Definitions	4
4 Abbreviations and acronyms	4
5 Environmental characteristics of optical fibre and cable.....	4
5.1 Temperature dependence of chromatic dispersion	4
5.2 Temperature dependence of polarization mode dispersion (PMD).....	5
6 Length related characteristics of optical fibre and cable	6
6.1 Cut-off wavelength.....	6
6.2 SBS power rating.....	6
6.3 FWM efficiency.....	7
Appendix I – Intrinsic material characteristics of optical fibre	10
I.1 Rayleigh scattering	10
I.2 Material dispersion	10
I.3 Non-linear refractive index.....	11
I.4 Raman gain coefficient.....	12

Supplement 47 to ITU-T G-series Recommendations

General aspects of optical fibre and cable

1 Scope

The purpose of this supplement is to understand the transmission properties of the cabled single-mode fibres during use, and to promote the proper and effective use of ITU-T G.65x-series Recommendations single-mode fibres and cables. In particular, when upgrading existing systems to high-speed transmission systems based on the installed transmission line and/or designing a new transmission line for a high-speed and large capacity transmission system, the system operators and designers should be provided with useful information that is not shown in the fibre Recommendations.

This supplement covers the general transmission characteristics of single-mode optical fibres and cables related to the practical use conditions. This supplement contains:

- Environmental characteristics of optical fibre and cable,
- Length-related characteristics of optical fibre and cable.

In Appendix I, the optical fibre characteristics related to the fibre material such as Rayleigh scattering and material dispersion are described for reference.

This supplement will be a useful guideline when designing the transmission lines and/or systems. Moreover, it should be updated as the optical fibre technologies.

2 References

- [ITU-T G.650.2] Recommendation ITU-T G.650.2 (2007), *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*.
- [ITU-T G.652] Recommendation ITU-T G.652 (2009), *Characteristics of a single-mode optical fibre and cable*.
- [ITU-T G.653] Recommendation ITU-T G.653 (2006), *Characteristics of a dispersion-shifted single-mode optical fibre and cable*.
- [ITU-T G.654] Recommendation ITU-T G.654 (2006), *Characteristics of a cut-off shifted single-mode optical fibre and cable*.
- [ITU-T G.655] Recommendation ITU-T G.655 (2006), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable*.
- [ITU-T G.656] Recommendation ITU-T G.656 (2006), *Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport*.
- [ITU-T G.657] Recommendation ITU-T G.657 (2009), *Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network*.
- [ITU-T G.663] Recommendation ITU-T G.663 (2000), *Application related aspects of optical amplifier devices and subsystems*.
- [ITU-T G.691] Recommendation ITU-T G.691 (2006), *Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers*.
- [ITU-T G.959.1] Recommendation ITU-T G.959.1 (2008), *Optical transport network physical layer interfaces*.
- [Agrawal1] Agrawal, G.P. (2001), *Nonlinear Fiber Optics*, 3rd ed. Academic Press.

- [Agrawal2] Agrawal, G.P. (2001), *Applications of Nonlinear Fiber Optics*, Academic Press.
- [Agrawal3] Agrawal, G.P. (2002), *Fiber-Optic Communication Systems*, 3rd edition, Wiley Interscience.
- [Anderson] Anderson, W.T., *et al.* (1984), *Length dependence of the effective cutoff wavelength in single-mode fibers*, IEEE J. Lightwave Technol., Vol. LT-2, pp. 238-242.
- [Andre] Andre, P.S., *et al.* (2003), *Effect of temperature on the single mode fibers chromatic dispersion*, Proceedings SBMO/IEEE MTT-S IMOC, pp. 231-234.
- [Boskovic] Boskovic, A., *et al.* (1996), *Direct continuous-wave measurement of n_2 in various types of telecommunication fiber at 1.55 μm* , Opt. Lett., Vol. 21, p. 1966.
- [Brodsky] Brodsky, M., *et al.* (2006), *Polarization mode dispersion of installed fibers*, IEEE J. Lightwave Technol., Vol. LT-24, pp. 4584-4599.
- [Cameron] Cameron, J., *et al.* (1998), *Time evolution of polarization mode dispersion in optical fibers*, IEEE Photon. Technol. Lett., Vol. 10, pp. 1265-1267.
- [Davey] Davey, S.T., *et al.* (1989), *Optical gain spectrum of $\text{GeO}_2\text{-SiO}_2$ Raman fibre amplifier*, IEE Proc., Vol. 136, pp. 301-306.
- [Fleming] Fleming, J.W. (1984), *Dispersion in $\text{GeO}_2\text{-SiO}_2$ glasses*, Applied Optics, Vol. 23, No. 24, p. 4486.
- [Fukai] Fukai, C., *et al.* (2004), *Effective Raman gain characteristics in germanium- and fluorine-doped optical fibers*, Opt. Lett., Vol. 29, pp. 545-547.
- [Geittner] Geittner, P., *et al.* (1989), *Intrinsic scattering and absorption losses of Ge- and F-doped optical fibres prepared by PCVD*, IEE Electron. Lett., Vol. 25, pp. 436-437.
- [Gisin] Gisin, N., *et al.* (1996), *How accurately can one measure a statistical quantity like polarization-mode dispersion*, IEEE Photon. Technol. Lett., Vol. 8, pp. 1671-1673, 1996.
- [Hamp] Hamp, M.J., *et al.* (2002), *Investigation into the temperature dependence of chromatic dispersion in optical fiber*, IEEE Photon. Technol. Lett., Vol. 14, pp. 1424-1526.
- [Harris] Harris, D., *et al.* (2004), *Temperature dependence of wavelength-averaged DGD on different buried fibers*, LEOS 2004, MJ2.
- [Hatton] Hatton, W.H., *et al.* (1986), *Temperature dependence of chromatic dispersion in single mode fibers*, IEEE J. Lightwave Technol., Vol. LT-4, pp. 1552-1555.
- [Hill] Hill, K.O., Johnson, D.C., Kawasaki, B.S., and MacDonald, R.I. (1978), *cw three-wave mixing in single-mode optical fibers*, J.Appl.Phys., Vol. 49, pp. 5098-5106.
- [Inoue1] Inoue, K. (1992), *Four-wave mixing in an optical fiber in the zero-dispersion wavelength region*, IEEE J. Lightwave Technol., Vol. 10, No. 11, pp. 1553-1561.
- [Inoue2] Inoue, K., and Toba, H. (1995), *Fiber Four-Wave Mixing in Multi-Amplifier Systems with Nonuniform Chromatic Dispersion*, IEEE J. Lightwave Technol., Vol. 13, No. 1, pp. 88-93.

