Characterization of Polarization Maintaining Fiber Optic Components

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Abstract: *The behavior of the optical polarization in fiber-based elements and the associated characterization methods are reviewed. The relevant figures of merit are defined and analyzed in relation to different measurement set-ups. Differences and similarities in the experimental results are considered and sources of discrepancies or misinterpretations clarified. The orientation procedures of high-quality polarization maintaining fiber elements and the evaluation of their polarization performance according to the current international standards are explained.*

Introduction

The use of polarization maintaining (PM) elements based upon optical fibers is relentlessly growing. One of the most powerful driving forces is often the need to spatially confine light and move it around with minimal losses while preserving the information embedded in the light polarization. The evolution of laser technologies together with the progresses in PM fiber manufacturing techniques and the advancements in optical integration into increasingly complex and performing systems have broadened the application fields to cover metrology, spectroscopy, telecommunications, sensing/monitoring, industrial tools, medical diagnostic instruments, etc. Along with the number of applications, the performance expectations for PM elements have increased and so the need for better and more accurate characterization methods and tools. Inevitably, with higher expectations the measurement criticalities have grown, as well.

There are several recurring issues when dealing with the evaluation of the optical performance of PM elements, the key ones being the characterization methods, and the correct interpretation of the measurement outcomes. Especially when performance is pushed to the limits, there are experimental details and theoretical subtleties that should not be misinterpreted nor neglected.

This document presents a quick review of the two most prevalent methods currently used for the determination of the relevant figures of merit for PM fiber-based optical elements. The goal is to offer a more in-depth description of the physical mechanisms that control polarized light through PM elements and how these may affect conceptually different characterization set-ups. First, an introduction to a few mathematical and physical tools necessary to the understanding of the concept of polarization shall be given in §2. The different kinds and structures of PM fibers will then be presented in §3 together with their operating principles. In §4 the figures of merit that usually characterize the performance of PM elements will be discussed before moving into the analysis and description of the experimental procedures needed to assess them in §5. The most relevant issues arising when connecting PM elements shall be finally reviewed in §6.

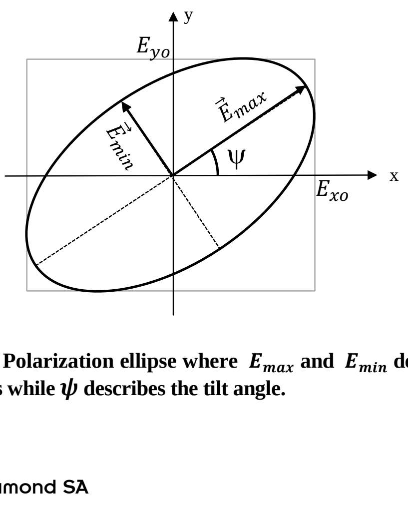

Figure 1. Polarization ellipse where E_{max} and E_{min} define the main axes while ψ describes the tilt angle.

Light polarization fundamentals

Within the frame of classical electromagnetism, light is described by its electric field vector $\boldsymbol{E}$ whose orientation defines the polarization direction [1]. The transverse nature of electromagnetic waves allows for the $\boldsymbol{E}$-field of a monochromatic plane wave propagating in free space to be expressed as

$$\boldsymbol{E} = \begin{pmatrix} E_{x0}\cos(\omega t - kz) \\ E_{y0}\cos(\omega t - kz + \phi) \end{pmatrix} \quad (1)$$

where E_{x0}, E_{y0} are amplitude components of the $\boldsymbol{E}$-field, ω is the angular frequency, k is the wave vector which for simplicity is assumed to be aligned along the z-axis, and ϕ is a phase. For a field propagating in time or in space along z, the tip of the $\boldsymbol{E}$-vector typically describes an elliptical trajectory when projected on a plane orthogonal to the propagation direction, as shown in fig. 1. This is commonly referred to as the polarization ellipse. With some simple algebra it can be shown that for $\phi = 0, \pi$ the polarization ellipse collapses into a straight line, i.e. the $\boldsymbol{E}$-vector oscillates along a fix line whose inclination depends on the E_{x0} and E_{y0} relative amplitudes; light is then said to be linearly polarized. In another configuration with $E_{x0} = E_{y0}$ and the relative phase $\phi = \pm\pi/2$, the trajectory turns into a circle, i.e. the $\boldsymbol{E}$-vector rotates; light is then said to be circularly polarized. For all other values of amplitudes and phase the polarization turns into a general elliptical polarization.

When light propagates through different media or optical elements, the polarization ellipse evolves readjusting its shape and tilt. To keep track of such changes, different mathematical approaches have been developed, the two most widespread ones being the formalisms introduced by Jones and Stokes, respectively [2-4].

2.1 Jones formalism

A representation of the ***E***-field propagation relies upon the use of field *amplitudes* and phases. Such a mathematical method describes the polarization ellipse and its evolution through the optical elements by means of 2x2 matrices in which the ***E***-field is considered to be a 2-dimensional complex quantity. Due to the vector nature of ***E***-fields, optical waves can be superposed by simply adding the individual field's amplitudes and by properly taking into account the phases. For this reason, the Jones formalism is suitable to describe the polarization of highly *coherent* light. Unfortunately, field's amplitudes and phases are no detectable physical quantities. Hence, the polarization ellipse cannot be measured directly, what may limit in many cases the effectiveness of the Jones' formalism.

