

S²-Method-Based Monitoring of Modal Composition in Optical Fibers during Fiber Component Manufacturing

N. Haverland,¹ F. Wellmann,^{1,2} J. Neumann,^{1,2} D. Kracht^{1,2}

1. Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany

2. Cluster of Excellence QuantumFrontiers, Welfengarten 1, 30167 Hannover, Germany

Fiber-based laser systems provide high output power, excellent beam quality and allow easy handling due to an all fiber-based setup and are therefore of high interest for several industries and applications, including material processing and state-of-the-art research. The reliability and stability of fiber-based laser systems is strongly connected to the use of fiber-based components (e.g. signal-pump combiners, cladding light strippers and fiber end caps). These fiber-based systems are often based on large mode-area fibers (LMA), which inherently support higher order modes (HOMs) and thus do not provide a pure single-mode output beam [1]. Recent research activities have developed several new fiber characterization methods in order to analyze the modal content of a beam emitted from a fiber: One example is the S²-method [1]. The S²-method was first introduced by Nicholson et al. and was later improved upon by Gray et al., who used a tunable laser source and a CMOS-camera, enabling data acquisition in under a second, making it possible for the S²-method to be used in real-time applications [1, 2]. In this work we use an in-house developed high-speed S²-method-based instrument to evaluate the modal content of the emitted beam out of a fiber, which is used for manufacturing of fiber components. This approach has, to the best of our knowledge, not been demonstrated so far. The application of the instrument enables improved manufacturing processes to obtain the best possible performance of the fiber components and thus the fiber laser setup. Specifically, the measurements shown in Figure 1 were carried out during the process of splicing a fused silica endcap to the end of an optical fiber (20 μm core with NA: 0.08, 400 μm cladding diameter) as needed for high-power laser development [3].

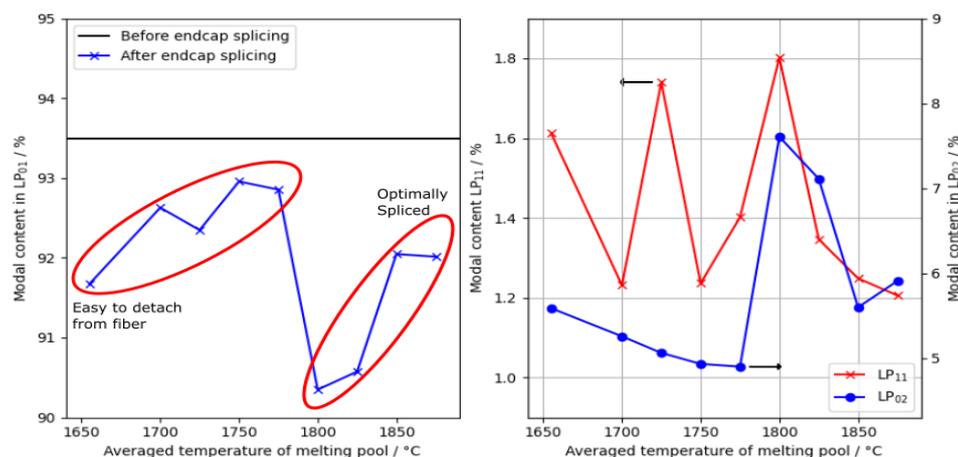


Fig. 1 a) Modal content of LP₀₁-mode compared to modal share before splicing; b) modal content of LP₁₁ and LP₀₂

The instrument operates as follows: By synchronizing a fiber-based Fabry-Perot filter, which is used to scan a wavelength range from 1015 nm to 1040 nm, with a CMOS-camera, we were able to obtain up to 400 images per second, with a repetition rate of 0.33 Hz, leading to 30 S²-method based measurements of the modal composition of the beam during the cooling phase of the endcap-splicing process. We used this method, to optimize the endcap splicing process, by varying the averaged melting pool temperature and observing their influence on the modal content. Figure 1 shows the modal share of the fundamental mode LP₀₁ (Fig. 1a) and the higher modes LP₁₁ and LP₀₂ (Fig. 1b). Even though the fundamental mode content increases with the splicing temperature up to 1775 °C, no sufficient splice between the substrate and the fiber was observed. Above 1800 °C stable splices were achieved, but a decreased splice LP₀₁ mode was observed. This is likely related to an insufficient melt pool temperature that cause fiber deformation. With increased melt pool temperatures the LP₀₁ content increases, indicating improved splicing conditions, which lead to lower deformation of the optical fiber.

References

- [1] J. W. Nicholson, A. D. Yablon, S. Ramachandran, and S. Galmi, "Spatially and spectrally resolved imaging of modal content in large-mode-area fibers," *Optics Express*, Vol. **16**, No. 10 (2008), 7233-7243.
- [2] D. R. Gray, M. N. Petrovich, S. R. Sandoghchi, N. V. Wheeler, N. K. Baddela, G. T. Jasion, T. Bradley, D. J. Richardson, and F. Poletti, "Real-Time Modal Analysis via Wavelength-Swept Spatial and Spectral (S²) Imaging," *IEEE Photonics Technology Letters* **28**, No. 9 (2016), 1034-1037.
- [3] F. Wellmann, M. Steinke, F. Meylahn, N. Bode, B. Wilke, L. Overmeyer, J. Neumann, and D. Kracht, "High power, single-frequency, monolithic fiber amplifier for the next generation of gravitational wave detectors," *Optics Express* **27**, No. 20 (2019), 28523-28533.