- [Kato1] Kato, T., *et al.* (2000), *Temperature dependence of chromatic dispersion in various types of optical fiber*, Opt. Lett., Vol. 25, pp. 1556-1556.
- [Kato2] Kato, T. (1995), *Estimation of non-linear refractive index in various silica-based glasses for optical fibers*, Opt. Lett., Vol. 20, p. 2279.
- [Kitayama] Kitayama, K., *et al.* (1984), *Length dependence of effective cutoff wavelength in single-mode fibers*, IEEE J. Lightwave Technol., Vol. LT-2, pp. 629-634.
- [Kobayashi] Kobayashi, S., Shibata, S., Shibata, N., and Izawa, T. (1977), *Refractive-index dispersion of doped fused silica*, Proceedings of IOOC'77 (Integrated Optics and Optical fibre Communication), pp. 309-312.
- [Koch] Koch, F., *et al.* (2001), *Broadband Raman gain characterization in various optical fibres*, IEE Electron Lett., Vol. 37, pp. 1437-1439.
- [Manolescu] Manolescu, G., *et al.* (2005), *Large spectral range Raman gain prediction for telecommunication glass fibers*, Glass Technology, Vol. 46, No. 2, pp. 85-88.
- [Mao] Mao, X.P., *et al.* (1992), *Stimulated Brillouin threshold dependence on fiber type and uniformity*, IEEE Photon. Technol. Lett., Vol. 4, pp. 66-69.
- [Marcuse] Marcuse, D., *et al.* (1991), *Effect of fiber nonlinearity on long distance transmission*, IEEE J. Lightwave Technol., LT-9, pp. 121-128.
- [Nagayama] Nagayama, K., *et al.* (2002), *Ultra-low-loss (0.1484 dB/km) pure silica core fibre and extension of transmission distance*, IEE Electron. Lett., Vol. 38, pp. 1168-1169.
- [Nakajima] Nakajima, K., *et al.* (2002), *Dopant dependence of effective nonlinear refractive index in GeO₂- and F-doped core single-mode fibers*, IEEE Photon. Technol. Lett., Vol. 14, pp. 492-494.
- [Okoshi] Okoshi, T. (1982), *Optical Fibers*, Academic Press.
- [Okude] Okude, S., *et al.* (1995), *GeO₂ concentration dependence of nonlinear refractive index coefficients of silica fibers*, IOOC'95, WA3-2, pp. 30-31, June, Hong Kong.
- [Pinnow] Pinnow, D.A., *et al.* (1973), *Fundamental optical attenuation limits in the liquid and glassy state with application of fiber optical waveguide materials*, J. Appl. Phys. Lett., Vol. 22, pp. 527-529.
- [Poggiolini] Poggiolini, P., *et al.* (2006), *Long-term PMD characterization of a metropolitan G.652 fiber plant*, IEEE J. Lightwave Technol., Vol. LT-24, pp. 4022-4029.
- [Shah] Shah, V., *et al.* (1989), *Curvature sensitivity study of the cutoff region of single-mode fibers exhibiting mode coupling effects*, Proc. ECOC'89, Gothenburg, Sweden, pp. 498-501.
- [Shibata1] Shibata, N., Baun, R.P., and Waarts, R.G. (1987), *Phase-Mismatch Dependence of Efficiency of Wave Generation through Four-Wave Mixing in a Single-Mode Optical Fiber*, IEEE J. Quantum. Electron, Vol. QE-23, pp. 1205-1210.
- [Shibata2] Shibata, N., *et al.* (1981), *Raman spectra of binary high-silica glasses and fibers containing GeO₂, P₂O₅ and B₂O₃*, J. Non-Cryst. Solids, Vol. 29, pp. 115-126.
- [Shiraki] Shiraki, K., *et al.* (1997), *SBS threshold of a fiber with a Brillouin frequency shift distribution*, IEEE J. Lightwave Technol., Vol. 14, pp. 50-57.