2.2 Stokes polarization parameters

An alternative description is based upon *intensities*, i.e. measurable physical quantities, and relies upon a set of four parameters [2]. These contain all relevant information needed to reconstruct the polarization ellipse from the following relationship:

$$\boldsymbol{S} = \begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix} = \begin{pmatrix} E_{x0}^2 + E_{y0}^2 \\ E_{x0}^2 - E_{y0}^2 \\ 2E_{x0}E_{y0}\cos\phi \\ 2E_{x0}E_{y0}\sin\phi \end{pmatrix} \tag{2}$$

Eq. 2 provides a few hints on how these Stokes parameters S_i $(i = 0,1,2,3)$ are linked to intensities: s_0 and s_1 are sum and difference of intensities measured through linear polarizers oriented along the x and y axis, respectively while s_2 and s_3 are derived from intensities measured through a combination of a linear polarizer and a waveplate, as we shall see later on in more details. Note that for a monochromatic wave, only three of the four parameters are independent since

$$s_0^2 = s_1^2 + s_2^2 + s_3^2 \tag{3}$$

The convenience of the Stokes parameters lies in the fact that it allows representing every state of polarization (SoP) by a unique point on the Poincaré sphere (see fig.2) instead of an ensemble of two dimensional ellipses. The evolution of the SoP as the light propagates through

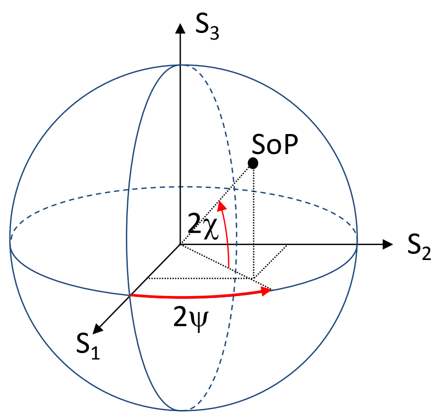

Figure 2. Representation of an arbitrary SoP (black dot) on the Poincaré sphere. The radius of the sphere is s_0.

different elements will then be described by a trajectory on the sphere.

Useful information can be derived from the azimuth and the elevation angles associated to a SoP on the Poincaré sphere, which provides a direct link to the angle ψ and the ellipticity of the polarization ellipse by means of

$$\tan(2\psi) = {}^{s_2}/_{s_1} \tag{4}$$

$$\tan(2\chi) = {}^{s_3}/_{s_1} \tag{5}$$

The Stokes' approach also offers additional advantages. For instance, it allows dealing with partly or even fully unpolarized light, something that the Jones formalism does not support. In such cases however eq.3 must be corrected into the inequality

$$s_0^2 \geq s_1^2 + s_2^2 + s_3^2 \tag{6}$$

This leads to the introduction degree of polarization of the light defined as

$$DoP = \sqrt{s_1^2 + s_2^2 + s_3^2}\ /\ s_0 \tag{7}$$

which, as we shall see below, sets stringent requirements to the measurement experimental conditions. Finally, since the Stokes parameters are linked to intensities, two fully independent and uncorrelated beams can be added by simply adding the individual Stokes vectors.

2.3 Polarization measurements

The Stokes parameters are typically determined through intensity measurements (not fields) carried out by means of traditional power meters, linear polarizers, and optical waveplates. Among the possible configurations, a typical arrangement consists of a power splitter that separates the incident beam into four identical portions each one filtered

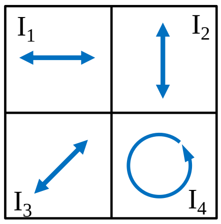

Figure 3. Example of a 4-quadrant polarimeter with three linear and one circular polarizer.

by polarizers oriented along different directions, as shown in fig. 3. In that example, the polarimeter comprises three linear polarizers oriented horizontally, vertically, and at 45°, respectively and a fourth circular polarizer consisting of a combination of a quarter waveplate and a linear polarizer [2]. The four intensities measured behind the associated polarizers can be mixed to calculate the four Stokes parameters according to

$$\begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix} = \begin{pmatrix} I_1 + I_2 \\ I_1 - I_2 \\ 2I_3 - I_1 - I_2 \\ I_1 + I_2 - 2I_4 \end{pmatrix} \tag{8}$$

From there, we can readily position the measured SoP on the Poincaré sphere and compute the original polarization ellipse with the help of eqs. 4, 5. Note that the assembly shown in fig. 3 does not represent the only possible configuration; different combinations of linear polarizers and waveplates can be used both in static or in rotating arrangements. The right hand side of eq. 8 will have to be

rearranged accordingly, always using intensity values only [2].
Now that a method for the determination of SoP's is available, the polarization characteristics of an optical element may be evaluated by comparing the output SoP to an input SoP, typically a linearly polarized one.

