Components and tools for polarization-maintaining fiber optics

Technology for industrial and scientific applications

Fiber cables open up new vistas for the design of modular devices and compact setups for industrial and scientific applications. Special fibers, such as polarization-maintaining singlemode fibers, are predestined for use in complex, self-contained setups, increasing laser safety by reducing the laser safety classification. Most importantly, a sensitive and delicate measurement system can still enjoy the benefits of a laser beam, with the desirable features of polarization state and coherence, but be physically separated from the laser source. The measurement setup and the laser source are decoupled mechanically and thermally in order to avoid any mutual negative impacts.

Singlemode fibers are light wave guides with a nearly Gaussian mode field and typical numerical apertures ranging from 0.09 to 0.14. The light is guided in a very small core. Its dimensions are in the range of only a few micrometers (starting at 2.5 µm) and are small compared to human hair (diameter around 50 µm). Unlike the core diameter, the mode field diameter is wavelength dependent. The fiber parameters (numerical aperture NA, cut-off wavelength λ_0, the core diameter, or the wavelength dependent mode field diameter) have to be chosen carefully for each application. Fibers used for telecommunication in the infrared region around wavelengths of 1.5 µm are characterized by fairly large core diameters around 9 µm. For high power applications large mode field diameters (small numerical apertures) are necessary as well, in order to prevent nonlinear optical effects caused by high power densities in the fiber.

Based on this, a high technical standard for optical and mechanical components is required, in order to achieve high coupling efficiencies: The smaller the wavelength, the higher the demand for high quality and high precision coupling components.

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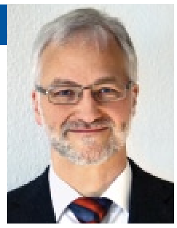

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Singlemode fibers

Laser beam sources with a Gaussian intensity profile are coupled into the Gaussian mode field of a singlemode fiber (Fig. 1) by using the appropriate optics. The mode field (Fig. 2) describes the distribution of light intensity across the fiber end face that is transmitted in the fundamental LP_{01} mode. The mode field diameter is:

$$MFD = \frac{2 \cdot \lambda}{0.82 \cdot \pi \cdot NA}$$

The factor 0.82 accounts for the different intensity levels at which the numerical aperture NA (5%-level) and the mode field diameter MFD (13.5%-level) are defined (Fig. 2). A singlemode fiber is characterized not only by its numerical aperture but also by its cut-off-wavelength λ_0. It is only at wavelengths above this threshold 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 or Gaussian.

The Gaussian singlemode beam is divergent when it exits the fiber with a divergence angle α at the 5%-level (see Fig. 2) determined by the numerical aperture NA of the fiber:

$$NA = \sin\left(\frac{\alpha}{2}\right)$$

The rotational symmetry of the fiber results in the state of polarization of the emitted light being undetermined and an arbitrary polarization state, ranging from linear to circular occurs. Any minor physical displacement of the fiber or a change in its temperature alters the polarization state.

