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SERIES G: TRANSMISSION SYSTEMS AND MEDIA,
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General aspects of optical fibres and cables

ITU-T G-series Recommendations – Supplement 47

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Supplement 47 to ITU-T G-series Recommendations

General aspects of optical fibres and cables

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 of Recommendations related to the practical use condition. It covers the environmental and length-related characteristic of ITU-T G.65x-series optical fibres and cables. The fibre material-related characteristics are also described in Appendix I.

Version 2 of this supplement introduces the general aspect of multi-path interference (MPI) in an optical fibre in order to support newly established test methods for coherent MPI which can be found in Appendix IV of Recommendation ITU-T G.650.1.

History

Edition	Recommendation	Approval	Study Group
1.0	ITU-T G Suppl. 47	2009-10-09	15
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FOREWORD

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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.

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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 for 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 fibres and cables,

– length-related characteristics of optical fibres and cables.

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 provide useful guidelines when designing the transmission lines and/or systems. Moreover, it should be updated as and when optical fibre technologies are updated.

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3 Definitions

Definitions can be found within the G series of Recommendations.

4 Abbreviations and acronyms

This supplement uses the following abbreviations and acronyms:

DGD Differential Group Delay

EDFA Erbium Doped Fibre Amplifier

FWM Four-Wave Mixing

MPI	Multi-Path Interference
NRZ	Non-Return to Zero
OSNR	Optical Signal to Noise Ratio
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 versus 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 a 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 ITU-T G.652 fibre with a 0.07 ps/nm^2/km dispersion slope, is about –0.0021 ps/nm/km/°C (= –0.03 nm/°C × 0.07 ps/nm^2/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. Regarding 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 the 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 that the measured DGD correlates strongly with an 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 the 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 on the 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 micro-bending, 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 ITU-T 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.

The cut-off wavelength also depends on the curvature applied to the fibre. A typical reduction of about 100 nm is measured with conventional ITU-T 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 proportionality coefficient k also depends on the bending loss sensitivity of the fibre since an improvement in bending loss characteristics affects not only the fundamental mode but also the higher order modes. A bending loss improvement in the higher order modes may change the cut-off mechanism in bending-loss insensitive fibre, influencing the evaluation of the cut-off wavelength using the test methods described in clause 5.3 of [ITU-T G.650.1]. In this case, the single-mode operability of an optical fibre can be investigated by evaluating the multi-path interference (MPI).

MPI arises when the light carrying the signal is affected by parasitic contributions, for example, generated by double scattering events which take place along the optical link. MPI is either "incoherent" or "coherent" depending on whether the time interval between the first and the second scattering in the double event is greater than or less than the coherence time of the light source (the coherence time is related to the source spectral width). An example of incoherent MPI is double Rayleigh scattering. Conversely, coherent MPI may be observed in deployments where some of the light from the fundamental mode is scattered into a high order mode at a splice, connector or small-radius-bend, and then re-coupled into the fundamental mode at a second scattering point whose distance from the first one is shorter than the source's coherence length. In these conditions an interference-induced beating between the original light and a parasitic copy of it can be observed. Test methods for coherent MPI, generated in the way just outlined, are described in Appendix IV of [ITU-T G.650.1]. The presence of MPI-induced noise causes degradation in the optical signal to noise ratio (OSNR), thus adding a power penalty to the optical transmission system. Therefore, single-mode operability and its influence on optical transmission performance can be discussed by evaluating the coherent MPI of an ITU-T G.65x fibre under deployed conditions (length, allowable offset, allowable bending and so on) with the test methods found in Appendix IV of [ITU-T G.650.1].

The following references contain further information: [Anderson], [Kitayama], [Shah], [Montmorillon], [Fukai1] and [Fludger].

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 the input power is transferred into back-scattered 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:

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

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 ($\alpha = 0.000058\ m^{-1}$, $1/\alpha = 17.24$ km).

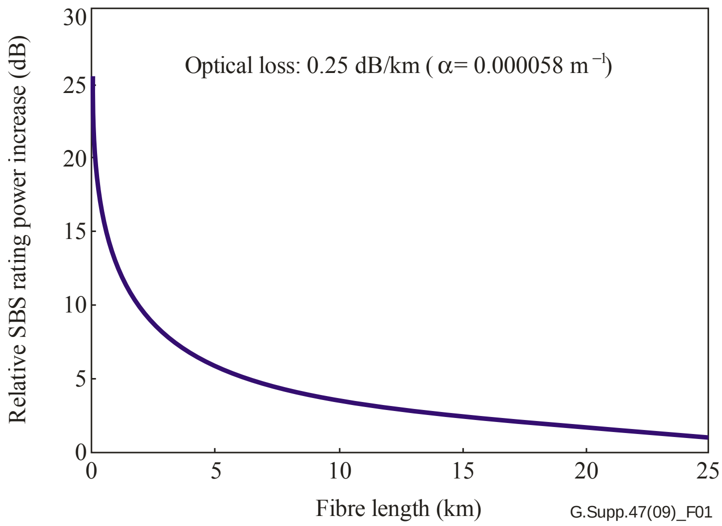

Figure 1 – Fibre length dependence of SBS rating power increase

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 (~40 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 a 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 Δβ 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 ITU-T G.652 fibres and ITU-T G.655 fibres experience much less FWM impairment compared to systems deployed over ITU-T 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 ($\alpha = 0.000058$ m^{-1}).

