Fiber Coupling to Polarization-Maintaining Fibers and Collimation

How measured fiber parameters help to choose the best coupling and collimation optics.

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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. But first decisions have to be made about which components to use. Detailed measurements of fiber parameters like e.g. an effective numerical aperture allow a better understanding which other fiber optic components are suitable for the application at hand. Indepth knowledge about the different parameters is key for this procedure. The online product configurators on the new Schäfter+Kirchhoff website provide this information quickly and easily and help narrow down the search to the most relevant choices.

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.

Single-mode and PM fibers

Single-mode 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 single-mode 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.

Polarization-maintaining single-mode 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. Single-mode and PM fibers are characterized by their numerical aperture NA, their mode field diameter (MFD) and their cut-off wavelength λ_0. 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 for a typical single-mode or a polarization-maintaining fiber, the nominal value is NA = 0.12.

Nominal vs. effective NA

The fibers obtained by most manufacturers usually come with a so-called nominal numerical aperture (nominal fiber NA) that is defined by the refractive indices of fiber core and cladding. For a typical single-mode or a polarization-maintaining fiber, the nominal value is NA = 0.12. This NA specification corresponds to the Gaussian angle distribution at a 1 – 5 % level, but in most cases, this is either not a measured value, the nominal NA is given with a large bandwidth or the level on which the NA was measured is not given or inaccurate.

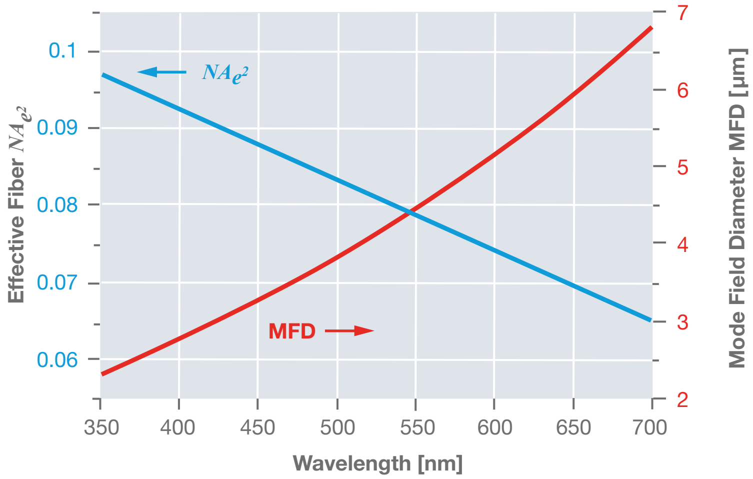
Often, the NA is measured in the preform but not for the finally drawn fiber. Some manufacturers measure the MFD, which allows recalculation of the NA, but only for one single wavelength. This measurement is usually given with a large error margin.

Since the fiber NA is crucial for choosing corresponding fiber optic components, these rough values should be substituted for actual measured values. This is done with an effective fiber numerical aperture defined on the $1/e^2$ level. For fiber-coupling purposes, this effective fiber NA_{e^2} is more convenient than the nominal fiber NA defined by the refractive indices since Gaussian beams are also generally defined by their $1/e^2$ diameter.

Schäfter+Kirchhoff defines an effective fiber NA_{e^2} which corresponds to the divergence of the power distribution emitted by the fiber taken at the $1/e^2$-level of the Gaussian angle distribution and measures this value for each fiber batch and for a number of wavelengths. This value is the designated effective numerical aperture NA_{e^2}.

For a PM fiber with cut-off 405 nm for example, the manufacturer gives a nominal NA of 0.12 defined somewhere between 1 – 5 % level. This corresponds to an effective NA_{e^2} of 0.079 to 0.098 with an uncertainty of almost 20 %. However, an actual measurement reveals that the measured value for the effective NA_{e^2} for 405 nm actually is 0.070 ± 0.005 providing a much more precise information.

