Perfectly coupled

Making single mode fiber coupling smooth and permanent

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Long-term stable fiber-coupling requires sub-micron precision and pointing stability. This is especially true when a polarization-maintaining single mode fiber is to be permanently attached to a free beam laser. Tests of a popular single mode coupler have shown that it is possible to achieve outstanding long-term stability over a wide temperature range while having a sensitive adjustment procedure.

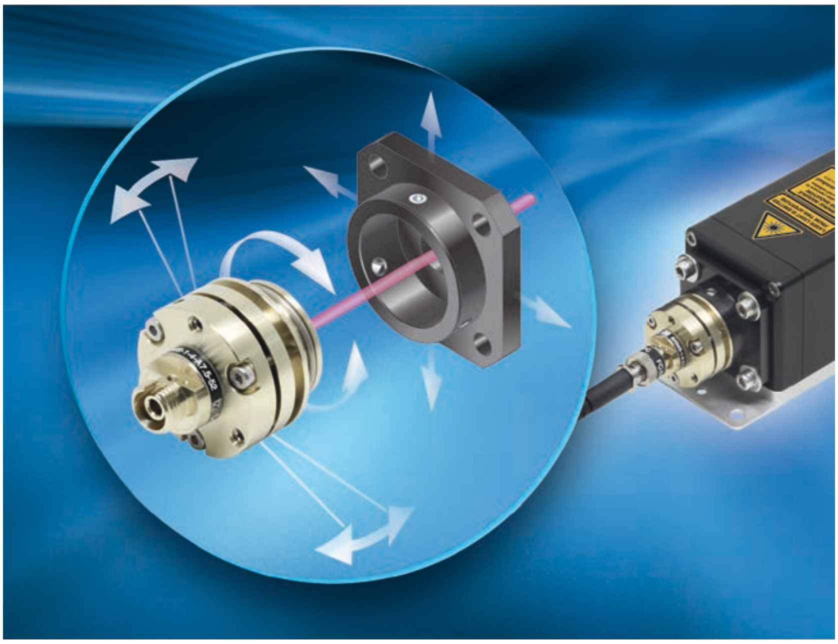

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Fig. 1 An adjustable laser beam coupler of type 60SMS which is to be permanently attached to a laser. The arrows visualize the required alignment properties (focussing or axial alignment is not shown). Lateral alignment on the beam is done with an adapter like the shown model 60A19.5-F.

Single mode fibers are specialized fibers that transmit light in the transverse fundamental mode LP01 only. The field distribution (mode field) of the light exiting the fiber is close to Gaussian. The coupling of an incoming Gaussian laser beam to the fiber is optimal when the beam's field distribution at the fiber entrance is the best possible match to the fiber's mode field. It is the task of an opto-mechanical device called laser beam coupler, or fiber coupler, to perform this matching (**Fig. 1**).

If the coupler is to be attached permanently to a laser, long-term stability during varying environmental influences is especially important.

Single mode fibers are primarily characterized by their numerical aperture (*NA*), their mode field diameter *MFD* and their cut-off wavelength λ_0. The *NA* describes the angular extend of a beam emerging from the fiber. For a multi mode fiber with large core diameter, the *NA* is calculated from the refractive indices of core and cladding, which determine the critical angle of total reflection. For single mode fibers, where the core diameter extends only a few wavelengths, matters are more complicated, and it has become common practice to use the measured divergence at the $1/e^2$ level as fiber *NA* for coupling calculations, rather than the nominal *NA* specified by fiber manufacturers. The *MFD* is the diameter of the Gaussian intensity profile, also measured at the $1/e^2$ level. It is wavelength-dependent and inversely proportional to the fiber *NA*. The relation between these three values is simply $MFD = 2\,\lambda/(\pi\,NA)$.

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 *MFD* in the UV is small, e.g., 2.6 µm for 405 nm and a fiber with *NA* 0.1.

Finally, it is only at wavelengths above the cut-off λ_0 that the coupled light is guided in a single, nearly Gaussian mode. Below the cut-off, there are multiple modes, where the beam and intensity profiles are no longer stable nor near to Gaussian.

Polarization maintaining single mode fibers

Standard single mode fibers do not maintain the polarization state of the guided laser light. Polarization-maintaining single mode fibers (PM fibers) do maintain linear polarization if the beam's polarization direction is aligned to one of the fiber's two principal axes.

PM fibers are rotationally non-symmetric, for example, because of integrated stress elements that break the degeneracy of the two principal states of polarization (SOP). Light is guided either in the so-called „fast" or the „slow" axis, thus, linearly polarized light coupled precisely 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.

