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MEASUREMENT METHODS FOR SINGLE-MODE OPTICAL FIBRES

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Measurement methods for single-mode optical fibres

Measurements Aims and Requirements

In general the experimental characterization of single-mode optical fibres and cables requires particular care, with respect to the multimode case due to the small dimensions of the core and the numerical aperture of the fibre itself and to its huge bandwidth. There are however some definite advantages in single-mode fibre cable measurements due mainly to the propagation of only one well defined field configuration. This means that very few transmission parameters are necessary for a full characterization. Moreover some characterizing quantities such as attenuation, bandwidth, joint losses, are univocally defined with, in principle, a more modest spread in the measurement results as compared to multimode fibres.

Single-mode fibre cable measurements can be roughly divided in: laboratory, factory and field measurements. Each one of these has its own aims and requirements.

Laboratory measurements

Laboratory measurements are mainly aimed to research and development. However in some cases they could be needed for particular product controls and tests. Consequently the requirements in this case are primarily adressed to the accuracy and the sensitivity of the measurement, while requirements on its practicability and handiness can be relaxed to a certain extent.

Factory measurements

Factory measurements are mainly aimed to quality control and possibly to acceptance tests. The industrial environment of this kind of measurements will necessarily require the maximum automation and reliability - in terms of repeatability - of the test techniques. At this stage it is also important to verify the cable quality, checking its safety margins. To this end, tests more severe than what required by the operating conditions may be needed as additional information.

Field measurements

Field measurements are mainly aimed to line testings and to maintenance tests. The main requirements, in this case, will be toward the practicabilty of the techniques and the handiness of the instrumentation. In particular portable instruments allowing accurate measurements in a wide range of environmental conditions, easy to be used, and able to permit point to point measurements, will be needed.

Reference and alternative test methods

For the product acceptance purposes, CCITT has recommended for each relevant parameter some measurement techniques, namely the REFERENCE TEST METHODS (RTMs) and the ALTERNATIVE TEST METHODS (ATMs). The RTM is strictly related to the definition of the parameter and it should provide accurate and reproducible results, that are relatable to practical use. The ATM is consistent, also if indirectly, with the definition of the parameter and it should be of practical use, providing results reproducible and relatable to the RTM. It is understood that in case of discrepancy among the results of different test methods, the RTM will provide the definitive measurement results.

According to the type of measurement parameters test methods can be divided in Transmission Tests (which include measurements on the transmissive parameters, namely attenuation, cut-off wavelength, mode field diameter and chromatic dispersion); Geometrical and Optical Tests (which include measurements on refractive index profile and geometry characteristics); and Mechanical and Environmental Tests (both on fibres and on cables). All these measurement methods are discussed in the following paragraphs, with full reference to official CCITT documents whenever possible.

Transmission Tests

Attenuation measurements

Attenuation measurements represent the most typical routine measurement of optical fibres and cables. The most relevant test methods for the attenuation are: the cut-back technique and the backscattering technique. Spectral attenuation measurements by the cut-back technique are usually performed at the factory on each uncabled fibre and repeated after cabling. This gives information not only about the fibre performance at different wavelengths but also on the fibre fabrication and cabling quality. Attenuation measurements by backscattering technique at operation wavelength, are generally repeated at the installation both for link and system testings and are typical maintenance tests.

In every case, owing to the small value of the attenuation coefficient, these measurements require particular care. An accurate suppression of cladding modes, by means of suitable effective cladding mode strippers, must be performed. However a considerable advantage is represented by the absence, above the cut-off wavelength, of any differential mode attenuation effects; this makes the measurement results more repeatable and independent of the launching conditions.

The cut-back technique has been recommended as RTM. This technique consists in determining the attenuation along the fibre measuring the optical power at the output of the whole fibre length and at the output of a short cut-back fibre section respectively, having left unchanged the launching conditions. Details about this technique can be found in Rec. G.652, Annex B, Section IV, Paragraph B.2.

The most remarkable advantage of the cut-back technique is that, as an RTM, it provides results absolutely coherent to the definition and consequently reliable from the point of view of system application. On the other hand the main problem is represented by the fact that this method is partially destructive since few meters of the fibre or of the cable must be sacrified at each measurement. These facts, while they make it possible a wide use of this technique for laboratory and factory measurements, prevent its extensive use for field measurements.

