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REDLINE VERSION

TECHNICAL REPORT

colour inside

Application guidelines for nonlinear coefficient measuring methods

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IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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INTERNATIONAL
ELECTROTECHNICAL
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CONTENTS

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APPLICATION GUIDELINES FOR NONLINEAR COEFFICIENT MEASURING METHODS

FOREWORD

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IEC TR 62285 has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics. It is a Technical Report.

This third edition cancels and replaces the second edition published in 2005. It constitutes a technical revision.

This edition includes the following signification technical changes with respect to the previous revision:

a) change fibre type of pigtail to B-652.D fibre or fibre of same type with the fibre under test;
b) modifications on Figure A.1 and Formulas (A.3), (A.4);
c) add example values and recommended method A test conditions for B-G.654.E fibre, update Table C.1.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
86A/2190/DTR	86A/2325/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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- withdrawn,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

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APPLICATION GUIDELINES FOR NONLINEAR COEFFICIENT MEASURING METHODS

1 Scope

This document provides ~~guidance~~ guidelines for uniform measurements of the nonlinear coefficient of class B single-mode fibres (see IEC 60793-2-50) in the 1 550 nm region.

Measurements of the nonlinear coefficient are used to characterise specific single-mode fibre designs for the purpose of system design relative to power levels and distortion or noise effects derived from the nonlinear optical behaviour.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 60793-1-1, *Optical fibres – Part 1-1: Measurement methods and test procedures – General and guidance*~~

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

~~IEC 60793-1-42, *Optical fibres – Part 1-42: Measurement methods and test procedures – Chromatic dispersion*~~

~~IEC 60793-2-50, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres*~~

~~IEC 61315, *Calibration of fibre optic power meters*~~

IEC 60793-1 (all parts), *Optical fibres – Part 1: Measurement methods and test procedures*

IEC 60793-2, *Optical fibres – Part 2: Product specifications – General*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60793-2 and IEC 60793-1 (all parts) apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Abbreviated terms and symbols

4.1 Abbreviated terms

ASE	amplified spontaneous emission
BPF	bandpass filter
CW	continuous wave
EDFA	erbium doped fibre amplifier
FWM	four-wave mixing
OSA	optical spectrum analyser
SPM	self-phase modulation
SBS	stimulated Brillouin scattering
VA	variable attenuator
XPM	cross-phase modulation

4.2 Symbols

A_{eff}	effective area
D	chromatic dispersion coefficient
I	intensity
k	slope
L	specimen length
$J_{\mathrm{n}}()$	Bessel function of the first kind of integer order n
L_{eff}	effective length
$n\mathrm{Lc}$	non-linear coefficient
n_2	Kerr nonlinear refractive index
n_2/A_{eff}	non-linear coefficient
P	input power
P_{peak}	peak input power
R	ratio
v	optical frequency
α	attenuation coefficient (Np/m)
α_{dB}	attenuation coefficient (dB/km)
φ	non-linear phase shift
λ	wavelength
ω	angular optical frequency

5 Background and overview of methods

The nonlinear coefficient ($n\mathrm{Lc}$) is the ratio of the Kerr nonlinear refractive index n_2 to the effective area A_{eff} [1] [1], expressed as:

[1] The numbers in square brackets refer to the Bibliography.

$$nLc = \frac{n_2}{A_{\text{eff}}} \qquad (1)$$

The nonlinear coefficient is related to the following nonlinear optical distortion effects as a combined parameter:

– self-phase modulation (SPM);
– cross-phase modulation (XPM);
– four-wave mixing (FWM).

Other fibre attributes, such as chromatic dispersion and polarisation mode dispersion, also influence the transmission.

Two methods are given, with details specific to each in normative annexes. They are:

– Method A Continuous wave dual-frequency;
– Method B Pulsed single-frequency.

Both methods require injecting very high power (5 dBm or more) into the fibre, measurement of this power (absolute) and measurement of the output spectrum (which is modified by nonlinear effects). Both methods use calculations that combine these measured results with those derived from other measurements such as attenuation (see IEC 60793-1-40) and chromatic dispersion (see IEC 60793-1-42). Both methods have limitations on the length of fibre that can be measured – in relationship with the chromatic dispersion at the wavelength being measured.

Method A [1] requires injecting the light of two wavelengths into the fibre. The light of both wavelengths is constant at various power levels. At higher power, the lights beat due to the nonlinear effect and produce an output spectrum that is spread. The relationship of the power level to a particular metric of spectrum spreading is used to calculate the nonlinear coefficient.

Method B [3], [4] requires injecting pulsed light at a single wavelength. The pulses ~~should~~ would be of duration substantially less than 1 ns and the input peak power of these pulses ~~should~~ would be measured and related to the nonlinear spreading of the output spectrum.

6 Apparatus

6.1 General

The following apparatus is common to both measurement methods. Annex A and Annex B include layout drawings and other equipment requirements for each of the methods, respectively.

6.2 Light source

See Annex A and Annex B for detailed characteristics of the light sources.

6.3 Input optics

The input optics can include one or more lasers, polarisation controllers, couplers, polarisers, amplifiers, bandpass filters, variable attenuators~~, couplers~~ and power meters. ~~Bandpass filters and~~ Oscilloscopes may be needed for method B. See Annex A and Annex B for specific details.

6.4 Input positioner

Provide means of positioning the input end of the specimen to the ~~light source~~ input optics. Typically, this connection is with a fusion splice to a short (1 m) pigtail of type ~~B1.1 fibre~~ B-652.D fibre or fibre of same type with the fibre under test.

6.5 Cladding mode stripper

Use a device that extracts cladding modes. Under some circumstances, the fibre coating will perform this function.

6.6 Output positioner

Provide a suitable means for aligning the fibre to the output optics. Typically, this connection is with a fusion splice to a pigtail of type ~~B1.1 fibre~~ B-652.D fibre or fibre of same type with the fibre under test.

6.7 Output optics

The output optics include a power meter and optical spectrum analyser (OSA). An oscilloscope may be required for method B. See Annex A and Annex B for details.

6.8 Computer

Use a computer to perform operations such as controlling the apparatus, taking intensity measurements and processing the data to obtain the final results.

7 Samples and specimens

A specimen is a known length of single-mode optical fibre (see IEC 60793-2-50). The sample and pigtails ~~should~~ would be fixed in position at a nominally constant temperature throughout the measurement. Standard ~~ambient~~ atmospheric conditions (see IEC 60793-1-1) ~~should~~ would be employed, unless otherwise specified.

End faces for the input and output ends of the test sample ~~should~~ would be prepared as appropriate to obtain low loss fusion splices.

The measurement method is limited with regard to the measurable length because of chromatic dispersion. For this reason, the specimen is normally cut from a longer piece of fibre that has been characterised for attenuation coefficient α_{dB} and chromatic dispersion D at the wavelength of interest (1 550 nm). The length of the fibre after being cut-back is referred to as L.

Annex C provides guidance on the optimum selection of length for different chromatic dispersion coefficient values.

The fibre may be deployed on a common shipping spool.

8 Procedure

The test procedure is as follows:

a) deploy the fibre or cable and prepare the ends;

b) attach the ends to the input and output optics;

c) engage the computer to complete the scans and measurements found in Annex A and Annex B for the measurement method;

d) complete documentation.

9 Calculations of interpretation of results

~~Unless otherwise specified, the units are in meters, seconds, watts, and radians.~~

The fundamental relationships for the two methods are nearly the same, so they are presented here for comparison.