Polarization maintaining fibers

The SoP of light propagating in a perfectly homogeneous medium is preserved, i.e. the polarization ellipse remains unchanged and the corresponding point on the Poincaré sphere does not move. However, any fluctuation in the medium may induce radical changes as typically seen in standard optical fibers. Fluctuations may be caused by a slight material inhomogeneity, environmental changes (temperature variations), or by a mechanical stress applied intentionally or produced by fiber bending, twisting or stretching. To mitigate such detrimental effects, PM fibers are made birefringent. This is typically achieved by introducing stress elements into the fiber structure that anisotropically compress the core region. On one hand, such fibers turn out to be more resilient towards external perturbations; on the other hand the radial symmetry is lifted since the refractive indices suffer small changes parallel and perpendicularly the internal stress direction. This effectively generates two orthogonal symmetry lines referred to as polarization optical axes or principal axes. When glass is compressed the refractive index usually increases, thus lowering the propagation speed of light polarized along the compression lines. This direction is commonly referred to as the slow axis in contrast to the orthogonal one known as the fast axis, as shown in fig. 4. Associated to the optical axes there are two polarization eigenmodes, i.e. two SoP's that can propagate unaltered along the fiber. These two particular polarization states

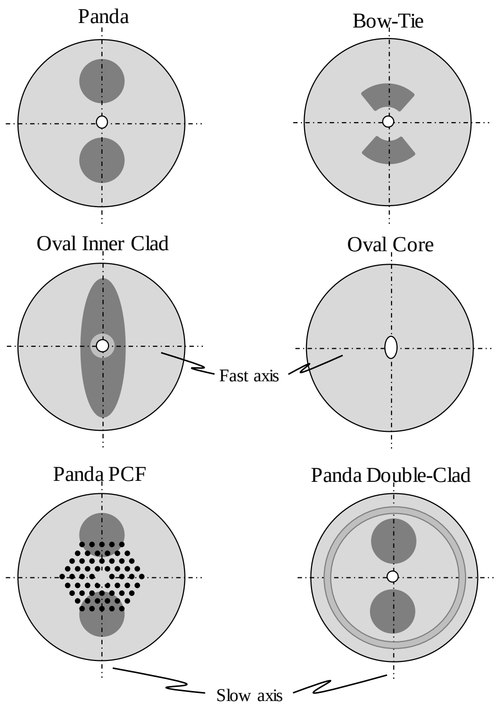

Figure 4. Examples of schematic cross-sections of a few PM fiber structures. The dark features represent the stress elements used to induce birefringence. Fast axes are oriented horizontally while the slow ones are vertical.

correspond to linearly polarized light whose electric field is perfectly oriented along either one of the principal axes. The polarization ellipse then collapses onto one of two possible perpendicular lines along the optical axes. Note that only these two linear polarization states remain linear all along the PM fiber; all others will sooner or later evolve into elliptical polarizations. This evolution is the natural consequence of the projection of the ***E***-field vector onto the main axes. The two components travel at two different speeds so that a phase delay ϕ (see eq. 1) accumulates as light propagates through the fiber. This modifies the corresponding polarization ellipse and the SoP changes. This applies of course to an ideal PM fiber. In reality the two eigenpolarizations actually suffer from perturbations due to material homogeneity or induced by external stresses. The consequences are discontinuities in the distribution of the refractive indices that can cause deviations in the local birefringence and consequently the orientation of the principal axes. This turns into power coupling between the two eigenpolarizations and thus a degradation of the linearity of these polarization states. It has to be noted that, although the index fluctuations are in absolute value comparable to those observed in standard fibers, the resulting variations of the *birefringence* are much less effective in PM fibers since they are much smaller compared to the natural fiber's birefringence. This explains why PM fiber are far less sensitive to external stresses (bending, twisting, etc.) compared to standard ones. In order to see an appreciable effect, the external stress must act on the fiber's core comparably to the natural internal forces.
There are several kinds of PM fibers characterized by different techniques or geometries used to achieve the desired birefringence [5]. The most popular fiber types rely upon two stress elements made of a slightly different glass placed at both sides of the core as shown in fig. 4 for the examples of Panda and Bow-Tie fibers. During the fiber's manufacturing, the different materials solidify at different temperatures effectively generating an anisotropic residual stress distribution, which in turn induces the desired birefringence. A similar approach is used for the oval-inner clad PM fiber where a single, oval stress element surrounds the core's region. Birefringence can also be achieved by pure geometrical means for example by making the core's cross-section oval. There has been a recent blooming of new PM fibers relying upon more complex material structures such as photonic crystal fibers (PCF) or double-clad fibers. There, birefringence is achieved either by taking advantage of previously existing schemes like in Panda fibers or by designing intrinsic birefringent photonic crystal structures. Note that for double-clad fibers, polarization can be preserved only for light propagating inside the inner core.

PM fiber performance

The variety of PM fiber types is partly driven by specific application requirements. A common denominator remains however their ability to preserve the integrity of the eigenpolarizations. Such capability is usually assessed by evaluating the polarization ellipse or the Stokes parameters at the fiber's output provided linearly polarized light is launched along one of the input main axes. The figure of merit typically used to quantify how efficiently a PM fiber can hold the power in its eigenpolarizations is the so-called polarization extinction ratio (*PER*) or polarization cross-talk. This scalar value defines how much of the power injected into one eigenpolarization leaks to the orthogonal one at the fiber's output. Mathematically, this is expressed on a linear scale as

$$PER = \frac{||E_{min}||^2}{||E_{max}||^2} \tag{9}$$

where the fields E_{min} and E_{max} represent the main axes of the polarization ellipse, as in fig. 1. It can be readily seen that by geometric reasons the *PER* is nothing else than

$$PER = \frac{1}{\tan^2 \chi} \tag{10}$$

i.e. closely tight to the ellipticity of the output polarization ellipse. It is not surprising that the same information can be extracted from the Poincaré sphere with the help of eq. 5; the *PER* is related to the elevation of the output SoP. The orientation of the polarization ellipse is given by the tilt angle ψ (fig. 1) or, equivalently, by half of the azimuth of the SoP on the Poincaré sphere (fig. 2)**.**

