Modal properties of the DC-200/40-PZ-Yb LMA fiber

Whitepaper

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This paper describes design, modal properties, and typical performance of the DC-200/40-PZ-Yb fiber from NKT Photonics

Introduction

Fiber amplifiers for ultrafast high power fiber lasers require large core designs in order to suppress nonlinear effects and to handle high heat loads at high power operation. At the same time, single-mode operation is critical, to ensure diffraction limited beam quality and optimum pointing stability.

The DC-200/40-PZ-Yb fiber is designed and qualified to amplify signals at around 1µm wavelength up to 100s of Watts output power while maintaining single mode operation and diffraction limited beam quality. The beam quality is robust against non mode-matched launch conditions, e.g. splicing to high NA signal fibers, which facilitates easy fiber handling and makes the fiber output robust against varying environmental conditions.

In the following, the fiber design and modal properties of the DC-200/40-PZ-Yb are illustrated and typical performance is demonstrated.

Fiber Design

Figure 1 shows an optical micrograph of the DC-200/40-PZ-Yb fiber, consisting of a 40µm diameter Yb-doped core, 200µm diameter pump cladding, and large stress applying parts that create a polarizing waveguide structure, i.e. only one spatial mode with one polarization can propagate. The outer cladding diameter is ~450µm, which effectively reduces microbend loss, and has two polished sides such that the fiber coils in a preferential coiling plane along the stress elements. Due to coil control in combination with the low index of the SAPs, bend loss is effectively reduced and the fiber can be coiled down to 25-30cm diameter (signal wavelength dependent) without notable bend loss. The pump absorption is as high as 10-11dB/m (@976nm), and only 1.5m fiber is needed to achieve a very high optical conversion efficiency.

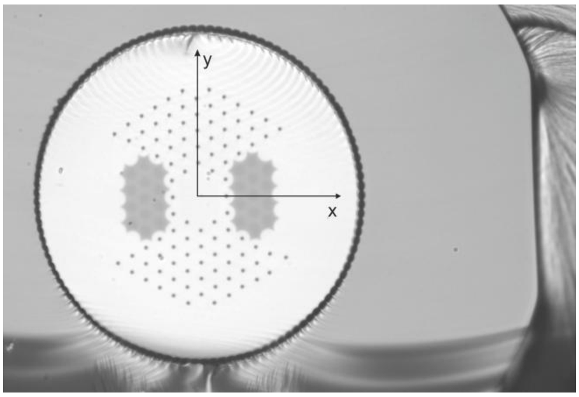

Figure 1: Fiber cross-section showing the microstructure, stress applying parts, air cladding and polished outer cladding sides.

Due to the precise control of cladding airhole diameter, core design and SAP induced birefringence; the DC-200/40-PZ-Yb is a single mode polarizing fiber with very stable diffraction limited beam quality.

Modal properties

Single mode properties are advantageous for fiber amplifiers as they provide diffraction limited beam quality and high beam stability. Furthermore, when the fiber is single mode, there is no need for careful mode matching of the seed input. This enables that a seed fiber with typically much smaller core/mode field diameter can be spliced to the amplifier without any degradation of beam quality and stability.

In order to achieve single mode guidance in large core fiber amplifiers with core diameter >15µm, the core NA has to be reduced. This is difficult in step-index fibers, since the required small index differences between core- and cladding are difficult to manufacture. On the other hand in PCFs, a low NA can be obtained by precise control of the cladding holes.

Due to careful design of the core refractive index as well as the cladding hole size, the DC-200/40-PZ-Yb fiber is single mode for wavelengths around 1064nm. Figure 2 shows near field images of the output from a fiber of ~2.5m length which was loosely coiled (coil diameter >30cm) on a table. The input signal beam is about 7µm in diameter and was moved along the x- and y- direction (as indicated in Figure 1) with the purpose of exciting higher order modes (HOMs). The output near field image shows the fundamental LP_{01} mode for all alignment positions and no HOMs could be excited.

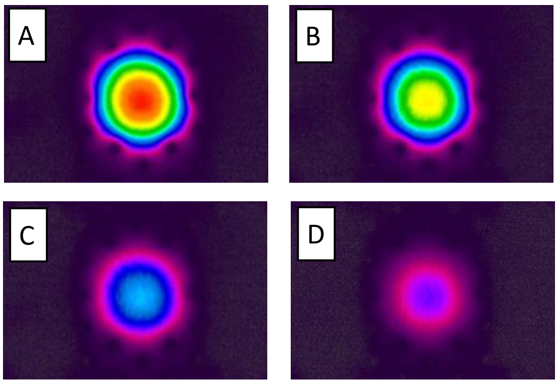

Figure 2: Near-field images of the fiber for optimum alignment (A) and gradually misaligned input beam (B-D). The output beam symmetry is maintained for all positions of the input beam and no higher order modes could be excited. The mode field diameter is 32 um. The images are obtained on a CCD camera.