Method A
$$\varphi = \frac{2\pi}{\lambda}\frac{n_2}{A_{\text{eff}}}L_{\text{eff}}\,2P \qquad (2)$$

Method B
$$\varphi = \frac{2\pi}{\lambda}\frac{n_2}{A_{\text{eff}}}L_{\text{eff}}\,P_{\text{peak}} \qquad (3)$$

where

φ is the nonlinear phase shift (rad);

λ is the wavelength (m) (centre of two wavelengths for method A);

L_{eff} is the effective length (m);

P is the input power (W) (~~both~~ either wavelength~~s~~ for method A);

P_{peak} is the peak input power (W) (method B).

If peak input power of method B were equal to twice the input power of method A, the two equations would be identical.

The effective length is defined as the following:

$$L_{\text{eff}} = \frac{1 - \exp(-\alpha L)}{\alpha} \qquad (4)$$

where

L is the length (m);

α is the ~~"natural"~~ attenuation coefficient (Np/m).

$$\alpha = \frac{\alpha_{\text{dB}}}{4{,}343} \times 10^{-3} \qquad (5)$$

where

α_{dB} is the ~~normal~~ attenuation coefficient (dB/km).

The two methods differ in how the phase shift is determined as a function of input power. Once the relationship between phase shift and power has been determined, the inverse of Formula (2) or (3), to obtain the nonlinear coefficient, is easily computed with the other known quantities.

~~For type B1.1 fibre, the non-linear coefficient has been measured to be approximately 2,9 × 10^−10 W^−1, provided as an example of the result.~~

Provided as examples of the result, the nonlinear coefficient has been measured to be

– approximately 2,9 × 10^{-10} W^{-1} for type B-652 fibre;

– approximately 2,0 × 10^{-10} W^{-1} for type B-654.E fibres with A_{eff} around 110 μm^2;

– and approximately 1,7 × 10^{-10} W^{-1} to 1,8 × 10^{-10} W^{-1} for type B-654.E fibres with A_{eff} around 130 μm^2[5].

10 ~~Documentation~~ Results

10.1 Information ~~to be provided~~ available with each measurement

The following information are reported with each measurement:

– date and title of measurement;
– specimen identification;
– ~~Measurement date~~
– nonlinear coefficient: n_2/A_{eff} (W^{-1});
– fibre dispersion coefficient (ps/(nm· km));
– fibre attenuation coefficient (dB /km);
– fibre length (m).

10.2 Information available upon request

The following information are available upon request:

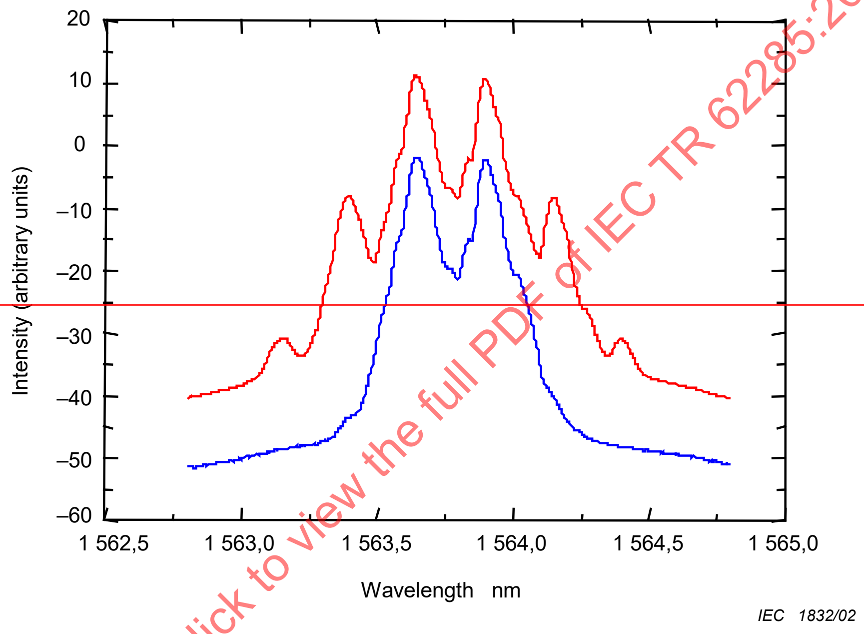
– measurement method used;
– description of the equipment set-up;
– wavelength(s) of the source;
– pulse duration (method B only);
– typical input power levels;
– fibre effective area: A_{eff} (μm^2).

Annex A
(normative)

Continuous wave dual-frequency method

A.1 ~~Introduction~~ General

Annex A contains requirements specific to method A. The principle of the method is to inject two continuous wave (CW) optical frequencies, ω_a and ω_b, into the specimen at various power levels. The two frequencies beat due to nonlinear effects and create sidebands at frequencies ($2\omega_a - \omega_b$) and ($2\omega_b - \omega_a$) (see Figure A.1). The relative intensity of the sidebands I_1 to the intensity of the main bands I_0 is related to both the phase shift and power injected.



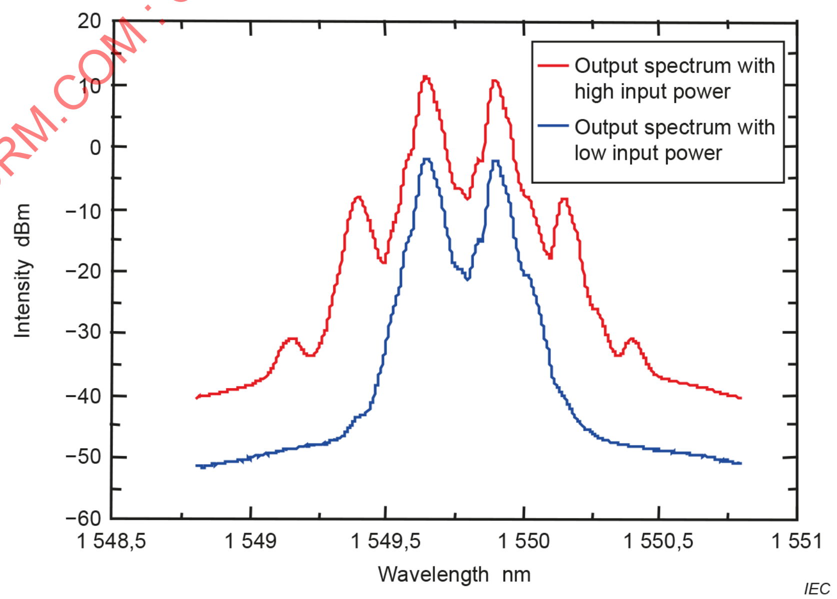


Figure A.1 – Output spectral characteristics

A.2 Apparatus

A.2.1 Layout of apparatus

Figure A.2 shows a typical arrangement of the test apparatus.