It must be noted that the description of the performance of a PM fiber is however unsatisfactory since the figures of merit introduced so far, *PER* and tilt angle, implicitly depends upon the relative phase ϕ in eq. 1. Any changes for example in the fiber's layout, in temperature or in mechanical forces applied to the fiber will modify the tilt angle ψ and/or the *PER*. To circumvent this fundamental limitation the definition of the *PER* has been extended to a worst-case scenario, i.e. the smallest obtainable *PER* value when the relative phase ϕ is swept over an entire 2π period.

PER and ψ measurements

There are at least two methods to evaluate the *PER* of a polarization maintaining fiber and both rely upon the determination of how light exits the PM fiber provided a linear polarization oriented along the principal axes is launched at the fiber's input [6]. The two methods will lead to the same results as long as the measurement procedures are carried out correctly and the measurement results are properly interpreted.

5.1 In-line measurement method (ILM)

The first characterization method follows very closely the description presented in §2.3. Briefly, monochromatic light with a perfect linear polarization aligned to one of the fiber's principal axes is coupled into the fiber under test (FUT). The output SoP is detected by a polarimeter and, as the phase is swept by heating or mechanically stretching a portion of the FUT, the SoP trajectory on the Poincaré sphere is recorded. The farthest point from the equator reached by the SoP's is then taken to calculate the *PER* according to eq. 10.

However, the implementation of such a procedure is not as straightforward as it reads. In fact, there are several parameters that need to be carefully considered in order to obtain a correct measurement.

Light source. To perform polarimetric measurements with a suitable accuracy, light must have a sufficient degree of coherence. The emission spectrum must then be narrow enough so that the associated time coherence appreciably exceeds the maximum delay that can accumulated between the two eigenpolarizations propagating along the fiber. In short, the linewidth of the source eventually limits the maximum length of the fiber that can be evaluated. Usually, in order to characterize 10 m long fiber with a typical birefringence of $\sim 3\times10^{-4}$ at a wavelength of 1550 nm the source line spectrum should be narrower than a few GHz, which makes narrow-line lasers very suitable for the task. Failure to comply to this requirement will lead to incorrect and unstable results.

The phase $\boldsymbol{\phi}$ needs to be swept over an entire period in order to identify the output SoP that lies the farthest from the equator on the Poincaré sphere. To visualize the changes of the SoP's it may be helpful to consider the FUT as a series of three simple waveplates tilted with respect to the reference system with angles β, γ, δ and each one imposing a delay φ, ϕ and ϑ, respectively. The first plate represents the initial portion of the FUT, the second one the portion where the thermal or mechanical perturbation is applied, and the third plate refers to the last fiber section. The three-section picture shall become handy when considering a pigtailed fiber; the first and last sections will represent the connectors while the middle one takes care of the fiber. Moreover, a series of waveplates whose axes are not necessarily aligned ($\beta \neq \gamma \neq \delta$) allow for power exchange between the two eigenpolarizations, i.e. the source of degradation in *PER* performance.

Experimentally, only the phase ϕ of the middle section needs to be varied while the other two may be considered as constants. However, despite the required temperature and/or elongation changes are modest, it may prove a challenge to achieve them in fibers that are not directly

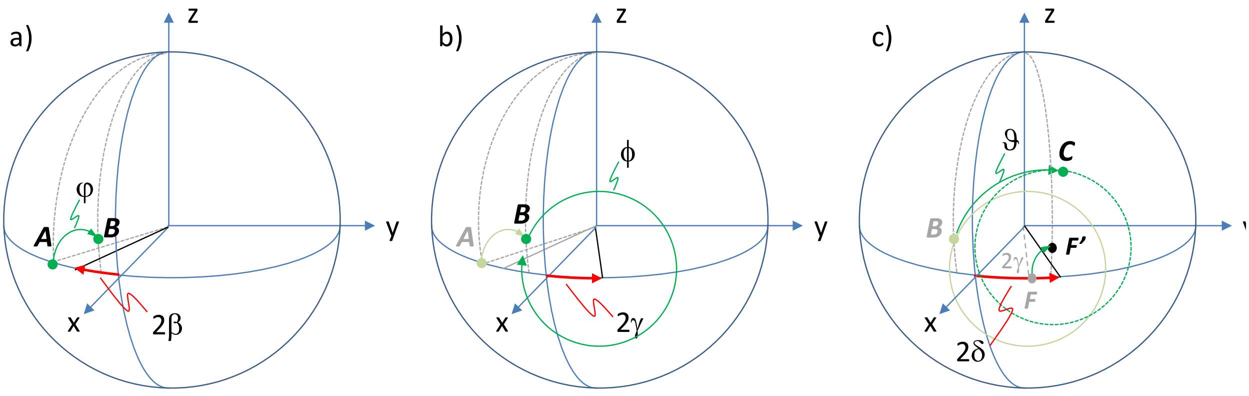

Figure 5. Evolution on the Poincaré sphere of a SoP during the propagation through three mutually misaligned waveplates. The first (a) and the last (c) waveplate impose a fix delay (φ and ϑ, respectively) while the phase ϕ of the central waveplate (b) is swept over 2π. More details in the text.

accessible or that are protected by thick cables. An insufficient phase swing will prevent the adequate description of the SoP trajectory on the sphere and thus limit the measurement accuracy.