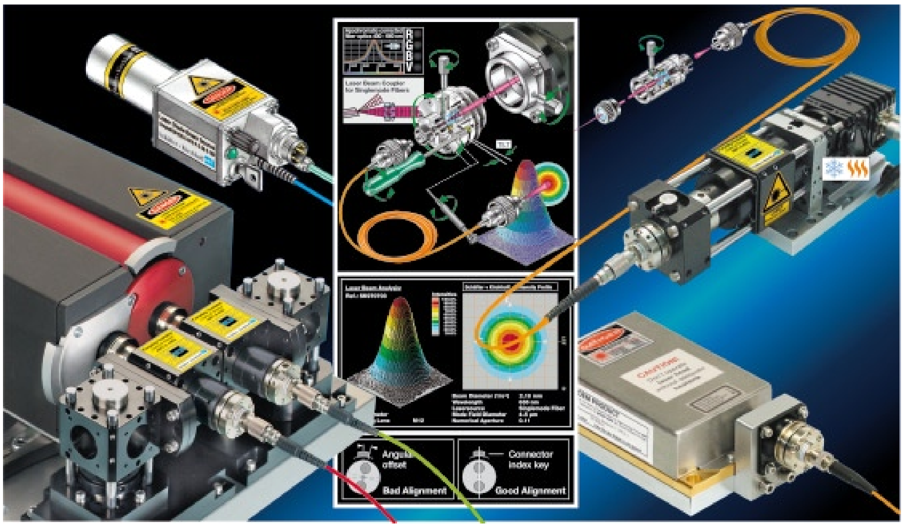


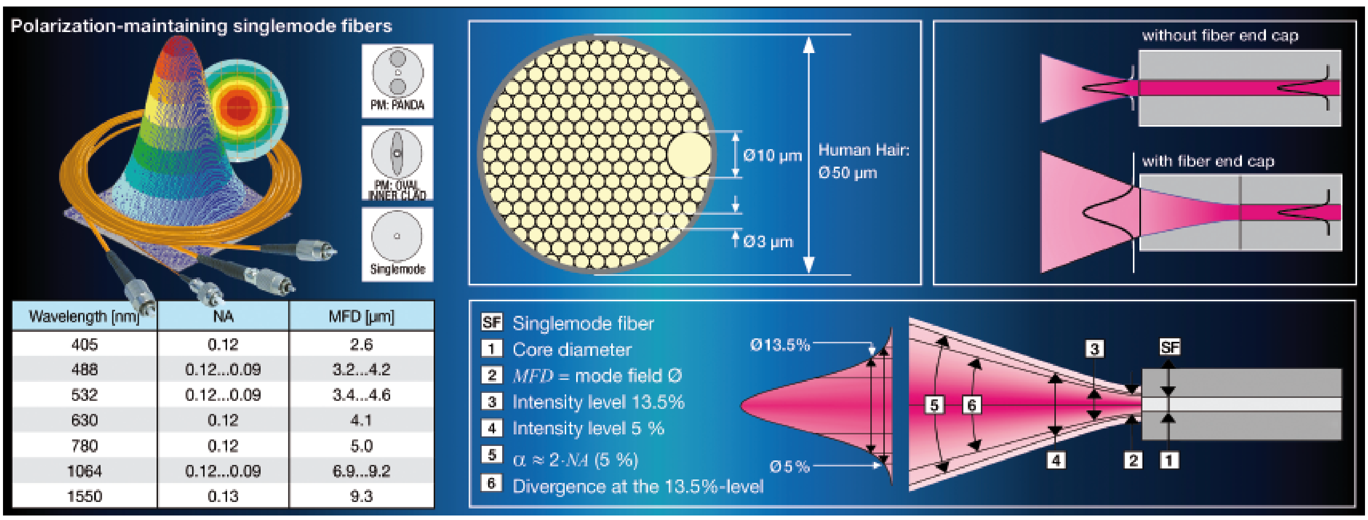
FIGURE 1: **Fiber coupled laser sources. Different laser beam sources are coupled into polarization-maintaining fibers with the help of specially developed fiber couplers (upper middle). Faraday isolators and anamorphic optics are used to protect the laser source and to improve the coupling efficiency, respectively. The Gaussian-shaped radiation exiting the fiber is collimated with fiber collimators. If laser speckle or coherence disturb the measurements, a specially RF-modulated laser source like the 51nano (upper left corner) can be used as a light source and considerably increases the measurement quality.**

Polarization-maintaining singlemode fibers

In order to preserve the state of polarization of a linearly polarized beam source, stress elements are built into the fiber (Fig. 2). The stress elements induce birefringence, leading to two perpendicular axes of light propagation, which are designated as the "slow" and "fast" axes. When the light is coupled exclusively into one of these two axes, the polarization state is maintained and is independent of changes in fiber temperature or displacement. Any deviation in the axis coupling leads to unstable elliptically polarized light, which is highly sensitive to vibration or changes in fiber temperature or its position. The highly precise orientation of the polarization maintaining fiber (PM-fiber) with the state of polarization of the laser beam source requires the help of a polarization analyzer. It determines the polarization extinction ratio, PER, that means the ratio between the powers coupled into the two axes. Higher polarization extinction ratios ensure a better conservation of the state of polarization.

