

# Low-energy distortion-free femtosecond pulse laser inscription in coated, free-standing optical fiber

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**Abstract.** Low-energy, distortion-free femtosecond pulse laser inscription in coated free-standing fiber is demonstrated for the first time. Methodology features radial plane beam-shaping to achieve optimal focusing and spot-like inscription within the fiber. Strong, first-order fiber Bragg grating is achieved in coated single-mode fiber using only 50nJ pulse energy.

## 1. Introduction

Femtosecond (fs) pulse laser inscription in fibers has been of interest for realizing monolithic fiber devices as it offers, amongst all, spatial control flexibility. Such inscriptions have since been adopted for fiber Bragg grating (FBG) fabrications with different optical setups [1-4]. It is worthwhile to note that though FBG inscriptions have been widely shown, the techniques are generally restrictive and, suited only for realizing fiber gratings. While these schemes do achieve high axial spatial resolution, the transverse profile, a function of the Rayleigh depth of the focusing lens, of the laser-induced feature remains significant [3,4]. Consequently, these methods do not achieve true spot-like inscription within the fiber. In addition, particularly for oil-immersion-based techniques, it is inherently impractical to keep the fiber in oil for large-scale production.

In this paper, we demonstrate for the first time to the best of our knowledge, a methodology that simultaneously achieves spot-like, laser-induced inscription in a fiber while alleviating limitations due to distortion on the incident focused beam in a free-standing fiber. The proposed method features radial plane beam-shaping of the incident beam by inclusion of cylindrical lens before the objective lens. Optimal focusing condition is achieved within the fiber to lead to ultra-low energy laser inscription in a free-standing fiber without the need for oil immersion-based compensations. To illustrate the effectiveness of the proposed scheme, first-order FBG with 55dB transmission stopband at Bragg resonance is achieved in a coated, free-standing single-mode fiber using lowest inscription energy to-date of 50nJ

## 2. Beam shaping

Due to the intrinsic cylindrical geometry of the optical fiber, the focused beam inside the fiber experiences differential divergence between the axial and radial axes that leads to dislocation of the focal region between the orthogonal axes. The laser-induced index modification preferentially occurs at radial focal region whereby the radial focusing exhibits the larger numerical aperture to give the stronger optical confinement, which leads to a typically-observed axially-elongated inscribed feature as depicted in Fig. 1.



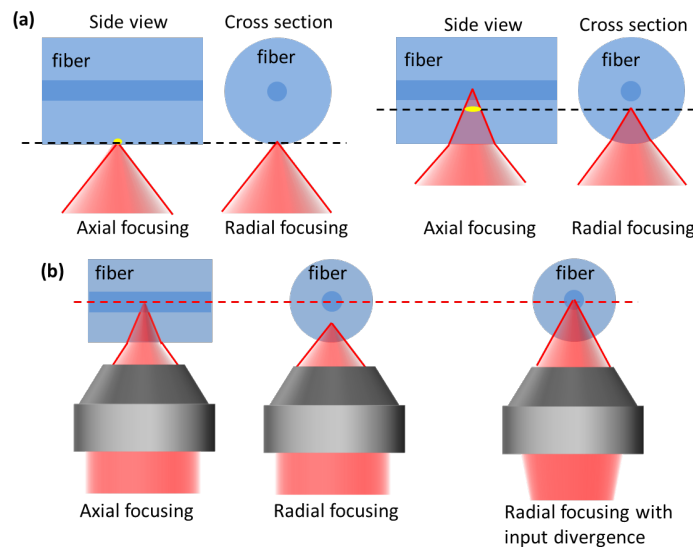


Fig. 1 Focusing conditions in a free-standing fiber (a) without radial plane beam shaping and, (b) with radial plane beam-shaping. Input divergence to radial plane in (b) lead to optimal convergence of focal points between the radial and axial planes.

On the other hand, by introducing beam divergence to the radial plane of the incident beam prior to the objective lens, one can adjust the focal position of the radial component to eliminate the focal point dislocation. When the axial and radial focal points coincide within the fiber, optimal focusing and hence inscriptions, is achieved as illustrated in Fig. 1b

To experimentally illustrate the proposed methodology, we introduce a dual-cylindrical-lens (dual-CL) system (focal length of 75mm and 50mm respectively) prior to the objective lens. By adjusting the separation between the two lenses, the beam divergence can be varied accordingly. Single point inscriptions with 10msec exposure each are carried out for setups with and without the dual-CL system. The divergence of the dual-CL is adjusted to effectuate optimal inscription at the fiber core. The pulse energy required for visible inscribed feature was 40nJ for inscription with dual-CL as compared to 150nJ without the dual-CL setup.

