Polarization Analyzer for Fiber Optics and Free Beam Applications

State of polarization measurement, precise alignment of polarization-maintaining fibers and accurate adjustment of arbitrary states of polarization

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The state of polarization plays an integral role in many optical measurement techniques. The defined adjustment and setting of the polarization as well as its precise measurement often is fundamental to further success. The polarization analyzer was developed for the precise coupling of linearly polarized light into polarization-maintaining fibers as well as for the setting of a well-defined state of polarization in free beam applications (Fig. 1). The compact design with communication and power supply via USB facilitates its easy incorporation into already existing setups, whether used as a mobile measuring device or permanently built into an industrial routine.

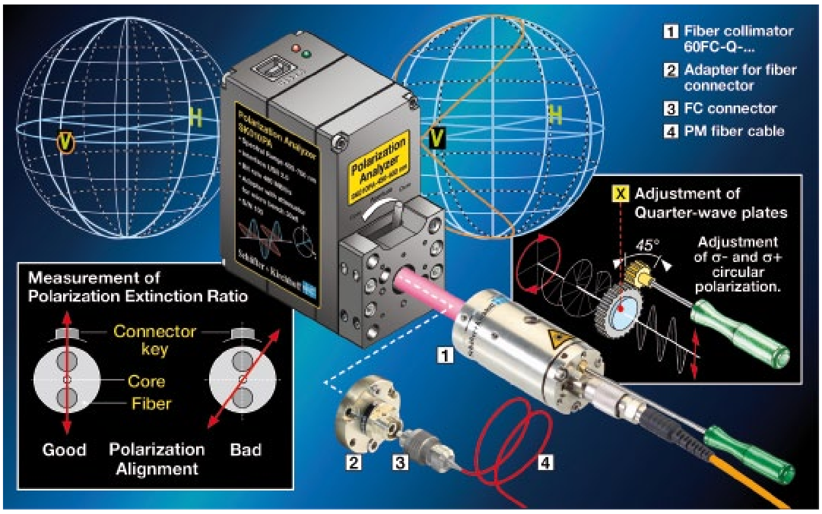

Fig. 1 SK010PA polarization analyzer and fiber collimator with integrated quarter-wave plate (1) and adapter (2) for fiber connector (3) for the adjustment of polarization-maintaining fibers (4). Time-consuming alignment tasks are completed efficiently for laser sources with large and small coherence length. The USB device is offered for different wavelength ranges from 350 – 1600 nm.

Polarization

The electromagnetic field $E(t)$ of a laser source can, because of the transversal properties of light, be expressed as the superposition of two orthogonal plane waves $E_x(t)$, $E_y(t)$ with frequencies ω, amplitudes E_x, E_y and phases δ_x, δ_y:

$$E_x(t) = E_x \cos(\omega t - \delta_x)$$
$$E_y(t) = E_y \cos(\omega t - \delta_y)$$

Depending on the phase difference $\delta = \delta_y - \delta_x$ and the amplitudes, all states of polarization from linearly ($\delta = n\pi$, $n \in N_0$) to elliptically and circularly ($E_x = E_y$, $\delta = \pm\pi/2$) polarized are described. Usually, light emitted by a laser source has a defined linear polarization. For unpolarized light, as emitted by filament lamps for example, all directions of polarization are statistically equally represented.

Each state of polarization (SOP) is mapped bijectively on a Poincaré sphere (Fig. 2, left). Linearly polarized states are found on the equator of the sphere and circularly polarized light on the north or south pole (depending on the sense of rotation of the electric field vector). Any other elliptical state is found on the remaining surface.

In order to fully describe polarization, a set of four independent parameters is necessary, e. g. $E_x(t)$, $E_y(t)$ and the phases δ_x, δ_y.