Fiber end caps and fiber confections

The maximum light 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 end cap (Fig. 2), in which a short



Wavelength [nm]	NA	MFD [µm]
405	0.12	2.6
488	0.12...0.09	3.2...4.2
532	0.12...0.09	3.4...4.6
630	0.12	4.1
780	0.12	5.0
1064	0.12...0.09	6.9...9.2
1550	0.13	9.3

FIGURE 2: **Polarization-maintaining fibers can have different designs (upper left) including Panda fibers. The mode field diameter is very small compared to a human hair (upper middle) and is wavelength dependent (Table lower left). The beam profile of singlemode fibers is Gaussian. The NA, the angle of divergence and the MFD are defined conventionally at different intensity levels (lower right). For a fiber without an end cap (upper right), the beam starts diverging at the fiber end face (high power density). When using an end cap, the power density at the end face decreases without changing the NA.**

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 without affecting the numerical aperture of the fiber or the polarization of the laser beam.

The fiber end face of FC-APC fiber connectors is polished at an angle of 8° in order to avoid back-reflections of the beam into the laser source. Back-reflections into the beam source cause frequency instability and severely diminish the life expectancy of the laser. An FC fiber connector also has a connector index key which indicates the orientation of the fiber axes. In general, fiber connectors should be mounted stress free, as the stress induces birefringence and a high polarization extinction ratio cannot be attained. A range of specially developed collimators and fiber couplers have been designed that have an inclined coupling axis, for acceptance of the APC connectors, and ensure a high coupling efficiency.

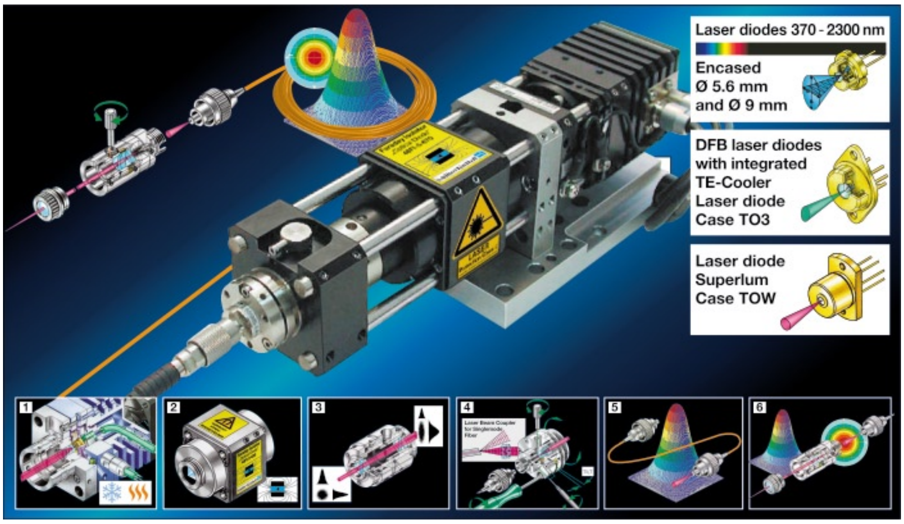


FIGURE 3: **Laser beam source 48TE. A laser diode is mounted in a base with integrated thermoelectric cooling (1). A Faraday isolator prevents the laser diode from back-reflection (2) and an anamorphic optics (3) with cylindrical lenses is used to correct the elliptical beam profile and astigmatism of the laser source if necessary. The beam is coupled into a PM-fiber (5) with a fiber coupler (4) and is transformed into a collimated beam by a fiber collimator (6). Attachable beam-shaping optics (6) generate micro-focus spots, laser lines or laser patterns.**

Laser beam sources

Various types of laser beam source can be used for fiber coupling. OPSL-sources (Optically Pumped Semiconductor Laser) for example, typically have a high beam quality, with $M^2 \leq 1.05$ and no astigmatism, which makes coupling efficiencies up to 85% possible with a polarization extinction ratio of 1:200. High power lasers with $M^2 > 1.2$ cannot be coupled to singlemode fibers. Further beam sources include the series 48TE (Fig. 3) from Schäfter+Kirchhoff. It provides thermoelectrical cooling (using a Peltier element and temperature sensor) and can use many different types of diodes, from simple Fabry-Perot diodes to DFB (distributed feedback), DBR (distributed Bragg reflector) or VCSEL (vertical cavity surface emitter) types.

