Polarization Maintaining Optical Components: The Importance Of High-Grade Connectors

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***Abstract**: In a polarization maintaining (PM) fiber system the quality of a connection plays a crucial role. In order to offer the best overall perfromance, PM fibers must be properly oriented inside the connectors and the alignment features on these must guarantee an appropriate orientation across the mating adapter. Due to different mechanical contructions, not all fiber connectors and mating adapters are suitable for PM applications. The orientation procedures of high-quality PM fiber connectors and the evaluation of their polarization performance are reviewed according to the current international standards.*

1 Introduction

The use of polarization maintaining (PM) elements based upon optical fibers is relentlessly growing. The evolution of laser technologies together with the progresses in PM fiber manufacturing techniques and the advancements in optical integration towards increasingly complex and performing systems have broadened the application fields to cover metrology, spectroscopy, telecommunications, sensing/monitoring, industrial tools, medical diagnostic instruments, and many others. Along with the number of applications, the performance expectations for PM elements and systems have increased to keep the pace with and also enable the innovation in this field.

There are a few important issues when dealing with the delivery of polarization information over PM fibers, the key ones being how to preserve such information over longer distances and how to quantify the polarization performance. The first aspect is influenced of course by the quality of the PM fibers themselves and by the role played by the junctions when fibers are concatenated. The second aspect relates to the evaluation of the system's polarization performance, the suitable characterization methods, and the proper interpretation of the measurement outcomes. When performance is pushed to the limits, there are experimental details and theoretical subtleties that should not be misinterpreted nor neglected.

2 Light polarization

Light is an electromagnetic wave consiting of an electric and a magnetic field that oscillate in a coupled fashion. Within the frame of classical electromagnetism, light can be fully described by its electric field vector ***E*** whose orientation defines the polarization direction [1]. Further, the transverse nature of electromagnetic waves allows for the ***E***-field of a monochromatic plane wave propagating in free space to be expressed as

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

where E_{x0}, E_{y0} are amplitude components of the ***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 ***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. It can be shown that for $\phi = 0, \pi$ the polarization ellipse collapses to a straight line, i.e. the ***E***-vector oscillates along a fix line; 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 ***E***-vector rotates; light is then said to be circularly polarized. For all other values of amplitudes and phase the polarization turns into an elliptical polarization [2-4].

It is worth pointing out that the polarization state of light propagating in a perfectly homogeneous medium remains unperturbed, i.e. both shape and tilt of the corresponding polarization ellipse stay constant. However, any deviation in the medium homogeneity may trigger variations of the polarization ellipse that will readjust its shape and tilt accordingly: light will change its polarization state. This is what it is commonly observed in standard optical fibers.

3 Polarization maintaining fibers

From a polarization perspective, standard fibers are very sensitive towards fluctuations caused by material inhomogeneity, environmental changes (temperature variations), or by a mechanical stress produced by fiber compression, bending, twisting or stretching. It is then hard to preserve the polarization state as light propagates through the fiber. To mitigate such disturbances, fibers are made birefringent by, for instance, introducing stress elements into the fiber structure that anisotropically compress the core region. On one hand, such fibers become more resilient towards external perturbations; on

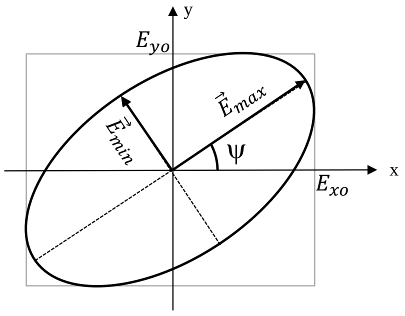

Figure 1. Polarization ellipse where E_{max} and E_{min} define the main axes while ψ describes the tilt angle.

the other hand the radial symmetry is lifted effectively generating two orthogonal symmetry lines known 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 (see fig. 2). Associated to the optical axes there are two linear polarization states, or eigenstates, that propagate unaltered along the fiber. Note that only these two particular polarization states remain linear all along the PM fiber; all others will ultimately turn into elliptical polarizations. In reality, the two eigen-polarizations as well suffer from perturbations due to material inhomogeneity or induced by external stresses. These create discontinuities in the distribution of the refractive indices and distortions in the local birefringence that will induce power coupling between the two eigenpolarizations thus degrading the linearity of these states.

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. 2 for the examples of Panda and Bow-Tie fibers. 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 exploiting existing schemes like in Panda fibers or by designing intrinsic birefringent photonic crystal structures.