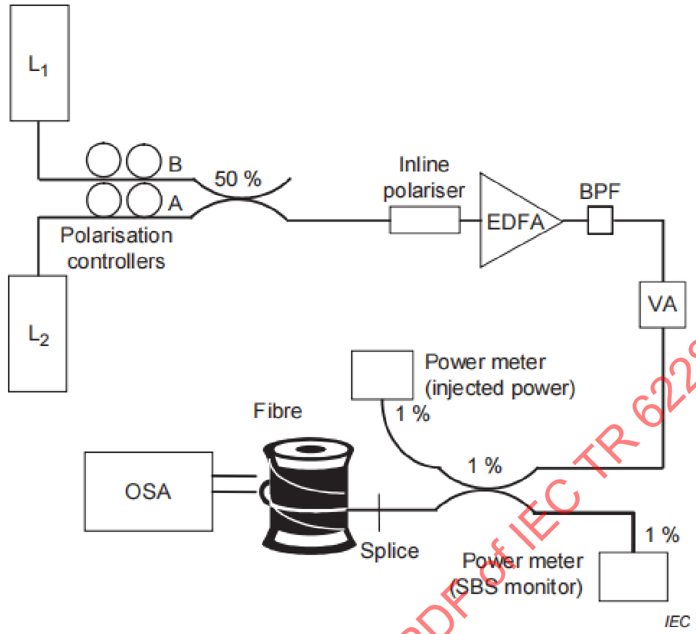


Figure A.2 – Apparatus for method A

A.2.2 Sources

Two laser sources, L_1 and L_2 in Figure A.2, are operated in the CW mode at optical frequencies, ω_a and ω_b, both within the frequency window ~~of~~ corresponding to optical wavelength (1 550 ± 10) nm. The frequency difference, $\Delta\omega_0 = \omega_a - \omega_b$, corresponds to a wavelength difference $\Delta\lambda_0$, which places an upper limit on the spectral width of each of the sources: the source spectral widths ~~should~~ would not exceed 0,1 × $\Delta\lambda_0$. The lower limit on the spectral width is set by the need to avoid stimulated Brillouin scattering (SBS) (see A.2.4).

The wavelength ~~separation~~ difference lower limit is set by the ability of the OSA to resolve the sidebands, and the upper limit is set by the chromatic dispersion of the specimen (see Clause A.3). A typical separation could be 0,035 THz (0,28 nm), but others are feasible depending on the other details of the set-up.

The source powers ~~should~~ would be within ±0,2 dB of one another. The source power is further conditioned by polarisers, optically amplified, and variably attenuated. The minimum injected power is set by the limit at which the sidebands are induced. The maximum is set by the need to avoid SBS.

A.2.3 Optical signal conditioning

Polarisation controllers, ~~combiners~~ couplers, amplifiers, variable optical attenuators and polarisers ~~should~~ would be used in combination so that the lights injected into the specimen are in the same polarisation state and within ±0,2 dB of one another.

In the example of Figure A.2, the erbium doped fibre amplifier (EDFA) is used to boost the power to levels sufficient to induce nonlinear effects. This generates amplified spontaneous emission (ASE) which ~~should~~ would be removed by either:

a) a bandpass filter (BPF) as shown in Figure A.2, or

b) a subtraction of the baseline as determined in the region of the sidebands of the OSA.

NOTE An accurate baseline subtraction can be obtained by measuring the phase response of the measurement system without a test fibre in place.

A.2.4 Power meters

Figure A.2 shows two power meters: one to monitor forward propagation of light injected into the specimen and the other to monitor back-reflected light that could be induced by SBS – to ensure that it remains in the spontaneous, and not the stimulated regime.

Power meters ~~should~~ would be linear and accurate to within ±3 % for the levels used in the test (see IEC 61315 for calibration details).

The power detected by the forward power meter can be calibrated with regard to the power injected into the specimen by cutting the specimen immediately after the splice and measuring the output power at this point.

NOTE 1 The output power emitted from the cut-back specimen will be reduced by Fresnel reflection of approximately 3 % – which ~~should~~ will be taken into account. The required power values are those that are launched into the specimen without the cut.

NOTE 2 Some set-ups feature a third power meter to confirm the splice loss at least one power level following the primary test measurements. Alternatively, measurement of the output of the full specimen, in conjunction with fibre attenuation coefficient and length, can be used to confirm the splice loss.

For a source whose spectral width is much less than the 0,038 THz spontaneous Brillouin linewidth, the threshold for SBS is approximately 20 mW. Increasing the source spectral width to 100 MHz raises this threshold to approximately 100 mW. Other strategies for reducing SBS include:

– modulating the sources at 100 MHz to 1 GHz to increase the effective width;
– reducing the maximum power level;
– reducing the fibre length.

A.2.5 Optical spectrum analyser

The optical spectrum emerging from the specimen is measured with an OSA. The resolution ~~should~~ would be sufficient to clearly resolve the sidebands.

A.3 Samples and specimens

The fibre chromatic dispersion coefficient D (ps/(nm·km)) should be known at the test wavelength before the test is conducted. The length of the specimen may be reduced so the following restriction is satisfied:

$$2\pi \times c\left(\frac{\Delta\omega_0}{\omega_0}\right)^2 \varphi_{max}\left|D\right|L << 1 \qquad \text{(A.1)}$$

where

c is the speed of light in vacuum (2,997 924 58 × 10^8 m/s);

φ_{max} is the maximum anticipated phase shift (rad);

$\Delta\omega_0$ is the difference in optical angular frequencies (rad/s);

ω_0 is the average of the two optical angular frequencies (rad/s);

$|D|$ is the absolute value of dispersion coefficient (s/(m·km));

L is the specimen length (km).

Example:

λ_a = 1 550,00 nm

λ_b = 1 550,28 nm

D = 17,0 ps/(nm·km) = 0,017 s/(m·km)

L = 0,5 km

φ_{max} = 0,3 rad

Formula (A.1) reduces to:

$$2\pi c\left[1\,550{,}14\left(\frac{1}{1550{,}00}-\frac{1}{1550{,}28}\right)\right]^2\times 0{,}3\times 0{,}017\times 0{,}5=0{,}157 \quad \text{(A.2)}$$

Annex C gives guidance on the selection of values to use for specimen test length, power, and wavelength difference (see Table C.1).

A.4 Procedure

A.4.1 General

The procedure requires stepping through a series of power levels. For each power level, the power injected into the specimen is measured or calculated and the ratio of the intensity of the sideband to the main band is measured on the OSA.

A.4.2 Calibration

Attach a calibrated power meter to the output of the source end of the system. Cycle through the desired power levels and at each measure the power with the forward power meter and with the calibration power meter. Remove the effect of Fresnel reflection on the light emitted from the system on the detected output power. The relationship between the measured powers ~~should~~ would be used to determine the power launched into the specimen based on the light measured by the forward power meter on normal measurements.

A.4.3 Operation

Attach the specimen to both the source and receive ends of the system with fusion splices.

Cycle through the power levels – indexed with i. For each:

– record the measured power levels and calculate the power injected into the specimen, P_i;

– complete the OSA scan of the output spectrum;

– if necessary, subtract the amplifier induced ASE noise from the OSA data;

– determine the intensity of the main ~~lobes~~ bands, I_0, and sidebands, I_1. See Figure A.1;

– determine the ratio of the ~~sidelobes~~ sidebands to main ~~lobes~~ bands as R_i = I1/I0;

– confirm the absence of ~~Brillouin scattering~~ SBS~~;~~

~~– take any output power measurements that may be used to confirm splice losses~~.

Disconnect the specimen and take any power measurements that may be needed to confirm the splice loss.

Complete any adjustments to the input power values that may be done with output power measurements or post disconnection measurements.