Frequency stabilized diodes can usually only be fiber-coupled in combination with a Faraday isolator, since feedback into the diode (back-reflection or back-scattering) disturbs the performance significantly, causing frequency instability, more noise and a shorter laser lifetime.

When using diodes with an elliptical beam profile, the coupling efficiency can be enhanced considerably by incorporating an anamorphic optics (5AN). The astigmatism inherent to some laser diodes is also corrected when using an anamorphic optics based on cylindrical lenses. The coupling efficiency is improved significantly. If the laser beam source has a low beam quality the fiber serves as a cleansing spatial filter.

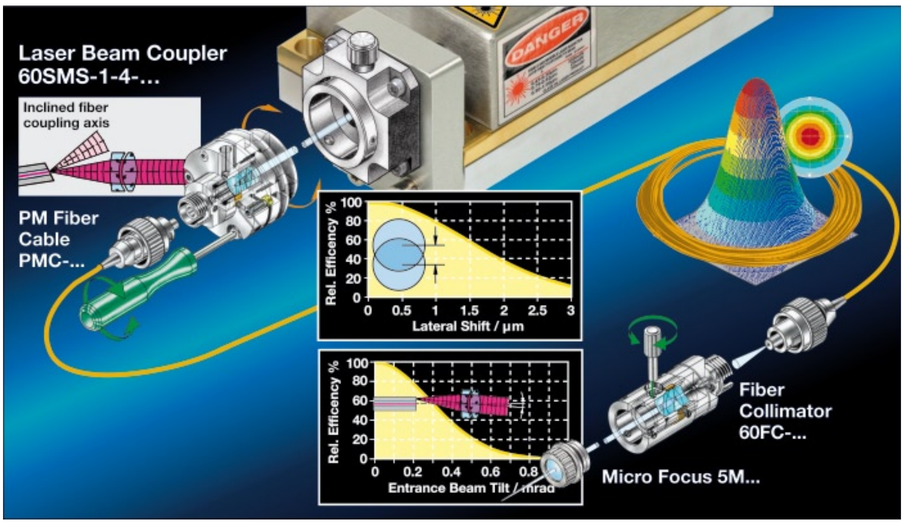


FIGURE 4: **The input beam is coupled into a singlemode fiber with a laser beam coupler. An integrated tilt adjustment allows a highly precise lateral placement of the focus spot onto the fiber end. Small lateral shifts of the spot or angular deviations considerably decrease the coupling efficiency.**

Laser beam coupler

The coupling of any laser beam source into a polarization-maintaining singlemode fiber with submicron precision requires an optically and mechanically sophisticated device, making coupling efficiencies of 85% of the initial laser power attainable. The lens of the laser beam coupler 60SMS (Fig. 4) produces a diffraction-limited spot, which needs to be adapted to the mode field of the fiber. The focal length and the lens type of the lens depends on the laser beam source. An optimum focal length is determined by

$$f' = \frac{0.61 \cdot \varnothing_{Beam}}{NA}$$

The factor 0.61 accounts for the different intensity levels at which the numerical aperture NA of the fiber (5%-level) and the beam diameter $\varnothing_{Beam}$ (13.5%-level) are conventionally defined. For elliptical beam profiles (small diameter $\varnothing_{||}$ large diameter $\varnothing_{\perp}$), an effective beam diameter $\varnothing_{eff}$ must be calculated for the determination of the optimum focal length:

$$\varnothing_{eff} = \sqrt{\varnothing_{\parallel} \cdot \varnothing_{\perp}}$$

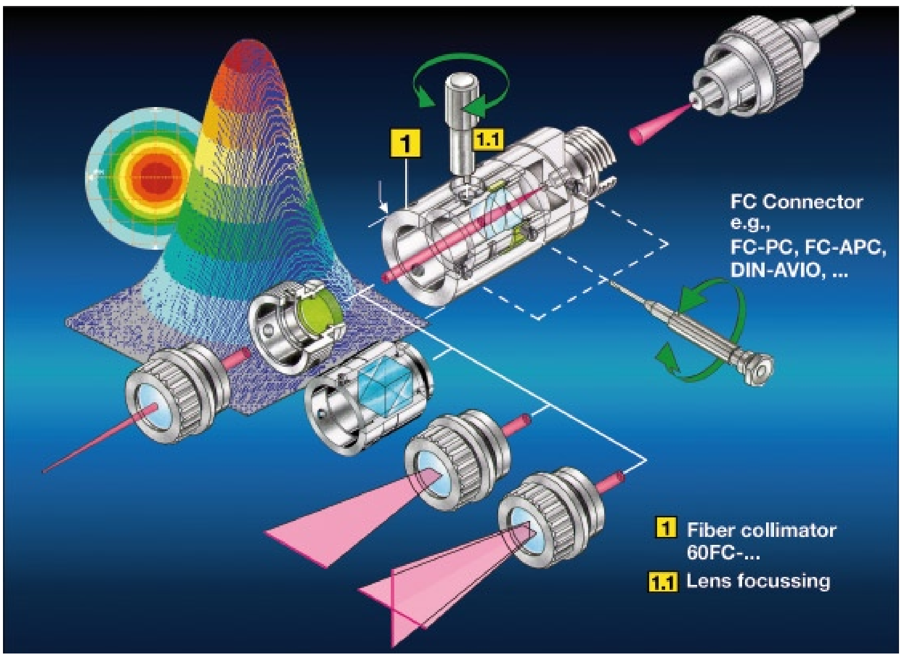


FIGURE 5: **Fiber collimator and attachable beam-shaping optics. The beam exiting the fiber is transformed into a collimated beam with a fiber collimator. Variation of the focus position leads to focused or defocused beams. Shaping of the collimated beam is achieved by adding lens attachments. Micro-spots, laser lines, laser patterns or specially polarized light can be generated.**

Polychromatic applications require specially designed, chromatically corrected lenses (achromats or apochromats), while the simpler spherically corrected monochromats or aspheres are sufficient for monochromatic applications.

An optimum coupling efficiency is achieved for an ideal Gaussian beam (M^2=1) when the convergence of the focussed beam equals the divergence α defined by the numerical aperture of the fiber. At this point, the width of the focussed laser spot at the fiber end face also matches the mode field diameter of the fiber. Apart from losses due to Fresnel reflection at both fiber ends of about 4% each, an ideal Gaussian beam is coupled almost completely. 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 sport is larger than the maximally acceptable divergence angle α of the fiber.

In order to accomplish optimum coupling efficiencies, the laser beam coupler needs to be centered within the propagation axis of the fiber. A lateral displacement with respect to the optical axis leads to aberrations such as coma or astigmatism. Furthermore, a part of the radiation may exceed the maximum acceptance angle α of the fiber and the coupling efficiency decreases. The beam focus is placed laterally on the fiber end face with submicrometer precision by using an integrated tilt adjustment for the coupling lens and its fiber end. A misalignment of a mere 0.2 mrad (0.01°) for a focal length of 5 mm, for example, is enough to cause a literal displacement of 1 µm between the laser spot and the fiber core, which significantly decreases the coupling efficiency (Fig. 4). The optimum axial position is achieved by adjusting the focus position.

