Fibers with End Caps

While maintaining polarization, the application is extended to higher powers and photocontamination effects are avoided.

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Fiber optic components have become more and more common for use in laboratories and in industrial applications. Singlemode fibers and polarization-maintaining fibers can be used in the ultraviolet (UV), visible and in the infrared (IR). A problem when using this technology: Once, the power levels reach a critical point the fibers can be destroyed. This effect is especially critical when using fibers in the UV.

Fiber end caps are used to extend the range of applications into higher laser powers with singlemode and polarization-maintaining fibers. By applying different measures of quality control, it is shown that the original performance of the fibers is not diminished when end caps are applied.

Singlemode fibers are special fibers that are characterized by transmitting 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 principle states of polarization with equal propagation constants. Imperfections in the fiber do, however, lead to random power transfer between the two principle states of polarization (SOP) because of the equal propagation constants in the principle SOPs and the resulting phase-match [1].

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 neither stable nor Gaussian. The MFD is directly proportional to the wavelength and inversely proportional to the fiber NA. While fibers used for telecommunication purposes 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., 3 µm for 405 nm and a fiber with nominal NA 0.12.

Polarization-maintaining fibers are rotationally non-symmetric through the integrating of, e.g., stress elements that break the degeneracy of the two principle 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

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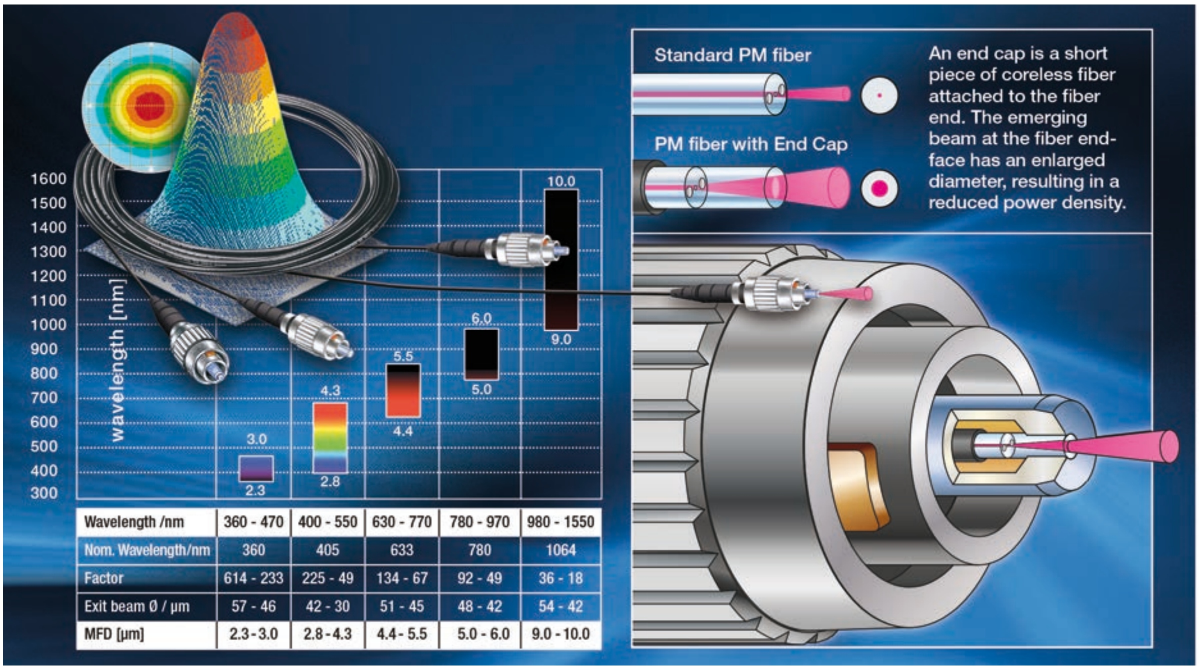

Wavelength /nm	360 - 470	400 - 550	630 - 770	780 - 970	980 - 1550
Nom. Wavelength/nm	360	405	633	780	1064
Factor	614 - 233	225 - 49	134 - 67	92 - 49	36 - 18
Exit beam Ø / µm	57 - 46	42 - 30	51 - 45	48 - 42	54 - 42
MFD [µm]	2.3 - 3.0	2.8 - 4.3	4.4 - 5.5	5.0 - 6.0	9.0 - 10.0

Fig. 1 End caps reduce the power density at the fiber end-face by a wavelength and numerical aperture dependent factor ranging from about 20 to 600. At the fiber end-face, the beam area of a fiber without end cap is small due to the rather small mode field diameters. Once, the beam starts to diverge within the fiber, which is the case when using end caps, the beam area at the end-face is much larger.