A.5 Calculations

A.5.1 Calculate phase values

For each power level, calculate the phase shift φ_i by inverting the following ratio of Bessel functions:

$$\cancel{R_i = \frac{J_0^2(\varphi_i/2)+J_1^2(\varphi_i/2)}{J_1^2(\varphi_i/2)+J_2^2(\varphi_i/2)}} \qquad \text{~~(A3)~~}$$

$$R_i = \frac{J_1^2(\varphi_i/2)+J_2^2(\varphi_i/2)}{J_0^2(\varphi_i/2)+J_1^2(\varphi_i/2)} \qquad \text{(A.3)}$$

This inversion can be done in various ways, one of which is to:

a) calculate the R intensity ratio for each of a range of phase values using Equation A.3;
b) plot phase versus R (see Figure A.3);
c) characterise the relationship across the range of phase values that are anticipated.

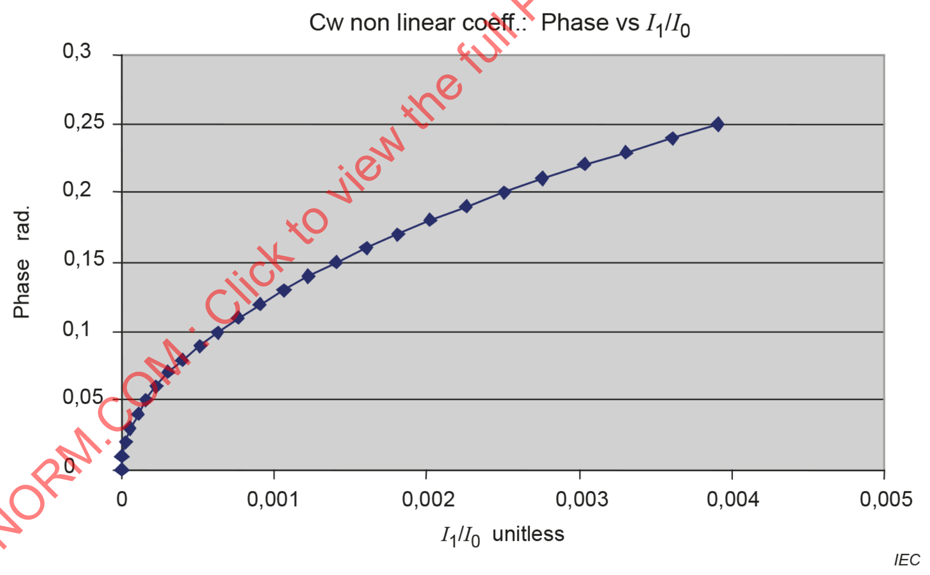


Figure A.3 – Relationship of phase to intensity ratio

A.5.2 Confirm assumptions

Confirm that the range of phase conforms with Formula (A.1). If this is not confirmed, either eliminate the data outside the limit or repeat the measurement with a different length of fibre.

A.5.3 Complete the calculation

Form a plot of phase (rad) vs. power (W) similar to that shown in Figure A.4 and perform a linear regression to obtain the intercept and slope k of the fitted data.

The nonlinear coefficient (W^{-1}) is computed with slope k of the linear regression as:

~~$$\frac{n_2}{A_{\mathrm{eff}}} = \frac{slope \cdot \lambda_0}{4\pi L_{\mathrm{eff}}} \qquad \text{(A.4)}$$~~

$$\frac{n_2}{A_{\mathrm{eff}}} = \frac{k \cdot \lambda_0}{4\pi L_{\mathrm{eff}}} \qquad \text{(A.4)}$$

where

~~slope~~ k is the fitted regression slope (rad/W);

λ_0 is the ~~test wavelength~~ average of input wavelengths (m);

L_{eff} is the effective length (m) [see Clause 9].

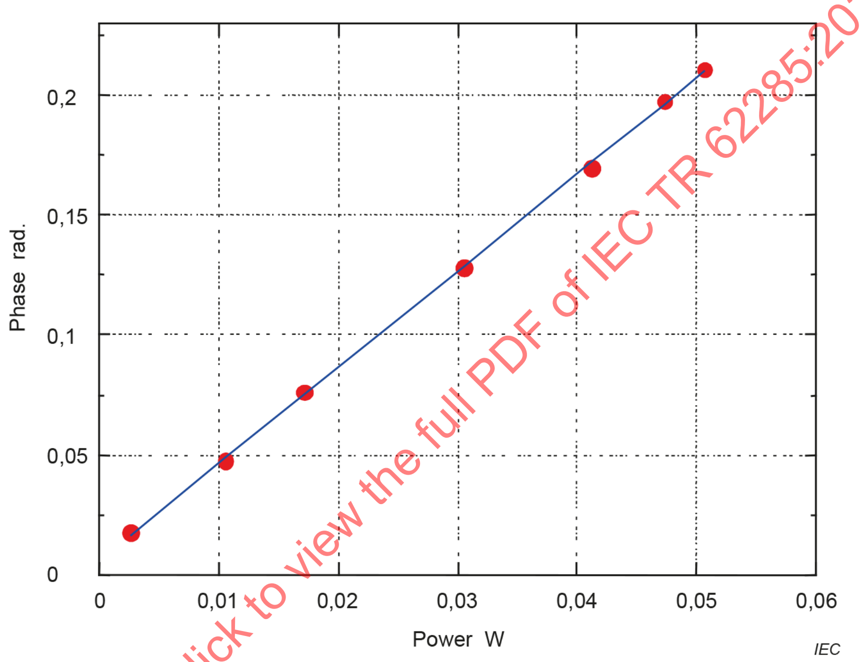


Figure A.4 – Relationship of phase to power

Annex B
(normative)

Pulsed single-frequency method (PM)

B.1 ~~Introduction~~ General

Annex B contains requirements specific to method B, pulsed single-frequency method. The principle of the method is to launch a pulsed, narrow spectral width light that is at a power sufficient to induce self-phase modulation at a given level. The peak-input power at this level is used to calculate the nonlinear coefficient.

B.2 Apparatus

B.2.1 Layout of apparatus

Figure B.1 shows a sample layout of the apparatus, along with some of the options.

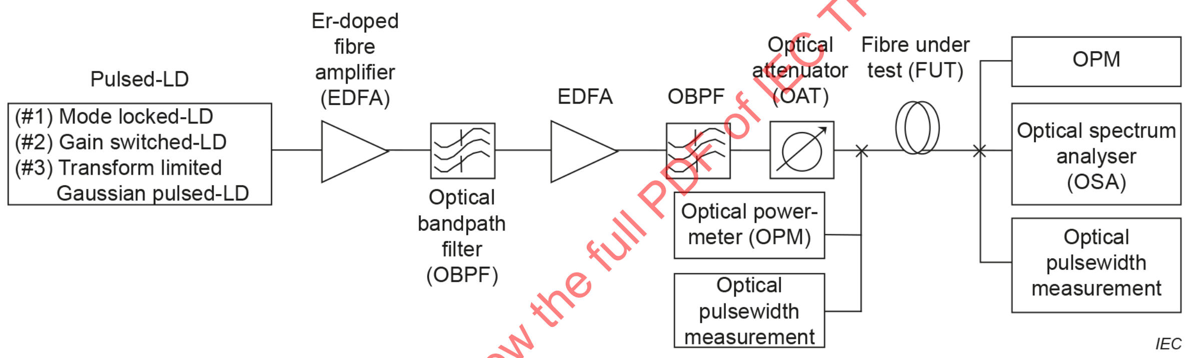


Figure B.1 – Test set-up for method B

B.2.2 Source

Use a transform limited Gaussian optical source with a stable wavelength (no mode hopping) such as:

– mode locked laser diode;

– gain switched laser diode;

– transform limited Gaussian pulsed laser diode.

