Polarization-maintaining Fiber Optics

Stable fiber-optic setups from the ultraviolet to the infrared

Anja Krischke, Christian Knothe and Ulrich Oechsner

A stable measurement setup is fundamental for any successful measurement. A major cause of frustration and error is the need to continuously readjust optomechanical equipment because of continuous instabilities. The use of fiber optics has proven to increase both stability and convenience significantly when compared with standard free-beam setups. These modular, complex and self-contained setups also often increase laser safety and reduce the laser safety classification. The defined interface between a laser source and the more sensitive environment of the measurement setup provides the physical separation that enables a mechanical and thermal decoupling, suppressing mutually negative effects.

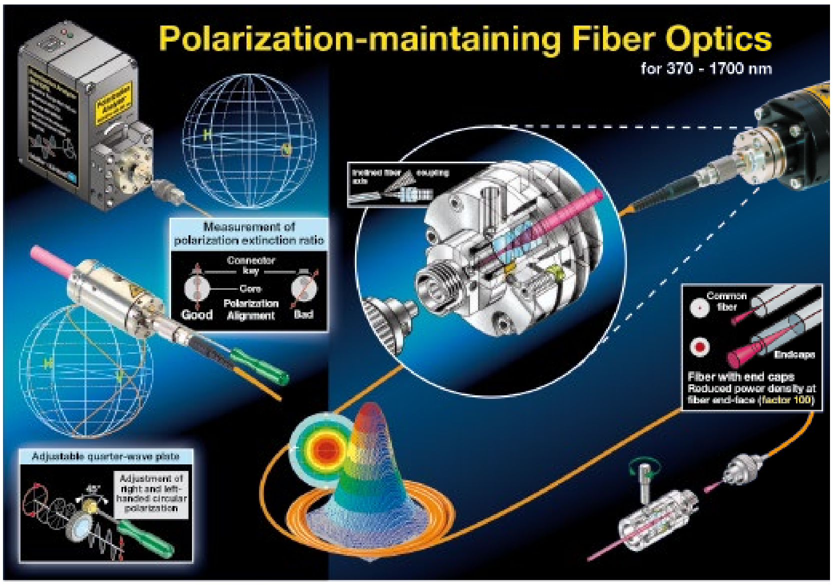


Fig. 1 Components and tools for polarization-maintaining fiber optics. The laser beam coupler couples the radiation into PM fibers with high coupling efficiency. The polarization Analyzer SK0101PA is utilized to perform the polarization alignment quickly and efficiently.

Singlemode fibers are specialized fibers that transmit light in the transverse fundamental mode LP_{01}. The field distribution (mode field) of the light exiting the fiber is close to Gaussian. For standard singlemode fibers the light is guided in two principle states of polarization. Imperfections in the fiber do lead, however, to random power transfer between the two principle states of polarization so that the polarization is not maintained.

Singlemode fibers are characterized by their numerical aperture *NA*, their mode field diameter MFD and their cut-off wavelength λ_o. It is only at wavelengths above this cut-off that the coupled light is guided in a single mode and not in multiple modes, where the beam and intensity profiles are no longer stable nor Gaussian.

The MFD is wavelength-dependent and inversely proportional to the fiber *NA*. While fibers used for telecommunication in the infrared region, around wavelengths of 1550 nm, are characterized by fairly large mode field diameters of around 10 µm, the MDF in the UV is small, e.g. 3 µm for 405 nm and a fiber with $NA = 0.12$.

Polarization-maintaining singlemode fibers (PM fibers) are rotationally non-symmetric because of integrated stress elements, for example, that break the degeneracy of the two principle states of polarization (SOP). Light is guided either in the so-called “fast” or the “slow” axis and linearly polarized light coupled into one of these axes is maintained. If light is guided partly in the other axis then the coherence of the light source determines the resulting polarization.

For sources where the coherence length is larger than the optical path difference between the light in the two principle SOPs of the fiber, the outcome polarization is elliptical. However, strain and temperature variations, 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 between the light guided in the two principle SOPs and, as a result, the exciting light is partly depolarized.