In PCFs, the single mode cutoff wavelength is defined by a crossing of the effective index of the LP_{11} mode and the fundamental cladding mode (FCM) [1,2]. At this crossing, the LP_{11} couples out of the core and into the cladding, and the remaining guided core light is the fundamental mode LP_{01}. Figure 3 shows the simulated effective mode indices depending on the wavelength for the first 5 highest effective index modes in the DC-200/40-PZ-Yb fiber.

The design exhibits a short wavelength cutoff, i.e. the fiber becomes single mode when going from longer to shorter wavelengths. This mechanism is attributed to the core composition (compared to the background silica material) and airhole size, and it is different from step-index fibers and standard PCFs, where the fiber becomes single mode when going from shorter to longer wavelengths. The cutoff wavelength in the presented fiber is ~1120nm, hence the fiber is single mode at 1064nm.

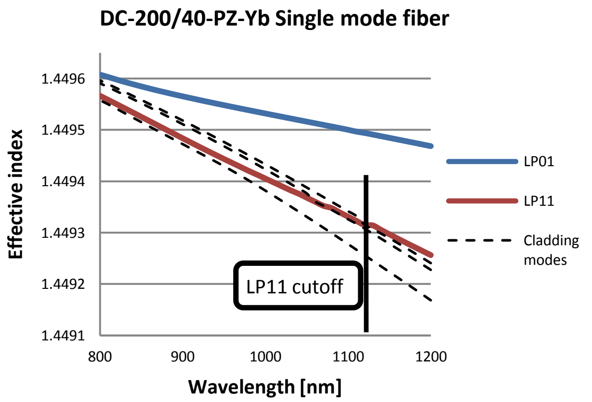

Figure 3: Simulated effective mode indices of the first 5 modes in a DC-200/40-PZ-Yb fiber. The LP11 mode exhibits a short-wavelength cutoff at ~1120nm, and the fiber is single mode for wavelengths below. The figure refers to the transverse (x-) polarized modes. The stress applying parts induce a strong birefringence, which lowers the effective indices of the corresponding y-polarized modes, which therefore are not guided in the wavelength range shown.

Increasing or decreasing the airhole diameter results in a blueshift or redshift of the cutoff wavelength respectively. If desired, this feature can be used to design fibers for operation at other signal wavelengths.

Experimentally, the modal content of the fiber was investigated using spatial and spectral imaging (S^2) [3,4]. Being an interferometric method, S^2 is very sensitive and can characterize multiple HOMs simultaneously from LMA fibers where conventional M^2 or cut-off measurements fail [3,4]. The analysis of HOM content of the fiber with various launching and coiling configuration revealed a HOM suppression of more than 24dB for a coil diameter of 28cm, confirming that it is single mode.

Figure 4 shows the HOM suppression for three different coupling conditions. The values were obtained as an average over 5 measurements for each coupling condition. Using optimum coupling conditions, the LP_{11} mode is relatively weak with an average HOM suppression of -32.7dB. When offsetting the input beam, one lobe of the LP_{11} mode overlaps with the input beam and is excited. Depending on the off-setting direction, different mode symmetries of the LP_{11} mode can be excited. Following the guidelines of the single-mode fiber standard TIA-455-80C, which requires a HOM suppression of >19.3dB for a single-mode fiber, the DC-200/40-PZ-Yb fiber has higher HOM suppression than required and is therefore a single-mode fiber.

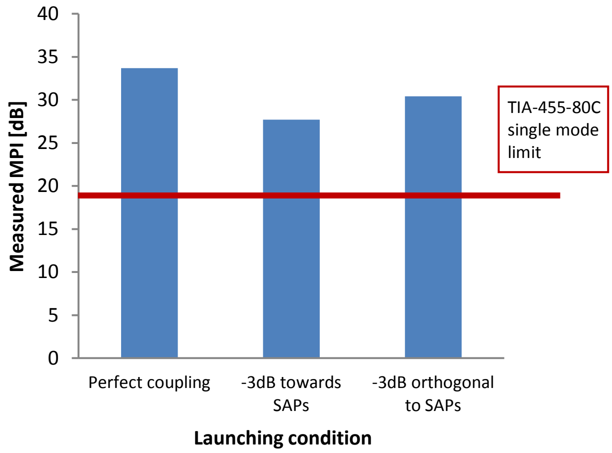

Figure 4: Relative power suppression of the LP11 mode with respect to the fundamental mode (MPI) measured on a 2.2 m piece of the DC-200/40-PZ-Yb fiber.

Due to this single mode operation, the fiber provides excellent beam quality. Figure 5 shows a typical M^2 measurement. Fitting the formula for nearly Gaussian beams to the measured data reveals an M^2 value of <1.15.