Often the Stokes parameters S_1, S_2, S_3 where

$$S_1 = E_x^2 - E_y^2$$
$$S_2 = 2E_x \cdot E_y \cdot \cos\delta$$
$$S_3 = 2E_x \cdot E_y \cdot \sin\delta$$

and the light intensity S_0 are used to describe polarized light [1]. The total light intensity S_0 consists of the intensity of both polarized light

$$\sqrt{S_2^1 + S_2^2 + S_3^2}$$

and unpolarized light. The degree of polarization *DOP* is thus defined as

$$DOP = \frac{\sqrt{S_2^1 + S_2^2 + S_3^2}}{S_0}$$

and has a value of 1 for fully polarized light.

For a $DOP \neq 0$, the Poincaré sphere can be normalized with respect to the intensity of the polarized light and the Stokes parameters equal the Cartesian coordinates (x, y, z) of the states of polarization on the Poincaré sphere.

Polarization, coherence and polarization-maintaining singlemode fibers

Singlemode fibers are special fibers that transmit light in the transversal fundamental mode LP_{01}. The field distribution (mode field) of the light exiting

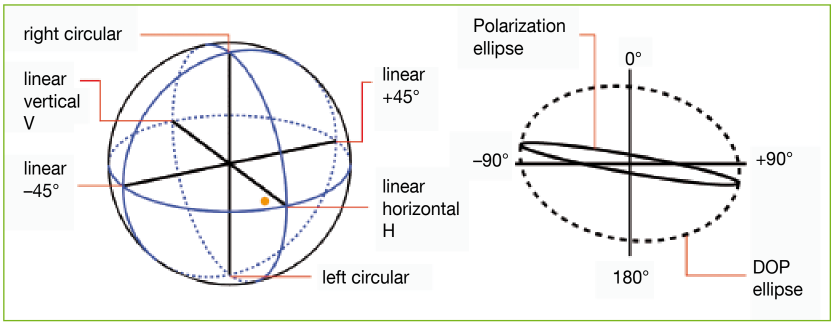

Fig. 2 The state of polarization is mapped bijectively on the Poincaré sphere (left, a SOP is colored in orange) and as a polarization ellipse (right). For incoherent sources the Poincaré sphere and the polarization ellipse are not convenient for the visualization of the state of polarization. In this case a DOP-ellipse can be used for fiber alignment.

the fiber is nearly Gaussian. The light is guided in two principle states of polarization with equal propagation constants. Imperfections in the fiber do, however, lead to random power transfer between the two principle states of polarization, due to the equal propagation constants in the principle SOPs and the resulting phase-match [2].

Polarization-maintaining fibers are rotationally non-symmetric, through the integrating of e. g. stress elements that break the degeneracy of the two principle states of polarization. Light is guided with two different propagation constants, either in the so called „fast“ or the „slow“ axis. The linear polarization of light coupled into one of the axes is maintained. If light is guided partly in the other axis, then the coherence of the light source determines the outcome polarization. If the coherence length of the light source is larger than the optical path difference between the light in the two principle SOPs than the outcome polarization is elliptical. Strain and temperature variations, however, change this arbitrary elliptical state. If the coherence length of the laser is smaller than the optical path difference, then there is no defined phase relationship between the exiting radiation guided in the two principle SOPs and as a result, the light is partly depolarized. For these reasons, it is extremely important to precisely align the polarization axis of the polarization-maintaining fibers with the linear polarization axis of the source.

The polarization extinction ratio (*PER*), the ratio between the powers guided in the two polarization axes, serves as a decisive measure for the fiber alignment.

Polarization measurement

The polarization analyzer described in detail here has two main applications. On the one hand monitoring the alignment of polarization-maintaining fibers with the polarization axis of the source, on the other hand determining of the state of polarization in general and for its defined setting according to requirements.