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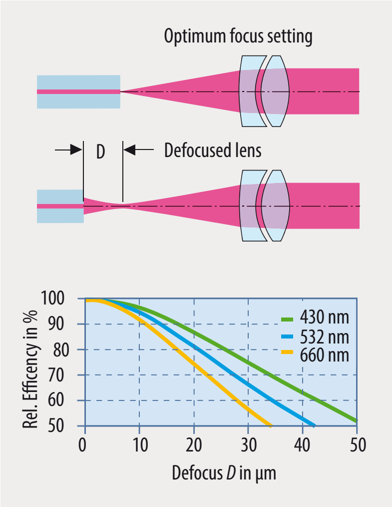

Fig. 2 Axial displacement or defocus: Coupling efficiency with defocused lens, for several wavelengths in the visual range and a fiber *NA* of 0.1.

Stable fiber coupling with maximum coupling efficiency

The laser beam coupler has to produce a diffraction-limited spot matching the mode field of the fiber in order to achieve maximum coupling efficiency. To match the size of the mode field is a selection task. The ideal lens for a laser beam diameter Ø would have the focal length $f = Ø / (2\,NA)$ and it is important to select a diffraction limited lens with focal length as near as possible to this ideal value. Therefore, a coupler needs a large variety of selectable lenses.

For the axial position of the mode field, the coupler needs to be focusable, i.e., the distance between optics and fiber entrance can be adjusted to compensate for variations in focal length (**Fig. 2**). To match the lateral position of the mode field, an angular adjustment is required (**Fig. 3**). The coupler in **Fig. 1** has a tripod tilt adjustment for this task. The fiber entrance and the optics are tilted until their optical axis is aligned to the beam.

To match the angular orientation of the mode field, the axis of the optics has to be centered on the beam (**Fig. 4**). And finally, for use with polarization maintaining fibers, the coupler has to be rotatable (**Fig. 5**).

Only if all these conditions are met, fiber couplings with high coupling efficiencies of near to 90 % are achieved. **Fig. 2** shows the influence of a change in axial position on the coupling efficiency for a fiber *NA* of 0.1 and a few wavelengths in the visual range. In these examples an axial displacement, or defocus, of 10 µm results in losses of 5 to 10 %.

In **Fig. 3**, a 405 nm beam is coupled with a 5 mm focal length optics to a fiber with *NA* 0.1. A beam inclined by 1 mrad results in a lateral offset of 5 µm which is larger than 4 µm, the approximate *MFD* of this fiber at 405 nm. Even a 0.1 mrad (0.04 degrees) misalignment, resulting in a 0.5 µm displacement (about one wavelength), reduces the efficiency by about 7 %. It can generally be shown that, at the fiber entrance, a displacement of about one wavelength leads to a loss of 5 to 10 % for most fibers. Compared to the small tolerances shown in **Fig. 3**, we find rather large values in **Fig. 4**. Depending on the focal length, beam decentrations of 0.1 to 0.4 mm are necessary for similar effects as in **Fig. 2**. Roughly estimated, this is about three orders of magnitude.

In case of a polarization maintaining fiber, the rotational accuracy required is about 1 degree (**Fig. 5**). This would reduce a – hypothetically – fiber with polarization extinction rate (PER) of 40 dB (1:10 000) to about 32 dB (1:3200), which is still a very good value.

The criteria and requirements listed so far had all their impact on the design of the 60SMS laser beam (**Fig. 1**). It has an internal focus and a high precision tilt mechanism. In both cases, the required accuracies are high, very high in the case of tilt alignment. The less demanding centering of the beam is mostly done manually with the help of an adapter like the 60A19.5-F also shown in **Fig. 1**. For the rotational polarization alignment, manual adjustment is also sufficient.

With long-term stability in mind, the idea was to keep the mechanical design as simple as possible and to renounce all fancy adjustments whenever they are not absolutely necessary.

Careful selection of materials and components led to a design of proven stability. As a consequence, the 60SMS laser beam coupler is popular in science and industry. It was convincing in demanding environments, like e.g. drop-tower experiments in Bremen or for Zero-G flight experiments.

Constant improvement and verification

But even with a well accepted high quality product, there is always the task of constant improvement. Currently, e.g., the coupler is subject of an ongoing investigation which focuses on the further improvement of the tilt mechanism. Several design alternatives have been identified which now have to resist against the current design in an extended test series. These include shock and vibration tests as well as temperature cycling (**Fig. 6**).

