Plane-by-Plane Inscription of Grating Structures in Optical Fibers

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***Abstract*—Plane-by-plane fabrication of fiber Bragg gratings in optical fibers using a short-pulse femtosecond IR laser is proposed and demonstrated. By incorporating a cylindrical lens in the fabrication setup, a plane of index modification can be directly inscribed in the fiber core by a single laser pulse. The planes of index modification are produced in the core of a free-standing fiber without an oil immersion objective. This plane-by-plane method simplifies the direct grating inscription process and allows for the fabrication of complicated grating structures.**

***Index Terms*—Cylindrical lens, direct inscription, femtosecond laser, fiber Bragg gratings, plane-by-plane.**

I. INTRODUCTION

FEMTOSECOND lasers have been used to fabricate Bragg grating structures in various fiber materials due to the laser-material interaction via nonlinear photoabsorption and photoionization mechanisms. Phase mask scanning [1], [2] and direct inscription point-by-point (PbP) method [3]–[9] are the two common techniques that have been widely used for grating inscription using ultrafast infrared lasers. In the phase mask approach, the grating parameters, such as Bragg wavelength, grating length, chirp, phase shift etc., are determined by the specific phase mask, which can be costly to produce when long and complex grating structures are required. By directly focusing the femtosecond laser beam into the fiber core, direct inscription methods have been demonstrated to be more flexible for writing grating structures with different Bragg resonant wavelengths, chirp and cladding mode coupling etc. However, the modified index regions produced by direct inscription methods are microvoids which are usually much smaller than the fiber core diameter resulting weak mode coupling coefficient [10]. For a fiber Bragg grating (FBG) inscribed in an optical fiber, the transverse coupling coefficient, $K^t_{jk}(z)$, between modes *j* and *k* is [11]

$$K^t_{jk}(z) = \frac{\pi}{\lambda}\iint_{\infty} n(x,y,z)\,\Delta n(x,y,z) \cdot \vec{e}_{kt}(x,y)\cdot \vec{e}^{\,*}_{jt}(x,y)\,dxdy \qquad (1)$$

where $n(x,y,z)$ is the refractive index of the fiber, $\Delta n(x,y,z)$ is the induced index change by laser radiation, $\vec{e}_{kt}(x,y)$ and $\vec{e}_{jt}(x,y)$ are the transverse fields of modes *k* and *j* respectively. From (1) we can see that the mode coupling coefficient is proportional to the overlap integral of the index change $\Delta n(x,y,z)$ and the transverse mode field. In the case that a fiber Bragg grating is inscribed in a single mode fiber with a phase mask, the induced index change Δn is usually in the form of sinusoidal function and is uniform across the fiber core, then the "ac" component, κ, of coupling coefficient at wavelength, λ, can be simplified as [11]

$$\kappa = \frac{\pi}{\lambda}\nu\overline{\Delta n}_{eff} \tilde{=} \frac{\pi}{\lambda}\nu\Gamma\overline{\Delta n}_{co} \qquad (2)$$

where ν is the fringe visibility of index change, $\overline{\Delta n}_{eff}$ is the is the "dc" index change spatially averaged over a grating period, Γ is the mode power confinement factor in the fiber core, and $\overline{\Delta n}_{co}$ is the average index change in the fiber core.

In the point-by-point direct FBG inscription method, the coupling coefficient κ cannot be simplified as described in (2) because the index change is usually not sinusoidal along the fiber and not uniform across the fiber core. The dimensions of the region of the index modification Δn in the fiber core is much smaller ($\sim\mu$m) compared to that produced by the phase mask approach. There is only a small overlap between the mode field propagating along the fiber core and the dimension of the index change resulting in weaker mode coupling according to (1). The small overlap causes a weak grating reflectivity for a given index change. From (1) we can also see that if the region of the induced index change Δn is not located at the center of the single mode fiber core, the coupling coefficient will drop because the peak intensity of mode field is at the center of the core in single mode fibers. As a result, the alignment requirement for the point-by-point method is more critical than that for the phase mask technique.