The polarization is determined by evaluating the light arriving at a photodiode after passing through a rotating quarter-wave plate and a static polarizer. The Stokes parameters are retrieved from a detailed analysis of the photodiode signal and the time/position information of the quarter-wave plate. The state of polarization is then depicted on the Poincaré sphere, where any change in the state of polarization as well as the sense of rotation (depicted on the northern or southern hemisphere) is easily visible. A polarization ellipse, a common representation of the state of polarization, is also shown (Fig.2). For sources with low coherence, a *DOP* ellipse complements the polarization visualization.

Fiber alignment of polarization-maintaining fibers with coherent laser sources

It is fundamental to the fast and precise alignment of polarization-maintaining fibers with the linearly polarized light sources that the polarization extinction ratio and the degree of polarization are efficiently determined and depicted.

Linearly polarized light that is not coupled completely into one of the polarization axes is not maintained, and the polarization changes with temperature and variations in strain. When a fiber is strongly jigged the state of polarization jumps wildly over a section of the Poincaré sphere. For more defined ambient changes, such as from varying the temperature of slowly bending the fiber, a data circle is produced on the Poincaré sphere resulting from the induced phase difference between the two principle states of polarization. This circle represents all states of polarization possible for the current alignment, with the center representing the mean polarization extinction ratio. For an ideal polarization-maintaining fiber, the mean polarization extinction ratio should be located at the equator. The data point, which is farthest from the equator shows the worst polarization extinction ratio possible for the current alignment.

When adjusting the coupling of the fiber the radius of the circle on the Poincaré sphere indicates the quality of the alignment, since it shows the angle deviation between fiber polarization axis and the polarization axis of the source. The circle radius is large for poorly aligned fibers – the polarization changes heavily with the ambient conditions – and is small for precisely aligned fibers. For an optimally aligned ideal fiber the data circle converges to a single point on the equator of the Poincaré sphere.

When adjusting the fiber coupling, a series of measurement points is acquired while changing the temperature or carefully bending the fiber to generate a circular cloud of data points. A circle is automatically fitted to the data points and the mean and minimal *PER* are displayed (Fig. 3a). The fiber axis

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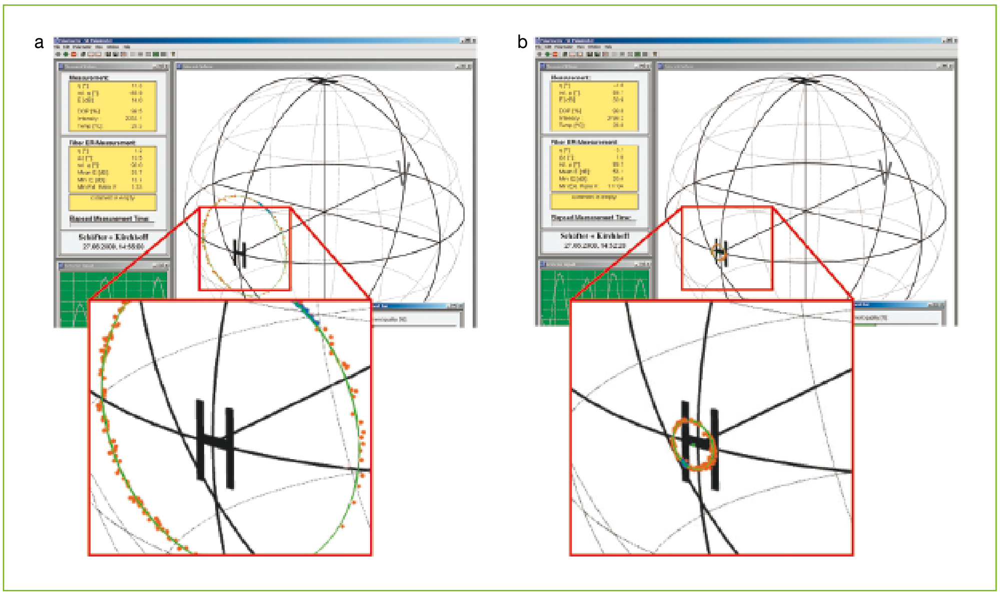

