

Spot-like inscription with large inscription depth in a free-standing single-mode fiber

Yijing Chen¹, Yicheng Lai¹, and Marcus W. O. Cheong¹

¹Data Storage Institute (DSI), Agency for Science, Technology and Research (A*STAR), 5 Engineering Drive 1, Singapore (117608)

E-mail: chenyi@dsi.a-star.edu.sg

Abstract. Spot-like femtosecond pulse laser inscription with large inscription depth in a free-standing fiber is demonstrated for the first time. Methodology uses axial plane slit beam-profiling to improve inscription uniformity near the core to enable spatially-large in-fiber structural inscription.

1. Introduction

There have been substantial interests in using a focused femtosecond (fs) pulse beam to inscribe arbitrary device structures in the optical fiber. However, the inscription flexibility can be restricted by the short inscription depth and the large inscription distortion due to the fiber curvature geometry. Although oil-immersion-based techniques can effectively remove the fiber curvature effect, it is inherently impractical to keep the fiber in the oil especially for large-scale fiber device production [1]. More recently, high-fidelity fs laser inscription is demonstrated in a free-standing fiber based on a radial-plane slit-beam profiling technique. However, the inscription feature is significantly elongated transversely and the short inscription depth remains [2].

In this paper, we report the first demonstration of spot-like inscription with large inscription depth in a free-standing fiber by utilizing an axial plane slit beam-profiling technique. With the improved inscription uniformity near the core, the inscription flexibility is enhanced, laying the foundation for arbitrary device inscription in the fiber. Spatially-large in-fiber structural inscriptions are further highlighted.

2. Inscription distortion in fiber

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, as shown in Fig. 1. The inscription preferentially takes place at the radial focal point due to the larger effective numerical aperture in the radial plane, which leads to a typically-observed axially-elongated inscribed feature. Increasing the focusing depth will increase the inscribed feature elongation, causing the drastic increment of the inscription energy requirement, thus limiting the inscription depth.

Experimentally, the inscription distortion in a free-standing single-mode fiber is as shown in Fig. 2, where each point is inscribed by a 10msec-interval fs pulse laser (830nm, 160fs) exposure at 100kHz.



At least twice higher inscription energy up to 215nJ is required to effectuate visually inscription near the core. The inscription feature is significantly elongated along the fiber axis in the vicinity of the core.

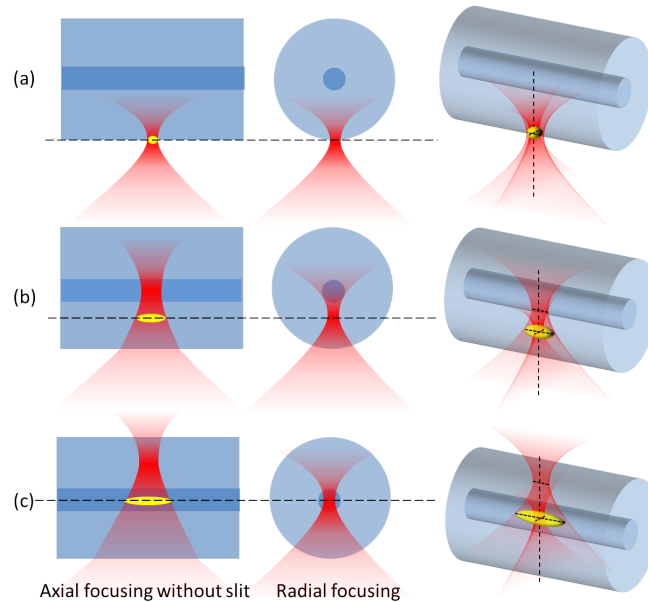


Fig. 1: Schematic illustration of inscription distortion inside a free-standing fiber.

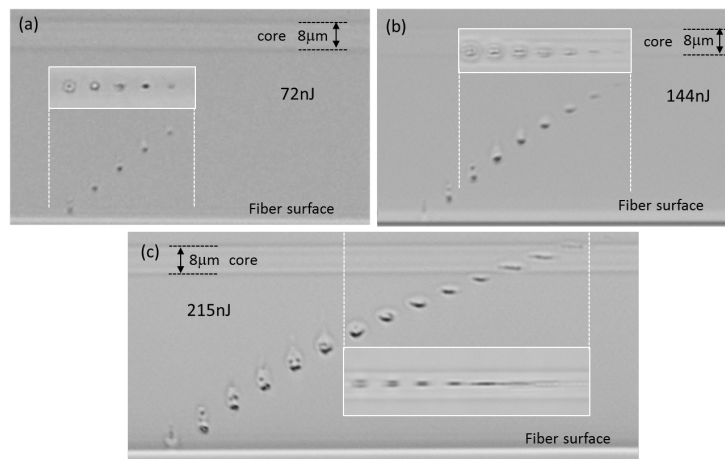


Fig. 2 Fs laser inscribed features in a free-standing fiber with pulse energy of (a) 72nJ (b) 144nJ (c) 215nJ. Beam incident from the bottom. Inserted figures show the orthogonal view.