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light is guided partly in the other axis then the coherence of the light source determines the outcome polarization. If the coherence length of the light source is larger than the optical path difference between the light in the two principle SOPs, the resultant polarization is elliptical. Strain and temperature variations, however, can change this arbitrary elliptical state. If the coherence length of the laser is smaller than the optical path difference, there is no defined phase relationship between the exiting radiation guided in the two principle SOPs. As a result, the light is partly depolarized. For these reasons, it is extremely important to align the polarization axis of the polarization-maintaining fibers precisely with the linear polarization axis of the source.

The polarization extinction ratio (PER), i.e., the ratio between the powers guided in the two polarization axes, serves as a decisive measure for the fiber alignment and also as a measure of the polarization-maintenance of the fiber.

How do end caps work?

The maximum power that can be guided within a fiber is mainly restricted by the power density at the fiber end-faces, if bulk, nonlinear optical effects within the fiber, such as Brillouin scattering, are not considered. Extreme power densities can cause scorching of the end-face or photo-contamination by the generation of a dipole trap. These detrimental effects can be obviated using a end cap fiber in which a short length of fiber (< 500 µm) without a core is spliced onto the polarization-maintaining fiber (**Fig. 1**). Without a fiber core to confine the beam, the mode field diameter of the beam starts to diverge already within the end cap fiber, and the resulting beam area at the fiber end-face is significantly larger.

The fibers are connectorized with standard FC-PC or FC-APC connectors. Fibers with end caps thus profit from all benefits known for these standard connectors including the possibility of cleaning the end-face using standard tools. In addition, the fibers can be used with laser beam couplers 60SMS and fiber collimators 60FC, respectively. They both have an easily and precisely adjustable focus position. This is of great importance when swapping a fiber without end cap for an end-cap fiber. In this case, the focus position of the lens within the collimator or coupler has to be adjusted typically < 300 µm to correct for the divergence within the end cap.

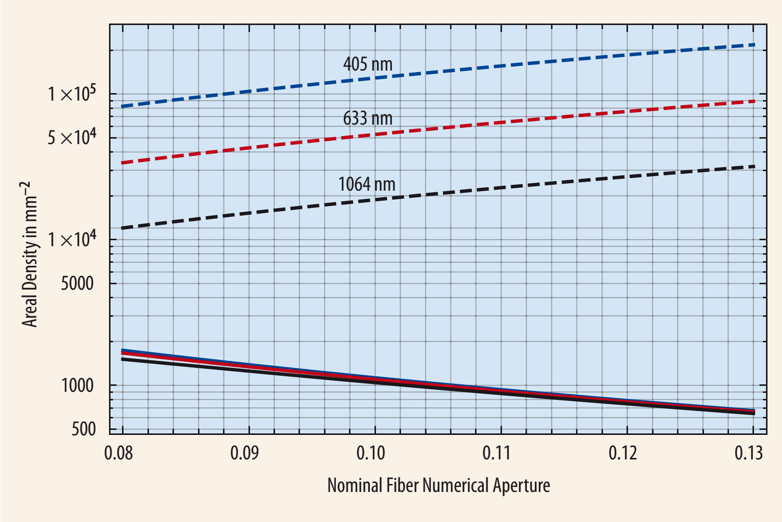

Fig. 2 Areal density at the fiber end-face with (solid lines) and without end-cap (dashed). The areal density is calculated using basic Gaussian beam propagation in a medium. It is much larger without end cap due to the small mode field diameters. By multiplying the power coupled into the fiber, the power density at the end-face can be calculated directly from the values of the plot.