For a well-defined polarization state, it is extremely important to align the polarization axis of the PM fibers precisely with the linear polarization axis of the source.

The maximum power that can be guided within a fiber is mainly restricted by the power density at the fiber end faces, when not considering nonlinear optical effects, such as Brillouin scattering. Extreme power densities can cause scorching of the end face or photo-contamination by the generation of a dipole trap, a phenomenon used to good effect in optical tweezers. These detrimental effects can be obviated using a fiber

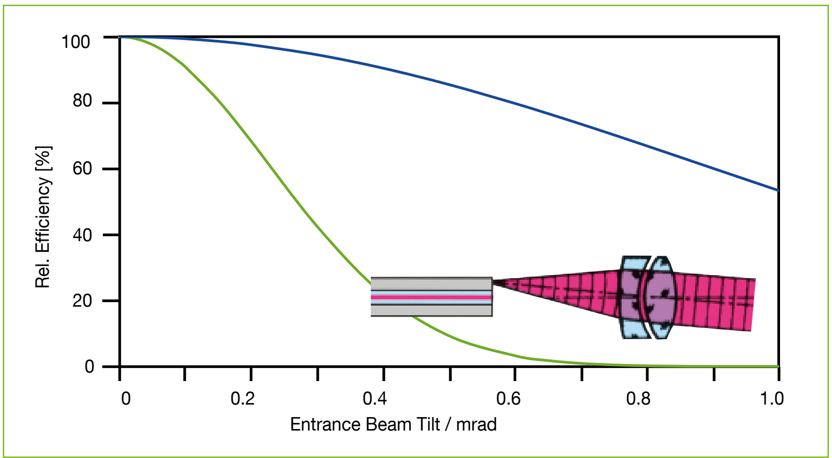


Fig. 2 Relative coupling efficiency plotted against the entrance beam tilt of a laser beam coupler for a focal length of 4 mm, fiber *NA* 0.12 and 400 nm (green) and 1550 nm (blue). A misalignment of 0.2 mrad (0.01°) causes a decrease in coupling efficiency for 1550 nm of < 5 % compared with about 30 % for 400 nm.

end cap, in which a short length of fiber (< 500 µm) without a core is connected to the polarization-maintaining fiber. Without a fiber core, the mode field diameter of the beam diverges to about ten times its prior size and the power density decreases by a factor of hundred, while hardly affecting the numerical aperture of the fiber or the polarization of the laser beam.

Stable fiber coupling – even at short wavelengths

When coupling into singlemode fibers, the laser beam couplers should produce a diffraction-limited spot that matches the mode field diameter and the numerical aperture of the fiber in order to achieve max. coupling efficiency. It is only when this condition is met that fiber coupling with high coupling efficiencies of up to 85 % are achieved. A focal length chosen too large is inefficient, since the focussed laser spot is larger than the mode field diameter. When using a focal length too small, the convergence angle of the focussed laser spot is larger than the maximally acceptable divergence angle α of the fiber – the coupling efficiency is diminished. For an optimally chosen focal length, apart from losses due to Fresnel reflection at both fiber ends of about 4 % each, an ideal Gaussian beam is coupled almost completely.

The high pointing-stability required for fiber coupling into a polarization-maintaining fiber can be visualized with an example (see Fig. 2): for a focal length of 4 mm, an angular misalignment of the coupler of only 0.2 mrad (0.01°) results in a lateral displacement of 0.8 µm between the laser spot and the mode field of the fiber and decreases coupling efficiency for 400 nm and *NA* 0.12 by as much as 30 %. The fiber coupling is much less sensitive for 1550 nm where the decrease in coupling efficieny is < 5 %. For λ = 400 nm and *NA* 0.12, a displacement of 0.4 µm alone is already sufficient to decrease the coupling efficiency by as much as 10 %. It is self-evident that high coupling efficiencies and long-term stability require sub-micron precision and pointing stability for the coupling optics, especially in the ultraviolet range.