3. Perpendicular slit-beam profiling

Here we propose a simple free-space approach to achieve large inscription depth inside a free-standing fiber without compromising the inscription energy efficiency and the inscription feature size. The proposed technique is based on the insertion of a perpendicularly-oriented slit before the objective lens to increase the depth of focus (DOF) of the axial focal plane, by means of reduction of its effective numerical aperture. With such modification to the field confinement at the radial focal point (inscription point), as illustrated in Fig. 3, the axial inscription elongation is significantly suppressed, resulting in spot-like inscription feature. Meanwhile, the long DOF of axial focusing effectively compensates the focal-point dislocation and thus improves the inscription uniformity near the core.

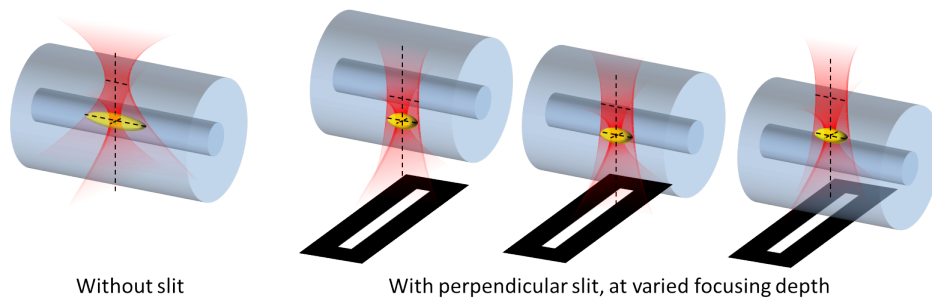


Fig. 3: Schematic illustration of free-space inscription inside the fiber without the slit and with the perpendicular slit beam-profiling at different inscription depth. Objective lens between the slit and the fiber is not explicitly shown.

To experimentally illustrate the proposed methodology, we introduce a 1.5mm-width perpendicular slit prior to the objective lens. First of all, in-core inscription of a $2\mu\text{m}$ -period dot chain is demonstrated in a free-standing single-mode fiber with inscription pulse energy of only 76nJ, as shown in Fig. 4. This is comparable with near-surface inscription energy in Fig. 2a for the set up without slit, indicating the significantly increased inscription depth here. The resultant dot chain also features both high transverse symmetry and large co-axial fidelity, as viewed from two orthogonal directions.

Next, dot chains are inscribed at varied depths with the fixed inscription energy to demonstrate high inscription uniformity near the core. As shown in Fig. 5a, with adoption of the perpendicular slit, high-fidelity dot chains are obtained over a wide depth of at least $10\mu\text{m}$ from the core at the inscription energy of 81nJ. In contrast, the near-core inscription without the slit (Fig. 5b) requires the higher inscription energy of 175nJ and the dot chain fidelity is drastically varied over the $10\mu\text{m}$ depth change, implying the poor uniformity. The zig-zag dot chain is axially broadened and got significantly merged.

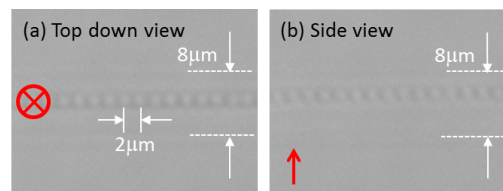


Fig. 4: Dot-by-dot inscription in the core of a free-standing single-mode fiber. (a) Top-down view and (b) side view.

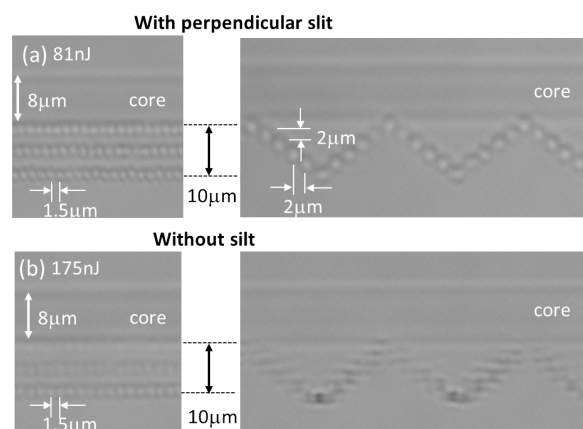


Fig. 5: Dot-by-dot inscription in the single-mode fiber (a) with perpendicular slit at fixed inscription energy of 81nJ and (b) without the slit at fixed inscription energy of 175nJ. Beam incident from the bottom of the picture.

4. Conclusion

We report the first experimental demonstration of large inscription depth in the free-standing single mode fiber, featuring spot-like, high-uniformity inscription in the vicinity of the core. Results obtained highlight the methodology potentially laid the foundation for spatially-large, arbitrary in-fiber device structure inscription.

References

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