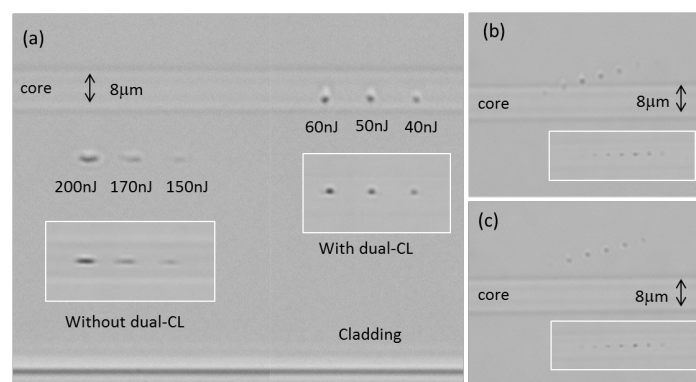


Fig. 2 (a) Comparing point inscriptions in free-standing fiber with and without dual-CL at different pulse energy. (b) and (c) illustrates changes in optimal inscription depth with adjusted input radial plane beam divergence. Beam is incident from the bottom of the pictures. All insets show the orthogonal views.

As shown in Fig. 2(a), the characteristics of the resultant inscribed features are consistent with Fig. 1b. With the dual-CL system, the inscribed features are within the core and exhibits spherical geometry. Without the dual-CL, the axially-elongated inscribed features appear in the cladding

indicating the shorter focal depth of the radial component. It is worthwhile to note that optimal inscription position increases with the beam divergence introduced. Since the dislocation of axial and radial focal points increases with the inscription depth, a larger beam divergence is required for achieving optimal inscription at a deeper position inside the fiber. This is consistent with experimental results obtained as shown in Fig. 2b and 2c.

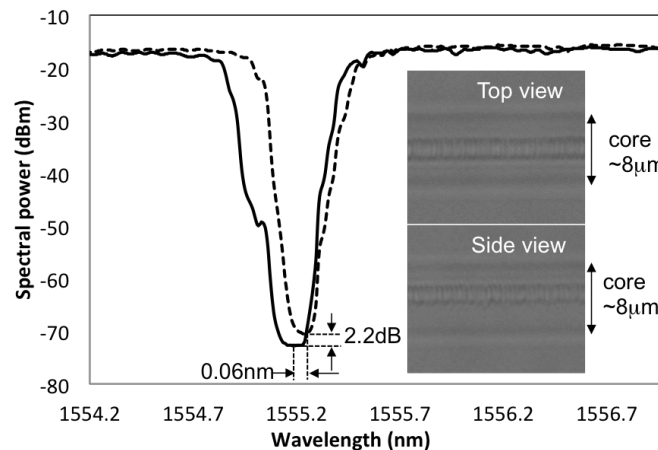


Fig. 3 Superimposed measured transmission spectra along orthogonal polarizations of the FBG. Inset show microscope images of the FBG with 1<sup>st</sup>-order period of  $\sim 0.52 \mu\text{m}$ .

As an exemplary application, the proposed methodology is adopted for point-by-point (PBP) fabrication of a 10mm-long, first-order FBG in a coated, free-standing single-mode fiber. The fs pulse laser repetition rate operates at 100 kHz while the fiber translates at 52.2mm/s, resulting in a grating period of 522nm. The measured incident fs pulse energy was 50nJ. The inscription took only 190msec and the obtained transmission spectral shows a 55dB stopband at Bragg resonance ( $\sim 1555.2\text{nm}$ ) as shown in Fig. 3.

Due to the symmetry of the inscribed features, the polarization dependency of the spectral response is less significant as compared to [3]. The birefringence measured  $\sim 5 \times 10^{-5}$  while the polarization-dependent Bragg response is  $\sim 2.2\text{dB}$ . The measured insertion loss of the fabricated FBG is  $\sim 1.2\text{dB/cm}$ , which is comparable to PBP FBG fabricated with oil-immersion [3]. It is important to note that the past demonstration of PBP FBG fabrication in a coated single-mode fiber only achieved 2<sup>nd</sup>-order grating with inscription energy at hundreds of nJ [5].

### 3. Conclusion

Ultra-low energy, distortion-free, spot-like fs pulse laser inscription in a coated, free-standing fiber is achieved for the first time based on beam-shaping by inclusion of cylindrical lens before the objective lens. Proposed scheme potentially lay the foundation for a truly versatile laser inscription suitable for large-scale implementation.

### References

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