For a given type of fiber, the only way to increase the coupling coefficient is to increase the amplitude of the index change Δn and/or the dimension of the region of the index change. Femtosecond lasers can produces very high index change and strong type II gratings in various fibers [12], but high scattering losses

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are introduced as well. Several approaches have been reported to increase the coupling coefficient in order to produce strong grating reflectivities while producing low scattering loss. Zhou *et al.* [5] showed a line-by-line method to increase the index change dimension by moving the oil-immersion objective perpendicularly to the fiber axis so that a line instead of a point of index change is produced across the fiber core. After one line is made, the fiber is moved along the fiber axis at a distance of the grating period and then another line of index change is made. Strong higher order gratings were fabricated by using this technique but with very high scattering loss (1.2 dB/cm), which is not desirable for chirped gratings. Williams *et al.* [6] presented a continuous core-scanning technique where a piezo stage was driven by a sine wave, resulting in a sinusoidal index change across the core. Strong first order gratings with low induced scattering loss were fabricated by using technique. The fabrication process however is complicated and time consuming when long gratings are inscribed. Strong cladding modes were also observed. In the two methods described above, oil-immersion objectives were used and the fiber is also immersed in the oil during grating fabrication. The process is further complicated by requiring the fiber to be cleaned after the grating inscription which weakens the mechanical strength of the grating and will make it harder to recoat the fiber. Without using an oil-immersion based setup, Lai *et al.* [9] presented the technique of beam profiling using a slit by which grating pitches were inscribed in free-standing fiber through a pitch-by-pitch process. Strong gratings were fabricated but the induced scattering loss is still high (0.2 dB/cm) that is not acceptable for some applications, such as long and large chirped gratings.

In this work, we report a modified approach to the point-by-point technique where by adding a cylindrical lens to the exposure setup before the final microscope objective, the cylindrical shape of the focal volume normally produced by the microscope objective alone is instead transformed into a planar strip or plane [13]–[15]. We will show that the proposed approach produces a grating structure in the fiber core that is written plane-by-plane with single laser pulses. This approach effectively increases the mode coupling in the fiber core simplifying the fabrication of strong Type I and Type II direct write gratings. The grating planes are inscribed in the core of free-standing fiber without using oil-immersion objective based approach, which simplifies the grating fabrication setup and makes possible the fabrication of long grating structures such as chirped and tilted gratings. Such structures are important for fiber laser and sensor applications involving fiber gratings.

II. SETUP OF FABRICATING GRATINGS BY PLANE-BY-PLANE METHOD

The diagram in Fig. 1 shows the setup for grating fabrication in an optical fiber through plane-by-plane method. It is similar to the setup for point-by-point grating inscription except that a long focal length cylindrical lens was added to the beam path with its focal point positioned at the same location as that of the microscope objective [13]. The regeneratively amplified Ti:sapphire laser (Spitfire, Coherent) operates at the wavelength of 800 nm, a repetition rate up to 1000 Hz and a pulse duration of 120 fs. Pulse energies incident on the fiber were between 1.4 to 1.9 μJ. A beam reduction telescope consisting of one plano-convex lens and one plano-concave lens was placed after the cylindrical lens to reduce the laser beam diameter to match the pupil diameter of the microscope objective (50 X/0.6, Nikon). The fiber (SMF-28) was mounted on an air bearing stage (Aerotech) that moves with a positional accuracy of ±10 nm. The objective was mounted on a piezo stage (NanoMax-TS, Melles Griot). By adjusting the axis tilt of the cylindrical lens, the focal line was oriented perpendicular to the fiber axis. When the focal line propagates across the fiber core, a plane of index modification can be produced by a single pulse. As a result, higher mode coupling efficiency and stronger grating strength can be achieved.

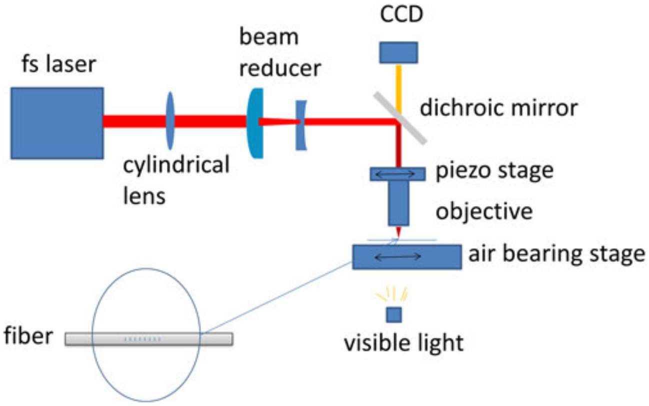


Fig. 1. Diagram of the setup for plane-by-plane grating fabrication in optical fibers.

