Low-loss, high reflectivity, first-order, pitch-by-pitch fiber Bragg grating fabrication in truly free-standing single-mode fiber

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Abstract. Low-loss, high reflectivity, first-order fiber Bragg gratings are achieved by pitch-by-pitch fabrication methodology in a truly free-standing fiber. Slit beam-profiling adopted attain transversely-extended index modification for each grating period defined by single laser pulse. Fiber Bragg grating of 0.52μm period with >27dB transmission stopband and <0.2dB/cm insertion loss are demonstrated.

1. Introduction
The use of intense femtosecond (fs) pulse laser beam to achieve refractive index modifications in optical fibers has enabled formation of fiber Bragg grating (FBG) in a pitch-by-pitch (PbP) process without the need for phase mask or interferometric setup. Indeed, such laser-induced PbP grating inscription methodology has yield FBGs of high spectral quality. However, low-order gratings are typically achieved only by using oil-immersion objectives or require compensating substrate in-proximity in order to overcome distortion effects due to the intrinsic geometry of the optical fiber [1,2]. More importantly, to address the out-of-band insertion losses associated with light scattering in PbP inscribed FBG, time-consuming laser scanning methodologies such as line-by-line inscription and core-scanning technique, are instead adopted to achieve index modification of increased transverse profile for each grating period [3,4]. One should also note that these proposed schemes do not encompasses the simplicity and flexibility of PbP grating fabrication. In particular, it is desirable to achieve rapid FBG generation in truly free-standing fiber where the grating period is simply the ratio of the translation speed of the fiber to the laser pulse repetition rate. And only such methodology can offer practical large scale or long-grating fabrications implementations.

In this paper, we demonstrate, for the first time to the best of our knowledge, a low-loss FBG, PbP fabrication methodology that truly features a free-standing fiber inscribed by a focused fs pulse laser, without the need for laser-scanning or oil immersion-based compensations. We highlight for the first time slit beam-profiling as a means to increased transverse profile of index modification that enable low-loss, high fidelity FBG formation. Proposed scheme retain merit of PbP FBG generation where each grating pitch are individually defined by single focused fs laser pulse. Uniform, 15mm-long first-order (grating period 0.519μm) FBG with >27dB transmission stopband at Bragg resonance and with
out-of-band insertion loss <0.2dB/cm are demonstrated in a free-standing single-mode fiber. Interesting polarization characteristics of the resultant FBG are further highlighted.

2. Slit beam profiling
The beam distortion experience by a focused inscription beam when incident into a free-standing optical fiber can be understood based on the simple schematic as shown in figure 1a, where the objective lens between the slit and the fiber is not explicitly depicted. Due to the intrinsic cylindrical geometry of the fiber, differential divergence between the axial and radial axes of the incident beam leads to dislocation of the focal region between the orthogonal axes. Laser-induced index modification occurs at a region of overlap with intensity above the inscription threshold, leading to a typically-observed axially-elongated inscribed feature.

![Figure 1. Focusing conditions within a free-standing fiber (a) without and (b) with slit beam-profiling. Index modification at overlap region reshapes transversely due to the slit.](image)

We have previously highlighted the use of slit beam-profiling as a means to reshape the focal energy of a laser within a free-standing fiber [5]. In particular, the inclusion of an axially-oriented slit serves to increases the depth of focus of the radial plane by means of reduction of its effective numerical aperture. With such modification to the field overlap between the two focusing component planes as illustrated in figure 1b, the inscription region reshapes transversely while maintaining a tight axial focusing condition. To visualize these considerations in free-space inscription of grating in a single-mode fiber, grating structure of 1.03μm period are inscribed by a step-wise, pitch-by-pitch methodology where each pitch is defined by a 10msec-interval fs pulse laser exposure at 100kHz. The resultant inscribed grating structures viewed under a microscope at orthogonal axes are as shown in figure 2.

![Figure 2. Microscope images (orthogonal view in inset) showing inscribed grating structures in a free-standing single-mode fiber (a) without and (b) with slit beam-profiling.](image)

It is evident that without slit beam-profiling, high fidelity grating inscription cannot be achieved since the focusing condition lead to poor axial spatial resolution. The 1.03μm-pitch inscription resulted in a quasi-continuous structure consisting of an array of laser-modified features that overlap spatially. In comparison to figure 2b, the high grating fringe visibility achieved highlights the effectiveness of slit-profiled inscription. Focal energy redistribution at inscription point is evident
leading to the increased aspect ratio of the inscribed feature. More importantly, the inscription yields the required transversely-extended index-modification that enables low-loss FBG pitch formations.

![Figure 3](image.png)

**Figure 3.** Superimposed measured transmission spectra along orthogonal polarizations of the FBG. Inset show microscope images of the FBG with 1st-order period of ~0.52μm.

To exemplify the merit of the proposed slit beam-profiled inscription methodology in free-standing single-mode optical fiber, a 15mm-long FBG was fabricated using pulse energy of 160nJ. The fiber was translated at a velocity of 51.6mm/sec with the fs pulse laser at 100kHz repetition rate. The inscription process took <300msec and the transmission spectral of the resultant FBG obtained is as shown in figure 3.

The uniform FBG exhibits a transmission stopband of >27dB at Bragg resonance of 1537.8nm. The out-of-band insertion loss of the FBG, monitored throughout the inscription process, measured <0.3dB leading to effective insertion loss of the FBG at <0.2dB/cm. The FBG observed under microscope reveals high grating fidelity of period ~0.52μm as shown in figure 3 inset. It is worthwhile to note that the grating exhibits very low birefringence of ~4x10⁻⁵ in comparison to ~1x10⁻⁴ [1,3] while the polarization-dependent Bragg response was >6.5dB. These suggest that the index modulation along the polarization axes differs while the average indices remain close. Polarization characteristics of such FBGs are under further investigations.

3. Summary
Low-loss, high reflectivity, first-order FBG are achieved by PbP fabrication methodology in a truly free-standing fiber for the first time. Results exemplify the scheme encompasses fully the simplicity and flexibility of laser-induced PbP grating fabrication.

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References
[1] Y. Lai et al., “Point-by-point inscription of first order fiber Bragg grating for C-band applications”, *Opt. Exp.*, 15(26), 18318-18325 (2007).
[2] G.D Marshall et al., “Point-by-point written fiber Bragg gratings and their applications in complex grating designs”, *Opt. Exp.*, 18(19), 19844-19859 (2010).
[3] K. Zhou et al., “Line-by-line fiber Bragg grating made by femtosecond laser”, *IEEE Photon. Tech. Lett.*, 22(16), 1190-1192 (2010).
[4] R.J. Williams et al., “Femtosecond direct-writing of low-loss fiber Bragg gratings using a continuous core-scanning technique”, *Opt. Lett.*, 38(11), 1918-1920 (2013).
[5] Y. Lai et al., “High fidelity, pitch-by-pitch grating inscription in free-standing single-mode optical fiber”, *IEEE 7th ICAIT*, 166-171 (2014).