To avoid electrostriction effects, the pulse width $\Delta\tau$ (ps)~~, should~~ would be less than 1 ns. Pulse widths in the range of 20 ps to 100 ps are recommended. For such pulses, a repetition rate of around 2 GHz is used.

The source ~~should~~ would be within (1 550 ± 10) nm. The spectral width $\Delta\nu$ (THz) requirement of the light injected into the specimen, which can also be modified with a BPF, is interactive with the pulse width. For the transform limited Gaussian case, the product, $\Delta\tau \times \Delta\nu$,~~ should~~ would be approximately 0,5.

B.2.3 Optical signal conditioning

The light is amplified to levels needed to induce significant nonlinear effects with one or more amplifiers and band pass filters to remove ASE.

A variable optical attenuator is used to fine tune the input power to obtain the optimum spreading of the output spectrum as viewed on the OSA.

B.2.4 Power meters

Power meters ~~should~~ would be linear and accurate to within ± 3 % for the levels used in the test (see IEC 61315 for calibration details).

The power meter at the source end of the system is used to determine the input power after the optimum power has been identified. This is done by cutting the specimen off the system and completing the measurement. This value, in conjunction with the pulse data, is used to calculate the peak-input power.

The power meter at the receive end of the system is used to evaluate the transmitted power to confirm proper set-up and to confirm that no SBS is occurring.

B.2.5 Optical pulsewidth measurement

This involves a combination of detector and oscilloscope.

Both units are used in conjunction with the power meter measurements to determine the peak-input power of the pulses.

B.2.6 Optical spectrum analyser

The optical spectrum emerging from the specimen is measured with an OSA. The resolution ~~should~~ would be sufficient to clearly resolve the sidebands which are induced by nonlinear effects. See Figure B.2.

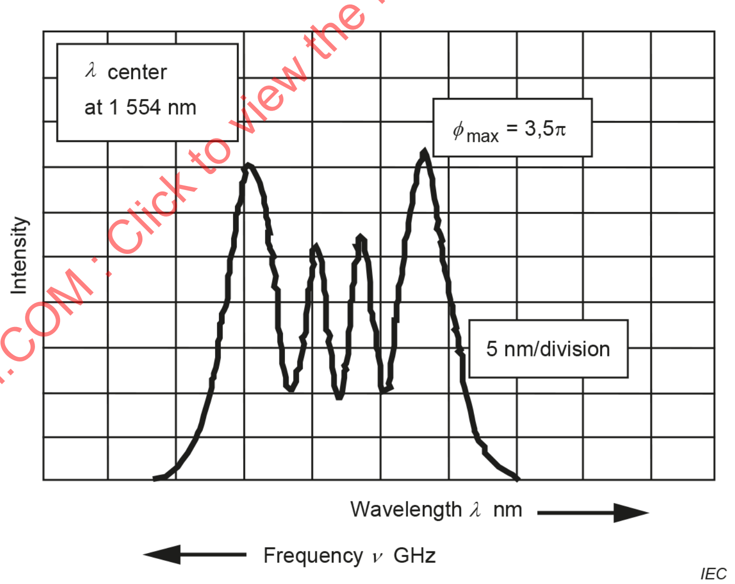


Figure B.2 – Output spectra

B.3 Samples and specimens

The combination of chromatic dispersion coefficient D (ps/(nm·km)), value and sign, at the test wavelength and effective area, are interactive with regard to the length L (km) of the specimen that can be tested.

The limiting condition is expressed with the product of dispersion coefficient and length, $D \times L$ (ps/nm). If this product is not suitable, the fibre ~~should~~ would be cut to a length that is suitable.

For specimens with higher effective area and positive dispersion coefficient, (~~types B1.1, B1.2, B1.3~~ types B-652, B-654, and some category ~~B4~~ B-655 fibres), $D \times L$ ~~should~~ would be less than 8,0 ps/nm.

For specimens with lower effective area and positive dispersion coefficient (category ~~B2~~ B-653 and some category ~~B4~~ B-655 fibres), $D \times L$ ~~should~~ would be less than 2,0 ps/nm.

For fibres with significant negative dispersion, such as those used for dispersion accommodation, pulse compression can alter the results. For these fibres, the pulse compression (ps) from the transform limit is calculated using $D \times L$, the pulse width, and the spectral width.

If the pulse compression is less than 15 ps, the length is suitable. If the pulse compression is larger, either the length ~~should~~ would be decreased or the pulse width ~~should~~ would be increased (but not over approximately 100 ps).

B.4 Procedure

The specimen is connected to the source and ~~receives~~ receive ends of the system with fusion splices.

The input power is varied with the variable attenuator until a symmetric spectrum with an integer number of peaks, M, such as shown in Figure B.2, is obtained. The output power and output pulse shapes are measured at this optimal setting.

The specimen is cut at the source end on the far side of the splice and the power and pulse shape at the optimum setting is measured.

NOTE To enhance the precision of the result, the test can be applied at multiple optimal power settings to produce output spectra with different numbers of peaks as long as the variable attenuator can be restored to these settings after the specimen is cut.

B.5 Calculations

B.5.1 Peak power

Use the power meter values, the measured pulse shape and the repetition rate to calculate the peak input power, P_{peak} (W), at the input and output ends of the specimen.

The peak output power in combination with the fibre attenuation coefficient can be used to confirm the input power value.

B.5.2 Phase shift

The phase shift φ (rad) is calculated from the number of peaks in the output spectrum, M (integer), as:

$$\varphi = \pi(M - 0{,}5) \tag{B.1}$$

B.5.3 Complete the calculations

If a single power setting was completed, the nonlinear coefficient (W^{-1}) can be calculated as:

$$\frac{n_2}{A_{\text{eff}}} = \frac{\varphi\lambda}{2\pi L_{\text{eff}} P_{\text{peak}}} \tag{B.2}$$

where

φ is the phase shift (rad);

λ is the test wavelength (m);

L_{eff} is the effective length (m) [see Clause 9];

P_{peak} is the peak input power (W).

If multiple power settings were completed, the phase shift vs. peak power can be plotted (see Figure B.3) and fitted with a linear regression to obtain the intercept and slope k. In this case, the nonlinear coefficient can be computed (using the same definitions) as:

$$\cancel{\frac{n_2}{A_{eff}} = \frac{slope \cdot \lambda}{2\pi L_{eff}}} \qquad \text{~~(B3)~~}$$

$$\frac{n_2}{A_{eff}} = \frac{k \cdot \lambda_0}{2\pi L_{eff}} \qquad \text{(B.3)}$$

where

k is the fitted regression slope (rad/W).