III. RESULTS AND DISCUSSION

A. *Type I Gratings*

Type I gratings were fabricated with a pulse energy of 1.6 μJ. The laser repetition rate was set at 250 Hz and the fiber was translated at a speed of 132 μm/second resulting in a fundamental 1st order grating period of 0.528 μm and the Bragg wavelength of 1540 nm (see Fig. 2). The focal length of the cylindrical lens was 50 cm. It was determined that this combination of cylindrical lens and the objective (50 X/0.6, Nikon), resulted in an IR beam line focus of $\sim$11 μm in length, however when focused inside a fiber, the line focus is shortened due to the lensing effect of the fiber. Several 10 mm long gratings were fabricated with various distances between the objective and fiber with the goal of producing strong gratings and low insertion loss. The spectra of a 10 mm long strong uniform grating are shown in Fig. 2. The grating strength is 25 dB and the broadband insertion loss in very low (<0.02 dB) which corresponds to an index modulation $\Delta n = 3.8 \times 10^{-4}$. Higher index change (a stronger grating) is expected if the Ge-doped fibers were loaded with H_2 or D_2 [16]. The size of the focal line at the fiber core was measured with an optical microscope to be around 8 μm. After passing through the fiber core, the laser beam was ultimately focused in the cladding

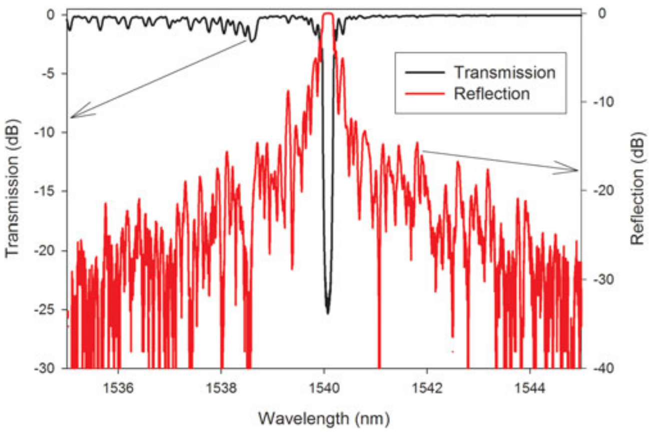


Fig. 2. Spectra of a 10 mm long type I grating inscribed by plane-by-plane method.

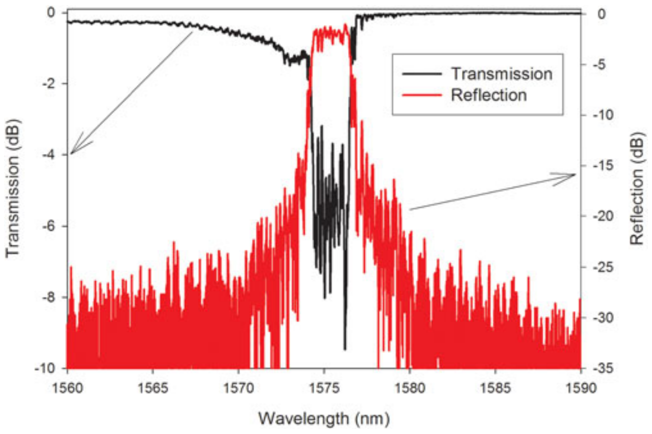


Fig. 3. Spectra of a 20 mm long type I chirped grating in SMF-28 fiber with a chirp rate of 1 nm/cm.

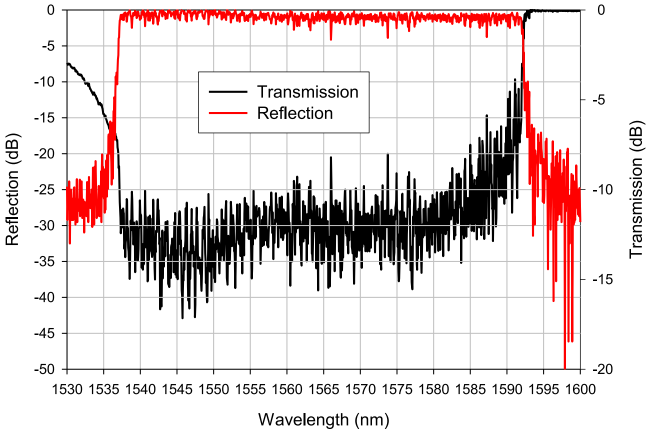


Fig. 4. Spectra of a 260 mm long and chirped grating with chirp rate of 2 nm/cm. The total insertion loss is 0.5 dB for the whole 260 mm long grating.