Figure 2 illustrates the effect of end caps for different wavelengths and shows the areal density at the fiber end-face with and without an end cap as a function of the fiber NA. Please note that the NA cannot be chosen freely in reality but it is rather a characteristics of the fiber in use. By multiplying the power of the light coupled into the fiber, the power density can be calculated directly from the values in the plot.

Without an end cap, the area of the beam at the fiber end-face is solely determined by the mode field diameter which is highly wavelength dependent. For example: The MFD is 2.9 µm for 405 nm and NA 0.11, 5.0 µm for 633 nm and 0.10, and 8.5 µm for 1064 nm and 0.10. All values are for a nominal numerical aperture.

As shown in **Fig. 2**, this relation results in large areal densities in the range of 10^4 to 10^5 where the areal density is largest for large NA and small wavelengths. This large factor must be considered comparing the acquired power densities at the fiber end-face. Due to the larger MFD for larger wavelengths, the areal density becomes smaller with increasing the wavelength at a fixed value of NA.

For fibers with end caps, the beam area at the fiber end-face is larger because of the divergence within the end cap. The areal densities are calculated using the usual Gaussian beam formulae for propagation in a medium. The divergence within the end cap leads to significantly lower areal densities by more than one magnitude.

Intriguingly, the resulting areal densities are now quite similar for 405 nm to 1064 nm and do not show an extreme wavelength dependency as without an end cap where only the wavelength dependency of the MFD is contributing. In this case, the area at the fiber end-face is only implicitly wavelength dependent because of the wavelength dependent refraction index and higher terms. Of course the dependency on the fiber NA still remains.

For 100 mW laser power coupled into the fibers listed above, the power density at the end-face

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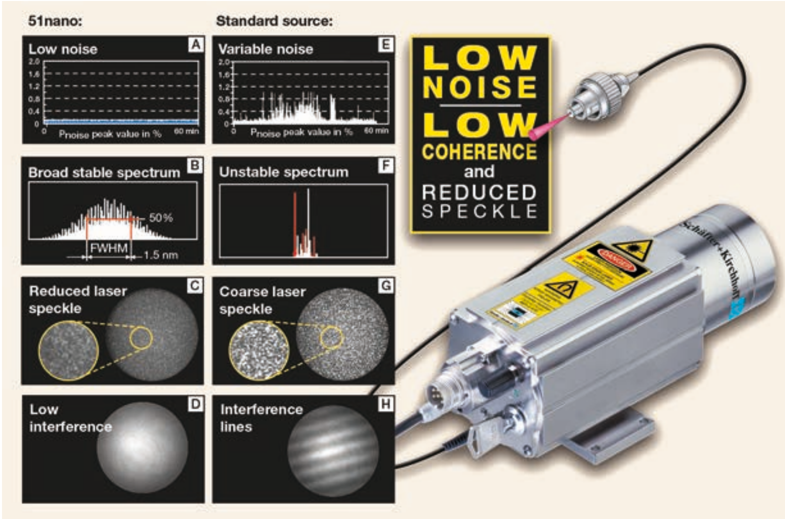

Fig. 3 Laser diode beam source 51nano with reduced coherence length (a – d) compared with a standard laser diode beam source (e – h). Advantages include low noise (<0.1 % RMS, a) because of the broadened spectrum (b) which leads to a reduced laser speckle contrast (c) and less interference effects (d), e.g., at a protective window.

without an end cap reaches, e.g., multiple kW/mm² whereas it is only hundreds of W/mm² with end cap. Therefore, the use of end caps extends the possible range of applications for singlemode fibers.

Beam profile and NA tests

In order to ensure that the end caps applied to the fibers do not compromise fiber performance, each fiber is closely inspected for quality control purposes. This includes but is not limited to measurements of the NA of the fibers, the beam profile exiting the fiber as well as the PER of polarization-maintaining fibers. A typical measurement setup includes a fiber-coupled laser source and a fiber-to-fiber coupler used to connect the light source to the test fibers.