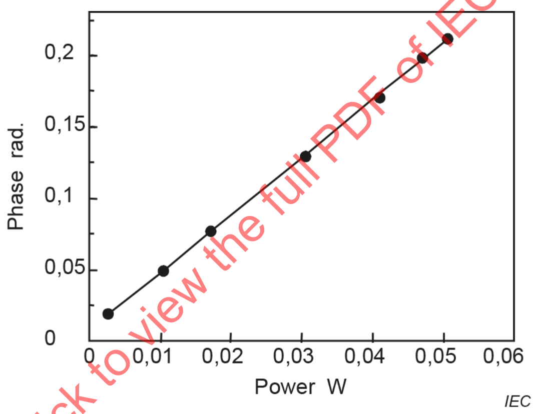


Figure B.3 – Phase vs. peak input power for method B

~~Annex C~~
~~(normative)~~

~~List of acronyms and symbols~~

~~nLc~~	~~Non-linear coefficient~~
~~n_2/A_{eff}~~	~~Non-linear coefficient~~
~~A_{eff}~~	~~Effective area~~
~~SPM~~	~~Self-phase modulation~~
~~XPM~~	~~Cross-phase modulation~~
~~FWM~~	~~Four-wave mixing~~
~~cw~~	~~Continuous wave~~
~~OSA~~	~~Optical spectrum analyser~~
~~EDFA~~	~~Erbium doped fibre amplifier~~
~~ASE~~	~~Amplified spontaneous emission~~
~~BPF~~	~~Bandpass filter~~
~~SBS~~	~~Stimulated Brillouin scattering~~
~~φ~~	~~Non-linear phase shift~~
~~λ~~	~~Wavelength~~
~~ω~~	~~Angular optical frequency (rad/ps)~~
~~ν~~	~~Optical frequency (THz)~~
~~L_{eff}~~	~~Effective length~~
~~P~~	~~Input power~~
~~P_{peak}~~	~~Peak input power~~
~~α_{dB}~~	~~Attenuation coefficient (dB/km)~~
~~α~~	~~Attenuation coefficient (nepers/m)~~
~~D~~	~~Chromatic dispersion coefficient~~
~~L~~	~~Specimen length~~
~~I~~	~~Intensity~~
~~$J_1()$~~	~~Bessel function~~
~~R~~	~~Ratio~~

Annex C
(informative)

Guidance on the selection of fibre test length, power and difference in optical wavelength when using method A

The specimen length L, minimum input power P_{min}, and difference in optical wavelength $\Delta\lambda$, as shown in Table C.1, are representative values that may be used when measuring the nonlinear coefficient of the indicated single-mode fibres when using method A.

Table C.1 – Fibre characteristics for method A (representative values)

		~~B1.1~~	~~B2 and B4~~	~~Dispersion compensating fibre~~
~~Chromatic dispersion D~~	~~(ps/nm·km)~~	~~17~~	~~0 to 10~~	~~−20 to −200~~
~~Attenuation coefficient α~~	~~(dB/km)~~	~~0,21~~		~~0,40~~
~~Effective area A_{eff}~~	~~(µm^2)~~	~~80~~	~~45 to 100~~	~~20~~
~~Specimen length L~~	~~(km)~~	~~1,0~~	~~1,0 to 1,7~~	~~3,82 · $\lvert D \rvert^{-0,75}$~~
~~Minimum input power P_{min}~~	~~(mW)~~	~~20~~	~~10 to 20~~	~~1,.59 · $\lvert D \rvert^{-0,66}$~~
~~Difference in optical wavelength $\Delta\lambda$~~	~~(nm)~~	~~0,20 to 0,35~~	~~0,20 to 0,50~~	~~0,20 to 0,38~~

Attribute	Unit	B-652 and B-657	B-653 and B-655	B-654.E	Dispersion compensating fibre
Chromatic dispersion D	(ps/(nm·km))	16 to 18	0 to 10	20	−20 to −200
Attenuation coefficient α	(dB/km)	0,19 to 0,21		0,18	0,40
Effective area A_{eff}	(µm^2)	70 to 90	45 to 100	110 to 130	20
Specimen length L	(km)	1,0	1,0 to 1,7	0,5 to 1,0	3,82 · $\lvert D \rvert^{-0,75}$
Minimum input power P_{min}	(mW)	20	10 to 20	40 to 80	1,.59 · $\lvert D \rvert^{-0,66}$
Difference in optical wavelength $\Delta\lambda$	(nm)	0,20 to 0,35	0,20 to 0,50	0,20 to 0,35	0,20 to 0,38

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TECHNICAL REPORT

colour inside

Application guidelines for nonlinear coefficient measuring methods

IEC TR 62285:2023-10(en)

CONTENTS

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APPLICATION GUIDELINES FOR NONLINEAR COEFFICIENT MEASURING METHODS

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IEC TR 62285 has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics. It is a Technical Report.

This third edition cancels and replaces the second edition published in 2005. It constitutes a technical revision.

This edition includes the following signification technical changes with respect to the previous revision:

a) change fibre type of pigtail to B-652.D fibre or fibre of same type with the fibre under test;
b) modifications on Figure A.1 and Formulas (A.3), (A.4);
c) add example values and recommended method A test conditions for B-G.654.E fibre, update Table C.1.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
86A/2190/DTR	86A/2325/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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APPLICATION GUIDELINES FOR NONLINEAR COEFFICIENT MEASURING METHODS

1 Scope

This document provides guidelines for uniform measurements of the nonlinear coefficient of class B single-mode fibres (see IEC 60793-2-50) in the 1 550 nm region.

Measurements of the nonlinear coefficient are used to characterise specific single-mode fibre designs for the purpose of system design relative to power levels and distortion or noise effects derived from the nonlinear optical behaviour.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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, *Optical fibres – Part 2: Product specifications – General*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60793-2 and IEC 60793-1 (all parts) apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Abbreviated terms and symbols

4.1 Abbreviated terms

ASE	amplified spontaneous emission
BPF	bandpass filter
CW	continuous wave
EDFA	erbium doped fibre amplifier
FWM	four-wave mixing
OSA	optical spectrum analyser
SPM	self-phase modulation
SBS	stimulated Brillouin scattering
VA	variable attenuator
XPM	cross-phase modulation

4.2 Symbols

A_{eff}	effective area
D	chromatic dispersion coefficient
I	intensity
k	slope
L	specimen length
$J_n()$	Bessel function of the first kind of integer order n
L_{eff}	effective length
$n\mathrm{Lc}$	non-linear coefficient
n_2	Kerr nonlinear refractive index
n_2/A_{eff}	non-linear coefficient
P	input power
P_{peak}	peak input power
R	ratio
ν	optical frequency
α	attenuation coefficient (Np/m)
α_{dB}	attenuation coefficient (dB/km)
φ	non-linear phase shift
λ	wavelength
ω	angular optical frequency

5 Background and overview of methods

The nonlinear coefficient ($n\mathrm{Lc}$) is the ratio of the Kerr nonlinear refractive index n_2 to the effective area A_{eff} [1] [1], expressed as:

$$nLc = \frac{n_2}{A_{\text{eff}}} \tag{1}$$

The nonlinear coefficient is related to the following nonlinear optical distortion effects as a combined parameter:

– self-phase modulation (SPM);
– cross-phase modulation (XPM);
– four-wave mixing (FWM).

Other fibre attributes, such as chromatic dispersion and polarisation mode dispersion, also influence the transmission.

Two methods are given, with details specific to each in normative annexes. They are:

– Method A Continuous wave dual-frequency;
– Method B Pulsed single-frequency.

1 The numbers in square brackets refer to the Bibliography.

Both methods require injecting very high power (5 dBm or more) into the fibre, measurement of this power (absolute) and measurement of the output spectrum (which is modified by nonlinear effects). Both methods use calculations that combine these measured results with those derived from other measurements such as attenuation (see IEC 60793-1-40) and chromatic dispersion (see IEC 60793-1-42). Both methods have limitations on the length of fibre that can be measured – in relationship with the chromatic dispersion at the wavelength being measured.

Method A [1] requires injecting the light of two wavelengths into the fibre. The light of both wavelengths is constant at various power levels. At higher power, the lights beat due to the nonlinear effect and produce an output spectrum that is spread. The relationship of the power level to a particular metric of spectrum spreading is used to calculate the nonlinear coefficient.

