Measurement of refractive index change of optical fiber core induced by femtosecond laser scanning

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Abstract. We report a new method to measure the refractive index change in optical fiber core induced by femtosecond (fs)laser exposure. An in-line Fabry-Perot interferometer, serving as the measurement platform, is constructed on a commercial single-mode optical fiber by one-step femtosecond (fs) laser fabrication. A positive refractive index change is observed and measured accurately as the laser pulse energy surpasses the ablation threshold. © *2010 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.3449113]

1 Introduction

Recent advancement in ultrafast ($\sim$ femtosecond) pulse laser technology has opened a new window of opportunity for one-step (without additional assembly) fabrication of micro- and even nanoscale photonic structures in various solid materials.[1,2] A femtosecond laser beam can be focused into a transparent object, creating localized optical features at the focal point on the surface or inside the solid material. Various miniaturized optical devices have been demonstrated using femtosecond lasers. Compared with other fabrication methods, the femtosecond-laser-based technique has the unique feature of fabricating 3-D microstructures with great flexibility.

Femtosecond-laser-based fabrication of optical devices can be either destructive or nondestructive. In a destructive fabrication, the femtosecond laser ablation effect is directly used to sculpture solid materials into desired 3-D shapes. Optical device examples include microlenses,[3] microfluidic channels,[4] fiber inline Fabry-Perot interferometers,[5,6] and optical switches.[7] Destructive fabrication is above the ma-

terial ablation threshold. Nondestructive fabrication, called subablation fabrication, is below the material ablation threshold. Although the point at which absorbed laser energy is not sufficient to break the bonds between molecules of a material, the short-pulse lasers cause nearsurface thermal stresses, which can lead to a wide variety of micromechanical responses.[8,9] In a nondestructive way, femtosecond laser irradiations can induce the refractive index in optical materials.[10–12] As a result, optical waveguides,[13,14] gratings,[15,16] and directional couplers[17] have been demonstrated, for instance, fiber Bragg gratings and long-period fiber Bragg gratings. The amount of refractive index variation induced by femtosecond laser exposure inside the photonic device is one of the most critical variables that determine the characteristic of the target structure, such as fiber Bragg grating. Quite a few research groups study laser induced refractive index change in different materials. However, up until now, although femtosecond-laser-induced refractive index change on bulk fused silicon has been studied, no precise measurement has been conducted toward this parameter in optical fiber.

This work mainly focuses on the measurement method of femtosecond-laser-induced refractive index change in
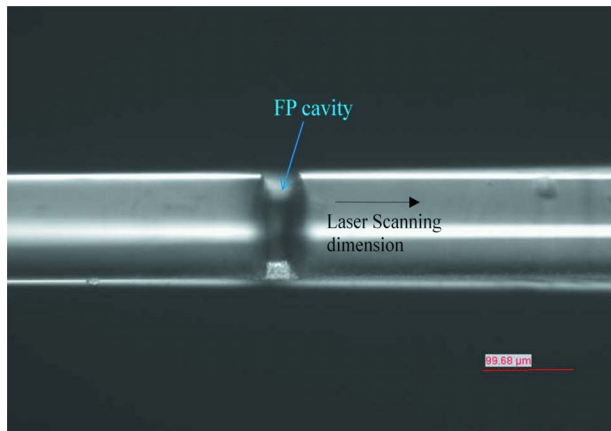
Fig. 1 The optical image of the fabricated fiber inline FPI device.

the optical fiber core. Assisted by the most recently developed femtosecond laser fabricated fiber inline Fabry-Perot interferometer (FPI), the refractive index change can be calculated by the optical length change measured in fiber inline FPI. Since the fiber inline FPI was fabricated on the optical fiber in one step, together with the fact that the refractive index measurement was carried out on the same device, the whole experiment was integrated on the same structure by one-time assembly, which further improved the measurement accuracy.

2 Measurement Platform Fabrication

Figure 1 shows the optical image of the fabricated fiber inline FPI device. The device was fabricated for an optical fiber (Corning SMF-28) by femtosecond laser micromachining following the procedures reported previously.[5] The cavity length was about 40 μm as estimated from the optical image. The depth of micronotch was around 72 μm, just passing the fiber core. The cavity was made 5 mm to the end of the cleaved fiber tip. The background loss of this particular device was about 20 dB. This device can be considered as a combination of two FPIs. The femtosecond laser ablated notch section is the extrinsic Fabry-Perot interferometer (EFPI), while the following fiber segment to the end of the fiber tip is the intrinsic Fabry-Perot interferometer (IFPI). The EFPI corresponds to interference spectra with a period of around 40 nm, and the IFPI has that of

around 0.15 nm. In this experiment, the IFPI was used as the measuring device, and the IFPI signal is relatively independent from that of EFPI as a result of the huge scale difference between the interference spectra. With femtosecond laser scanning close to the IFPI cavity, the shift of IFPI interference can be detected due to the refractive index change in the fiber core.