These detailed measurements show that for short wavelength fibers, the numerical aperture varies with wavelength and is not constant as it is assumed in the standard model and for telecommunication fibers. For single-mode fibers and for polarization-maintaining fibers, the effective NA_{e^2} typically decreases with increasing wavelength λ.
This makes it essential to measure the NA for a number of wavelengths. If the NA or the MFD is measured or given for a single wavelength, the significant change with wavelength is completely missed.



Values:
NA_{e^2} (405nm) = 0.092 ± 0.005 NA_{e^2} (514nm) = 0.082 ± 0.005
NA_{e^2} (450nm) = 0.088 ± 0.005 NA_{e^2} (450nm) = 0.071 ± 0.005

Fig. 1:
Effective numerical aperture NA_{e^2} and the corresponding MFD for an RGB fiber that can be used between 400 nm and 640 nm. The NA_{e^2} decreases significantly with increasing wavelength.

Wavelength dependence of the effective NA_{e^2}

In order to illustrate how much the effective NA_{e^2} changes with wavelength, its values are measured for a broadband RGB fiber that is designated for use between 400 nm and 640 nm. Fig. 1 shows the NA_{e^2} profile between 400 and 640 nm. The effective NA_{e^2} decreases with increasing wavelength and has significantly different values for 405 nm (NA_{e^2} = 0.092) and 635 nm (NA_{e^2} = 0.071). The almost linear relationship between NA_{e^2} and the wavelength can be seen by extrapolating the measured values. Besides the effective NA_{e^2}, the MFD is also shown. The MFD is calculated (and not measured directly) from the obtained values of NA_{e^2} for each wavelength λ using

$$MFD = \frac{2 \cdot \lambda}{\pi \cdot NA_{e^2}}$$

It is also important to note that the values for the effective numerical aperture change from fiber batch to fiber batch making it necessary to constantly remeasure for each new role.

The NA_{e^2} curves and other useful information can be obtained for each Schäfter+Kirchhoff fiber cable using the new fiber cable product configurator. By choosing the operating wavelength, the fiber type (single-mode or PM), fiber cable properties (e.g. vacuum-compatible, 900 µm buffer or 3 mm cable) and fiber connectors (with end cap, amagnetic connectors, FC or other connectors) the product configurator finds the adequate fibers and gives a short overview about the most important features. Fiber cables can be compared using the comparison function.

Once the adequate fiber is found, key information can then be downloaded and used as basis for deciding other fiber optic components e.g. the correct fiber coupler to couple into this fiber or the correct fiber collimator to collimate the light exiting this fiber cable.

Fiber coupling

When coupling into single-mode 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 maximum coupling efficiency. It is only when this condition is met that fiber coupling with high coupling efficiencies of up to 85 % are achieved.

The adequate focal length can be chosen using

$$f' = 0.5 \cdot \varnothing_{beam} / NA_{e^2}$$

Where f' is the optimum focal length, $\varnothing_{beam}$ is the beam diameter on the $1/e^2$-level, and NA_{e^2} the effective numerical aperture at the coupling wavelength λ.

For a nominal fiber NA, the adequate focal length is determined by

$$f' = F_{NA} \cdot Ø_{beam} / NA$$

The nominal fiber NA corresponds to the Gaussian angle distribution at a 1 – 5 % level requiring the factor F_{NA} to correct for the different definitions of the NA. F_{NA} is 0.76 for 1 %, 0.66 for 3 %, and 0.61 for 5 %.

A focal length that was chosen too large is inefficient, since the focused laser spot is larger than the mode field diameter. When using a focal length too small, the convergence angle of the focused laser spot is larger than the maximally acceptable divergence angle 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.

It becomes clear that an accurate value for the effective fiber NA_{e^2} has a high impact on the value for the optimum focal length.