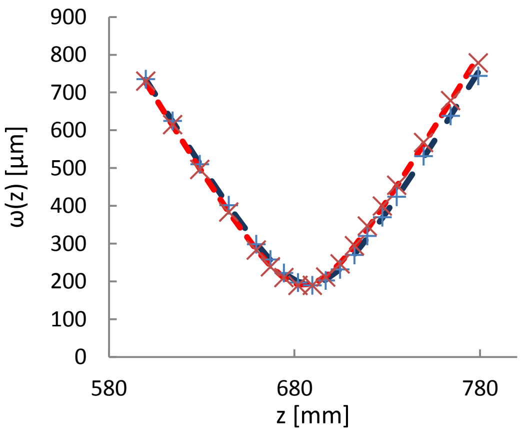

Figure 5: Measured spot size vs. propagation distance for a collimated beam from a DC-200/40-Pz-Yb fiber. The spot size was measured both in x-direction and y-direction. The fits yield an M^2 value better than 1.15.

This result was obtained using a signal input spliced to the DC-200/40-PZ-Yb fiber. The signal fiber was a step-index fiber having a mode field diameter of only 15μm. Despite the large difference in mode field diameter, and the absence of mode-matching, the DC-200/40-PZ-Yb fiber maintains diffraction limited beam quality.

The large stress applying parts as shown in figure 1 create a polarizing waveguide structure and only one transversal mode with one polarization can propagate. The induced birefringence in the core leads to a higher refractive index component in direction of the plane of the stress elements (slow axis / x-direction) than the perpendicular component (fast axis / y-direction). The core NA for the slow axis mode is therefore higher than the NA for the fast axis mode, resulting in a spectral band where only the slow axis mode is guided. This can be seen in a transmission scan for the two polarization directions, shown in figure 6.

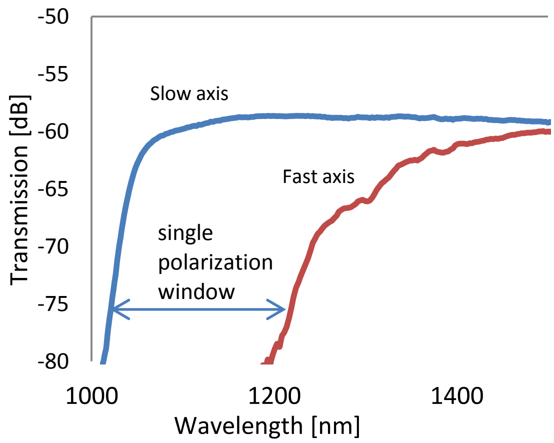

Figure 6: Transmission scan for the two polarization directions. The polarizing fiber structure yields a strong attenuation for the fast axis (y-polarization) for wavelengths <1200nm, while the slow axis (x-polarization) is well guided down to <1000nm.

While the slow-axis is well guided down to wavelengths <1000nm, the fast axis is highly attenuated for wavelengths below 1200nm. This behavior significantly reduces polarization crosstalk and yields a highly stable polarized output beam.

Furthermore, the fiber can be coiled to a minimum diameter of 25-30cm (depending on the signal wavelength) without notable bend loss. Figure 7 shows typical bend loss at 1064nm operating wavelength. The fiber shows bend loss below 1dB/m down to 25cm, which enables amplifier designs with compact form factors.

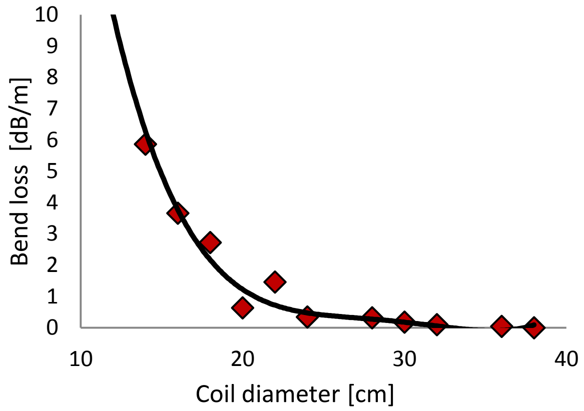

Figure 7: Bend loss as function of coil diameter at 1064nm. The fiber can be bent to coil diameters 25-30cm (signal wavelength dependent) without significant bending losses.

Summary

The DC-200/40-PZ-Yb is a polarizing single mode fiber, which is easy to handle and provides highly stable output beam and high beam quality.

The output beam quality was demonstrated to be independent of the launching condition, which manifests in a maintained beam symmetry under misalignment as well as a measured HOM suppression of >24dB for a 2 m fiber piece coiled to 28cm coil diameter. The M^2 value was determined to be <1.15, illustrating nearly diffraction limited beam quality. The polarizing properties of the fiber ensure high polarization stability and the design allows for bending diameters of 25-30cm.

With a mode field diameter of ~31µm, its single mode properties as well as its easy handling, the fiber is a reliable high performance amplifier platform for ultrafast high power fiber lasers.

References

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