The backscattering technique has been chosen as an ATM. It consists in evaluating the attenuation from the slope of the time distribution of power backscattered along the fibre (reported in logarithmic scale). This method is based upon the consideration that the amount of power scattered (mainly by Rayleigh effect) and guided backward in every longitudinal section of the fibre is proportional to the total power actually propagating in that section. Such an assumption is correct if the fibre has uniform characteristics along its length. However if this assumption is not verified the backscattering technique can be able to provide additional quantitative information about possible characteristics fluctuations, physical defects, joint losses. This stresses the versatility of applications of such a test method, also if particular measurement configurations or further elaborations of the experimental data can be necessary to derive information about quantities besides attenuation. Details about the backscattering technique can be found in Rec. G.652, Annex B, Section IV, Paragraph B.3.

A peculiar advantage of the backscattering technique is that it requires the access of only one end of the fibre or the cable and in principle it is non destructive. For this reason it represents the ideal test method for the attenuation in field measurements. However its use for factory measurement, to control the longitudinal uniformity of the fibre characteristics, is largely spread.

The backscattering technique requires particular care in the case of single-mode fibres due to the lower power level and to polarization effects. This last problem has been solved using polarization insensitive optical couplers. A way to overcome possible problems due to a low power level, consists in increasing the sensitivity of the receiver. To this end three main solutions have been exploited: use of very low noise transimpedance amplifiers, coherent detection and photon counting. Concerning this last approach, detectors working at room temperature have been recently demonstrated.

Cut-off wavelength measurements

The cut-off wavelength of the higher order mode (LP11) is very important to characterize a single-mode optical fibre cable, since it limits the region of single-mode operation of the fibre. This suggests to have a cut-off wavelength as low as possible, with respect to the operating wavelength, in so that to avoid bimodal operation or possible modal noise, that could severely degrade the dispersion performance of the fibre.

However the cut-off wavelength indirectly influences also the fibre performance at higher wavelengths. This is important in view of employing the fibre in the 1550nm region. At such wavelengths the fibre is more sensitive to bending, and there is an indirect relation, depending on the fibre design, between this additional bending loss and the cut-off wavelength. Generally this fact suggests to have a cut-off wavelength as high as possible to ensure a greater mode confinement with consequent lower bending losses at higher wavelengths.

Apart the indications about the admissible cut-off wavelength range itself, these two different requirements do affect the definition of the measurement configuration of this parameter. In particular if the first requirement is privileged, the cut-off wavelength should be better measured on a reasonably short uncabled fibre sample, free of external stresses, and including a loop of reasonably large radius. This will ensure to prevent modal noise or bimodal operation, in the fibres characterized in this way, also in the worst case of short fibre sections (such as pig-tails, short fibre links, repair sections). On the contrary if the second requirement is privileged, the cut-off wavelength should be better measured on the cabled fibre, in the elementary cable section. This will ensure a better resistance of the fibre to bending at higher wavelengths, without problems of contamination from the higher order modes at lower wavelengths, provided that no short sections of fibre will be present along the link.

As it can be envisaged from what considered, these two opposite requirements may also refer to different fibre applications: the first refers mainly to applications in which fibre cable sections of very different lengths can be present, including possible repair sections; the second refers mainly to applications in which long fibre cable sections only can be present.

Having left the theoretical definition of the cut-off wavelength, that results of poor practical utility, the cut-off wavelength actually measured is an effective parameter. This is defined as that wavelength at which the ratio between the total power (including the higher order contribution) and the fundamental mode power has been decreased to a suitably fixed low quantity.

Such a definition gives a cut-off wavelength value of practical use and unambiguous, provided that a certain number of measurement conditions are fixed - i.e. included in the definition - and accurately controlled. These relevant measurement conditions include: length and curvature of the fibre sample, external stresses, coating and cabling conditions, launching conditions. Recommendation G.652 has presently fixed these parameters as follows:

a) ratio of the total-to-fundamental mode power in the cut-off wavelength definition: 0.1dB;

b) length of the fibre sample: 2m;

c) curvature condition: one loop of 14cm radius and lower curvatures in the remaining part of the sample;

d) external stresses: as low as possible;

e) cabling conditions: uncabled sample;

f) launching conditions: uniform to ensure equal excitation of both the fundamental and the higher order modes.