- [Sillard] Sillard, P., *et al.* (2005), *Modeling the non-linear index of optical fibers*, OFC'05, Anaheim, OFH4.
- [Smith] Smith, R.G. (1972), *Optical power handling capacity of low loss optical fibers as determined by stimulated Raman and Brillouin scattering*, Appl. Opt., Vol. 11, pp. 2489-2494.
- [Tsujikawa1] Tsujikawa, K., *et al.* (1994), *Scattering property of F and GeO₂ codoped silica glasses*, IEE Electron. Lett., Vol. 30, pp. 351-352.
- [Tsujikawa2] Tsujikawa, K., *et al.* (2007), *Method for Predicting Rayleigh Scattering Loss of Silica-based Optical Fibers*, IEEE J. Lightwave Technology, Vol. 25, No. 8, pp. 2122-2128.
- [Wada] Wada, A., *et al.* (1992), *Measurement of nonlinear-index coefficients of optical fibers through the cross-phase modulation using delayed-self-heterodyne technique*, ECOC'92, Berlin, Germany, Mo B1.2, pp. 45-48.

3 Definitions

Formal definitions are found in the primary Recommendations.

4 Abbreviations and acronyms

This supplement uses the following abbreviations:

DGD	Differential Group Delay
EDFA	Erbium Doped Fibre Amplifier
FWM	Four-Wave Mixing
PMD	Polarization Mode Dispersion
PMD _{MEAS}	Measured Polarization Mode Dispersion
SBS	Stimulated Brillouin Scattering
SPM	Self-Phase Modulation
XPM	Cross-Phase Modulation

5 Environmental characteristics of optical fibre and cable

5.1 Temperature dependence of chromatic dispersion

The chromatic dispersion coefficient curve vs wavelength has been observed to shift to the right with increased temperature. This shift is roughly the same for the many fibres studied and is approximately 0.03 nm/°C. The zero-dispersion wavelength therefore shifts in a similar way, but the dispersion slope is hardly affected.

It is also reported that the variation of the chromatic dispersion coefficient (ps/nm·km) with temperature could be expressed as the negative of the product of the shift of zero dispersion wavelength and the dispersion slope. For fibres with higher dispersion slope, the temperature dependence of the chromatic dispersion coefficient is larger than for a lower slope fibre. For example, the temperature dependence of the chromatic dispersion for a typical G.652 fibre with a 0.07 ps/nm²/km dispersion slope, is about -0.0021 ps/nm/km/°C (= -0.03 nm/°C × 0.07 ps/nm²/km). Some have concluded that the main effect is a shift in the refractive index and material dispersion.

Since the temperature-induced chromatic dispersion variation is not very large, it may not have a significant impact on most systems operating at less than 10 Gbit/s. However, it may need to be taken into account for higher bit-rate systems operating at or above 40 Gbit/s, which may require accurate dispersion management. For fibre-based dispersion compensation, and where the compensating fibre is exposed to the same temperature variation as the main transport fibre, the degree of compensation remains approximately constant.

The following references contain further information: [Hatton], [Kato1], [Andre], and [Hamp].

5.2 Temperature dependence of polarization mode dispersion

Polarization mode dispersion (PMD) is the mean differential group delay (DGD) time between two orthogonal polarization modes (see [ITU-T G.650.2] for further details on the PMD definition and its measurement). To find the PMD, the DGD can be averaged over wavelength, temperature, or low-stress mechanical fibre/cable configurations (with rearrangement of the fibre in-between each measurement). Note that high DGD is the cause of a system outage. PMD is a measured quantity which, given appropriate DGD statistics, can allow estimation of the probability of the DGD exceeding the value that the system can tolerate and hence causing system outage. DGD results from optical birefringence caused by internal imperfection of fibre geometry (i.e., internal factor) and/or external mechanical stresses in the fibre after manufacture (i.e., external factors). The imperfections in fibre geometry are related to manufacturing processes, which include non-circularity and imperfect concentricity as well as external stresses applied during the fibre cabling. As regards the external factors, optical fibre cables are subjected to external stresses that originate from a variety of sources (e.g., temperature or external perturbations) along the fibre length after installation and these external stresses cause DGD in installed optical fibres. Therefore, the DGD behaviour in the field is strongly affected by the environmental conditions as well as operating wavelength, and its value fluctuates with time following environmental changes, resulting in the dynamic nature of the DGD in deployed fibres. PMD has been found to be much more stable with respect to temperature and time in installed cabled fibres.