region (a few μm away from the core) creating some damage to the cladding. Compared to the size of index change (<1 μm) produced by the objective itself, the advantage of adding the cylindrical lens in the setup to increase mode coupling coefficient is evident, according to (1). The grating was completely erased after baking for an hour at 1000 °C indicating that type I index change is occurring in the core region. The pulse energy (1.6 μJ) used to produce the low loss type I grating in this experiment is much higher than the pulse energy used for the point-by-point method [6]. This higher pulse energy is needed because the energy is spread onto a much larger focal volume when the cylindrical lens is used in the setup. As a result, the higher pulse energies produce similar power densities as those produced using the point-by-point approach.

By using this plane-by-plane approach, chirped gratings were also produced. The grating chirp was created by varying slightly the laser repetition rate while the fiber sample was translated at a constant velocity. The RF frequency of 80.216 MHz from the seed laser (Tsunami, Spectra-Physics) was sent to a Synchronization and Delay Generator (SDG Elite, Coherent) which was then divided by an integer called the RF divisor and sent to the pump laser (Empower, Spectra-Physics). The repetition rate can then be tuned by changing the RF divisor, for an example, if the RF divisor is varied from 80216 to 80296, the laser repetition rate is tuned from 1000 Hz to 999 Hz. In our experiments, the laser repetition rate was around 250 Hz by setting the trigger divisor to be 4. By changing the repetition rate rather than the stage velocity, the perturbation to grating period produced during the changing of air-bear stage velocity can be reduced over long distances up to 260 mm. The spectra of a 20 mm grating with a chirp rate of 1 nm/cm are shown in Fig. 3, the laser repetition rate is from 250 Hz to 249.6 Hz in 0.01 Hz increments while the fiber sample was translated at a constant velocity of 136 μm/s.

In order to fabricate strong as well as long gratings with large chirp for sensor applications [17], photo-sensitive fiber or deuterium loaded Ge-doped fiber can be used. Fig. 4 shows the spectrum of a 260 mm long grating with chirp of 2 nm/cm fabricated in deuterium loaded SMF-28 fiber. The fs laser pulse energy (1.6 μJ) was chosen to produce index change as high as possible while maintaining the small insertion loss. The laser induced total insertion loss on the whole 260 mm long grating is only 0.5 dB (less than 0.02 dB/cm). The fiber was translated at a speed of 132 μm/s, the laser repetition rate was tuned from 250 Hz to 248.7 Hz with a step of 0.02 Hz. The step chirped grating was composed 428 uniform grating sections, each section is 608 μm in length.

The reflection spectra shown in Figs. 3 and 4 are not smooth, this is due to the phase errors generated in the grating by the air-bearing stage (Aerotech). The maximum position error of the air-bearing stage is ±10 nm, while most of time the position error is a few nanometers. Fig. 5 shows a simulation result, based on coupled mode theory [11], of the reflection spectrum of a chirped grating with the same length, laser induced index change and chirp rate as those used in the experiment with result shown in Fig. 4. The position error of the stage in the simulation is random from -3 to 3 nm.

The alignment of the laser beam focus in the fiber core is critical in order to get strong gratings with low insertion loss even with the elongation of the laser focus in the fiber core due to the

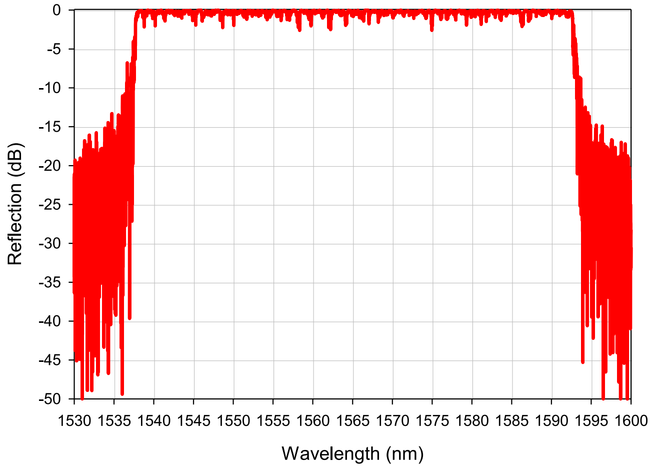


Fig. 5. Simulation of the reflection spectrum of a 260 mm long grating with chirp rate of 2 nm/cm. The errors of grating periods are assumed to be random from −3 to 3 nm.