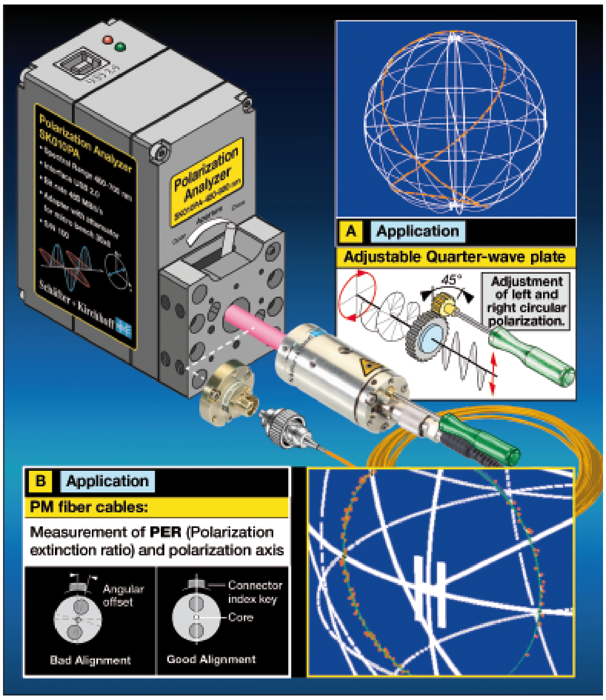


FIGURE 6: **Polarization analyzer. The polarization analyzer can either be used for fiber coupling tasks (B) or for free beam applications (A).The radiation coming out of a fiber can be collimated with a fiber collimator with integrated λ/4-retardation optics. Circularly polarized light is produced if the retardation optics is adjusted in the right manner. In order to achieve a precise alignment of the polarization-maintaining fiber to the laser beam source the coupling process is monitored with a polarization analyzer to ensure a high polarization extinction ratio. The smaller the circle on the Poincaré sphere, the better the alignment.**

For a highly precise alignment of the polarization-maintaining fiber with the laser beam source, the laser beam coupler is equipped with a positively locating circumferential V-groove and an orientation slot for aligning the fiber connector index key, allowing the fiber and coupler to be rotated as a unit for alignment with the fiber polarization axis. The efficiency is monitored by the polarization analyzer to ensure coupling into one of the fiber axes and the attainment of the best polarization extinction ratio.

Fiber collimators

The divergent radiation exiting the fiber is transformed into a Gaussian-shaped, collimated beam by a fiber collimator (60FC, 60FC-T, Fig. 5). The resulting beam diameter $\varnothing_{Beam}$ is defined by the numerical aperture NA of the fiber and the focal length f' of the collimation lens:

$$\varnothing_{Beam} = 0.82 \cdot f' \cdot NA$$

The factor 0.82 accounts for the different intensity levels at which the numerical aperture of the fiber NA (5%- level) and the beam diameter $\varnothing_{Beam}$ (13.5%-level) are defined. Larger focal lengths f' produce larger beam diameters. In order to prevent vignetting and diffraction of the collimated beam, the numerical aperture of the collimator needs to be larger than the numerical aperture of the fiber.

Besides collimation, fiber collimators can also be used for focussing or defocussing beams by varying the focus position of the collimator directly.

Specially developed optics can additionally be attached to a fiber collimator for the generation of micro-focus spots, laser lines or laser patterns.

Fiber collimators for quantum optics with integrated λ/4-retardation optics

As a consequence of good alignment the state of polarization of the fiber's emitted light usually equals the linear polarization of the laser beam source. For applications such as magneto-optical traps in quantum optics, for example circularly polarized light is needed. This can be achieved with λ/4-retardation optics already integrated into the fiber collimator (60FC-Q, Fig. 6). The collimator is equipped with an alignment tool for the λ/4-retardation optics and the state of polarization can be adjusted on the fly. The state of polarization is measured with a polarization analyzer, making an optimum adjustment of the retardation optics possible.

Polarization analyzer

The Polarization Analyzer SK010PA (Fig. 6) is an indispensable aid during fiber-coupling tasks as well as for free beam applications. In fiber coupling, it is used to maximize the polarization extinction ratio, while in free beam applications, a polarization analyzer can be used for aligning the state of polarization induced by retardation optics, for example. With its fist-size dimensions, it is one of the most compact devices of its class.