Research has shown that if PMD is measured using an inadequate range of wavelength, temperature or low-stress configurations, the resulting value, PMD_{MEAS} , will retain some of the variability of the underlying DGD distribution. The expected difference between PMD_{MEAS} and the true PMD can be estimated (see [Gisin]). This problem becomes more severe for low PMD links (PMD value < 1 ps).

In fact, the results of long-term DGD measurements in installed optical fibre cables show that DGD varies in accordance with daily and seasonal temperature changes. In general, it is observed that the DGD variation of underground cables in a relatively thermally stable environment is less rapid than that of aerial optical cables exposed to the atmosphere. However, even with underground cable, when it contains sections exposed to the atmosphere, such as bridge attachments, the polarization variation in those short sections that results from temperature change can greatly affect the DGD value of the entire route. These conclusions also hold, to a varying degree, for PMD_{MEAS} . Measurements seem to indicate that true PMD variation (as opposed to variation in DGD, or PMD_{MEAS}) is most likely in aerial installations.

On the other hand, the amount of DGD variation with temperature varies greatly depending on individual fibre conditions because DGD characteristics can be affected in a complex way by a variety of factors, including fibre type, fibre jacket, cable structure, installation conditions and other external perturbations. Most field measurement results indicate the measured DGD correlates strongly with ambient temperature but the reported correlation factors are different from each other. In some cases, it is positive and in others it is negative. Moreover, opposite correlations are possible even in the same fibre depending on the wavelength.

A tolerable maximum DGD for an optical path is assumed to be approximately 30% of the bit duration for NRZ format. This means that the allowable maximum DGD for systems with 10 and 40 Gbit/s signals are 30 and 7.5 ps, respectively. (The details for the path penalty due to PMD are

described in [ITU-T G.691] and [ITU-T G.959.1].) In the reports of variation of PMD in installed optical fibres, which supposedly originates from the temperature change, the variation has a maximum value of a few picoseconds, and is less than 0.1 ps in most studies. The reported PMD variation due to mechanical stresses in aerial installations is similarly small. Most, if not all, of this variation can be accounted for by the uncertainties in PMD_{MEAS} . Thus, the variation in the true PMD in installed fibres induced by temperature change and mechanical stress can be largely disregarded in most systems. When implementing systems operating at higher bit rates of 40 Gbit/s or more, in some cases, it may be necessary to take account of the environmental condition of the optical path and reduce the maximum allowable PMD.

The following references contain further information: [Brodsky], [Poggiolini], [Cameron], [Harris], and [Gisin].

6 Length related characteristics of optical fibre and cable

6.1 Cut-off wavelength

The cut-off wavelength of a single-mode fibre is the wavelength above which only the fundamental mode propagates through the fibre, or more precisely above which higher order modes can be neglected due to their high losses. The operation of an optical fibre system at a wavelength above the cut-off wavelength ensures single-mode operation, because the secondary mode cannot propagate through the fibre. If the secondary mode is not completely eliminated, it may recombine with the fundamental mode at a subsequent connection or splice and cause signal degradation.

In general, the cut-off wavelength depends on the fibre length because the secondary mode is affected by perturbations along a fibre such as curvature, and microbending, particularly near the cut-off wavelength. It is reported that as the fibre length increases, the cut-off wavelength decreases almost linearly on a logarithmic scale of fibre length up to a length of several kilometres, and this length dependence can be approximately expressed as:

$$\lambda_c(L) = -k \log \frac{L}{L_0} + \lambda_{c0}$$

where L (m) is the fibre length, λ_{c0} (μm) and L_0 are the cut-off wavelength and length for a reference fibre, respectively, and k is the proportionality coefficient, which indicates the length dependence of the cut-off wavelength. Several experimental studies have reported that the k value is approximately 0.03 (μm) for conventional G.652 fibres. This means that the cut-off wavelength for a 1 km-long cable could be about 0.1 μm shorter than that of a 2 m-long fibre. Further work is needed to address the behaviour of other fibre categories.

Cut-off wavelength also depends on the curvature applied to the fibre. Typical reduction of about 100 nm is measured with conventional G.652 fibres when characterizing cut-off with two additional applied 80 mm-diameter loops. Here again, further work is needed to address the behaviour of other fibre categories.

The loss of the secondary mode near the cut-off wavelength is also affected by the refractive-index profile of a fibre, the coating material, the cable structure and the cable deployment conditions. Therefore, it should be noted that the amounts of wavelength shift with fibre length could be somewhat different depending on these factors.

