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Deep ultraviolet femtosecond laser tuning of fiber Bragg gratings

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Abstract

A deep ultraviolet femtosecond laser operating at wavelength 258 nm was demonstrated to be effective in trimming fiber Bragg gratings in telecommunication fibers. A smooth tunable resonance wavelength shift of up to 0.52 nm has been observed, corresponding to a refractive index change of $\sim 5 \times 10^{-4}$ after an accumulated laser fluence of 63.3 kJ/cm^2 at a single pulse fluence of 124 mJ/cm^2. The ultrafast laser enhancement of ultraviolet photosensitivity response and modification of anisotropic index profile in silica fiber is a powerful technique to precise control of the performance of fiber Bragg grating devices for applications in optical filtering and polarization mode dispersion management.

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1. Introduction

Ultrafast lasers have distinct advantages that are favorable to materials processing [1–3], nonlinear optics [4], device fabrication and processing [5]. The benefits of strong localization of energy, increased controllability and reduced residual damage are attractive for revealing ultrafast processes, miniaturizing and integrating functional components and devices. Owing to the extremely short duration of the individual pulses, ultrafast lasers offer unparallel capabilities for utilizing nonthermally driven interactions, especially nonlinear optical processes, and reduced heat effects. As a result of the temporal compression of extremely high energy, almost any type of material, including large bandgap materials, can be processed and structurally altered micrometer size regions can be produced in the bulk material [6].

In this article, we investigate precise wavelength tuning of fiber Bragg gratings (FBGs) using femtosecond laser pulses. FBGs are one of the most important components in telecommunications with applications such as dispersion compensators and add/drop multiplexers [7,8]. Currently, hydrogen loading is applied in the fabrication of FBGs to improve the ultraviolet photosensitivity response of telecommunication fiber [9]. Thermal post annealing is required to outgas the residual hydrogen and to stabilize the FBG spectrum [10], which diminishes the process control owing to a variable resonance wavelength shift (~2 nm) and a reduced grating strength. Post ultraviolet-laser trimming of thermally annealed FBGs has therefore been proposed to precisely tune the final grating characteristics [11]. While such trimming has been most promising in high-germanium-content fibers, application in standard telecommunication fibers such as Corning SMF-28 (3% GeO_2) is scarce due to its inherently weak photosensitivity in the absence of hydrogen loading [12]. New technique

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to realize enhancement and controllable tuning of the photosensitivity is highly desired. Ultrafast lasers, with their prominent merits, show a great potential for this purpose. In this work, a deep ultraviolet femtosecond laser operating at a wavelength of 258 nm was used to realize the precise wavelength tuning of a FBG in standard telecommunication fibers (Corning SMF-28).

2. Experimental details

The single-mode fiber was pre-soaked with H_2 gas at 1900 psi for ten days at room temperature prior to FBG formation. The fiber Bragg grating was formed with 248 nm KrF laser and a phase mask, and then baked at 150 °C for 24 h to eliminate the residual hydrogen. For the post-process laser trimming, a 40 mm-long section of the fiber with the inscribed FBG was irradiated with femtosecond laser pulses. The ultrafast laser system consisted of a diode-pumped fiber oscillator, frequency-doubled Nd:YAG pump laser, and a Ti:sapphire regenerative amplifier (CPA-2010, Clark-MXR, Inc.) with a third harmonic generation system (STORC). The resultant output pulses had a maximum energy of 0.1 mJ at 258 nm and a pulse width of 150 fs. The pulse repetition rate was maintained at 1 kHz. A microscope objective was used to focus the Gaussian beam to 80-μm diameter spot. Samples were mounted on XY translation stages with a 0.1-μm step resolution for scanning along the fiber with a linear translation rate of 6 mm/min. The on-target peak intensity measured after the focusing objective was estimated to be ~825 GW/cm^2, which was well below the damage threshold of the glass material as evident from the microscopic study of the sample. The accumulated laser fluences were calculated on the total laser fluence gained through different scans. Refractive index changes and the device characteristics were monitored in-situ from the transmission spectra measured by an optical spectrum analyzer (Ando 6317B).