Fig. 3 Adjustment of a polarization-maintaining fiber with a coherent laser source. Goal of the adjustment is minimizing the data circle radius. When the fiber polarization axis and the laser polarization axis have a high angular deviation the state of polarization varies significantly when bending the fiber or when the ambient temperature changes (a). The better the angular alignment of the fiber the smaller the change in polarization and the smaller the radius of the data circle (b).

can now be rotated with respect to the polarization axis of the source until the radius of the circle reaches a minimum (Fig. 3b). The success of the adjustment is clearly visualized with a color-coded logarithmic bar plot. A second measurement then reveals the parameters of the optimized alignment of the fiber.

Localization of disturbances using the polarization analyzer

The polarization analyzer can, making some assumptions, additionally be used to locate disturbances in the fiber connectors or the incoupling and outcoupling optics, e. g. caused by birefringence.

Birefringence characterizes the optical property of matter that the refractive index and the corresponding travel velocities are polarization and direction dependent, altering the state of polarization of light passing through. Stress-induced birefringence describes an optical anisotropy caused by mechanical stress.

Assuming that the disturbances only occur in the fiber connector these disturbances can be located when swapping fiber input and output and performing two successive *PER* measurements after optimizing the fiber adjustment to a linearly polarized light source. The larger the circle, the more disturbances occur in the current input fiber connector. Thus the minimal radius possible when adjusting the fiber alignment serves as a measure of the stress-induced birefringence in the input fiber connector. Swapping fiber input and output, the distance of the center of the circle from the equator (the mean polarization ratio) becomes the new radius of the circle, and the former circle radius (the angular deviation) becomes the new distance of the center of the circle from the equator.

If it is the stability of the state of polarization that is of major importance and not the *PER*, swapping fiber input and output will reveal the most stable fiber configuration.

Fiber alignment of polarization-maintaining fibers with low coherence

For incoherent light sources the use of the Poincaré sphere for the *PER* measurement or the common polarization ellipse (Fig. 2, solid line) is not convenient. Since there is no defined phase relationship between the light guided in the two principle states of polarization of the fiber, only one measurement point occurs on the sphere and not a data circle. In this case a special ellipse, the *DOP*-ellipse (Fig. 2, dotted line) can be used to determine the optimal fiber alignment. The *DOP*-ellipse corresponds to the amplitude a rotating polarizer would detect and it represents the sum of linearly and circularly polarized and unpolarized light. The *DOP*-ellipse becomes a circle for fully depolarized light. The narrower the *DOP*-ellipse becomes, the better the coupling is into one of the polarization axes.