Proven stability

The high stability of fiber-coupling using a laser beam coupler is demonstrated in temperature-stability tests using different focal lengths and wavelengths. The test setup is depicted in Fig. 3a. The light emitted by the temperature-stabilized laser diode beam source 48TE (with integrated Faraday isolator) is guided to the test setup using a polarization-maintaining fiber, collimated by laser beam coupler, and then coupled back into a polarization-maintaining fiber using a second laser beam coupler, with both placed 12 mm apart. The recoupled power is monitored using a photodetector. The coupling setup is placed on a thermo-controlled plate, to vary the temperature between 15 °C and 35 °C in successive cycles with a rate of 0.5 °C per minute. The temperature of the coupling system is monitored by a temperature sensor placed on one of the two laser beam couplers. In order to minimize any temperature impact on the measurement equipment, the laser source as well as the photo detector and the data logger are all placed on a

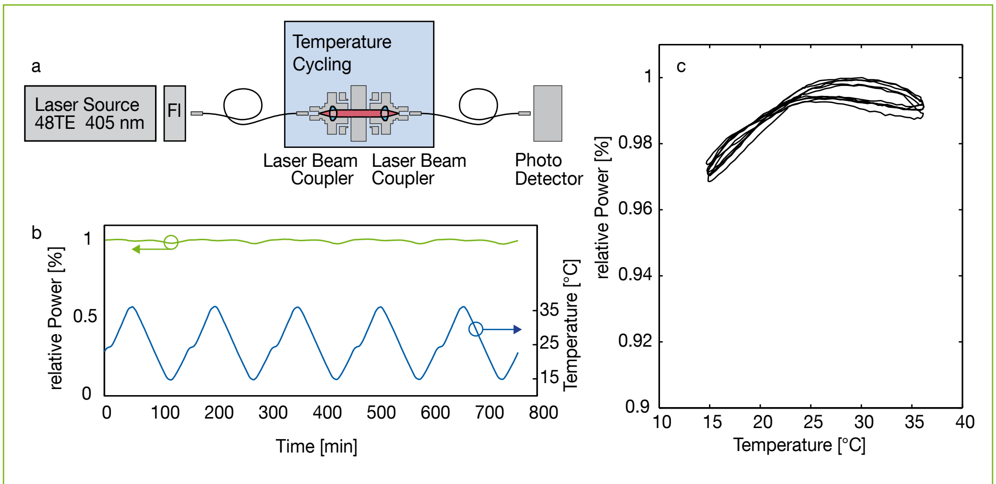


Fig. 3 Test setup for measuring the stability of two laser beam couplers (f = 4.5 mm, λ = 405 nm) (a). The relative power (b) shows a repetitive pattern following the temperature (below). The relative power curves (c) are almost coincident and confirm the high reproducibility of the pointing stability during temperature cycling.