Method B [3], [4] requires injecting pulsed light at a single wavelength. The pulses would be of duration substantially less than 1 ns and the input peak power of these pulses would be measured and related to the nonlinear spreading of the output spectrum.

6 Apparatus

6.1 General

The following apparatus is common to both measurement methods. Annex A and Annex B include layout drawings and other equipment requirements for each of the methods, respectively.

6.2 Light source

See Annex A and Annex B for detailed characteristics of the light sources.

6.3 Input optics

The input optics can include one or more lasers, polarisation controllers, couplers, polarisers, amplifiers, bandpass filters, variable attenuators and power meters. Oscilloscopes may be needed for method B. See Annex A and Annex B for specific details.

6.4 Input positioner

Provide means of positioning the input end of the specimen to the input optics. Typically, this connection is with a fusion splice to a short (1 m) pigtail of type B-652.D fibre or fibre of same type with the fibre under test.

6.5 Cladding mode stripper

Use a device that extracts cladding modes. Under some circumstances, the fibre coating will perform this function.

6.6 Output positioner

Provide a suitable means for aligning the fibre to the output optics. Typically, this connection is with a fusion splice to a pigtail of type B-652.D fibre or fibre of same type with the fibre under test.

6.7 Output optics

The output optics include a power meter and optical spectrum analyser (OSA). An oscilloscope may be required for method B. See Annex A and Annex B for details.

6.8 Computer

Use a computer to perform operations such as controlling the apparatus, taking intensity measurements and processing the data to obtain the final results.

7 Samples and specimens

A specimen is a known length of single-mode optical fibre (see IEC 60793-2-50). The sample and pigtails would be fixed in position at a nominally constant temperature throughout the measurement. Standard atmospheric conditions (see IEC 60793-1-1) would be employed, unless otherwise specified.

End faces for the input and output ends of the test sample would be prepared as appropriate to obtain low loss fusion splices.

The measurement method is limited with regard to the measurable length because of chromatic dispersion. For this reason, the specimen is normally cut from a longer piece of fibre that has been characterised for attenuation coefficient α_{dB} and chromatic dispersion D at the wavelength of interest (1 550 nm). The length of the fibre after being cut-back is referred to as L.

Annex C provides guidance on the optimum selection of length for different chromatic dispersion coefficient values.

The fibre may be deployed on a common shipping spool.

8 Procedure

The test procedure is as follows:

a) deploy the fibre or cable and prepare the ends;

b) attach the ends to the input and output optics;

c) engage the computer to complete the scans and measurements found in Annex A and Annex B for the measurement method;

d) complete documentation.

9 Calculations of interpretation of results

The fundamental relationships for the two methods are nearly the same, so they are presented here for comparison.

Method A
$$\varphi = \frac{2\pi}{\lambda}\frac{n_2}{A_{\text{eff}}} L_{\text{eff}}\, 2P \tag{2}$$

Method B
$$\varphi = \frac{2\pi}{\lambda}\frac{n_2}{A_{\text{eff}}} L_{\text{eff}} P_{\text{peak}} \tag{3}$$

where

φ is the nonlinear phase shift (rad);

λ is the wavelength (m) (centre of two wavelengths for method A);

L_{eff} is the effective length (m);

P is the input power (W) (either wavelength for method A);

P_{peak} is the peak input power (W) (method B).

If peak input power of method B were equal to twice the input power of method A, the two equations would be identical.

The effective length is defined as the following:

$$L_{eff} = \frac{1-\exp(-\alpha L)}{\alpha} \tag{4}$$

where

L is the length (m);

α is the attenuation coefficient (Np/m).

$$\alpha = \frac{\alpha_{dB}}{4{,}343} \times 10^{-3} \tag{5}$$

where

α_{dB} is the attenuation coefficient (dB/km).

The two methods differ in how the phase shift is determined as a function of input power. Once the relationship between phase shift and power has been determined, the inverse of Formula (2) or (3), to obtain the nonlinear coefficient, is easily computed with the other known quantities.

Provided as examples of the result, the nonlinear coefficient has been measured to be

- approximately 2,9 × 10^{-10} W^{-1} for type B-652 fibre;
- approximately 2,0 × 10^{-10} W^{-1} for type B-654.E fibres with A_{eff} around 110 μm^2;
- and approximately 1,7 × 10^{-10} W^{-1} to 1,8 × 10^{-10} W^{-1} for type B-654.E fibres with A_{eff} around 130 μm^2[5].

10 Results

10.1 Information available with each measurement

The following information are reported with each measurement:

- date and title of measurement;
- specimen identification;
- nonlinear coefficient: n_2/A_{eff} (W^{-1});
- fibre dispersion coefficient (ps/(nm· km));
- fibre attenuation coefficient (dB /km);
- fibre length (m).

10.2 Information available upon request

The following information are available upon request:

- measurement method used;
- description of the equipment set-up;
- wavelength(s) of the source;
- pulse duration (method B only);
- typical input power levels;

– fibre effective area: A_{eff} (µm^2).

Annex A
(normative)

Continuous wave dual-frequency method

A.1 General

Annex A contains requirements specific to method A. The principle of the method is to inject two continuous wave (CW) optical frequencies, ω_a and ω_b, into the specimen at various power levels. The two frequencies beat due to nonlinear effects and create sidebands at frequencies $(2\omega_a - \omega_b)$ and $(2\omega_b - \omega_a)$ (see Figure A.1). The relative intensity of the sidebands I_1 to the intensity of the main bands I_0 is related to both the phase shift and power injected.

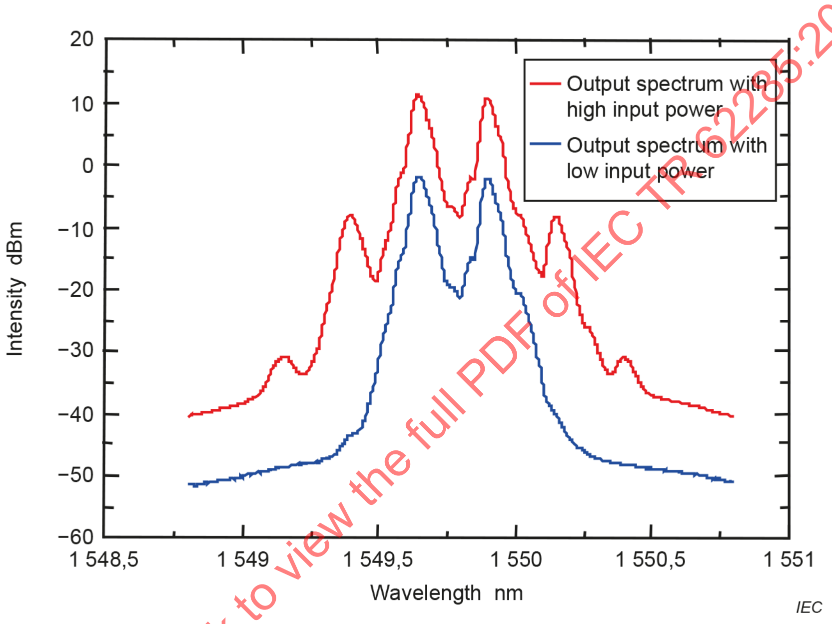

Figure A.1 – Output spectral characteristics

A.2 Apparatus

A.2.1 Layout of apparatus

Figure A.2 shows a typical arrangement of the test apparatus.