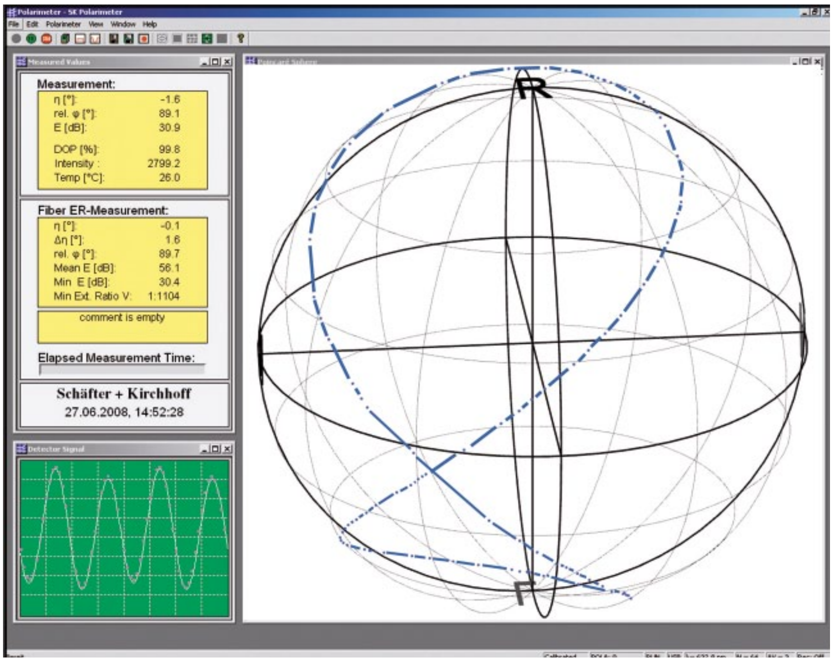

Fig. 4 Alignment of a quarter-wave plate depicted on a Poincaré sphere. During rotation of the quarter-wave plate the state of polarization produces a figure-of-eight. For a circular SOP the extreme values of this figure reach the poles: the north pole for right-handed circular polarization and the south pole for left-handed circular polarization.

Alignment of retardation optics

In a free beam configuration, the polarization analyzer can be used to align and quantify retardation optics, e.g. fiber collimators with integrated quarter-wave plates produced by Schäfter+Kirchhoff such as used in quantum optics for magneto-optical traps.

The outcome polarization is manipulated by rotating the quarter-wave plate with a special tool (see also scheme in Fig. 1). A full rotation corresponds to a figure-of-eight on the Poincaré sphere (Fig. 4). Circularly polarized light is achieved when the poles are reached, with right-handed circular polarization located at the north pole, and left-handed polarization located at the south pole. If the actual retardation of the optics deviates from the desired value then the extreme values do not reach the poles. The polarization analyzer thus provides a measure of the actual retardation of the optics.

Integration into measurement routines

The polarization analyzer has dimensions of 40 × 70 × 82 mm and is one of the most compact measuring devices in its class. It is available in various versions to cover the wavelength range from UV to IR (350–1600 nm).

The polarization analyzer receives its power from the USB 2.0 port of the evaluating computer. Since an external power supply is unnecessary, it is ideally suited as a mobile measuring device.

The polarization analyzer is compatible with the microbench system. Standard microbench adapters for optics of different diameters for the standard fiber collimators are available from Schäfter+Kirchhoff. Fiber adapters for FC-APC and FC-PC (and other adapters on request) are used for the alignment of the fiber coupling. The analyzer can be fitted with connections for most of the common optical bench systems.

Besides the SKPolarimeter software, a runtime library (DLL) for integration in special measurement routines and customer software is provided. Any features of the SKPolarimeter software can be included into customer projects using C, C++, C# or Labview. This includes all dialogue boxes for the input of different parameters, all graphical displays and all routines for the measurement of the polarization extinction ratio for PM fiber alignment.

Conclusion

The polarization analyzer SK010PA is one of the most compact measurement devices of its class. Time-consuming alignment tasks are completed efficiently for free beam and fiber optic applications and sources with low and high coherence. Special routines allow the precise coupling of linearly polarized light into polarization-maintaining fibers. The state of polarization is continuously updated and visualized on a Poincaré sphere.

The graphic visualization of the state of polarization and of the success of the measurement as well as the depiction of *DOP* and polarization extinction ratio ensure that the alignment process is completed quickly and efficiently. The polarization analyzer can also be used for setting a well-defined state of polarization in free beam applications, such as for fiber collimators with integrated quarter-wave plate from Schäfter+Kirchhoff.

The polarization analyzer communicates and receives its power via USB. Different versions cover the wavelength range 350–1600 nm. The standard delivery includes the polarization analyzer, compatible with the microbench system as well as a fiber adapter for FC-APC connectors. The DLL runtime library enables the analyzer to be easily integrated into customer-specific measurement routines and software without losing the benefit of the various graphic displays and routines.

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[1] *F. Pedrotti, L. Pedrotti, W. Bausch, H. Schmidt*: Optik für Ingenieure, Grundlagen, 2. Edn, Springer, Berlin (2002).

[2] *M. Born, E. Wolf*: Principles of Optics, Pergamon Press (1984).

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