These conditions are such to privilege to a certain extent the requirement of preventing higher order mode contamination rather than the requirement about a lower sensitivity to bending at higher wavelengths. To balance this situation in order to meet the demands of long fibre cable sections applications, the debate within CCITT has produced a second definition of the cut-off wavelength, substantially similar to the previous one but referred to a cabled length of fibre. Works about this new definition are still in progress and Rec. G.652 (Paragraph 1.5 and Annex A, Paragraph A.1) is referred for the final version of the definition. However some general consideration can already be drawn: unfortunately it is not possible to find a general relation between these two cut-off wavelengths, since it strongly depends on the structure of the particular cable; generally the cut-off wavelength on the uncabled fibre will result greater than that of the cabled fibre by various tens of nanometers: this means that the cut-off wavelength defined on the uncabled fibre length could exceed the operating wavelength while that defined on the cabled fibre length does remain sufficiently lower than the minimum operating wavelength. Consequently each one of these two cut-off wavelengths can be used in practice, depending on the particular application. The use of the definition on the uncabled fibre length should assure the single-mode operation in every practical situation and it permits relatively easier measurements. On the other hand the use of the definition on the cabled fibre length can also assure the single-mode operation, provided that no cable sections of length shorter than that given in the definition are present and once the the single-mode operation of other cable structures possibly present in the link is verified. The use of this last definition will give the additional advantage of a better reliability in longer wavelengths operation.

In every case the problem of possible bending losses in the 1550nm wavelength region is presently faced by an additional qualification test that is reported in Rec. G.652, Paragraph 1.6.

The RTM for cut-off wavelength is the transmitted power technique that consists in measuring the spectral transmitted power of the single-mode fibre referred to that either of a multimode fibre or of the same fibre but with a smaller loop. The spectral attenuation curve of both versions of the technique presents a falling edge followed by a certain plateau beginning when the the LP11 mode ceases to propagate. This edge permits a precise determination of the cut-off wavelength as the point of the spectral attenuation at 0.1dB above the plateau. This means that about 2% of power is propagated in the higher mode, with an attenuation of the LP11 mode of about 20dB in the measurement conditions: a quite acceptable figure. Details concerning this technique are described in Rec. G.652, Annex B, Section III, Paragraph B.1.

A considerable advantage of the transmitted power technique is that it requires substantially the same experimental set-up used for spectral attenuation measurements; this usually allows these two kinds of measurement to be performed together. Moreover this technique seems the most practical and the most accurate among the methods proposed so far; it permits to derive not only the cut-off wavelength but also - coherently to the definition - the spectral behaviour of the total-to-fundamental mode power ratio and of the attenuation coefficient of the LP11 mode, provided that the uniform excitation of both modes be accurately assured.

However a lot of other techniques have been devised for the measurement of the cut-off wavelength; all of them are based on the spectral scanning of some parameter (mode field diameter, near-field pattern, refracted near-field, polarization degree, etc.). Among these the mode field diameter vs. wavelength technique has been chosen as ATM; its description can be found in Rec. G.652, Annex B, Section III, Paragraph B.2.

Mode field diameter measurements

The mode field diameter characterizes dimensionally the single-mode fibre from the point of view of the propagating optical field. In fact, it fundamentally represents the width of the radial distribution of the optical field of the single-mode fibre and it provides useful information about possible cabling and joint losses and, to a certain extent, on cut-off wavelength and dispersion. CCITT has recommended to adopt this transmission parameter instead of the core size for the dimensional characterization of the single-mode fibre.

A certain debate occurred until recently about what definition to adopt for the mode field diameter. In fact different definitions have been given for this parameter, corresponding to different measurement techniques. This problem has been recently solved, at least from the standardization point of view, adopting the mode field diameter given by the inverse of the r.m.s. width of the far-field intensity distribution of the fibre. This definition adds the advantage of a practical physical meaning to that of a versatility of measurement.

The experimental characterization of this parameter is not so dependent on the fibre condition as in the case of the cut-off wavelength: care is only needed to avoid the propagation of cladding modes. Thus tests on this parameter are usually performed on a limited and representative set of fibre samples.

The most immediate measurement techniques for the mode field diameter are based upon the scanning of the near- or of the far-field intensity of the fibre, and the use of the defining equations. These scannings can be divided in optical scannings (exploring the optical field by a small area photodetector or a pig-tail connected to the photodetector) and electronic scannings (using vidicon tubes or CCD devices). The latter are faster but less precise. Other scanning techniques are based on the insertion of a scanning spatial filter onto the fibre beam, such as a knife edge, a slit, a variable aperture or an axially scanning aperture. They allow the determination of functions related to the near- or to the far-field intensity distribution that, through derived equations, can permit a practical evaluation of the mode field diameter.