4 PM fiber performance

The fiber's PM properties can be assessed by comparing the polarization ellipse at the fiber's output to a linearly polarized one launched along one of the input main axes. The figure of merit 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 in one eigenpolarization leaks onto the orthogonal one at the fiber's output. Mathematically, this is expressed on a linear scale as

$$PER = \frac{\|E_{min}\|^2}{\|E_{max}\|^2} \qquad (2)$$

where the fields E_{min} and E_{max} represent the main axes of the polarization ellipse, as in fig. 1. The *PER* is also often expressed on a logarithmic scale, as well

$$PER = -10 \times \log\left(\frac{\|E_{min}\|^2}{\|E_{max}\|^2}\right) \qquad (3)$$

and it is therefore measured in dB.

The orientation of the polarization ellipse is given by the tilt angle ψ (fig. 1) that allows for the reconstruction of the polarization ellipse when combined with the *PER*.

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 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 avoid 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.

5 PER and ψ measurements

There are two conventional methods used to evaluate the *PER* of a PM fiber and both rely upon the determination of how light exits the PM fiber provided a linear polarization oriented along one of the principal axes is launched [6]. The physical principles behind the two methods are quite different and they are related to the degree of coherence of the light used in the experimental set-up. In the following we will focus on the so-called *cross-polarizer method* (CPM), which relies upon perfectly incoherent light. Due to its robustness, this approach is the reference method by international standards [7,8] and it is also the most widely used although, occasionally, misused.

Incoherent light allows light in a birefringent material behaving effectively as a superposition of two independent waves, each one linearly polarized along one of the principal axes. Therefore, the influences due to the phase between the two components and thus all interference effects vanish, which makes characterization set-up and measurement procedure simpler and more reliable.

The ***measurement principle*** is conceptually simple: the *PER* is evaluated by launching linearly polarized light oriented along one optical axis and measure the portion of the power that emerges with the polarization oriented along the orthogonal axis. By properly rotating an input polarizer and an output analyzer with respect to the input and output fiber's principal axes all relevant information needed to determine *PER* and tilt angle can be extracted from minimum and maximum transmitted intensity.

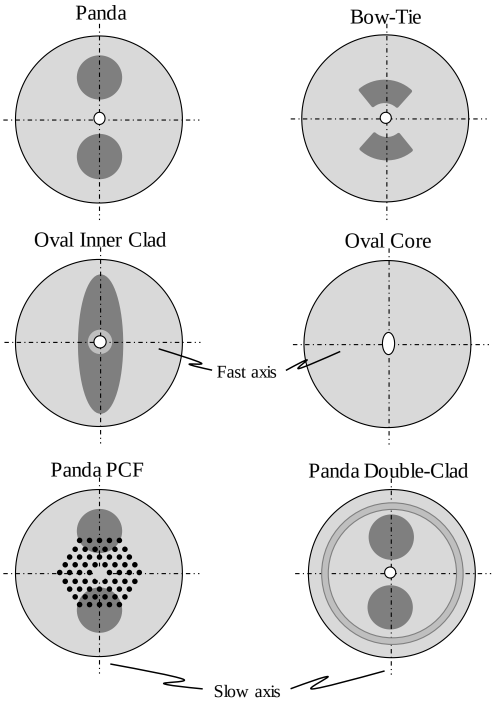

Figure 2. Examples of schematic cross-sections of a few PM fiber structures. The dark features represent the stress elements used to induce birefringence. Fast axes are oriented horizontally while the slow ones are vertical.

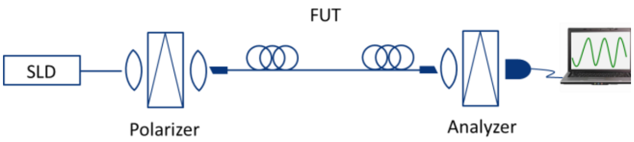

Figure 3. Schematic set-up of the cross-polarizer method for the characterization of the polarization performance of fiber-based optical elements. A super-luminescent diode (SLD) provides the incoherent light that is coupled into the fiber under test (FUT) after being filtered by a high-extinction rotatable polarizer. A power meter collects the transmitted intensity as a function of the tilt angle of a linear analyzer with respect of the orientation of the FUT output principal axes.