The following references contain further information: [Anderson], [Kitayama], and [Shah].

6.2 SBS power rating

Stimulated Brillouin scattering (SBS) sets a limit on input power. With SBS, the forward-propagating input light is scattered and creates backward-propagating light, which is downshifted (Brillouin frequency shift) by approximately 11 GHz against the input signal at a

wavelength of 1.55 μm . As the input power increases and exceeds a certain level called the "SBS power rating", most of input power is transferred into backscattered light and the transmitted signal power cannot be increased. In general, the SBS power rating, i.e., the maximum input power, varies with length. It is also known that the SBS power rating is inversely proportional to the effective length, which is expressed as follows:

$$L_{\text{eff}} = \frac{1 - \exp(-\alpha L)}{\alpha}$$

where α is the attenuation coefficient (m^{-1}) and L is the fibre length. For a fibre with a constant attenuation coefficient throughout its length, as the fibre length increases, L_{eff} also increases and approaches a certain value ($= 1/\alpha$) asymptotically. Therefore, a shorter length fibre has a higher SBS power rating, while fibres that exceed a certain length have almost the same SBS power rating. Figure 1 shows the theoretical fibre length dependence of the SBS power rating for a fibre with an optical loss of 0.25 dB/km ($\alpha = 0.000058 \text{ m}^{-1}$, $1/\alpha = 17.24 \text{ km}$).

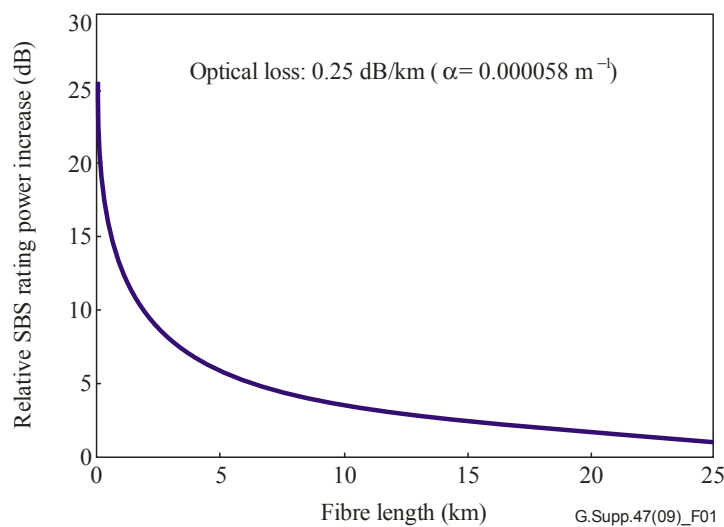


Figure 1 – Fibre length dependence of SBS rating power increase

As the fibre length increases beyond 20 km ($>1/\alpha$), the SBS power rating reaches a certain value. On the other hand, its value increases rapidly as the fibre length becomes shorter. The respective SBS power ratings of 5 and 1 km long fibres are about 6 and 12 dB higher than a fibre longer than 20 km.

The SBS power rating also changes depending on the uniformity of the Brillouin frequency shift along the length. If the amount of change in the Brillouin frequency shift along the length is greater than the intrinsic Brillouin gain bandwidth ($\sim 40 \text{ MHz}$), the SBS power rating could be increased. The Brillouin frequency shift changes depending on the amount of dopant material. With the typical dopant, GeO_2 , it is reported that a 10 wt% change in GeO_2 concentration, which is equivalent to a 0.1% change in refractive-index difference, causes about 40 MHz change in the Brillouin frequency shift. Therefore, when the transmission span consists of relatively short fibre pieces with different Brillouin frequency shifts, the Brillouin power rating can be increased compared with a span consisting of a single fibre.

Induced transmission limitations due to SBS are described in Appendix II of [ITU-T G.663].

The following references contain further information: [Smith], [Shiraki], and [Mao].

6.3 FWM efficiency

Four-wave mixing (FWM) is a type of optical Kerr effect. Through the FWM process, three optical waves of frequencies f_i , f_j and f_k , co-propagating into the fibre, generate a new optical wave. In multiple-channel systems, generated FWM components induce channel crosstalk and degrade system performance. Assuming that the phase shifts induced by SPM and XPM are neglected and all channels have the equal frequency spacing Δf , the FWM power P is proportional to:

$$P \propto \eta \left(\frac{n_2}{A_{eff}} \right)^2 e^{-\alpha L}$$

where α is the attenuation coefficient, L is the fibre length, A_{eff} is the effective area, n_2 is the fibre non-linear refractive index and η is the FWM efficiency defined as:

$$\eta = \left| \frac{1 - \exp[-(\alpha + i\Delta\beta)L]}{(\alpha + i\Delta\beta)} \right|^2$$