For beam profile measurements, the fiber is plugged into a CCD camera which commonly is equipped with a protective window. When performing the profile measurements using a standard laser diode beam source (or any source with significantly long coherence length), the measurement is disturbed by unwanted interferences caused by this protective window and the accuracy of the measurement decreases. Often, the window cannot be removed easily, thus, a specialized laser source such as the 51nano helps to increase the accuracy.

The 51nano (**Fig. 3**) is a fiber-coupled low noise laser source in which power noise and mode-hopping are eliminated by modulating the current of the laser diodes at a high frequency. This RF-modulation excites numerous longitudinal modes of emission and lowers the signal noise significantly to < 0.1 % RMS. The broadening of the spectrum is induced in a controlled and stable way and has the advantage of considerably reducing the coherence length of the laser beam which, in turn, reduces laser speckle contrast and suppresses the generation of interference patterns.

Fig. 4 shows an exemplary beam profile for a PM fiber at 488 nm with an end cap. The beam profile and the *x*/*y* cross section shows very good agreement with a Gaussian fit and are symmetrical – just as if no end cap was present.

The NA of the fiber with and without end cap is also measured. To account for the slight wavelength dependency of the NA, each fiber is measured for multiple wavelengths, and a test sheet is supplied for every fiber. For fibers with end caps, the acquired NA may not differ significantly from the original value.

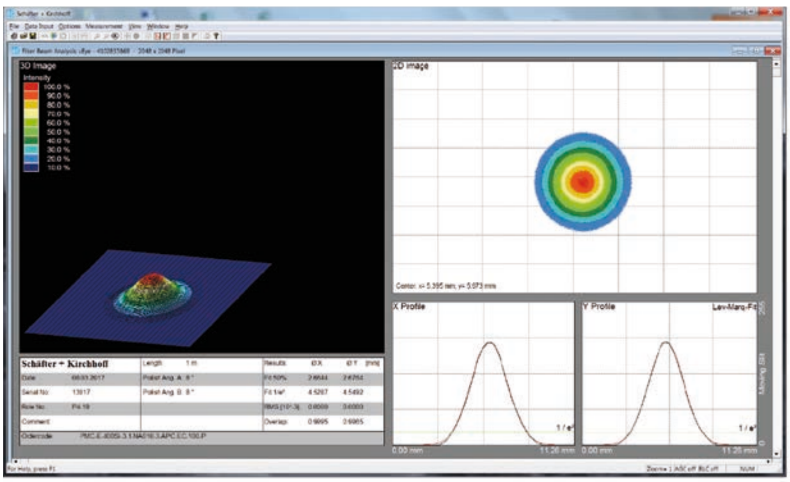

Fig. 4 Exemplary measurement of a beam profile of a fiber with end cap at 488 nm. The *x*/*y* cross section is in very good agreement with a Gaussian fit. The beam profile is symmetrical.

Does the end cap affect the PER?

For measurements of the polarization extinction ratio, PER, a SK010PA polarization analyzer (**Fig. 5a** and described in detail in [2]) is used instead of the CCD camera. To avoid depolarized portions of radiation in the fibers, the Coherence length of the laser is longer than in the case of 51nano.
The PER, the ratio between the powers guided in the two polarization axes, serves as a decisive measure for the fiber alignment when coupling into PM fibers and of the ability of the fiber to maintain the polarization. Typical values for the