Specially developed software routines enable a fast and straightforward alignment when coupling into polarization-maintaining fibers. The polarization extinction ratio and the degree of polarization are displayed continuously in real-time. The degree of polarization describes the polarized fraction of the examined laser light and this information is processed for the depiction of an ellipse, which represents the sum of linearly and circularly polarized and unpolarized fractions of light, respectively. This depiction is especially important for incoherent light sources, since no polarization extinction ratio can be determined.

In free beam applications such as the alignment of retardation optics, the precise determination and depiction of the state of polarization is critical and is calculated from the Stokes parameters of the laser light. It is displayed on a Poincaré sphere.

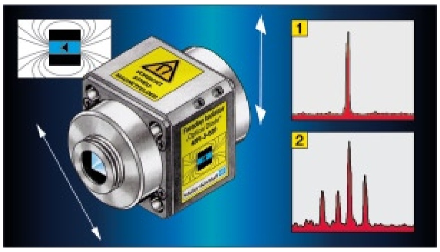


FIGURE 7: **Faraday Isolator. Faraday isolators serve as an optical diode. Only light propagating in forward direction is transmitted. Light propagating in the opposite direction is blocked. If back reflections reach the laser source, the once frequency stabilized spectrum (1) is considerably disturbed. Frequency instability (2), increasing noise and a shorter lifetime of the laser beam source are the consequence.**

Faraday isolators

Faraday isolators serve as an optical diode and only light propagating in the forward direction is transmitted. Light propagating in the opposite direction is blocked (>30 dB) while losses due to absorption are rather small (<0.5 dB). A Faraday isolator (Fig. 7) consists of a Faraday isolator placed between two polarizers that are orientated at an angle of 45° with respect to each other. The Faraday Effect is utilized when the beam is directed through the crystal under the influence of a strong magnetic field, which causes the polarization of light to rotate by 45°. While light in the direction of radiation is rotated in such a way that it is transmitted by the second polarizer, light in the opposite direction is rotated in the opposite direction and cannot be transmitted by the first polarizer. This light is blocked, preventing back-reflections into the laser source and increasing its frequency stability, lowering noise and increasing its lifetime.

Fiber-optic beam splitters

A fiber-optic beam splitter splits the radiation from a singlemode fiber into two singlemode fibers, while maintaining its monomode character. Fiber-optic beam splitters are characterized by their compact architecture and small insertion losses in the range of 1 dB. Radiation emitted by a single source can thus be transferred in a self-contained setup and used in different locations without compromising laser safety. Beam splitters of this type are used for particle detection and fiber-optic Fabry-Perot interferometry.

Optical modulators

Some applications call for modulated pulses instead of continuous radiation. A modulation can be provided by an AOM (acousto-optical modulator) or an EOM (electro-optical modulator). High switching frequencies are reached in both cases while maintaining the polarization of the input radiation.

Fiber-coupled optical modulators enhance laser safety by confining the beam to optical fibers and increase the stability and reproducibility in comparison with free beam setups.

The laser radiation exiting a polarization-maintaining singlemode fiber is collimated by a fiber collimator and passed through the optical modulator. With an AOM, the laser light is diffracted by an acoustic wave and its intensity is regulated by the acoustic power. With an EOM, birefringence is induced by an electrical field (Pockels effect) and, just as for retardation optics, the polarization of the incoming light is rotated. In combination with two polarizers, the intensity of the laser light is modulated by defined variations in the electrical field.

Conclusion

The coupling of laser sources into polarization-maintaining singlemode fibers is the basis for an efficient utilization of lasers in scientific and industrial applications. A high technical standard is required for the optical and mechanical components, in order to achieve high coupling efficiencies. Various fiber coupling components for 400–1100 nm allow the design of modular and compact setups.

THE COMPANY

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Schäfter+Kirchhoff has accumulated a lot of experience in the development of opto-mechanical and opto-electronic 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 for customers worldwide.

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