The input polarization must be as linear and as parallel as possible to one of the fiber's principal axes in order to keep the SoP's trajectory near the equator as the light propagates along the fiber. Knowing that on the Poincaré sphere a waveplate induces a rotation of the SoP position by angle equal to the phase delay about an axis lying in the equator plane and tilted by twice the angle between the waveplate's axis and the reference system, the SoP's trajectory can be sequentially constructed as light moves down the fiber. By entering the first fiber section, a linear SoP *A* rotates by a fix angle φ about an axis tilted by 2β with respect to the xyz ($s_1 s_2 s_3$) reference system and ends up in SoP *B*, as shown in fig. 5a. Were the input polarization direction and the waveplate axis coincident, then *B*=*A* for the radius of the arc would drop to zero. In the second section where ϕ is swept over a 2π period, SoP *B* will draw a circle still centered on the equator but with an axis tilted by 2γ (fig. 5b). Finally, the propagation through the third section will induce an additional rotation of a fix angle ϑ about an axis tilted by 2δ and *B* will move to *C*. If the second and the third waveplates are not aligned ($\gamma \neq \delta$) the center of the circle *F* will move out the equatorial plane (fig. 5c).

It must be emphasized again that the input polarization state plays a crucial role in determining the worst-case *PER* that is intended to be measured. In fact, deviations from a perfect linear state and a misalignment to the fiber's main axes may cause change in the radius of the circular path on the Poincaré sphere and therefore induce an appreciable inaccuracy of the calculated *PER*.

The *PER* and the orientation angle $\boldsymbol{\psi}$ are extracted from the trajectory of the output SoP on the Poincaré sphere obtained according to the above procedures. The half value of the azimuth of the trajectory's farthest point from the equator defines the orientation of the fiber's main axes with respect to the polarimeter's axis. This is therefore a relative measurement and in order to identify the absolute orientation of the fiber's main axes a suitable calibration procedure of the polarimeter's orientation is necessary. Still, the polarimeter alone cannot distinguish between fast and slow axis. This ambiguity can however be lifted by a visual check of the geometric structure of the fiber's front face.

The *PER* is instead extracted from the angular elevation of the farthest SoP from the equator according to eq. 10. This value refers to the *PER* loss that linearly polarized light suffers when travelling along the *entire* fiber. The Poincaré sphere offers additional information: the radius and the elevation of the center of the circle relate to the *PER* degradation that separately occurred *before* and *after* the thermal/mechanical perturbation, respectively. The connection between the contributions of the individual sections and the whole fiber can be derived from simple trigonometric relations. Clearly, the larger the elevation of the circle's center and/or the larger the radius, the poorer the fiber's polarization maintaining performance. It is worth noting that by reversing the propagation direction of the light, the roles of the radius and the center of the trajectory are switched while preserving the elevation of the farthest SoP from the equator.

The characterization set-up is schematically shown in fig. 6 and consists of a narrow-band light source whose light is filtered by a high-extinction linear polarizer. For a

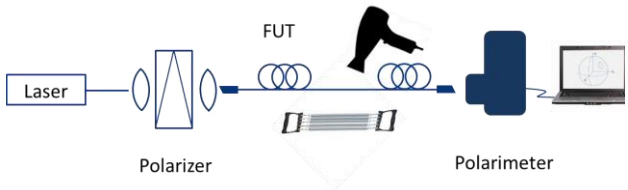

Figure 6. Schematic set-up for in-line characterization method of the polarization performance of fiber-based optical elements.

reliable measurement the extinction supplied by the polarizer should be at least an order of magnitude higher than the *PER* expected from the fiber to be tested. It is also of primary importance that all other optical elements like focusing and collimating lenses along the optical path provide a vanishing birefringence in order not to interfere with the measurement.

Light is then coupled into the FUT by making sure that the fiber's optical axes match the input polarization. This is empirically achieved by rotating the input polarizer so to minimize the radius of the circle on the Poincaré sphere. This procedure requires a dynamic perturbation of the phase along the FUT, which is achieved either by thermally cycling or by continuously stretching a portion of the fiber. Once this iterative alignment procedure is completed, the polarimeter that collects the output light can determine the trajectory of the output SoP and, from there, extract both *PER* and orientation angle. Due to the complexity of the measurement and the not uncommon whimsical behavior of the results, both measurement procedures and characterization set-ups have been accurately defined and standardized by several normative organizations, like in Ref [7]. Yet, a different method is usually preferred due to its intrinsic enhanced stability and reliability.

5.2 Cross-polarizer method (CPM)

A second approach to the characterization of polarization maintaining elements is based upon an alternative physical mechanism. The major difference resides in the nature of the light that must now be fully incoherent. Under this constraint, light propagating in a birefringent material behaves effectively as a superposition of two independent waves, each one linearly polarized along one of the main axes with no phase cross correlation. The consequences are substantial and shall be discussed here below in connection with the different aspects affecting both the characterization method and the experimental set-up.