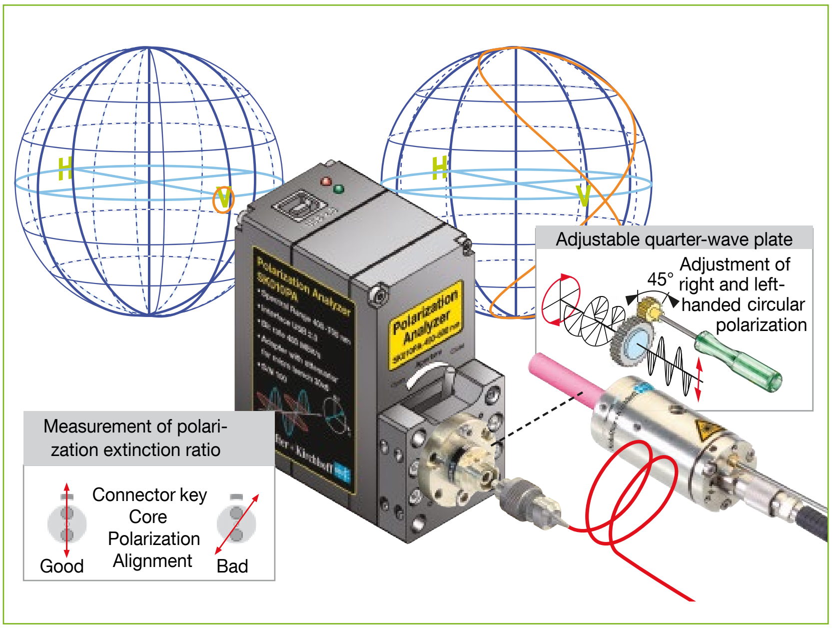


Fig. 4 SK010PA polarization analyzer for the adjustment of polarization-maintaining fibers as well as free beam applications such as the alignment of fiber collimators with integrated quarter-wave plate. Time-consuming alignment tasks are completed efficiently for laser sources with large and small coherence length.

thermo-controlled plate at a constant temperature of 25 °C.

Fig. 3b shows the typical results of the relative transmitted power over five measurement cycles using a focal length of 4.5 mm and a wavelength of 405 nm. The power is normalized with respect to the mean power acquired over all measurement cycles. The power deviation from the mean power is ±1.5 %. The repetitive pattern in the relative power caused by the temperature cycling is demonstrated more clearly in Fig. 3c, in which the relative power (normalized to the maximum) is plotted against the temperature of the laser beam couplers. The maximum coupling efficiency is reached a little above 25 °C and it decreases faster towards lower temperatures than higher temperatures, with the smallest slope near the requested operating point (25 °C). The respective power curves for each measurement cycle are almost coincident and the power variation at points with equal temperatures is < 1 %, which demonstrates the reproducibility of the pointing stability during temperature cycling and the long-term stability of the fiber-coupling. The maximum deviation with respect to the maximum power here is 3 %.

Fast and high-quality polarization alignment

Stable long-term stable coupling efficiencies are only part of the success when coupling into PM fibers. 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 on the fiber.

The SK010PA polarization analyzer (Fig. 4) has been specially designed to perform fiber alignment tasks as well as to determine the polarization state quickly and efficiently. The measurement principle is based on a rotating quarter-wave plate and a static polarizer in front of a photodiode. A detailed analysis of the photodiode signal and the time/position information of the quarter-wave plate reveals e. g. the state of polarization, which is then depicted on the Poincaré sphere. Linear polarization states are found on the equator whereas circularly polarized light is located at the poles.

An indicator of the maintenance of the polarization state is the ratio of the coupled power into the two axes: the polarization extinction ratio (PER in dB). A high PER indicates a successful preservation of the polarization state. The fibers used in the stability measurement setup (Fig. 3) for example, have a polarization extinction ratio of more than 32 dB (measured at 405 nm). The polarization analyzer additionally evaluates the degree of polarization (DOP) – the ratio of transmitted polarized light relative to the total transmitted power. A

Company

Schäfter+Kirchhoff
Hamburg, Germany

Schäfter+Kirchhoff has accumulated a lot of experience in the development of optomechanical and optoelectronic systems for use in research, aviation and in space, as well as for demanding medical and industrial applications. Schäfter+Kirchhoff designs and manufactures their own CCD line scan camera systems, laser sources, beam-shaping optics and fiber-optic components, including laser beam couplers, fiber collimators and fiber port clusters for customers worldwide.