The ***characterization set-up***, schematically shown above, comprises an incoherent light source whose emitted light is filtered by a high-extinction linear polarizer before being coupled into the fiber under test (FUT). The input polarization is aligned to one of the fiber's optical axes by first rotating the analyzer till the minimum intensity transmission and then by adjusting the input polarizer to further minimize the transmitted 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 then given by the difference between minimum and maximum transmitted intensities as the analyzer takes a full rotation. Despite the apparent simplicity, there a few aspects that require careful consideration.

The ***light source*** must be broadband, i.e. with a large enough spectral width to ensure the shortest possible coherence length. For accurate measurements, the residual coherence length must be much smaller than the shortest fiber length that needs to be evaluated. With a source bandwidth of 20 nm at a wavelength of 1550 nm and assuming a typical fiber birefringence of $\sim 3\times10^{-4}$, 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. Lasers should be avoided.

The ***phase ϕ*** in eq. 1 loses its physical relevance, which brings a significant advantage to the measurements for it removes any direct dependence of both *PER* and tilt angle ψ on temperature and fiber movements. This is a significant experimental advantage that would not be available in the presence of coherent light.

The ***input polarization*** needs to be as linear and as parallel as possible to one fiber's principal axis in order to obtain an accurate *PER* evaluation. The polarizer's extinction must be at least an order of magnitude higher than the *PER* expected from the FUT and all other beam-shaping optical elements along the light path must be free of birefringence. Unsuitable coupling optics will limit the sensitivity of the entire characterization set-up.

The ***PER*** and the ***orientation angle ψ*** 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 curve whose extremal values are used to calculate the *PER* according to eqs. 2-3. This result refers to the *PER* loss that linearly polarized light suffers when travelling along the *entire* fiber. By reversing the propagation direction, 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. However, the crossed polarizers alone cannot distinguish between fast and slow axis. This uncertainty is removed by a visual check of the geometric structure of the fiber's front face.

For the sake of completeness, it is worth mentioning that the alternative characterization method relies on perfectly coherent light and it is usually referred to as the *in-line method* (ILM) [6,9]. This interferometric test procedure uses the relative phase between one eigenpolarization and the power portion that leaks onto the orthogonal one. This is assessed via polarimetric measurements that involve an external thermal or mechanical intervention on the FUT needed to sweep the phase ϕ and make the measurements possible. This iterative procedure is required for the evaluation of both *PER* and orientation angle. The very same technique is also needed to align the input polarization to the FUT's optical axes. Furthermore, the measurement outcomes must be interpreted with care for the *PER* values may refer either to the entire FUT or to a portion thereof depending upon the exact measurement procedure and data manipulation.

6 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 principal axes of the different sections must be kept parallel to each other. This is made possible by adding a mechanical reference, or a key, to each fiber connector so that a locking system passively ensures that the axes are properly aligned when the fibers face each other. These mechanical features vary with the geometry of the connectors' body, as shown in fig. 4 for a few examples. 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 widespread E-2000$^{\mathrm{TM}}$, F-3000$^{\mathrm{TM}}$ or LC, SC, MU, etc. take advantage of the rectangular symmetry of the connector's body. How accurately the mechanical references agree with the actual orientation of the fiber's principal axes obviously depends on how exactly the fiber's axes are determined and how precisely the fibers inside the ferrules are encapsulated into the connector's body. A third critical factor is represented by

Figure 4. Examples of DMI (top), E-2000$^{\mathrm{TM}}$ (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$^{\mathrm{TM}}$ relies upon its rectangular cross section.

how accurately two mated connectors are held in place inside a mating adapter. These issues are mostly of geometrical nature and defined by mechanical tolerances and mechanical plays between the different parts involved in the connection.

6.1 Connector's orientation

The first manufacturing step 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 so that the ferrules may be correctly locked into the keyed connector's body. For the sake of completeness, it is mentioned that a 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 principal optical axes (see fig. 2). However, this *passive orientation* is not as accurate as the procedures described above 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 other inhomogeneities along the fiber. Such perturbations often occur inside the connectors and deviations of up to several degrees can be observed. For this reason, an *active orientation* procedure is always preferred.

6.2 Mating accuracy

An impeccable alignment between the fiber's principal axes and the connector's mechanical key is no guarantee for an acceptable mutual orientation of two mated fibers. In fact, this is mediated by the geometric tolerances of the connectors' mechanical key and the hosting counterpart inside the mating adapter. As already mentioned, different connector families are characterized by different mechanical tolerances and even within single families there are dissimilar dimensional conventions. For example, the 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 may allow for angular misalignments ranging from ±0.57° to ±1.05° per connector. It is also to be considered that not all FC connectors are compatible with all mating adapters. Other connectors offer 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^{TM}) to as much as 5.0° (AVIM), as reported in Tab. 1. Note that these values do not include any contribution due to the inaccuracies between the position of the fiber's optical axes and the mechanical keys of the individual connectors. These values again can vary upon connector type and upon manufacturers with angular offsets as large as ±3°.