Light source. Contrarily to the requirements in §5.1, the light source must be broadband, i.e. with a large enough spectral width to ensure the shortest possible coherence length. This time, the residual coherence length must be much shorter than the shortest fiber length that needs to be evaluated. With a bandwidth of 20 nm at a wavelength of 1550 nm and assuming again a typical birefringence of ~3×10^{-4}, the length that can be accurately characterized should be longer than 1 m. Were this requirement not met then incorrect and unstable results could be obtained. Suitable light sources are for instance super-luminescent diodes (SLD) that combine sufficient spectral bandwidth and adequate output power.

The phase $\boldsymbol{\phi}$ between the two eigenpolarizations loses any physical meaning since light is incoherent and hence the two polarization components become uncorrelated. This offers a significant advantage for it removes any direct dependence of both *PER* and tilt angle ψ upon temperature and/or fiber movements. However, the lack of such phase correlation may induces deviations from eq. 3; eq. 6 should be considered instead. The SoP's will then no longer necessarily lie on a sphere with radius s_0 but will also fill the enclosed volume since incoherent light can be partly polarized or even fully unpolarized, i.e. $s_1, s_2, s_3 = 0$. While for monochromatic (coherent) light $DoP = 1$, for incoherent light $1 \geq DoP \geq 0$. Issues may arise when the DoP drops below unity because most polarimeters become unsuitable for measuring accurately the SoP, therefore the whole procedures described in §5.1 cannot be applied for the evaluation of either the *PER* nor the tilt angle ψ.

Nevertheless, it is possible to measure both parameters in agreement with eq. 7 by replacing the polarimeter with a linear polarizer and by adapting the characterization process as explained below.

The input polarization still needs to be as linear and as parallel as possible to one fiber's principal axis in order to provide a *PER* evaluation in line with the definition of eq.7. While the linearity of the input polarization is set by the high-extinction polarizer, its orientation with respect to the fiber's principal axes can be easily performed by looking for the absolute minimum transmissivity when polarizer and analyzer are independently rotated before and after the FUT (see fig.7). In the configuration of minimum intensity transmission the input polarization will be parallel to one fiber main axes while the analyzer will lie parallel to the orthogonal one (crossed polarizers).

The *PER* and the orientation angle $\boldsymbol{\psi}$ are extracted from the analysis of the transmitted intensity as the analyzer is rotated provided the polarizer is aligned to one of the fiber's main axes. The transmission function follows a simple trigonometric function whose extremal values are used to calculate the *PER* according to eq. 7. This value refers to the *PER* loss that linearly polarized light suffers when travelling along the *entire* fiber. With the cross-polarizers method it is therefore not possible to separate contributions generated at the input or at the output portions of the FUT, as it was the case with the previous in-line method in §5.1. By reversing the propagation direction of the light, no changes are expected in terms of *PER*.

It can be easily shown that the angular positions of the minimum and the maximum transmitted intensities with respect to the analyzer's orientation correspond to the directions of the fiber's main axes. The orientation angle ψ, i.e. the angle between the fiber's axes and an external reference system, can then be determined in an unambiguous and straightforward manner. As in the case of the in-line method, the crossed polarizers alone cannot distinguish between fast and slow axis. This uncertainty can however be lifted by a visual check of the geometric structure of the fiber's front face

The characterization set-up is schematically shown in fig. 7 and consists of a broadband light source (SLD) whose emitted light is filtered by a high-extinction linear

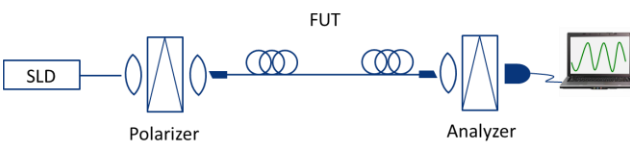

Figure 7. Schematic set-up of the cross-polarizer method for the characterization of the polarization performance of fiber-based optical elements.

polarizer. The launching conditions are identical to those described for in-line method, i.e. the polarizer's extinction should be at least an order of magnitude higher than the *PER* expected from the fiber to be tested (FUT) and all other beam-shaping optical elements along the beam path should be free of birefringence.

With incoherent light, the input polarization is aligned to the fiber's optical axes through a faster and more reliable procedure by first rotating the analyzer to the minimum intensity transmission and then by adjusting the input polarizer to further minimize the output power. In this configuration, the polarizers' axes end up oriented each one along a different optical axis of the FUT. The angles ψ at both end of the FUT can be readily extracted.

The PER is determined from the difference between minimum and maximum transmission intensities as the analyzer is rotates about an angle of at least π.

The cross-polarizer characterization method is robust and reliable and for these reasons it also considered as the reference method by international standards [8,9].

5.3 In-line vs. cross-polarizer measurement method

In the following the most significant similarities and differences between the two characterization methods are summarized. Regardless of the degree of coherence of the light source and provided the measurements are carried out correctly, both the ILM and the CPM are expected to deliver the same *PER* values when referred to the *entire* fiber under test. The same orientation angle ψ irrespective of the measurement method is also expected. It has to be emphasized that with both methods the stability and reproducibility of the results may suffer whenever the required degree of (in-)coherence of the light sources is not met.