Finally, there are two further techniques based on different philosophies, namely the transverse offset technique and the mask technique. The transverse offset technique permits the determination of the mode field diameter through the behaviour of the coupling losses in intentionally offset joints; it exploits the fact that the coupling loss in a joint between two identical single-mode fibres with a modest tranverse offset is proportional to the inverse square of the mode field diameter.

The mask technique is based on an optical processing of the output beam of the fibre under test, using a mask of transmittivity proportional to the square of its transverse coordinate. The ratio between two total power measurements, the first without the mask and the other having centred the mask onto the fibre beam, allows a direct determination of the r.m.s. width of the field distribution, and thus of the mode field diameter, without any scanning.

The direct scanning techniques require a relatively higher dynamic range (about 30dB) to avoid the inaccuracies due to the noise in the tails of the field distributions, which are overweighted in the defining equations. The near-field scanning technique is slightly more critical due to the presence of derivatives in the defining equation. The quality of the measurement can be however substantially improved, in these cases, introducing suitable smoothing algorithms of experimental data. The far-field techniques have the additional advantage to require a simpler measurement apparatus, e.g. without need of any magnifying optics. On the other hand, the near-field techniques have the advantage that a similar set-up can be used for geometry measurements; so, with this technique, these two kinds of measurements can be performed in conjunction.

The indirect scanning techniques are very practical and, in principle, precise; thus they seem well suited for field instruments.

The transverse offset technique has the problem of requiring several accurate joint loss measurements for transverse offsets in a submicron range. However the choice of a suitable fitting functions of loss-vs.-offset experimental points can substantially improve the practicability of this measurement permitting the exploitation of offset data up to few microns.

The mask technique represents a very syntethic test method and in principle it is also very precise. This makes this technique particularly fit for practical instruments. Particular care is only needed in the fabrication of the mask in order to avoid possible systematic errors that could arise from imperfections of the mask, such as a residual transparency or a poor resolution in the centre.

The RTM for the mode field diameter includes three different versions, coherent with the three equivalent definitions of this paramater, based on the near-field, the far-field, and the autocorrelation function respectively (Rec. G.652, Annex A, Paragraph A.1). Thus these three versions of the RTM are the near-field, the far-field and the transverse offset techniques. Some other far-field scanning techniques - the variable aperture and the knife edge methods - have been chosen as possible versions of the RTM. The mask technique is presently under study as ATM. Details concerning these methods will be found in Rec. G.652, Annex B, Section I.

Chromatic dispersion measurements

Chromatic dispersion measurements allow the determination of the transmission capacity of single-mode fibres. In fact the temporal pulse broadening (r.m.s. width) along a single-mode fibre is given with good approximation by the product of the fibre length, the spectral (r.m.s.) width of the optical source and the chromatic dispersion, defined as the derivative of the group delay per unit fibre length with respect to the wavelength. Since, due to the small dispersion of a single-mode fibre, the direct determination of the bandwidth or of the pulse broadening is impractical, these quantities are evaluated through chromatic dispersion measurements.

The chromatic dispersion is not a too critical parameter and its characterization in the factory can be limited to a representative set of fibre samples. Portable and handy instruments can be needed if chromatic dispersion measurements are required for field testing of the installed links.

Measurement techniques for chromatic dispersion can be divided in full-length and short-length methods. Full-length methods can be either time domain or frequency domain measurements. Short-length methods can be either direct, such as the interferometric technique, or indirect, such as the spectral scanning of mode field diameter.

The typical time domain measurement is represented by the pulse delay technique consisting in determining the relative time delay, suffered along the fibre, among pulses at different wavelengths. The typical frequency domain measurement is represented by the phase shift technique and is based on the determination of the relative phase shift (from which the relative time delay can be obtained), occurred along the fibre, among sinusoidally modulated optical carriers at different wavelengths.

The interferometric technique permits to determine the phase shift occurred in a short fibre sample at different wavelengths, and thus the corresponding time delay, through an inspection of the fringe visibility curves in a suitable interferometer, in which the fibre sample can be inserted. Finally the spectral scanning of the mode field diameter allows a direct determination of the waveguide dispersion, that is given by the derivative of the mode field diameter with respect to the wavelength. However both the material and profile dispersion contributions should be independently known for the determination of the total chromatic dispersion.