3. Results and discussion

The transmission spectra of the FBG during laser trimming showed the spectral shift ($\Delta\lambda$) towards longer wavelengths governed by an increase in the effective refractive index (Δn). Fig. 1 shows the evolution of the transmission spectra of a FBG formed by 248 nm KrF laser following uniform post exposure of the deep ultraviolet femtosecond laser at 258 nm with a single pulse fluence of 124 mJ/cm^2. The corresponding resonance wavelength shift of the transmission spectra is shown in Fig. 2(a). The initial FBG resonance wavelength λ_0 was at 1548.12 nm and gradually red-shifted with the post laser exposure at 258 nm. The resonance wavelength was shifted to 1548.64 nm, corresponding to a shift of 0.52 nm after accumulated laser fluence of 63.3 kJ/cm^2. The dependence of the resonance wavelength λ on the accumulated fluence F can be followed by the equation $\lambda = \lambda_0 + k \cdot F$, where k is the resonance wavelength shift coefficient indicating the effectiveness of changing the resonance wavelength of the FBG by the accumulated fluence of the femtosecond laser. In this case, the value for k is 8.6×10^{-3} nm/(kJ/cm^2). Fig. 2(b) shows the evolution of the grating strength of the FBG during the femtosecond laser trimming as a function of laser fluence. Trimming on a 28.8 dB grating indicated that the

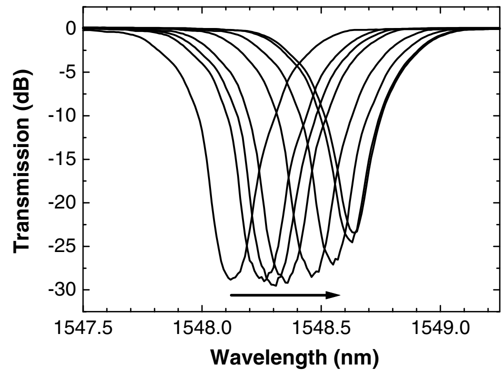

Fig. 1. Resonance wavelength shift in the transmission spectra of a FBG following uniform post laser exposure by a deep ultraviolet femtosecond laser at 258 nm. The spectra correspond to pristine FBG and the FBG after femtosecond laser exposure with accumulated fluences of 9.9, 19.8, 29.7, 39.6, 49.5, 59.4 and 63.3 kJ/cm^2 from left to right. The resonance wavelength shifts from initial 1548.12 to 1548.64 nm at 63.3 kJ/cm^2.

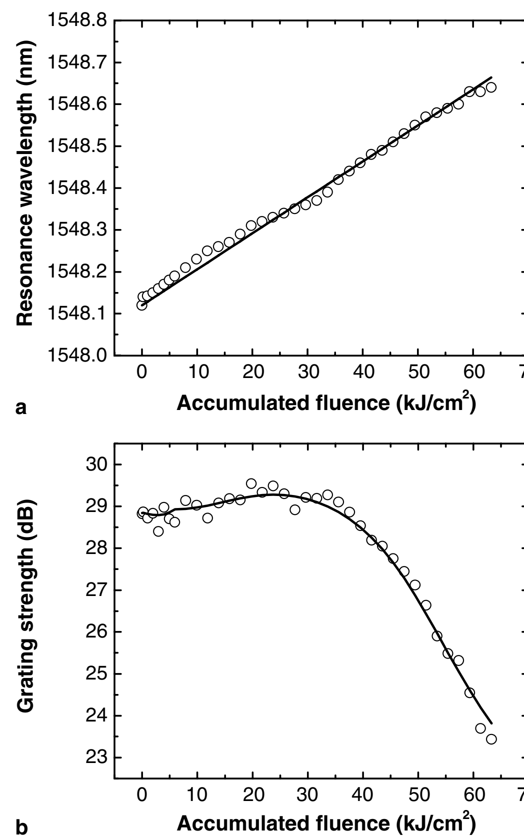

Fig. 2. Resonance wavelength: (a) and grating strength (b) of the FBG as a function of accumulated femtosecond laser fluence. The single pulse fluence was 124 mJ/cm^2.

reflectance of the grating kept the original value (∼99.9%) during the initial trimming stage with an accumulated fluence of up to 35 kJ/cm^2 followed by a decrease with further increase in the accumulated fluence. The reflectance decreased to ∼99.5% after an accumulated laser fluence of 63.3 kJ/cm^2.

