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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Fig. 1:
SK010PA polarization analyzer for the adjustment of polarization-maintaining fibers. Time-consuming alignment tasks are completed efficiently. The USB device is available for different wavelength ranges from 370 – 1660 nm.

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 is often 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.

Polarization

The electromagnetic magnetic 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 $\hat{E}_x$, $\hat{E}_y$ and phases δ_x, δ_y:

$$E_x(t) = \hat{E}_x \cos(\omega t + \delta_x)$$
$$E_y(t) = \hat{E}_y \cos(\omega t + \delta_y)$$

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 ($\hat{E}_x = \hat{E}_y, \delta = \pm \pi/2$) polarized are described. In the x-y plane the vector $(E_x(t), E_y(t))$ describes an ellipse, see Fig 2a. This ellipse is defined by two values. The first one is the azimuth angle φ with respect to the x-axis and the ellipticity η

$$\sin 2\eta = \frac{2 \cdot \hat{E}_\mathrm{x} \cdot \hat{E}_\mathrm{y} \cdot \sin\delta}{\hat{E}_\mathrm{x}^2 + \hat{E}_\mathrm{y}^2}$$

$$\tan 2\varphi = \frac{2 \cdot \hat{E}_\mathrm{x} \cdot \hat{E}_\mathrm{y} \cdot \cos\delta}{\hat{E}_\mathrm{x}^2 - \hat{E}_\mathrm{y}^2}$$

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 SOP can be mapped bijectively on a sphere, the so-called Poincaré sphere (Fig. 2b). 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, i.e. $\hat{E}_x(t)$, $\hat{E}_y(t)$ and the phases δ_x, δ_y.The Stokes parameters S_1, S_2, S_3 and the light intensity S_0 or the normalized Stokes parameters $\bar{S}_1$, $\bar{S}_2$, $\bar{S}_3$ with $\bar{S}_\mathrm{i} = S_\mathrm{i}/\mathrm{S}_\mathrm{o}$ are used where [1]

$$\bar{S}_1 = \cos 2\eta \cdot \cos 2\varphi = \frac{\hat{E}_\mathrm{x}^2 - \hat{E}_\mathrm{y}^2}{\hat{E}_\mathrm{x}^2 + \hat{E}_\mathrm{y}^2}$$

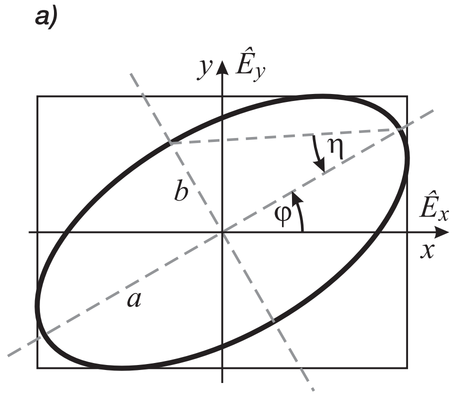
$$\bar{S}_2 = \cos 2\eta \cdot \sin 2\varphi = \frac{2 \cdot \hat{E}_\mathrm{x} \cdot \hat{E}_\mathrm{Y} \cdot \cos\delta}{\hat{E}_\mathrm{x}^2 + \hat{E}_\mathrm{y}^2}$$

$$\bar{S}_3 = \sin 2\eta = \frac{2 \cdot \acute{E}_\mathrm{x} \cdot \hat{E}_\mathrm{y} \cdot \sin\delta}{\hat{E}_\mathrm{x}^2 + \hat{E}_\mathrm{y}^2}$$

The total light intensity S_0 consists of the intensity of both polarized light

$$\sqrt{S_1^2 + S_2^2 + S_3^2}$$

and unpolarized light.



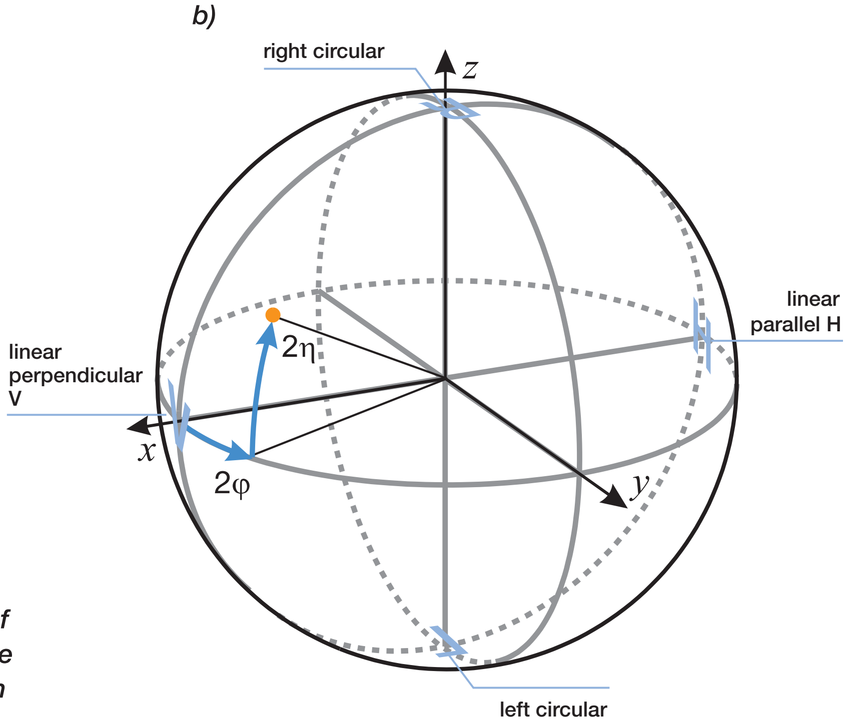


Fig. 2:

Definition of azimuth angle φ and ellipticity η in the ellipse (a). The state of polarization is mapped bijectively on the Poincaré sphere – one SOP is colored in orange (b).

The degree of polarization DOP is thus defined as

$$\mathrm{DOP} = \frac{\sqrt{S_1^2+S_2^2+S_3^2}}{S_0}$$

and has a value of 1 for fully polarized light. For a $\mathrm{DOP} \neq 0$ 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 single-mode fibers

Single-mode fibers are special fibers that transmit light in the transversal fundamental mode LP_{01}. The field distribution (mode field) of the light exiting the fiber is nearly Gaussian. The light is guided in two principal states of polarization with equal propagation constants. Imperfections in the fiber do, however, lead to random power transfer between the two principal states of polarization, due to the equal propagation constants in the principal SOPs and the resulting phase-match [2].

Polarization-maintaining fibers are rotationally non-symmetric, through the integrating of stress elements that break the degeneracy of the two principal 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 resultant polarization.

If the coherence length of the light source is larger than the optical path difference between the light in the two principal SOPs, then the light guided separately in the principal axes recombines at the output to an arbitrary elliptical state. The ellipticity depends on the phase shift of the two components with respect to each other. Pressure and temperature changes influence this phase difference and thus also the resulting 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 principal 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.

Fig. 3 shows the angular accuracy required when adjusting the angle between the laser source and the fiber axis of a hypothetical fiber. We can take from Fig. 3 that the angular accuracy required is about

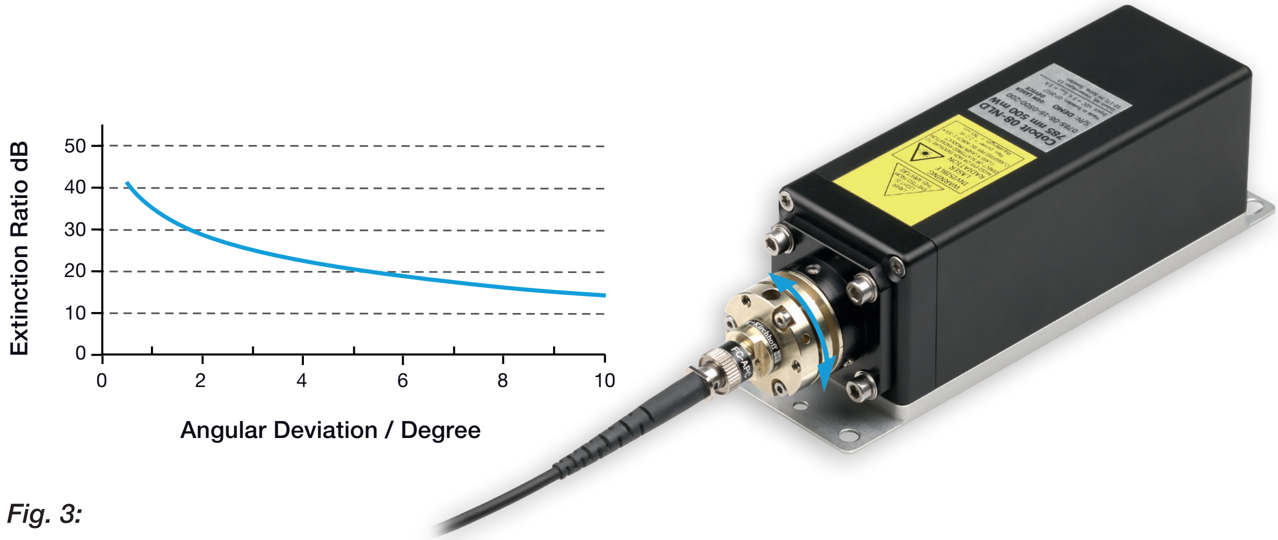


Fig. 3:

Alignment of the polarization axis using the 60SMS laser beam coupler: polarization extinction ratio (PER) when the polarization axis of the source is misaligned to the polarization axis of the fiber.