By relying upon two distinct physical principle, the ILM will limit the maximum DUT length while the CPM will restrict the shortest distance that can be reliably tested. The different physical principles behind the two methods also cause differences between measurement set-ups and procedures. The ILM being an interferometric test procedure relies upon the relative phase between the two eigenpolarizations, which can be gauged from polarimetric measurements. This involves an external thermal or mechanical intervention on the FUT to sweep the phase and make the measurements possible. This is a prolonged and iterative procedure needed for the evaluation of both *PER* and orientation angle. The very same procedures are also needed in order to align the input polarization of the light to the FUT's optical axes. In the case of the CPM, the same initial polarization conditions are necessary but their preparation is considerably simpler since phases do not play any relevant role. This also appreciably speeds up the measurements that can be performed by means of two conventional linear polarizers. Restrictions that may arise whenever the FUT is not accessible to thermal of mechanical control of the phases are removed, as well.

Finally, although both methods are recognized by several standards, due to its reduced complexity, the CPM is considered as the method of reference.

Orientation of PM fibers and connectors

In most applications the precise orientation of the optical axes of the PM elements needs to be readily recognized, especially when multiple elements are to be connected in series. In fact, to preserve the overall, best polarization performance the main axes of the different sections must be kept parallel to each other. This is made possible by

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<tr><td rowspan="3">Figures of merit</td><td rowspan="2">PER</td><td colspan="2">PER of entire patchcord/element
Same PER, if measurement performed correctly</td></tr>
<tr><td>Some indication about localization of PER drops</td><td></td></tr>
<tr><td>Orientation</td><td colspan="2">Same orientation of the optical principal axes is measured</td></tr>
<tr><td rowspan="5">Characterization principles</td><td>Physical principles</td><td>Comparison between input and output state of polarization provided…</td><td>Determination of power coupling between eigenpolarizations provided…</td></tr>
<tr><td>Light source</td><td>...highly coherent…</td><td>…incoherent …</td></tr>
<tr><td>Input SoP</td><td colspan="2">… and perfectly linearly polarizated light is coupled to one of the input optical principal axes of the DUT.</td></tr>
<tr><td>Output SoP</td><td>Required, worst-case output SoP determined by delaying phase between eigenpolaritazions</td><td></td></tr>
<tr><td>Results</td><td>Results extracted from analysis of data on Poincaré sphere</td><td>Results extracted from intensity measurements</td></tr>
<tr><td rowspan="7">Measurement procedures</td><td>Light source</td><td>Highly coherent narrow band lasers</td><td>Incoherent broadband SLD</td></tr>
<tr><td rowspan="2">Input SoP</td><td colspan="2">High extiction linear polarizer and birefringence free coupling optics (lenses) required.
Input polarization aligned to DUT's principal axes…</td></tr>
<tr><td>...through iterative procedure aiming at minimization of radius of SoP's trajectory on Poincaré sphere as phase between eigenpolarizations is varied.</td><td>…by adjusting input polarizer and output analyzer to the absolute minimum transmission intensity positions.</td></tr>
<tr><td rowspan="2">DUT</td><td>Phase between eigenpolaritazions needs to be perturbed thermally of mechanically</td><td></td></tr>
<tr><td>Maximum length DUT limited by coherence of source</td><td>Minimum length DUT set by bandwidth of source</td></tr>
<tr><td>Output SoP</td><td>Output SoP determined by means of polarimeter</td><td></td></tr>
<tr><td>Standards</td><td>Allowed by international standards</td><td>Preferred method by international standards</td></tr>
</table>

Table 1. Summary of the main similarities/differences between the In-line and the Cross polarizer characterization methods.

adding to each fiber connector a mechanical reference, or a key, so that a locking system may passively ensure that the main axes are properly aligned when fibers face each other. These mechanical features vary with the geometry of the connectors' body: connectors with cylindrical symmetry usually rely upon a combination of notches and slits like the popular FC, DMI, Mini-AVIM, AVIM, ST interfaces, while connectors like the common E-2000™, F-3000™, LC, SC, MU, etc. take advantage of the rectangular symmetry of the surrounding body (see fig. 8). How accurately the mechanical references agree with the actual orientation of the fiber's main axes obviously depends on how exactly the fiber's axes can be determined and how precisely the fibers inside the ferrules are encapsulated into the connector's body carrying the keys. A third critical factor is represented by how accurately two mated connectors are held in place inside a mating adapter. These issues are essentially of geometrical nature and defined by mechanical tolerances and mechanical plays between the different parts involved in a connection.

6.1 Connector's orientation

The first step in the manufacturing of optical connectors for PM fibers generally consists of fixing the fiber inside a ferrule. The principal optical axes inside this initial subassembly must then be identified according to the procedures described in the previous paragraphs so that the ferrules may be correctly locked in place into the keyed connector's body. For the sake of completeness, it should be mentioned that the coarse orientation of the fiber's axes can be guessed from the structure of the fiber's cross section, in which the geometrical symmetry axes are assumed to be parallel to the main optical axes (see fig. 4). This *passive orientation* method however is not as accurate as the procedures that rely upon the active determination of the true optical axes. In fact, geometric and true optical axes may not coincide especially in the presence of external mechanical stresses applied to the fiber or in the presence of material, geometric, or structural inhomogeneities along the fiber. Deviations of up to several degrees may arise when such perturbations occur quite frequently inside the connectors. This is the reason why, whenever possible, an *active orientation* procedure is always preferred.