For example, for a beam diameter $Ø_{beam}$ of 0.72 ($1/e^2$-level), wavelength 405 nm and a standard fiber with nominal NA of 0.12 (given on the 1 – 5 % level), the optimum focal length f' is calculated to be f' = 3.7 – 4.6 mm. Using the actual measured value for the effective numerical NA_{e^2} for this fiber (NA_{e^2} = 0.07), the optimum calculated focal length is f' = 5.1 mm. The coupling efficiency can be calculated as the overlap between the MFD and the Gaussian spot. An overlap of 1 means, that apart from losses due to Fresnel reflection at both fiber ends of about 4 % each, imaging aberrations, and stray loss and beam distortion (8 %), as well as transmission loss (1 %), an ideal Gaussian beam is coupled almost completely (max. coupling efficiency ≈80 %). The overlap between the MFD of the fiber is 0.99 using an optics of focal length f' = 5.1 mm whereas the overlap is only 0.94 for an optics with focal length f' = 4 mm, the next best choice. Please note that optics are not available for each focal length and that 4 mm would the best choice for the calculated range. The choice based on the inaccurate nominal values for fiber NA such leads to a possible decrease in coupling efficiency of 6 %. Of course, these are theoretical considerations. In reality, optics quality also plays an important role.

For applications with multiple wavelengths achromatic or apochromatic optics should be chosen that allow for a large coupling efficiency for two or more wavelengths, whereas for single wavelengths aspheres are appropriate as well. Please note that for coupling into PM fibers, the polarization direction of the laser source must be aligned with the polarization axis of the fiber as well. This procedure is described in detail in [1].

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. 2. The light emitted by a temperature-stabilized laser diode beam source with integrated Faraday isolator is guided to the test setup using a polarization-maintaining fiber, collimated by a 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 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

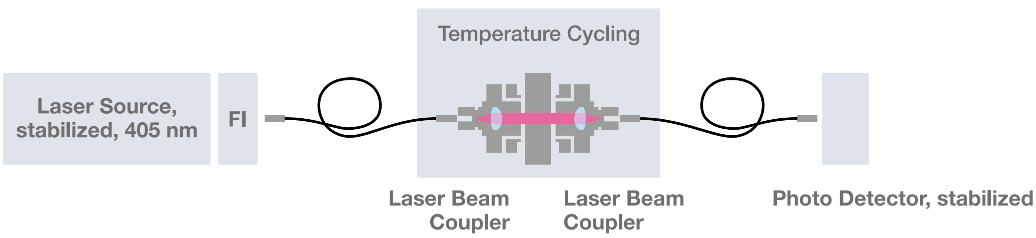


Fig. 2:

Test setup for measuring the stability of two laser beam couplers (f = 4.5 mm, λ = 405 nm) during successive temperature cycling between 15 °C and 35 °C.

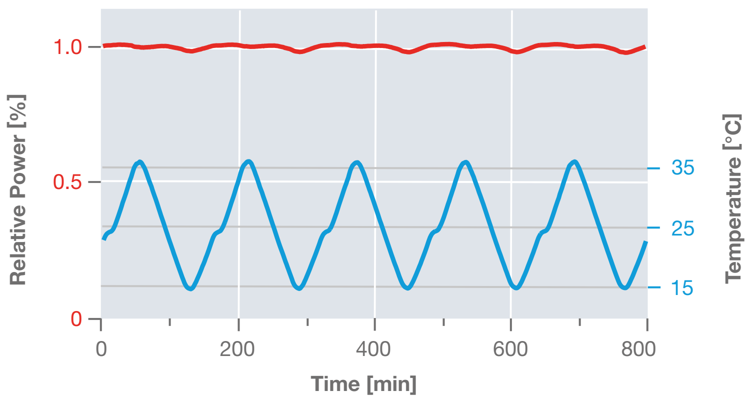


Fig. 3:

The relative power (normalized with respect to the mean power) shows a repetitive pattern following the temperature (below) and has a maximum deviation of ±1.5 %.

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 of 25 °C.

Fig. 3 shows the typical results of the relative transmitted power over 5 meawsurement 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. 4, 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 %.