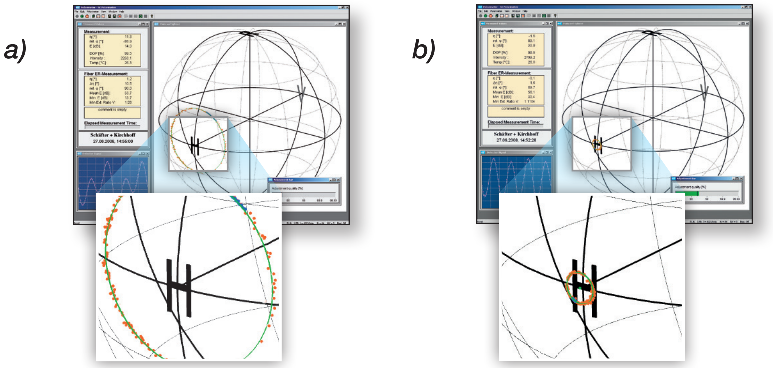


Fig. 4:

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).

1 degree. This would reduce a theoretical polarization extinction rate (PER) of 40 dB (1:10000) of the hypothetical fiber to about 32 dB (1:1585), which is still a very good value.

Polarization measurement

The polarization analyzer described in detail here has two main applications: On one hand monitoring the alignment of polarization-maintaining fibers with the polarization axis of the source; on the other hand, determining the state of polarization in general and 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. A DOP ellipse complements the polarization visualization for sources with low coherence.

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 PER and the degree of polarization DOP are efficiently determined and depicted.

The polarization of 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 shift between the two principal 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. Assuming an ideal linearly polarized 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 trajectory of data points. A circle is automatically fitted to the data points and the mean and minimal PER are displayed (Fig. 4a). The fiber polarization axis can now be rotated with respect to the polarization axis of the source until the radius of the circle reaches a minimum (Fig. 4b). 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, also be used to locate disturbances in the fiber connectors or the incoupling and outcoupling optics, caused by birefringence for example.

Birefringence describes 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.

Measurement accuracy

The polarization analyzers are carefully calibrated for different wavelength ranges. From statistical considerations some insight can be taken concerning the uncertainties and measurement errors. The azimuth angle φ and the ellipticity η, both have a measurement inaccuracy of $\pm 0.4°$. Assessing the accuracy of the PER measurement is not trivial. It is itself PER dependent and increases disproportionately with PER value. For a typical PER of 25 dB, the PER measurement accuracy can be given to be ± 0.5 dB. PER Measurements with values above 35 dB have a much larger measurement inaccuracy in the order of already a few dB and should not be taken too literally.

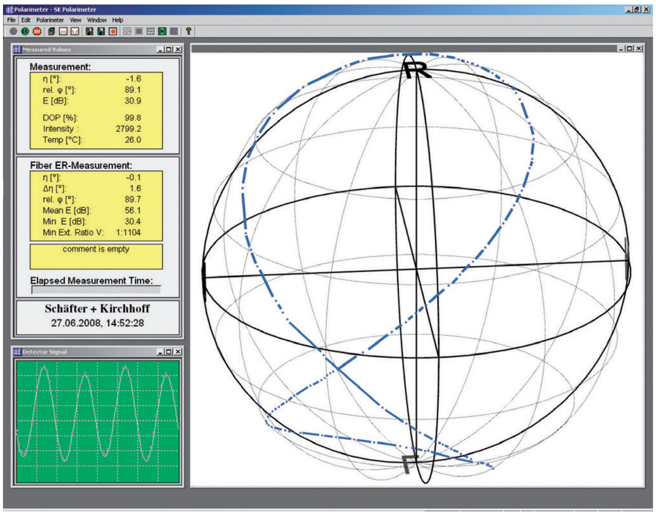
Alignment of retardation optics

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

The emerging polarization is manipulated by rotating the quarter-wave plate with a special tool. A full rotation corresponds to a figure-of-eight on the Poincaré sphere (Fig. 5). 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 then provides a measure of the actual retardation of the optics.

Integration into measurement routines

The polarization analyzer has dimensions of 40 x 70 x 82 mm and is one of the most compact measuring



Measurement:

η [°]: -1.6
rel. φ [°]: 89.1
E [dB]: 30.9

DOP [%]: 99.8
Intensity : 2799.2
Temp [°C]: 26.0

Fiber ER-Measurement:

η [°]: -0.1
Δη [°]: 1.6
rel. φ [°]: 89.7
Mean E [dB]: 56.1
Min E [dB]: 30.4
Min Ext. Ratio V: 1:1104

comment is empty

Elapsed Measurement Time:

Schäfter + Kirchhoff
27.06.2008, 14:52:28

Fig. 5:

Alignment of a quarter-wave plate depicted on a Poincaré sphere. The state of polarization produces a figure-of-eight during rotation of the quarter-wave plate. 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.

devices in its class. It is available in various versions to cover the wavelength range from UV to IR (370 – 1660 nm). The polarization analyzer receives its power from the USB 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 (cage system). Microbench adapters for optics of different diameters for the standard fiber collimators from Schäfter+Kirchhoff are available. Fiber adapters for FC-APC and FC-PC (SC and E2000) are used for the alignment of the fiber coupling. The analyzer can be fitted with connections for most of the common optical bench systems. A quick change between free beam mode and fiber coupling mode using a fiber adapter is also possible as the device does not need additional recalibration after switching.

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#. 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. 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 370 - 1660 nm. The scope of 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.

References

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

[2] M. Born, E. Wolf: Principles of Optics, Pergamom Press , 1984.