Connection	Total angular offset
E-2000^{TM}	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 1. 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 relates to Diamond's product.

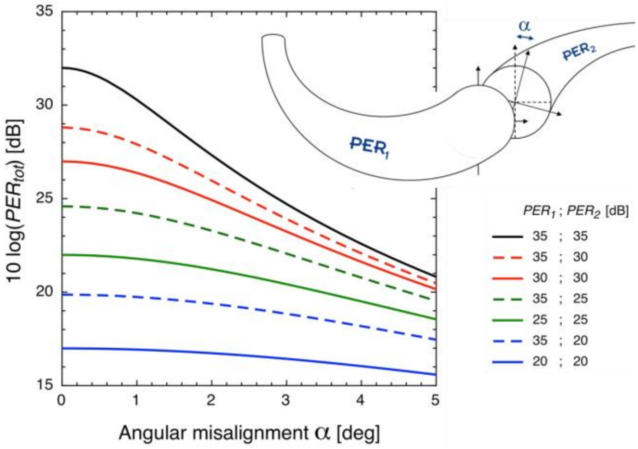

Figure 5. Total polarization performance of two PM elements in series with selected *PER* values vs. the angular mismatch α. Solid lines represent fibers with the same *PER*, dotted lined show examples with a fix fiber (PER_1=35 dB) connected to fibers with decreasing PER_2. Note that the *PER* values are expressed on a logarithmic scale.

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 be calculated according to

$$PER_{tot} = \frac{1 + \Delta.tan^2\alpha}{\Delta + tan^2\alpha} \qquad (4)$$

where α is the angular misalignment between the principal axes of the mated polarization maintaining elements and $\Delta = (PER_1 + PER_1)/(1 + PER_1 \times PER_1)$. From eq. 4, as well as from Fig. 5, it can be readily be recognized that by connecting two fibers 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 mostly determined by the less performing element in the system, regardless of its position in the chain. From 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 or not to build long chains of PM elements in series since the final PM performance will quickly become an issue.

7 Conclusions

The performance of a polarization maintaining system is described by how well an input linear polarization state is preserved as light propagates. Besides the polarization properties of PM fibers, an essential role is played by connectors at the interface between various PM elements. The accuracy of the orientation of the fiber's principal axes inside the connectors in combination with how precisely connectors are mutually aligned in a mating adapter represent the key issue in providing the best overall PM system quality. To prevent abrupt performance degradation when PM elements are connected in series, connection arrangements with the tightest alignment tolerances should always be preferred. There is a huge variety of fiber connctors available today on the market but there is also an equally wide range of alignement tolerances associated with them.

The intrinsic quality of a PM connector is additionally determined by the orientation accuracy of the optical axes of the enclosed fiber. To achieve the best results, characterization set-ups that fully complies with the correct theoretical principle are required. For example, the degree of coherence of the light source and the quality of the optical components play a fundamental role in the choice of the testing method, the necessary optical instruments, and most notably the interpretation of the measured values. Failure to comply with the correct test requirements may quickly lead to unreliable or even contradicting outcomes.

References

1. M. Born and E. Wolf, “*Principle of Optics”*, Pergamon Press Inc., 6th Ed., USA, 1991.
2. E. Collet, “*Polarized Light in Fiber Optics*”, Polawave Group, USA, 2003.
3. D. Goldstein, “*Polarized Light”*, 3rd Ed., CRC Press, USA, 2011.
4. M. Bass, et al., “*Handbook of Optics”*, Vol. II, 3rd Ed., McGraw Hill, USA, 2009.
5. A. Méndez, T. Morse, *“Specialty Optical Fibers Handbook”*, Academic Press, USA, 2007.
6. D. Derickson, et al., *“Fiber Optic Test & Measurements”*, Prentice Hall PTR, USA, 1989.
7. IEC 61300-3-24, *“Key accuracy of optical connectors for polarization maintaining fiber”*, Switzerland, 2006.
8. TIA 455-193, “*Polarization crosstalk test method for polarization-maintaining optical fibers”*, USA, 2013.
9. TIA 455-199, “*In-line polarization crosstalk measurements method for polarization-maintaining optical fibers, components, and systems”*, USA, 2012.