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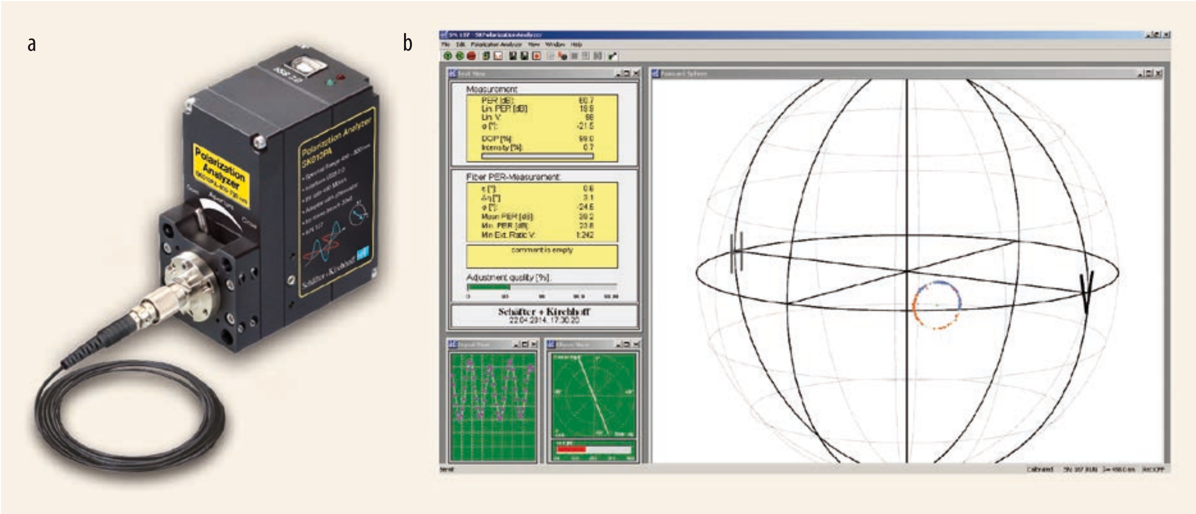

Fig. 5 Polarization Analyzer SK010A (a) and exemplary PER measurement for an end cap fiber at 488 nm (b). A circle is automatically fitted to the measurement points while slowly bending the fiber. The small distance of the circle center from the equator shows a very good mean PER, i. e., the end cap does not induce additional stress birefringence in the output connector.

min PER are 21 dB for 405 nm and 27 dB for 780 nm.

The PER is determined using one of the polarization analyzer routines. The measured state of polarization is depicted on the Poincaré sphere (**Fig. 5b**) where any change in the state of polarization as well as the sense of rotation (depicted on the northern or southern hemisphere) is made visible. A polarization ellipse, a common representation of the state of polarization, is also depicted.

First, the fiber has to be perfectly aligned to the income polarization. Measurements are performed by slowly bending the fiber which leads to a data circle on the Poincaré sphere that results from the induced phase difference between the two principle states of polarization. This circle represents all the states of polarization that are possible for the current alignment.

The radius of the circle on the Poincaré sphere indicates the quality of the alignment, since it shows the angle deviation between the polarization axis of the fiber and the one of the source. The circle radius is large for poorly aligned fibers – the polarization changes strongly with the ambient condition – and is small for precisely aligned fibers. A circle is automatically fitted to the data points and the mean and minimal PER are displayed. Then, at first, the fiber is aligned to minimize that radius, and, afterwards, the measurement is restarted.

The minimum acquired PER – the point farthest from the equator shows the worst PER for the current alignment – is a measure how well the confectioned fiber is able to maintain the polarization both with and without an end cap. The mean PER – the center of the circle – reveals if the end cap in the output connector has induced any stress birefringence and has therefore diminished fiber performance. For an ideal (non-realistic) polarization-maintaining fiber, the mean polarization extinction ratio would be located at the equator.

Figure 5b depicts a typical PER measurement for a PM fiber with end cap at 488 nm. The nearness of the circle center to the equator indicates the very good mean PER and confirms that the end cap is not detrimental and does not induce additional stress birefringence in the output connector. The high performance of the complete fiber is revealed by the minimum PER. It is 21.7 dB with an end cap whereas a typical value without end cap is 22 dB.

Conclusion

End caps extend the range of applications of singlemode and polarization-maintaining fibers to higher powers. In the UV, where mode field diameters are small, end caps significantly reduce the areal density at the fiber end-face and as a consequence reduce power density avoiding scorching of the fiber and photocontamination. The FC connectorized end-cap fiber cables are just as easy to handle as standard PM patch cables. In order to ensure that end caps do not compromise fiber performance, the fiber NA, the beam profile, and the minimum and mean PER are closely inspected.

[1] *M. Born* and *E. Wolf*, Principles of Optics, Pergamon Press, Oxford (1984)
[2] *A. Krischke, M. Schulz, C. Knothe* and *U. Oechsner*, Polarization Analyzer for Fiber Optics and Free Beam Applications, Optik & Photonik **8**(1), 54 (2013)