Femtosecond laser trimming also resulted in the change in the refractive index over the entire fiber core (DC index modulation) as well as the change in the index modulation of the grating (AC index modulation). The values of DC index modulation Δn_{DC} can be evaluated from the corresponding shifts in the resonance wavelength of the transmission spectra using the equation $\Delta n_{DC} = n \cdot \Delta\lambda/\lambda$, where n is the effective refractive index of the fiber, λ is the resonance wavelength of the FBG, and $\Delta\lambda$ is the resonance wavelength shift [11]. The DC index modulation Δn_{DC} is shown in Fig. 3 as a function of accumulated laser fluence. An unsaturated Δn_{DC} value of about 5.0×10^{-4}, corresponding to the observed spectral shift ($\Delta\lambda$) of 0.52 nm at an accumulated fluence of 63.3 kJ/cm^2, was noted. For comparison, trimming of hydrogen-free standard fiber (SMF-28) with pulses from a 10-ns, 248-nm, KrF laser under an accumulated fluence of 45 kJ/cm^2 (400 mJ/cm^2 single pulse fluence) yielded only a change of 2.0×10^{-5} in the refractive index [13]. Index modulation with a magnitude of 3.6×10^{-4} at an accumulated fluence of 45 kJ/cm^2 under the 258 nm femtosecond laser exposure indicates 18 times the corresponding modulation induced by the KrF laser exposure at the same accumulated fluence, highlighting the effectiveness of the ultrafast laser-induced refractive index changes. The wavelength shifts achieved here indicate the possibility to realize tuning of the grating resonance wavelength to ±1 pm with an ultrafast laser. Compared to trimming with KrF laser, a significant photosensitivity enhancement was observed. The phenomenon can be attributed to the short-pulse effects from the femtosecond lasers, which results in significant increases in the changes in the glass structures and formation of point defects. Although the microscopic mechanism responsible for the fiber photosensitivity has not been fully understood, the densification model and the color center model are the two main models currently available to explain the mechanisms of photosensitivity.

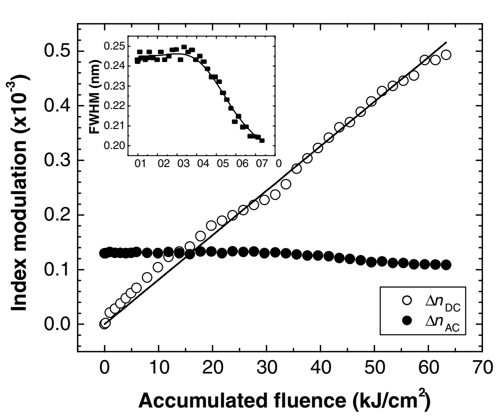

Fig. 3. DC and AC index modulations of the FBG as a function of accumulated femtosecond laser fluence. The inset is the change of the FWHM grating bandwidth. The single pulse fluence was 124 mJ/cm^2.

The dependence of AC index modulation on the accumulated laser fluence is also shown in Fig. 3. The AC index modulation amplitude Δn_{AC} is related to the grating peak reflectance R by the equation: $\Delta n_{AC} = \lambda \cdot \tanh^{-1}(R^{1/2})/(\pi \cdot L)$, where L is the grating length [14]. For a highly reflective grating, the reflectance does not give a very sensitive measure of Δn_{AC} However, the FWHM grating bandwidth $\Delta\lambda_{FWHM}$ is approximately linearly proportional to the AC index modulation Δn_{AC} The values of Δn_{AC} can be estimated from the equation $\Delta n_{AC} \approx \Delta n_{AC0} \cdot \Delta\lambda_{FWHM}/\Delta\lambda_{FWHM0}$, where Δn_{AC0} and $\Delta\lambda_{FWHM0}$ are parameters of the grating before laser trimming. The inset in Fig. 3 gives the change of the FWHM grating bandwidth $\Delta\lambda_{FWHM}$ as a function of the accumulated laser fluence. The $\Delta\lambda_{FWHM}$ values were about 0.24 nm for low accumulated laser fluence up to 30 kJ/cm^2 and gradually decreased to about 0.20 nm at a fluence of 63.3 kJ/cm^2. The corresponding AC index modulation Δn_{AC} shows slight decrease at large accumulated fluence resulting in the decrease of the reflectance, which is likely due to a slight washing out of the grating.