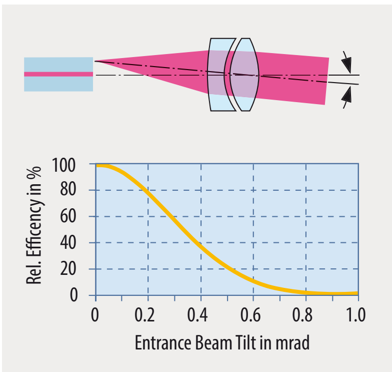

Fig. 3 Lateral adjustment of the mode field and laser spot: Coupling efficiencies for inclined beam propagation. The lateral displacement at the fiber entrance is due to an angular misalignment of the beam. The plot shows an example for wavelength 405 nm, fiber *NA* 0.1, and focal length 5 mm.

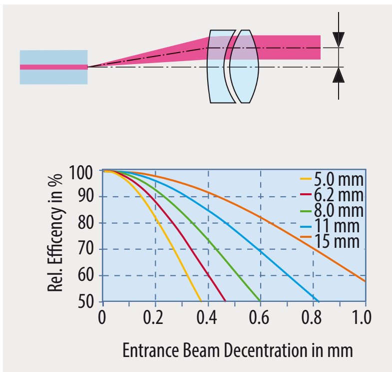

Fig. 4 Centering of laser beam coupler with the propagation axis: Coupling efficiencies with f′ 5 – 15 m lenses for uncentered parallel beams. Examples for wavelength 405 nm and fiber *NA* 0.1.

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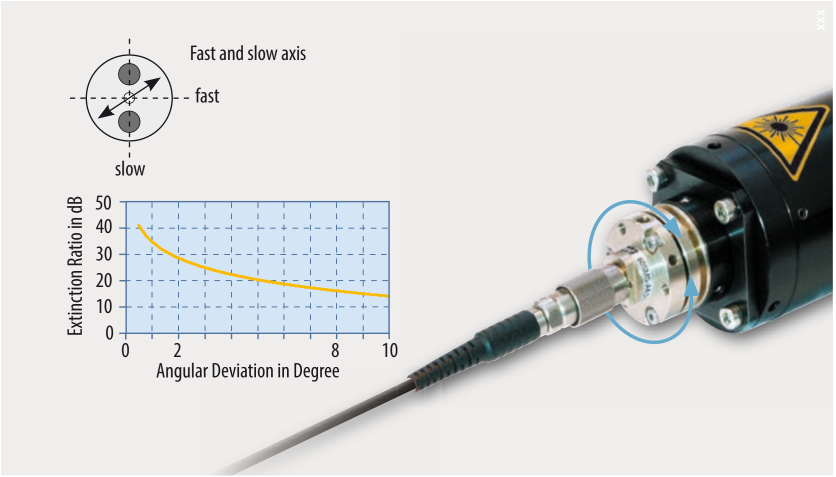

Fig. 5 Alignment of the polarization axis: Polarization extinction ratio when the polarization axis of the source is misaligned to the polarization axis of the fiber.

Temperature cycling tests answer the questions how the coupling efficiency varies with temperature and wether there is any drift like an efficiency change if the test is repeated several times. To exclude possible pointing errors of the laser source, two laser beam couplers of the same design are used against each other for these tests.

The light emitted by a temperature-stabilized laser beam source with integrated Faraday isolator is guided to the test setup using a polarization-maintaining fiber, collimated by the first laser beam coupler, and then coupled back into a polarization-maintaining fiber using a second laser beam coupler. The recoupled power is monitored using a photo detector. The coupling setup is placed on a thermo-controlled plate to vary the temperature between 15 °C and 35 °C in successive cycles. 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 thermo-controlled plate at a constant temperature.

Typical results with the current design are shown in **Fig. 6b** and **c**. Obviously, there is a small variation of output power with temperature. The repetitive pattern in the relative power caused by the temperature cycling is demonstrated most clearly, if the relative power is plotted against the temperature of the laser beam couplers (**Fig. 6c**). In this case, the maximum coupling efficiency is reached a little above 25 °C. It decreases faster towards lower 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 %, demonstrating 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 %.

It is an ambitious task to improve the outstanding temperature-cycling results of the current design. But there are other aspects besides stability, like the smoothness of the coupling, the maximum achievable coupling efficiency and the steepness of the learning curve, when a new person starts on the sometimes cumbersome path of fiber coupling. Any improvements here would be welcome, but stability is mandatory.