The pulse delay technique does not seem to exhibit any decisive advantage with respect to the phase shift technique. On the contrary, being it based on short time interval measurements, it requires a more sophisticated instrumentation. The phase shift technique, besides being simpler, is highly accurate permitting to detect time delays as low as 1ps or less. Both long-length techniques can use a compact multilaser system at different wavelengths; the phase shift technique, however, can also be implemented on LED sources, permitting a very large number of wavelength measurement points. The dynamic range of this technique, even using LED sources results conspicuous enough to permit an adequate characterization of a whole link. For these reasons the phase shift technique seems ideal for field instruments.

The interferometric technique balances the drawback of a delicate interferometric set-up with an excellent resolution: about 0.1ps. The technique of the spectral scanning of the mode field diameter is good to control the dispersion properties at a research stage, but it is too indirect for industrial characterizations. Moreover both these short-length techniques present the problem of the extrapolation of measured quantities to full-length fibre cable sections, whose reliability will depend on the longitudinal uniformity of the fibre characteristics.

A general problem of all these techniques is that they actually measure directly the time delay as a function of the wavelength. Consequently a fitting curve to the delay-vs.-wavelength experimental points, whose derivative will provide the chromatic dispersion, is needed. An accurate choice of this fitting curve is essential for a correct determination of the chromatic dispersion. For single-mode fibres, dispersion optimized around 1300nm, a reasonable three-terms Sellmeier fitting equation has been normalized (Rec. G.652, Annex B, Section V, Paragraph B.1.3). However the problem remains open for other single-mode fibres.

Only very recently an effective direct measurement technique for chromatic dispersion has been proposed: the "double demodulation" method (see A.J.Barlow and I.Mackenzie, in Proc. of OFC/IOOC'87, Reno (ND, USA) 19-22 January 1987, Paper TUQ1). It essentially consists in a phase shift apparatus in which the monochromator is further modulated at a low frequency around a central wavelength, so that the phase shift after the fibre length results similarly modulated with an amplitude proportional to the delay difference among the chromatic components of the propagated radiation. Thus a further demodulation of the signal will provide directly a quantity substantial proportional to the fibre chromatic dispersion at the central wavelength.

CCITT has recommended the pulse delay technique and the phase shift technique as two versions of the RTM for the chromatic dispersion, in the time domain and in the frequency domain respectively. This method is described in Rec. G.652, Annex B, Section V.

Geometrical and Optical Tests

Refractive index profile measurements

Refractive index profile measurements in single-mode fibres in general are not strictly necessary, since, as mentioned, the mode field diameter already provides full information about relevant dimensional properties of the fibre. However refractive index profile measurements could be required at factory stage for process and product quality control. In this case refractive index profile measurements both on preform and fibre samples could be necessary.

Refractive index measurements on the preform are normally performed by instruments based on a computer elaboration of the deviation of light crossing laterally the preform itself.

The most popular refractive index profile measurement technique on fibres is the refracted near-field technique. This technique is suggested by CCITT for single-mode fibres (Rec. G.652, Paragraph 1.4.3) and recommended as RTM for multimode fibres. A full description of this technique is then given in Rec. G.651, Annex B, Section I, Paragraph B.2.

Finally the refractive index profile of a single-mode fibre can also be determined by means of a computer elaboration of the transmitted near-field measurement data. In fact, the square root of the measured near-field intensity provides the amplitude of the optical field, which is connected to the refractive index profile of the fibre by the scalar wave equation. Thus the index profile can be simply determined by inverting the scalar wave equation. This technique has the advantage to require a simpler experimental set-up - the one used for near-field measurements, e.g. of the mode field diameter determination - but also the intrinsic drawback of providing reliable results in the core and in the inner cladding regions only.

Geometrical measurements

Geometrical measurements concern the mode field (that takes the role of the core in single mode fibres) and the cladding non-cicularity, their non-concentricity and cladding diameter. All these parameters are important to ensure good connection and splice performances, but they are not critical; thus tests on a limited fibre sample can be in general sufficient in the factory.

These tests are usually performed measuring the near-field at the fibre output by video systems with suitable digitizing facilities. A linear and uniform TV camera could be necessary in this case; alternatively suitable software compensation could be used. Finally particular calculation algorithms are required for determining both the mode field area and the cladding area.