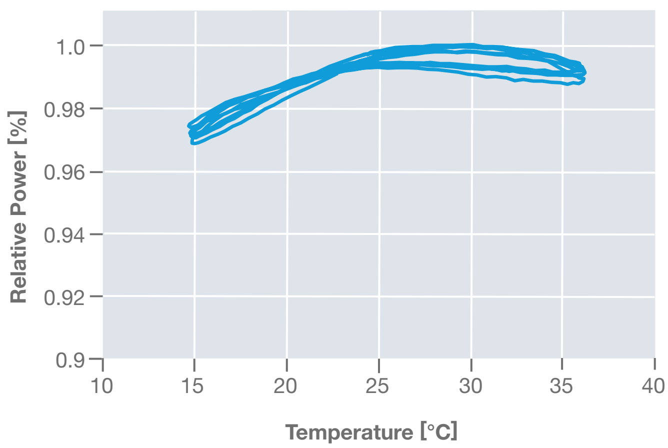


Fig. 4:

The relative power curves (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 %.

Choosing the right collimating optics

Fiber collimators are designed for collimating radiation exiting optical fiber cables. They can also be used in reverse-mode as fiber incouplers. They are suitable for single-mode and polarization-maintaining fiber cables leading to collimated beams with a Gaussian intensity profile. Just as finding the right coupling focal length in many applications the optimum focal length of the fiber collimator has to be chosen in order to get a certain collimated beam diameter. The designated collimated beam diameter $Ø_{beam}$ (defined on the $1/e^2$-level) is calculated using

$$Ø_{beam} = 2 \cdot f\,' \cdot NA_{e^2}$$

with $f\,'$ being the focal length of the fiber collimator and NA_{e^2} being the effective fiber numerical aperture.

The new online product configurators for fiber couplers and collimators allow to insert fiber information and features like wavelength, NA, or purpose (coupling or collimation) and then adequate fiber collimators and couplers are shown. Using the fiber properties, the corresponding beam diameters and the Rayleigh range are calculated.

If a certain beam diameter is needed, sliders are used to adjust the limits and the large selection of possible collimators is narrowed down to the best choices. This makes selecting quick and easy. The comparison function is used to compare key features. For each fiber collimator / coupler, further information and a data sheet can be downloaded.

Just as for the focal length of the coupling optics accurate values of the numerical aperture of the fiber here also have a large impact on determining the right collimating optics in order to get a certain beam diameter.

For example, in order to get a beam diameter ($1/e^2$-level) of 1 mm the focal lengths are calculated to be f ’ = 5.1 – 6.3 mm for a nominal NA of 0.12 (1 – 5 % level), where as using the actual measured values of NA_{e^2} for 405 nm leads to a focal length f ’ of 7.1 mm.Just to illustrate: the wrong choice of focal length f ’ = 5.1 mm in reality leads to a beam diameter of only 0.71 mm.

Apart from the right focal length, the right choice of optics type also plays a role. Monochromic optics that are corrected for spherical aberration are a great choice or single wavelength application. Unlike for in-coupling, very few selected aspheres can also be used that provide a good quality collimated beam profile. Achromats are a great choice for multiple wavelength applications.

Conclusion

Fiber optics can significantly increase the stability and convenience of measurement setups and allow large bread-board 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. Accurate measurements of the effective fiber numerical NA_{e^2} provide the basis for choosing the most appropriate coupling and collimating optics. Suitable fiber cables can be selected using the online fiber cable product configurator on the new Schäfter+Kirchhoff website that also provides the NA_{e^2} curves for downloading. These values can then be used as basis to put into the fiber coupler and collimator online product configurator that narrows down the search quickly and easily in order to find the most adequate coupler or collimator.

References

[1] Schäfter+Kirchhoff GbmH: Polarization Analyzer for Fiber Optics and Free Beam Applications, https://www.sukhamburg.com/support/technotes/fiberoptics/SK010PA/art_polarizationanalyzer.html