Polarization stability

Stable long-term 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. 7**) 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 reveal the state of

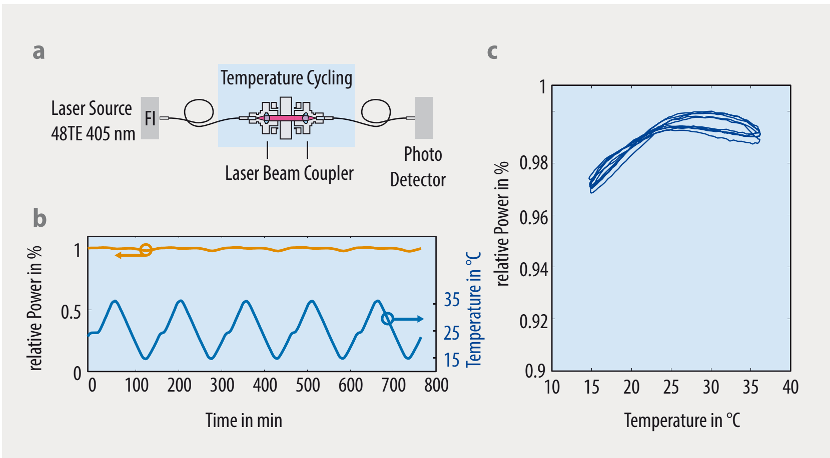

Fig. 6 Test setup for measuring the stability of two laser beam couplers (f = 4.5 mm, φ = 405 nm) during successive temperature cycling between 15 °C and 35 °C (a). The relative power (normalized with respect to the mean power) (b) shows a repetitive pattern following the temperature (below) and has a maximum deviation of ± 1.5 %. The relative power curves (c) (normalized with respect to the maximum power) are almost coincident and confirm the high reproducibility of the pointing stability during temperature cycling. The maximum deviation is only 3 %.

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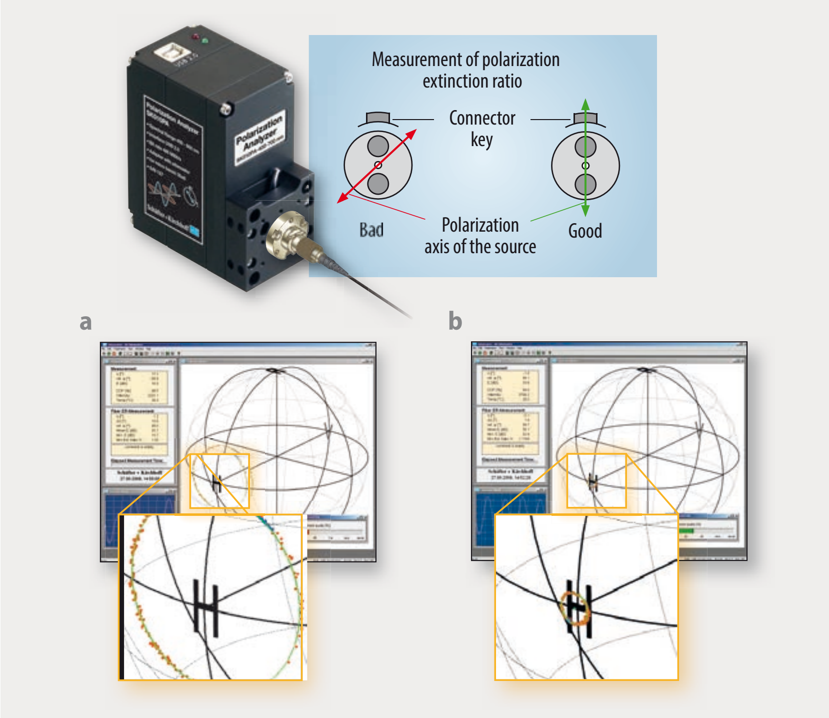

Fig. 7 SK010PA polarization analyzer for the adjustment of polarization-maintaining fibers as well as free beam applications. Adjustment of a PM fiber: The aim is to minimize the data circle radius. With a poor fiber alignment, the state of polarization varies significantly e.g. when bending the fiber (a). With a better angular alignment of the fiber, the change in polarization and the radius of the data circle become smaller (b).

polarization, which is then depicted as a dot on a 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.

When a PM fiber is gently bended or when the temperature changes, the exit polarization changes, and all observed polarization states lie on a common circle on the surface of the Poincaré sphere. This circle represents all possible states of polarization for the current polarization 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 circle point located farthest from the equator reveal the worst possible polarization extinction ratio for the current polarization alignment.

When adjusting the coupling of the fiber, the radius of the circle on the Poincaré sphere indicates the quality of the alignment, showing 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 circle on the Poincaré sphere converges to a single point on the equator.

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 measurement points. A circle is automatically fitted to the data points and the mean and minimal PER are displayed (**Fig. 7a**). 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. 7b**).

If the major importance is the stability of the state of polarization 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 with the smallest 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.

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