6.2 Mating accuracy

An impeccable alignment between the fiber's main axes and the connector's mechanical key is no guarantee of an acceptable mutual orientation between two mating fibers. In fact, this step is mediated by the geometric tolerances

Figure 8. Examples of DMI (top), E-2000™ (middle) and FC (bottom) connectors with the corresponding mating adapters. DMI and FC connectors rely upon alignment keys based upon o notch-slots combinations, while the E-2000™ relies upon its rectangular cross section.

between the mechanical key of the connectors and the hosting counterpart on the mating adapter. As mentioned above, different connector families are characterized by different mechanical tolerances and even within single families there are different dimensional conventions. For example, the common FC connector family is split in two main categories generally referred to as wide and narrow keyed. Moreover, within the two groups there are substantial variations that alone may allow for angular misalignments from ±0.57° to ±1.05° per connector. It is also worth mentioning that not all FC connectors are compatible with all mating adapters.

Connection	Total angular offset
E-2000™	1.2°
DMI / Mini-AVIM	1.4°
SC	1.8°
FC (narrow)	1.9°
FC (wide)	2.4°
DIN	4.7°
AVIM	5.0°

Table 2. Worst-case total angular misalignment due to mechanical tolerances between two connectors and a mating adapter. Contributions from fiber-to-connector's key offset is not included. Values related to Diamond's product.

Other connectors provide different degrees of accuracy that, for a full fiber-to-fiber configuration (two connectors and a mating adapter), can guarantee a worst-case total angular offset ranging from 1.2° (E-2000™) to as much as 5.0° (AVIM), as reported in Tab. 2. Note that the values presented there do not include any contribution to the angular misalignment due to the inaccuracies between the position of the fiber's optical axes and the mechanical keys of the single connectors. These values again can vary upon connector type, as well as upon manufacturers with angular offset as large as ±3°.

6.3 Cascaded PM connections

Angular mismatches between mated connectors rapidly degrade the PER performances of the overall system. This can be easily calculated by joining two PM elements each one characterized by its own polarization coupling PER_1, PER_2. A first-order estimation of the total linear *PER* can obtained from

$$PER_{tot} = \frac{1 + \Delta . tan^2\alpha}{\Delta + tan^2\alpha} \qquad (11)$$

where α is the angular misalignment between the main axes of the mated polarization maintaining elements and $\Delta = (PER_1 + PER_2)/(1 + PER_1 \times PER_2)$. From eq. 11, as well as from Fig. 9, it can be readily be recognized that by connecting two elements with equal *PER* (solid lines), the total performance drops by a factor of two even with the axes perfectly aligned to each other ($\alpha = 0$). It can also be noted that, as a function of the angular offset, the *PER* values drop faster the higher their individual initial values. Finally, it is worth pointing out that the final result is predominantly determined by the less performing element in the system, regardless of its position in the chain. From

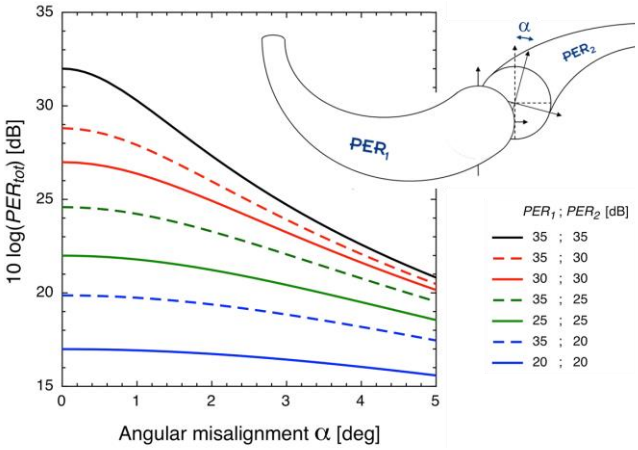

Figure 9. Total polarization performance of two PM elements in series with selected *PER* values vs. the angular mismatch α. Solid lines represent fibers with the same *PER*, dotted lined show examples with a fix fiber (PER_1=35 dB) connected to fibers with decreasing PER_2. Note that the *PER* values are expressed on a logarithmic scale.

this simple estimation it is immediately clear that in order to provide the best total performance in a PM system connectors with both the highest angular accuracy and the best initial *PER* values should be used. Moreover, it should be carefully considered whether to build long chains of PM elements in series since the final PM performance will quickly become an issue.

Conclusions

The performance of a polarization maintaining optical element is typically described first by how well an input linear polarization state is preserved as light propagates along the fiber-based device and second by how precisely the orientation of the optical principal axes of the device can be determined. These tasks require an experimental set-up that fully complies with the underlying theoretical assumptions. For instance, the degree of coherence of the light source plays a fundamental role in the choice of the testing method, the necessary optical instruments, and most notably the interpretation of the measured values.
It has been shown that the two prevalent characterization methods operate in two opposite coherence regimes of the light sources and are associated to two substantially different kinds of detection hardware and measurement procedures. Results such as the *PER* and the orientation of the principal optical axes obtained from these two approaches can be compared provided the right quantities are considered and the measurements have been carried out properly. Failure to comply with the correct test requirements may quickly lead to unreliable or even contradicting outcomes. This risk grows as the PM performances improve, which emphasizes the importance of an appropriate understanding of all the physical effects involved. Finally, it has been shown how the polarization performance may degrade as PM elements are connected in series. Besides the *PER* values of the single portions, a major role is played by the mutual orientation of the optical axes. Connection arrangements (connectors and mating adapters) with the tightest alignment tolerances should therefore always be preferred.

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