www.sukhamburg.com

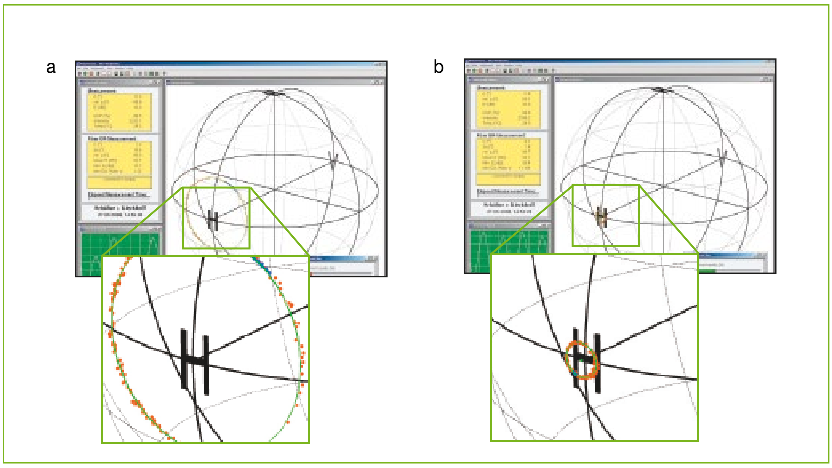


Fig. 5 Adjustment of a PM fiber. The aim is to minimize the data circle radius. With a poor fiber alignment, the state of polarization varies significantly e.g. when bending the fiber (a). With a better angular alignment of the fiber, the change in polarization and the radius of the data circle become smaller (b).

DOP of 1 indicates fully polarized light, a totally unpolarized beam produces a DOP value of zero.

When a fiber is strongly jigged, the state of polarization jumps wildly over a section of the Poincaré sphere, whereas a more defined ambient change, such as a gentle bending of the fiber, produces a data circle. This circle represents all possible states of polarization for the current alignment, with the center representing the mean polarization extinction ratio. For an ideal polarization-maintaining fiber, the mean PER should be located at the equator. The data point that is farthest from the equator reveals the worst possible polarization extinction ratio 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, as 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 significantly 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. 5a). The fiber axis is now rotated with respect to the polarization axis of the source until the radius of the circle reaches a minimum (Fig. 5b).

If it is the stability of the state of polarization that is of major importance and not the PER itself, simply swapping the fiber input and output and performing another PER measurement will reveal the most stable fiber configuration (assuming that any disturbances only occur in the fiber connector). The most stable configuration is the one having the smaller data circle. When swapping the 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.

Stable, complex fiber-optic setups – the fiber port cluster

Fiber port clusters are compact optomechanical units that combine or split the radiation from one or more polarization-maintaining fibers into one or multiple output polarization-maintaining fiber cables – with both high efficiency and variable splitting ratio. The beam delivery system consists of compact, modular optomechanical units (Fig. 6a). A basic component in these fiber port clusters is the laser beam coupler, which is used both as an input and an output, and collimates the fiber-coupled radiation that enters the system and launches the split radiation into the output fiber cables. The modularity ensures that almost any desired system can be assembled that is both compact and enclosed. Because of the polarization sensitive properties of some of the optical components within the fiber port cluster, PM fibers are used to transport the light to the cluster with defined linear polarization.

There are several ways to achieve beam splitting into several output ports. When working with one input wavelength, radiation splitting is achieved by using a cascade of rotary half-wave plates in combination with polarization beam splitters. Integrated photodiodes, for example, provide data that allow insightful monitoring of the input powers. By rotating the half-wave plates, almost any desired splitting ratio can be realized.

If using several inputs with multiple wavelengths, the wavelength difference between the input ports determines how the combination can be achieved. For two laser sources with a large wavelength difference, a dichroic beam combiner is used (Fig. 6b). If the wavelength difference is too small for dichroic beam combination, a polarization beam splitter and subsequent dichroic wave plates allow multiplexing (Fig. 6c).

Fiber collimators can then be used to collimate the exciting beam. The optimal collimation focal length is determined by the beam diameters required by the experiment and can be calculated from the *NA* of the fiber and the target beam diameter. Special collimators with an integrated quarter-wave plate, for example, transform the linear output radiation into circularly polarized light for