3 Principle and Theory

The refractive change can be measured using a fiber inline FPI as schematically shown in Fig. 2. The IFPI section serves as an interferometer, in which the reflections at the two endfaces, coupling back to the lead in fiber through the femtosecond ablated notch (EFPI section), superimposed to form an interference signal at the optical power meter (HP8163). By stepping the tunable laser through its available wavelength range and coordinating the signal detection at the power meter using a computer, the interference spectrum of the IFPI can thus be recorded. When exposed to femtosecond laser irradiations, the IFFPI section at the end of the fiber tip changes its refractive index, resulting in a phase shift in the interference signal. The femtosecond-laser-induced fiber refractive index change can thus be calculated based on the amount of phase shift after laser irradiation.

Assuming that the two reflected lights from the IFPI section have the intensities of I_1 and I_2, respectively, the interference signal I_i generated by these two reflections is given by:[6]

$$I_i = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left[\frac{4\pi}{\lambda}(OL) + \phi_0\right], \qquad (1)$$

where OL is the optical length of IFPI, defined as the product of length and the refractive index of the core; Φ_0 is the initial phase of the interference; and λ is the optical wavelength in vacuum.

As shown in Fig. 2, the two adjacent valleys at λ_1 and λ_2 in the interference spectrum have a phase difference of 2π, that is:

$$\left(\frac{4\pi}{\lambda_1}OL\right) - \left(\frac{4\pi}{\lambda_2}OL\right) = 2\pi. \qquad (2)$$
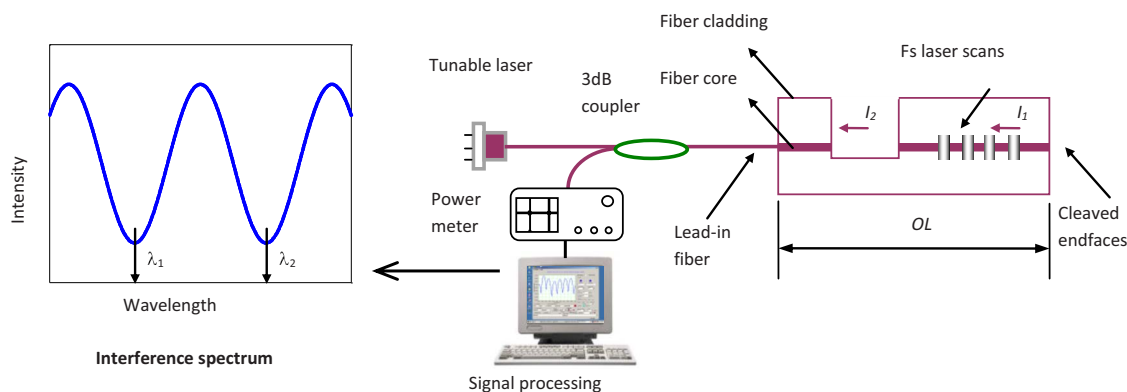

Fig. 2 The schematic of refractive change detection using a fiber inline FPI.

Therefore, the initial optical length of the IFPI section can be calculated using the following equation:

$$OL = \frac{\lambda_1 \lambda_2}{2(\lambda_1 - \lambda_2)}. \tag{3}$$

Since the device is fixed under a tension-free circumstance, and the IFFPI section is considerably short (~ 5 mm), the change in optical length is mainly caused by the laser irradiation-induced refractive index change inside the fiber core. For multiple-point laser irradiations at different locations, the accumulated change in optical path (ΔOL) is given by

$$\Delta OL = m \cdot (\Delta OL_{\text{single}}) = m \cdot (\Delta n \cdot W), \tag{4}$$

where m is the total number of laser irradiations, Δn is the refractive index change, and W is the width of one femtosecond laser exposure scan.

When the change in optical path length is small enough that the phase shift is less than 2π, the phase ambiguity issue can be avoided. The relative optical length change can be calculated based on the spectral shift of the interferogram at the featured points such as the peak, valley, and center of the interference fringes, given by [6]

$$\Delta OL = \frac{\Delta \lambda_1}{\lambda_1} OL. \tag{5}$$

Combining Eqs. (4) and (5), one finds the refractive index change:

$$\Delta n = \frac{1}{mW} \frac{\Delta \lambda_1}{\lambda_1} OL. \tag{6}$$

In the experiments, the laser pulse energy was tunable. The laser pulse length (width), which is equal to the pulse wavelength, was fixed. An alternative way of calculating the refractive index change is directly based on Eq. (4), in which the change in optical length is a linear function of the number of laser exposures, and the slope of the line is linearly proportional to Δn. Experimentally, one can measure the optical length change after a various number of laser exposures, and curve-fit the measurement results into a line. The slope of the fitted line can thus be used to calculate Δn. This method uses multiple data points in calculation and can effectively reduce measurement uncertainty.