The FWM efficiency depends on the phase-matching factor $\Delta\beta$ governed by:

$$\Delta\beta \approx -\frac{4\pi\lambda_c^2}{c} \Delta f^2 D(\lambda_c)$$

where $D(\lambda_c)$ is the chromatic dispersion coefficient, c is the velocity of light in a vacuum and λ_c ($= 2c/(f_i + f_i)$) is the wavelength. The FWM generation is affected by the fibre characteristics such as the fibre length, the loss, the chromatic dispersion and the frequency spacing. The system penalties induced by FWM can be reduced by increasing the frequency spacing and chromatic dispersion in order to break the phase matching between the interacting waves. Multichannel systems deployed in the 1550 nm operating window over G.652 fibres and G.655 fibres experience much less FWM impairment compared to systems deployed over G.653 fibres. Figure 2 shows the FWM efficiency plotted as a function of WDM channel spacing (GHz) for three values of dispersion (1, 5, 17 ps/nm/km at 1550 nm) with a fibre length of 50 km and an optical fibre loss of 0.25 dB/km ($\alpha = 0.000058 \text{ m}^{-1}$).

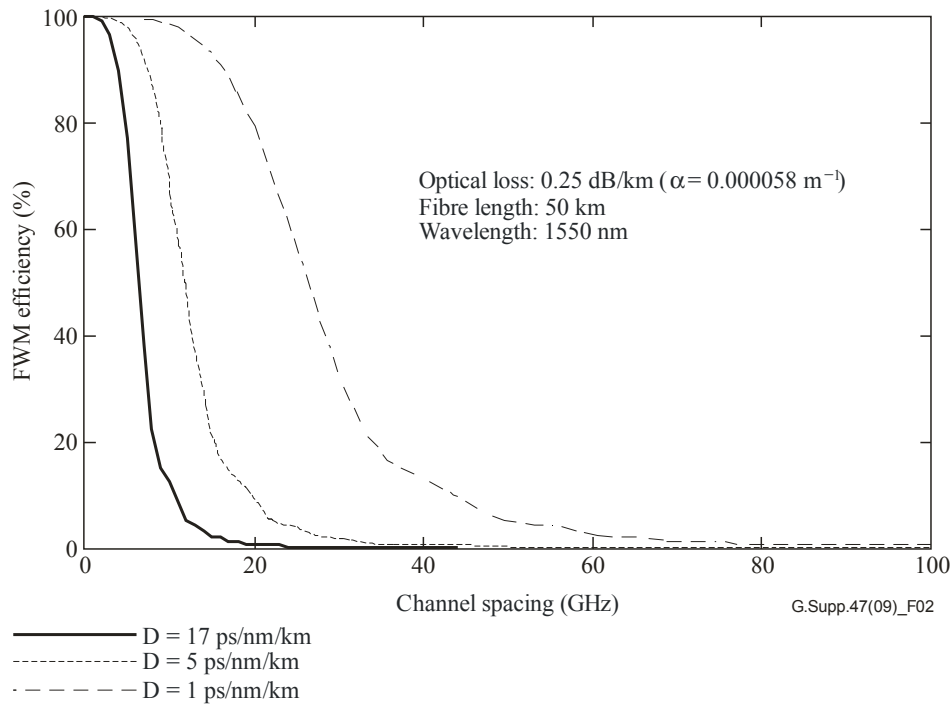


Figure 2 – Channel spacing dependence of FWM efficiency

In the case of a 50 km length fibre cable link with dispersion coefficient $D = 1$ ps/nm/km, the FWM component nearly vanishes for channel spacing of 100 GHz or more.

The FWM power is also affected by the chromatic dispersion change along the fibre cable link. In actual terrestrial systems, the fibre cable link is composed of many fibre cable sections, whose chromatic dispersions are independent of each other. It is reported that the FWM efficiency in these systems composed of G.653 fibres is different from that in systems with uniform chromatic dispersion. In case of the assumed system conditions with 20 channels, 100 GHz channel spacing, 500 km transmission distance and -10 dBm/ch fibre input power, the FWM crosstalk of the non-uniform fibre link composed of 2.5 km fibres with 0.56 ps/nm/km variance of the absolute dispersion value is about 10 dB smaller than that of the uniform chromatic dispersion fibre link. The results also showed the limitation imposed on the fibre input power in a system with non-uniform dispersion is relieved by several dBs, compared with that in a system with uniform dispersion.

Furthermore, the FWM generation also changes by the perturbation of polarization states of waves propagating throughout a fibre by the fibre polarization mode dispersion, the temperature fluctuation and the vibration. Note that FWM efficiency is not influenced by increasing bit rate.

Induced transmission limitations due to FWM are described in Appendix II of [ITU-T G.663].

The following references contain further information: [Agrawal1], [Agrawal2], [Hill], [Shibata1], [Inoue1], and [Inoue2].