The UV femtosecond laser trimming introduced herein offers significant photosensitivity enhancement compared to that realized with nanosecond pulse lasers. Laser-induced modified structures have been suggested as the mechanism causing refractive index changes induced by infrared (∼800 nm) ultrafast laser radiation [1,5,15–17]. In these studies, significantly large peak intensities varying from 10^{12} to 10^{18} W/cm^2 were used to alter the refractive indices [1,5,15]. Although index changes with a magnitude up to 10^{-2} have been reported, the optical damages also induced large optical losses, adding limitations to the applications of photonic device fabrication based on infrared ultrafast lasers. It should be noted that the peak intensities used in the present experiments were substantially lower, e.g., at ∼825 GW/cm^2, for the deep ultraviolet femtosecond laser and no noticeable increase in the optical loss was found at these intensities. Two-photon absorption might be responsible for the observed index change. These results are consistent with previous work on the inscription of gratings by UV femtosecond laser radiation [18].

In order to understand the polarization properties of the FBGs after fs laser trimming, detailed characterization of the polarization mode dispersion (PMD) was performed. PMD in optical fiber communication networks, which results in pulse broadening and high bit error rate (BER), is one of the main factors that limit the capacity of ⩾40 Gb/s optical networks. Photonic components with both small and large PMD are needed in applications for polarization control and compensation. PMD characteristics of photonic components are fully described by the polarization mode dispersion vector in Poincaré sphere, whose orientation is parallel to the output principal states of polarization and whose magnitude is the differential

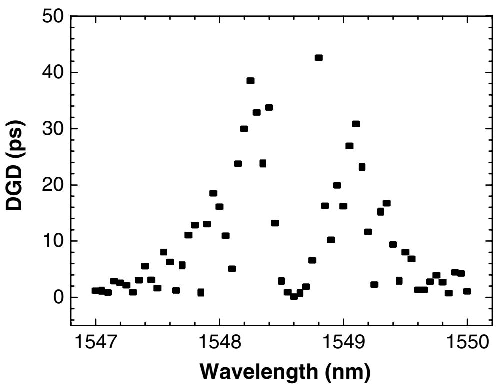

Fig. 4. Differential group delay (DGD) as a function of wavelength for the FBG after uniform femtosecond laser exposure with an accumulated fluence of 63.3 kJ/cm^2 by the femtosecond laser at 258 nm.

group delay (DGD). PMD is defined as the mean or rms value of the DGD averaged over wavelength. DGD of fiber Bragg gratings is due to both intrinsic and photon-induced fiber birefringence. Agilent tunable laser source 8164A and Tektronix/Profile polarization analysis system PAT9000B were used to measure the DGD. Fig. 4 shows the DGD of the FBG after uniform laser exposure with an accumulated fluence of 63.3 kJ/cm^2 by the ultrafast femtosecond laser at 258 nm. DGD values of ~42 ps can be found in the resonant wings, which is about twenty-fold larger than the corresponding value of 1–3 ps for the FBG we fabricated by the KrF laser prior to femtosecond laser trimming. Photon-induced birefringence can be attributed to the orientation of the trimming beam polarization or the asymmetry of the index change in the transverse plane, where one side of the core was exposed more to the laser beam compared to the other side for the side-writing technique used in these experiments. A reduction of the birefringence by more than 75% was observed when the side-writing process was replaced by dual-exposure method [19]. The advantage of our technique by using femtosecond laser to trim the FBGs is that we can precisely tune the magnitude of birefringence when we control the laser fluence. Besides the controlling of the laser fluence, other techniques, such as adjustment of exposure configuration [19], or combinations of these methods, provide controllable magnitudes of birefringence in germanosilicate optical fibers, which offers new opportunities for birefringence compensation and polarization management photonic component fabrication.

4. Conclusions

We demonstrate that a deep ultraviolet femtosecond laser is a valuable tool for precise tuning of fiber Bragg gratings. Trimming with femtosecond laser pulses at 258 nm on a fiber Bragg grating achieved a refractive index change of $\sim 5.0 \times 10^{-4}$ at lower laser fluence, indicating the possibility to achieve precise femtosecond laser tuning of the grating resonance wavelength to ±1 pm. Trimming of FBGs with the ultraviolet femtosecond laser at 258 nm presents a photosensitivity enhancement by a factor of 18 over what can be achieved with a nanosecond KrF laser at 248 nm. This fs laser trimming technique induced approximately twenty-fold larger birefringence than the corresponding value in the FBG, presenting a powerful method for birefringence compensation and polarization management. The ultrafast laser drives strong interactions in fiber Bragg gratings and offers an attractive new approach to precisely trim permanent and stable gratings that augment present-day manufacturing technology for applications in telecommunications and sensor systems.

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