4 Experiment

The experiment was carried out on a home-integrated femtosecond laser 3-D micromachine. The repetition rate, center wavelength, and pulse width of the femtosecond laser (Legend-F, Coherent, Incorporated), were 1 kHz, 800 nm, and 80 fs, respectively. The maximum output power of the femtosecond laser was approximately 1 W. A combination of a half-wave plate and a polarizer was used to reduce the laser power to 20 mW in the first place, and then several neutral density (ND) filters were applied to further reduce the laser pulse energy to desired values of 0.5, 0.8, and 1 μJ, based on different experimental conditions. The attenuated laser beam was directed into objective lenses
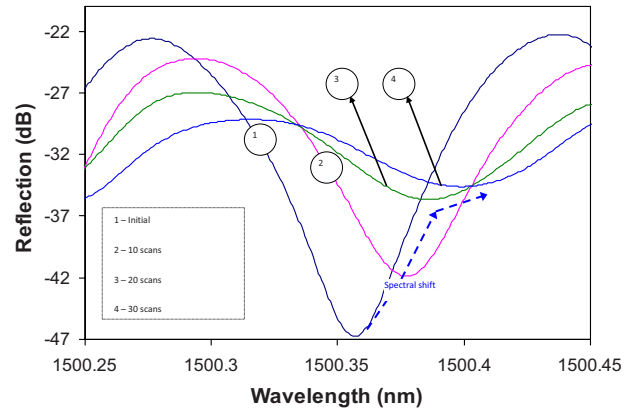

**Fig. 3** The initial interference spectrum.

(Olympus UMPLFL 20X) with a numerical aperture (NA) of 0.45, and was focused at the center of the IFPI section. Each time, with the help of a five-axis motion stage (Aerotech, Incorporated), providing 1-μm resolution, a block ($20 \times 15 \times 15$ μm) was scanned covering the fiber core potion with a width of 20 μm, defined as one femtosecond laser exposure scan. We altered the distance between the single laser scans, as the experiment went along, to avoid the grating effect, which might disturb the interference signal.

5 Results and Discussion

Figure 3 shows the initial interference spectrum and those after 10, 20, and 30-fs laser scans with laser pulse energy of 0.8 μJ. The large fringe visibility—the ratio of the size or amplitude of oscillations to the sum of the powers of the individual waves—indicated the high quality of the interference signals. Since each laser scan induced a small amount of energy loss, the fringe visibility of the interference signal reduced as the number of laser exposures increased. This is still an open topic; some groups employed the Kramers-Kronig relations to explain laser pulse properties and refractive index change.[18,19]

The interference spectrum shifts to the short wavelength as the number of laser scans increases. By tracing the interferogram shift, we calculated the changes of optical length based on Eq. (4). The results, as a function of the number of laser scans, are plotted in Fig. 4, where the measured data points fit nicely into a line with a slope of 6.9 nm per fs laser scan. The induced Δn was 3.45×10^{-4} based on Eq. (4).

To investigate the induced refractive index at alternative laser pulse energy, we repeated the previous experiments by varying the femtosecond laser pulse energy by adding or dropping ND filters. Figure 4 shows the change in fiber optical length as a function of the number of the laser scans with different pulse energy of 0.5, 0.6, 0.8, and 1 μJ. For comparison, the refractive changes induced by different pulse energy are 2.5×10^{-6}, 2.78×10^{-5}, 3.45×10^{-4}, and 8.95×10^{-4}, respectively. Obviously, the refractive index change induced by 0.5 μJ, approximately the refractive index modification threshold for fusion silicon ablation, is ignorable. The experiment revealed that pulse energy less than the refractive index modification threshold cannot pro-
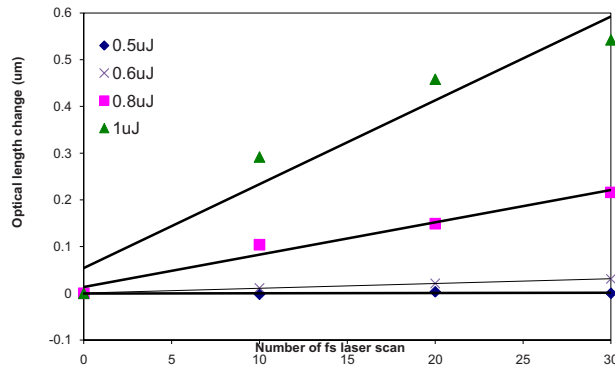
Fig. 4 The change in fiber optical length versus numbers of the laser scans.

duce an observable refractive index change, which we believe is because smaller pulse energy below the threshold is not able to significantly change the material thermal stresses, inducing refractive index modification. Still, it is an open issue that needs further verification and investigation.

6 Conclusion

We demonstrate a fiber inline IFPI-based measurement method to investigate the femtosecond-laser-induced refractive index change in an optical fiber core. The femtosecond-laser-induced refractive index change is found to be 2.5×10^{-6}, 2.78×10^{-5}, 3.45×10^{-4}, and 8.95×10^{-4} at different pulse energy levels 0.5, 0.6, 0.8, and 1 μJ, respectively. We believe accurate refractive index change values can help develop and design nondestructive femtosecond laser fabricated photonic devices.

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