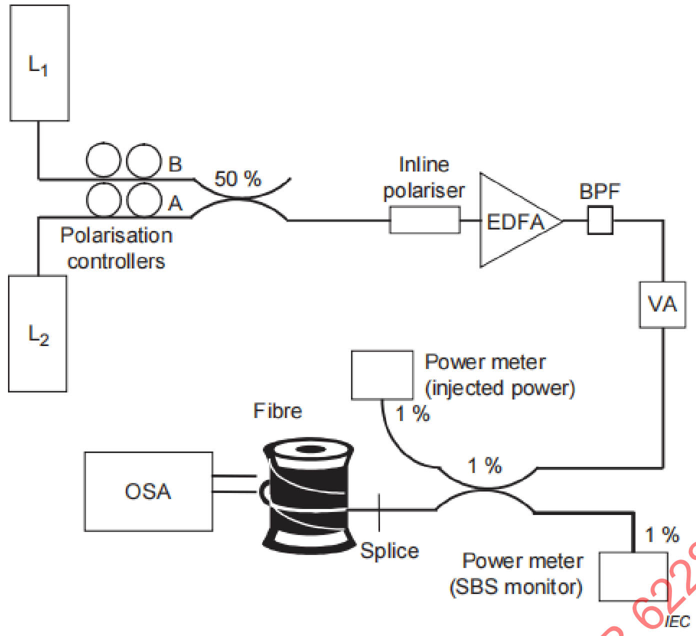

Figure A.2 – Apparatus for method A

A.2.2 Sources

Two laser sources, L_1 and L_2 in Figure A.2, are operated in the CW mode at optical frequencies, ω_a and ω_b, both within the frequency window corresponding to optical wavelength (1 550 ± 10) nm. The frequency difference, $\Delta\omega_0 = \omega_a - \omega_b$, corresponds to a wavelength difference $\Delta\lambda_0$, which places an upper limit on the spectral width of each of the sources: the source spectral widths would not exceed $0{,}1 \times \Delta\lambda_0$. The lower limit on the spectral width is set by the need to avoid stimulated Brillouin scattering (SBS) (see A.2.4).

The wavelength difference lower limit is set by the ability of the OSA to resolve the sidebands, and the upper limit is set by the chromatic dispersion of the specimen (see Clause A.3). A typical separation could be 0,035 THz (0,28 nm), but others are feasible depending on the other details of the set-up.

The source powers would be within ±0,2 dB of one another. The source power is further conditioned by polarisers, optically amplified, and variably attenuated. The minimum injected power is set by the limit at which the sidebands are induced. The maximum is set by the need to avoid SBS.

A.2.3 Optical signal conditioning

Polarisation controllers, couplers, amplifiers, variable optical attenuators and polarisers would be used in combination so that the lights injected into the specimen are in the same polarisation state and within ±0,2 dB of one another.

In the example of Figure A.2, the erbium doped fibre amplifier (EDFA) is used to boost the power to levels sufficient to induce nonlinear effects. This generates amplified spontaneous emission (ASE) which would be removed by either:

a) a bandpass filter (BPF) as shown in Figure A.2, or

b) a subtraction of the baseline as determined in the region of the sidebands of the OSA.

NOTE An accurate baseline subtraction can be obtained by measuring the phase response of the measurement system without a test fibre in place.

A.2.4 Power meters

Figure A.2 shows two power meters: one to monitor forward propagation of light injected into the specimen and the other to monitor back-reflected light that could be induced by SBS – to ensure that it remains in the spontaneous, and not the stimulated regime.

Power meters would be linear and accurate to within ±3 % for the levels used in the test (see IEC 61315 for calibration details).

The power detected by the forward power meter can be calibrated with regard to the power injected into the specimen by cutting the specimen immediately after the splice and measuring the output power at this point.

NOTE 1 The output power emitted from the cut-back specimen will be reduced by Fresnel reflection of approximately 3 % – which will be taken into account. The required power values are those that are launched into the specimen without the cut.

NOTE 2 Some set-ups feature a third power meter to confirm the splice loss at least one power level following the primary test measurements. Alternatively, measurement of the output of the full specimen, in conjunction with fibre attenuation coefficient and length, can be used to confirm the splice loss.

For a source whose spectral width is much less than the 0,038 THz spontaneous Brillouin linewidth, the threshold for SBS is approximately 20 mW. Increasing the source spectral width to 100 MHz raises this threshold to approximately 100 mW. Other strategies for reducing SBS include:

– modulating the sources at 100 MHz to 1 GHz to increase the effective width;
– reducing the maximum power level;
– reducing the fibre length.

A.2.5 Optical spectrum analyser

The optical spectrum emerging from the specimen is measured with an OSA. The resolution would be sufficient to clearly resolve the sidebands.

A.3 Samples and specimens

The fibre chromatic dispersion coefficient D (ps/(nm·km)) should be known at the test wavelength before the test is conducted. The length of the specimen may be reduced so the following restriction is satisfied:

$$2\pi \times c\left(\frac{\Delta\omega_0}{\omega_0}\right)^2 \varphi_{\max}|D|L << 1 \qquad \text{(A.1)}$$

where

c is the speed of light in vacuum (2,997 924 58 × 10^8 m/s);

$\varphi_{\max}$ is the maximum anticipated phase shift (rad);

$\Delta\omega_0$ is the difference in optical angular frequencies (rad/s);

ω_0 is the average of the two optical angular frequencies (rad/s);

$|D|$ is the absolute value of dispersion coefficient (s/(m·km));

L is the specimen length (km).

Example:

λ_a = 1 550,00 nm

λ_b = 1 550,28 nm

D = 17,0 ps/(nm·km) = 0,017 s/(m·km)

L = 0,5 km

φ_{max} = 0,3 rad

Formula (A.1) reduces to:

$$2\pi c\left[1\,550{,}14\left(\frac{1}{1550{,}00}-\frac{1}{1550{,}28}\right)\right]^2\times 0{,}3\times 0{,}017\times 0{,}5=0{,}157 \quad \text{(A.2)}$$

Annex C gives guidance on the selection of values to use for specimen test length, power, and wavelength difference (see Table C.1).

A.4 Procedure

A.4.1 General

The procedure requires stepping through a series of power levels. For each power level, the power injected into the specimen is measured or calculated and the ratio of the intensity of the sideband to the main band is measured on the OSA.

A.4.2 Calibration

Attach a calibrated power meter to the output of the source end of the system. Cycle through the desired power levels and at each measure the power with the forward power meter and with the calibration power meter. Remove the effect of Fresnel reflection on the light emitted from the system on the detected output power. The relationship between the measured powers would be used to determine the power launched into the specimen based on the light measured by the forward power meter on normal measurements.

A.4.3 Operation

Attach the specimen to both the source and receive ends of the system with fusion splices.

Cycle through the power levels – indexed with i. For each:

– record the measured power levels and calculate the power injected into the specimen, P_i;

– complete the OSA scan of the output spectrum;

– if necessary, subtract the amplifier induced ASE noise from the OSA data;

– determine the intensity of the main bands, I_0, and sidebands, I_1. See Figure A.1;

– determine the ratio of the sidebands to main bands as R_i = I1/I0;

– confirm the absence of SBS.

Disconnect the specimen and take any power measurements that may be needed to confirm the splice loss.

Complete any adjustments to the input power values that may be done with output power measurements or post disconnection measurements.