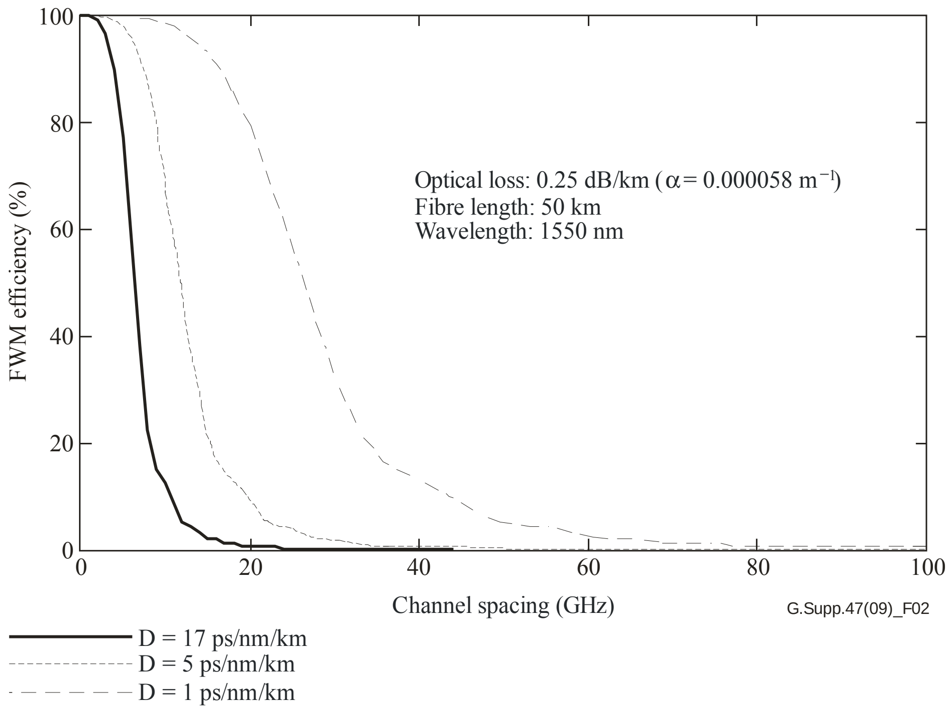

Figure 2 – Channel spacing dependence of FWM efficiency

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 ITU-T 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 an 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). With regard to these two dopants and the fictive temperature effect, it is reported by Tsujikawa *et al.* that the Rayleigh scattering coefficient R (dB/km/μm^4) of fibre with GeO_2 and/or F doped silica could be expressed by:

$$R = 4.1 \times 10^{-4} (T_f + 273) \times (1 + 0.62\Delta_{GeO2} + 0.60\Delta_F^2 + 0.44\Delta_{GeO2}\Delta_F^2)$$

where Δ_{GeO2} and Δ_F denote the relative-index difference changes in per cent induced by GeO_2 and F, respectively. The value of the Rayleigh scattering coefficient in pure silica is reported to be generally around 0.8 dB/km/μm^4. Therefore, a fibre with a pure silica core has less Rayleigh scattering loss than a fibre with a doped silica core. The ITU-T 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 GeO_2 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 $D_M = 1/c\ (dn_g/d\lambda)$. With regard to pure silica glass, the D_M value is 0 at $\lambda = 1.276\ \mu m$, which is called the zero material dispersion wavelength of pure silica. As for GeO_2 doped silica glass, a higher fraction of GeO_2 causes a 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 results 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 GeO_2, 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 GeO_2 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:

$$n_2\left[\times 10^{-20} m^2 / W\right] = 0.0556\eta_{GeO2}[mol\%] + 2.61$$

Here η_{GeO2} is the effective GeO_2 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 the 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_{GeO2}) at its peak is expressed as:

$$g_r(\eta_{GeO2},\nu) = [1 + C(\nu)\eta_{GeO2}]g_r(SiO_2,\nu)$$

where ν is the pump frequency, $g_r(\eta_{GeO2},\nu)$ and $g_r(SiO_2,\nu)$, 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 ITU-T G.653 fibres with a relatively high GeO_2 concentration (~7 mol% which corresponds to ~1% refractive index difference Δ) reportedly have about 1.5 times larger Raman gain coefficients than those for ITU-T G.654 fibres with a pure silica core. With regard to 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], [Fukai2] and [Manolescu].

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