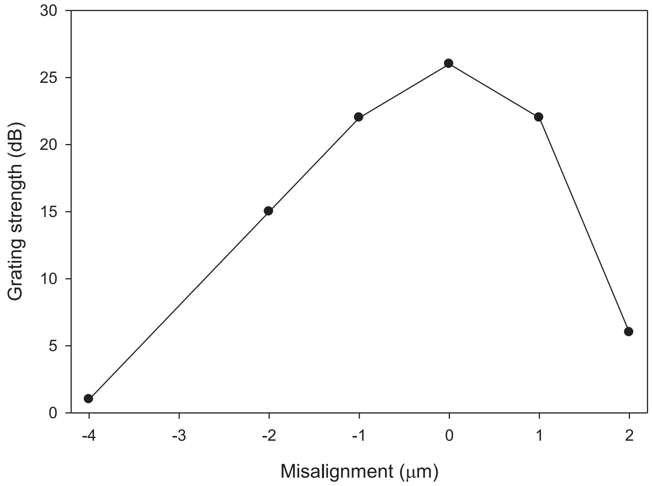
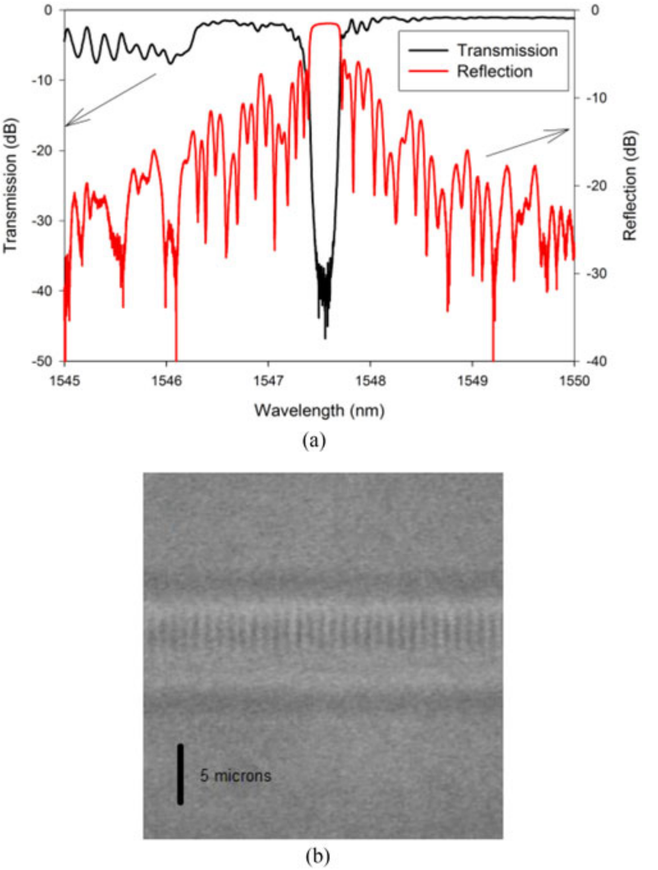


Fig. 6. Strength of 10 mm long gratings fabricated with the same inscription conditions except that the fiber core displaced away from the ideal alignment position.

cylindrical lens in the setup. Fig. 6 shows the changes in grating strength in transmission of 10 mm long gratings inscribed with the same pulse energy (1.4 μJ) but with the fiber shifted along the laser beam direction from the alignment position producing strongest grating. As we can see, when the fiber is shifted 2 μm from the ideal position, the drop of grating strength is significant. In this work, the stages we used are ANT130-060-L (Aerotech) with a resolution of 200 nm.