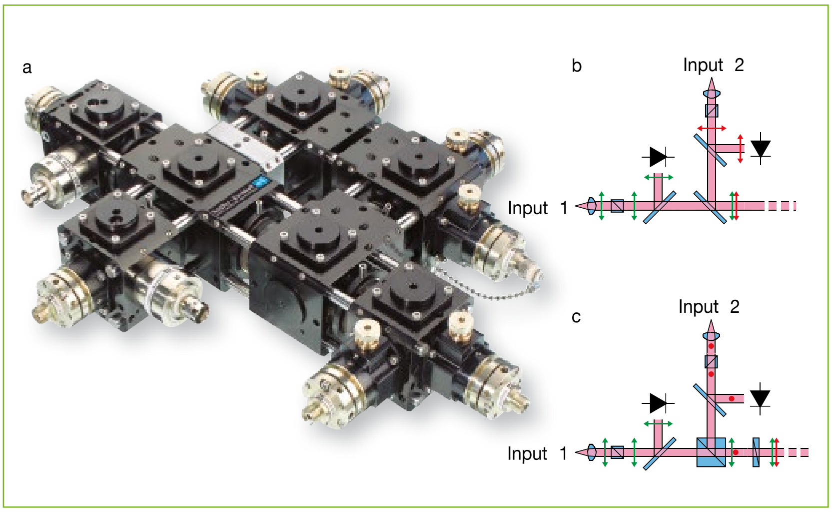


Fig. 6 Fiber port cluster (a). For laser sources with a large wavelength difference (b), a dichroic beam combiner is used. If the wavelength difference is too small for dichroic beam combination (c), a polarization beam splitter and subsequent dichroic wave plates allow multiplexing.

uses such as in a magneto-optical trap. The retardation plate is integrated into the divergent beam and can be rotated with respect to the linear input polarization producing right-handed as well as left-handed circular polarization.

Similar to the test setup proving the long-term stability of the laser beam coupler, a test demonstrating the stability during temperature cycling (here between 20 °C and 26 °C in successive cycles with a rate of 0.5 °C per minute) was performed for a fiber port cluster splitting one input into six output ports. The relative power (@ 780 nm) transmitted in one of the six output ports while the temperature of the cluster was varied, reveals a power deviation from the mean power of ±1.0 %. This is especially small considering that the low-order wave plates used within the cluster themselves already exhibit a strong temperature sensitivity.

Conclusion

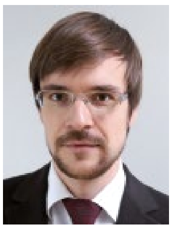
Fiber optics can significantly increase the stability and convenience of measurement setups and allows large breadboard setups to be replaced by stable, compact, transportable, sealed fiber-optic systems. The stability of any fiber-optic system strongly depends on the long-term stability of the laser beam couplers used for both coupling in and out of PM fibers. Power stability during temperature cycling, with a typical maximum deviation of 3 % was achieved in a test setup for laser beam couplers with a focal length of 4.5 mm at 405 nm and at temperatures between 15 and 35 °C. This high stability is fundamental for the successful use of fiber-optic equipment. Fiber port clusters - more complex compact modular units that can be used to split radiation into multiple polarization-maintaining fibers – also exhibit very good long-term stability as well.

Time-consuming alignment tasks can be completed efficiently for free beam as well as fiber-optic applications by using a polarization analyzer. Special routines allow the precise coupling of linearly polarized light into polarization-maintaining fibers and help identifying the configuration with the most stable polarization.

DOI: 10.1002/opph.201400065

Authors

Anja Krischke studied Physics at the University of Würzburg with a focus on the description of ultrashort laser pulses and quantum control. She joined Schäfter+Kirchhoff in 2011 and now works in optics development.



Christian Knothe first studied Physics at the University of Freiburg i.Br. with a focus on laser-spectroscopy before completing his doctoral thesis in fiber optics at the Technical University of Hamburg-Harburg. Since he joined Schäfter+Kirchhoff in 2005, he has been responsible for the advanced fiber optic applications.

Ulrich Oechsner studied Physics before completing his doctoral thesis at the University of Hamburg. After research in the fields of electrophysiology and physiological optics, he joined Schäfter+Kirchhoff in 2000 where he is responsible for optical design and system development.

Anja Krischke, Dr. Christian Knothe and Dr. Ulrich Oechsner, Schäfter+Kirchhoff GmbH, Kieler Str. 212, 22525 Hamburg, Germany, E-mail: info@SuKHamburg.de