Appendix I

Intrinsic material characteristics of optical fibre

I.1 Rayleigh scattering

In silica-based optical fibres, Rayleigh scattering accounts for most of the optical loss around the 1.3 μm and 1.55 μm telecommunication windows. It is caused by intrinsic fluctuation in the density of the glass, and the optical loss caused by Rayleigh scattering is in inverse proportion to the fourth power of the wavelength. Thus, Rayleigh scattering loss α_R can be expressed as:

$$\alpha_R = R/\lambda^4$$

where λ is the wavelength and R is the Rayleigh scattering coefficient. The R value is related to the kind of dopant and the amount of dopant used to achieve a given refractive index profile. The smaller the R value is, the smaller value of the Rayleigh scattering loss α_R becomes. Although the Rayleigh scattering coefficient of fibre is slightly dependent on its refractive-index profile, it can be expected to increase approximately linearly with the amount of dopant added to the core for most dopant materials. This is the case of germanium oxide (GeO_2) and fluorine (F), which have been widely used as dopant materials for controlling the refractive-index. In addition to this dopant effect, the thermal history of the glass (mainly related to the drawing stage) also influences the Rayleigh scattering level through the glass fictive temperature (T_f). As regards these two dopants and the fictive temperature effect, it is reported by Tsujikawa *et al.* that the Rayleigh scattering coefficient R ($\text{dB/km}/\mu\text{m}^4$) of fibre with GeO_2 and/or F doped silica could be expressed by:

$$R = 4.1 \times 10^{-4} (T_f + 273) \times (1 + 0.62\Delta_{\text{GeO}_2} + 0.60\Delta_F^2 + 0.44\Delta_{\text{GeO}_2}\Delta_F^2)$$

where Δ_{GeO_2} and Δ_F denote the relative-index difference changes in per cent induced by GeO_2 and F, respectively. The value of Rayleigh scattering coefficient in pure silica is reported to be generally around $0.8 \text{ dB/km}/\mu\text{m}^4$. Therefore, a fibre with a pure silica core has less Rayleigh scattering loss than a fibre with a doped silica core. The G.654 fibre, which is a cut-off shifted fibre with a very low loss, is generally achieved with a pure silica core.

The following references contain further information: [Pinnow], [Geittner], [Tsujikawa1], [Tsujikawa2], and [Nagayama].

I.2 Material dispersion

The chromatic dispersion of optical fibres comprises three factors, namely intermodal dispersion, waveguide dispersion and material dispersion. Of these dispersion factors, only material dispersion is an intrinsic material characteristic.

Material dispersion is induced by the wavelength dependence of silica material. For single-mode fibres, chromatic dispersion can be approximated by the sum of the material and waveguide dispersion.

The wavelength dependence of the refractive index of silica-based glass can be approximated by the three-term Sellmeier equation as:

$$n^2(\lambda) = 1 + \sum_{j=1}^3 \frac{A_j \lambda^2}{\lambda^2 - \lambda_j^2}$$

where A_j is the oscillator strength and λ_j is the resonance wavelength for a given glass.

These coefficients of the pure silica glass have been obtained experimentally as shown in Table I.1. Here, the A_j values are non-dimensional and the λ_j values are given in μm .

Table I.1 – Three-term Sellmeier equation coefficients for pure silica glass

A_1	λ_1	A_2	λ_2	A_3	λ_3
0.69616630	0.068404300	0.40794260	0.11624140	0.89747940	9.896161

With respect to composite glass, such as GeO₂ doped silica glass, the refractive index can be calculated by incorporating the oscillator strength and resonance wavelength of the doped glass in the Sellmeier equation with the fraction of the dopant.

The group index $n_g(\lambda) = n - \lambda(dn/d\lambda)$ can be obtained by using the parameters and the Sellmeier equation. Material dispersion D_M is represented as $D_M = 1/c (dn_g/d\lambda)$. As regards pure silica glass, the D_M value is 0 at $\lambda = 1.276 \mu\text{m}$, which is called the zero material dispersion wavelength of pure silica. As for GeO₂ doped silica glass, higher fraction of GeO₂ causes higher refractive index and longer zero material dispersion wavelength.

The following references contain further information: [Agrawal3], [Okoshi], [Fleming], and [Kobayashi].

I.3 Non-linear refractive index

Non-linear interactions between a signal and a silica fibre transmission medium begin to appear as the optical signal power is increased to achieve longer span length transmissions at high bit rates. With a long-haul transmission system with EDFA repeaters, such a high optical power and long interaction length result in deformation of the transmitted pulse through the non-linearity of the fibre and this degrades the system performance. These non-linearities can be generally categorized as either scattering effects (stimulated Brillouin scattering and stimulated Raman scattering) or effects related to the Kerr effect (self-phase modulation, cross-phase modulation and four-wave mixing). The Kerr effect is a change in the refractive index of a material in response to an electric field. For particularly intense fields, the refractive index of optical fibres is dependent on the optical intensity inside the fibres, and can be expressed as follows:

$$n = n_0 + n_2 I$$

Here n is the refractive index, n_0 is the linear part of the refractive index, n_2 is the non-linear refractive index and I is the optical intensity inside the fibres.