B. Type II Gratings

Type II gratings in silica fiber have the potential for sensing at high temperatures up to 1000 °C. By using the proposed technique, strong type II gratings were fabricated in SMF-28 fiber with grating periods around 1.07 μm (2nd order grating for Bragg wavelengths around 1550 nm). The minimum pulse energy needed to produce type II gratings in SMF-28 fiber depends on both the objective and the cylindrical lens used in the setup. With the Nikon objective (50 X/0.6), the minimum pulse energies needed to produce type II gratings are 1.3 and 1.7 μJ when the focal lengths of the cylindrical lenses are 1 and 0.5 m respectively. By using a cylindrical lens with a longer focal length ($f = 1$ m), the IR laser beam was then tightly focused on the core rather than in the cladding past the core as in the type I case above. Higher insertion loss (up to 1 dB/cm) and strong cladding modes were produced. Fig. 7 shows the spectra and top view microscope image of a 10 mm long 2nd order grating. The laser repetition rate and pulse energy were set at 250 Hz and 1.4 μJ, respectively, while the fiber moved at a speed of 267.5 μm/s. From the top view microscope image shown in Fig. 7 it is clear that the fs-laser pulses produce lines in the fiber core with an approximate length of 5 μm. The side view image recorded after rotating the fiber 90 degrees along its axis is roughly the same as the top view image. The scattering loss of the grating shown in Fig. 7 is ~0.8 dB.

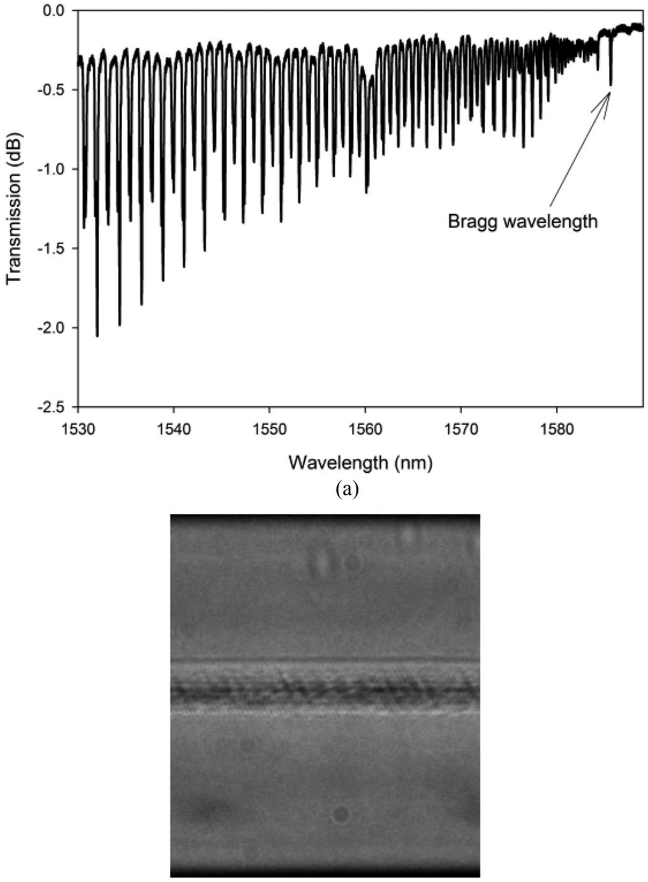


(a)

(b)

Fig. 7. Spectra and top view microscope image of a 10 mm long uniform type II grating in SMF-28 fiber. Small vertical lines in the middle of the core in Fig. 4(b) are perpendicular to the laser beam direction.

Due to the fact that a plane of index change can be produced by a single fs-IR pulse, the demonstrated grating fabrication setup can be easily applied to produce more exotic grating structures such as tilted gratings, which are far more complicated and time consuming to produce if the point-by-point method is used. By using a cylindrical lens with a shorter focal length ($f = 0.5$ m)



(a)

(b)

Fig. 8. Spectrum and top view microscope image of a 10 mm tilted grating in SMF-28 fiber.

and rotating it so that the IR laser-produced plane is not perpendicular to the fiber axis, tilted gratings with strong cladding modes can easily be made. By reducing the repetition rate to 125 Hz and increasing the pulse energy to 1.9 μJ, and rotating the cylindrical lens 20° from the position used to fabricate planes perpendicular to the fiber axis, a tilted grating with an interplane separation of 1.09 μm is produced (see Fig. 8). The distortion of the image of the grating plane shown in Fig. 8 is due to the focusing effect of the fiber [18]. Again, a higher scattering loss (0.5 dB) is observed.

IV. CONCLUSION

A simple method of fabricating both type I and type II gratings using a femtosecond IR laser was proposed and demonstrated experimentally. The proposed plane-by-plane approach was shown to be an effective way of fabricating strong, low loss and complicated type I grating structures in SMF-28 fiber without the need of H_2 or D_2 loading. Gratings were inscribed in free-standing fiber avoiding the use of oil-immersion objective-based setups, which simplifies the grating inscription process and makes it easier for practical grating production.

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