The non-linear refractive index in silica-based optical fibres varies depending on the dopant material and its concentration. With GeO₂, which is a typical dopant that is added to increase the refractive index of the core region, the non-linear refractive index increases linearly with GeO₂ concentration. When the index profile and field distribution of the optical fibre are taken into account, the non-linear refractive index in the optical fibre can be expressed as follows:

$$n_2 [\times 10^{-20} \text{ m}^2 / \text{W}] = 0.0556 \eta_{\text{GeO}_2} [\text{mol}\%] + 2.61$$

Here η_{GeO_2} is the effective GeO₂ concentration. The constant term on the right-hand side represents the n_2 value of pure silica.

The following references contain further information: [Agrawal1], [Marcuse], [Wada], [Okude], [Kato2], [Boskovic], [Sillard], and [Nakajima].

I.4 Raman gain coefficient

Raman amplification in optical fibres has been applied to long-haul optical communication as one way of compensating for fibre losses and extending the fibre span length. In the Raman amplification process, the input signal is amplified by the gain g_R (Raman gain coefficient) via Raman interaction in which the power from the pump light is shifted and transferred to the signal wavelength by the vibrational modes of glass. This Raman gain shift defines the choice of Raman pump by the relation: the difference of frequency between the pump and signal would be equivalent to the Raman gain shift. Typically, in fused silica the shift at the peak of Raman gain is about 13.2 THz. There are two types of Raman amplifier, distributed Raman amplifiers and discrete Raman amplifiers. In a distributed Raman amplifier, some or all of the transmission fibres are used as amplification media via the Raman amplification effect that occurs in optical fibres. Therefore, existing transmission line fibres can also be used as Raman amplifiers in distributed Raman amplifier systems.

In discrete Raman amplifiers, the optical fibres for amplification are completely contained inside the device and specially designed fibres with high Raman gain coefficient are used.

The Raman gain coefficient g_R in silica-based fibres varies depending on the dopant material and its concentration. With GeO_2 , which is a typical dopant that is added to increase the refractive index of the core region, the Raman gain coefficient increases linearly with GeO_2 concentration. The change in the Raman gain coefficient with GeO_2 doping in mol% (η_{GeO_2}) at its peak is expressed as:

$$g_r(\eta_{\text{GeO}_2}, \nu) = [1 + C(\nu)\eta_{\text{GeO}_2}]g_r(\text{SiO}_2, \nu)$$

where ν is the pump frequency, $g_r(\eta_{\text{GeO}_2}, \nu)$ and $g_r(\text{SiO}_2, \nu)$, respectively, represent the Raman gain coefficients of GeO_2 doped silica and pure silica, and $C(\nu)$ is a linear regression factor whose value is reported in several studies to be around 0.08 (/mol%). Therefore, as the GeO_2 concentration in the fibre increases, the Raman gain coefficient increases. For example, typical G.653 fibres with a relatively high GeO_2 concentration (~ 7 mol% which corresponds to $\sim 1\%$ refractive index difference Δ) reportedly have about 1.5 times larger Raman gain coefficients than those for G.654 fibres with a pure silica core. As regards fluorine (F), which is widely used as a dopant to decrease the refractive index, it reduces the Raman gain coefficient slightly, unlike a GeO_2 dopant. Here, the effective Raman gain characteristics in a fibre also depend on the effective area and the refractive-index profile. Raman gain efficiency is generally expressed by the Raman gain coefficient g_R divided by the effective area A_{eff} . Therefore, a highly GeO_2 doped fibre, i.e., a fibre with a high refractive-index difference and small effective area, has a high Raman gain efficiency.

The following references contain further information: [Shibata2], [Davey], [Koch], [Fukai], and [Manolescu].

SERIES OF ITU-T RECOMMENDATIONS

Series A	Organization of the work of ITU-T
Series D	General tariff principles
Series E	Overall network operation, telephone service, service operation and human factors
Series F	Non-telephone telecommunication services
Series G	Transmission systems and media, digital systems and networks
Series H	Audiovisual and multimedia systems
Series I	Integrated services digital network
Series J	Cable networks and transmission of television, sound programme and other multimedia signals
Series K	Protection against interference
Series L	Construction, installation and protection of cables and other elements of outside plant
Series M	Telecommunication management, including TMN and network maintenance
Series N	Maintenance: international sound programme and television transmission circuits
Series O	Specifications of measuring equipment
Series P	Terminals and subjective and objective assessment methods
Series Q	Switching and signalling
Series R	Telegraph transmission
Series S	Telegraph services terminal equipment
Series T	Terminals for telematic services
Series U	Telegraph switching
Series V	Data communication over the telephone network
Series X	Data networks, open system communications and security
Series Y	Global information infrastructure, Internet protocol aspects and next-generation networks
Series Z	Languages and general software aspects for telecommunication systems