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DIRECT FEMTOSECOND INSCRIPTION OF FIBER BRAGG GRATINGS.

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ABSTRACT.

Direct, point-by-point inscription of fiber Bragg gratings by infrared femtosecond laser is reported. Using this technique, highly reflective gratings can be rapidly inscribed in standard, untreated fiber. Thermal studies demonstrate increased thermal stability compared to the UV-inscribed gratings.

INTRODUCTION.

Femtosecond laser inscription of photonic devices has been a subject of active research work in recent years. The technique proved to be useful for fabrication of a variety of devices, such as waveguides [1], couplers [2], photonic crystals [3] and data storage prototypes [4].
Recent reports demonstrate the feasibility of inscribing high quality, strong fiber Bragg gratings (FBG) using a femtosecond laser and a phase mask [5,6] and a point-by-point method [7].

Growing interest in femtosecond laser inscription is based, among other factors, on the fact that the physical mechanism of this process is essentially different to that of the UV inscription. It is commonly understood that the refractive index change in femto-inscribed glass structures is initiated by formation of localized plasma in the bulk of the material causing subsequent restructuring of the latter. The process involves highly nonlinear photo-ionization, thus requiring high intensity of light which can only be achieved in a tightly focused laser beam. Previous reports indicate that, contrary to UV inscription, femto-inscription does not necessarily depend strongly on formation of defects [8]. As a result, this method does not require photosensitized fibers, furthermore the decay of defects caused by thermal annealing is likely to be insignificant in femto-inscribed structures. Hence, femtosecond inscription should produce structures with improved thermal robustness compared to the UV-written structures.

Point-by-point techniques had been previously used to inscribe FBG and LPG by using UV light sources [9]. The main advantage of the method is the flexibility in altering the grating parameters. At the same time, the practicality of the direct UV writing of fiber gratings is very limited, mainly due to the major disadvantages, such as long processing time, short grating length, poor control of the grating uniformity.

In this paper, we demonstrate the fabrication and investigate the properties of FBGs produced by direct, point-by-point femtosecond laser writing. The proposed method utilizes the unique specific characteristics of femtosecond inscription in order to eliminate the above disadvantages and thus to allow fast, accurate alignment and inscription of highly retro-reflective FBG using a point-by-point technique. In particular, it presents a remarkably short processing time of less than 60 seconds per grating and does not require a phase mask.

INSCRIPTION METHOD.

An amplified laser system, operating at a wavelength of 800nm, was used in the inscription procedure. This laser system produced 150fs-long pulses at a repetition rate of 1 kHz, reaching a maximum average power of 1W. The experimental set up is shown in Figure 1. The fiber was placed on a ~~high-precision, two-coordinate translation stage~~ with 10nm resolution. The stage moved at a constant speed along the fiber axis, translating the fiber with respect to the focal point of the beam.

The amplified spontaneous emission from a broadband light source (EDFA) was coupled into the fiber and used as a reference to monitor the inscription process in real time. Reflection and transmission spectra were measured by two optical spectrum analyzers. After the inscription, the gratings were characterized using a high-performance analyzer with a resolution of 5pm.
A X100 (NA-0.65) microscopic objective was used to focus the laser beam into the fiber core. Due to the high nonlinearity of the process, beam energy was only absorbed in the vicinity of the focal point. The beam size in the focal point was estimated to be 1μm approximately.
The grating was inscribed by moving the fiber at constant speed along the focal point of the focused beam. The pitch size was determined by the ratio of the stage speed to the pulse repetition rate.
Gratings were inscribed in non-photosensitive, standard telecommunications fiber with a core diameter of 8μm, and dispersion shifted fiber (DSF) with a core diameter of 6μm

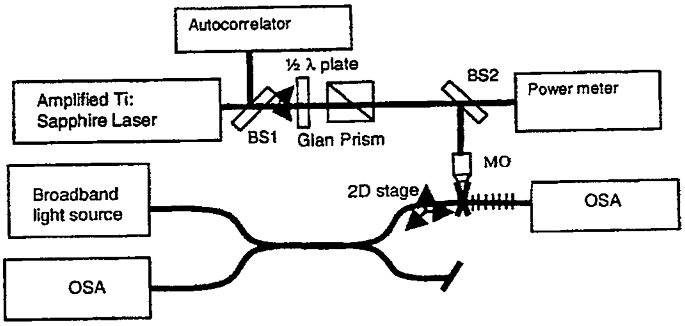

Figure 1. Experimental set-up for femtosecond inscription of FBG using a point by point technique. MO - microscopic objective, ½λ - half-wave plate and BS - beam splitter.

PROPERTIES OF THE FEMTO-INSCRIBED FBGs.

The grating response is determined by the Bragg resonance condition, $m\lambda_B=2n_{eff}\Lambda$, where λ_B is the resonant wavelength, n_{eff} is the effective refractive index of the core, Λ is the grating pitch and m is the resonance order. In the experiment, each pitch of the grating was produced by a single laser pulse. It is evident that in order to attain high quality of the grating it is necessary for the beam waist to be smaller than the grating pitch.
We inscribed and compared structures with the pitch sizes of 0.535μm (writing speed of 0.535mm/s), 1.07μm (1.07mm/s) and 1.605μm (1.605mm/s), corresponding to the gratings of first to third order for an operating wavelength of 1550nm. Gratings were approximately 30mm long.

Measured transmission spectra for the above gratings are shown in Figure 2. One can see that the second order grating shows the strongest response. This is in line with an earlier study of the gratings produced by femtosecond writing with a phase mask [3]. Lower reflection of the first order grating is likely to be a result of overlapping of adjacent pitches. At the same time, we believe that the increased efficiency of the higher orders is an attribute of the femtosecond inscription process, as this efficiency is usually low in the UV-inscribed devices. The process only occurs in a localized region with very high intensity of light, created by a tightly focused laser beam. Hence, modulation of refractive index in the femto-inscribed structures is localized in small spots defined by the focusing geometry. Localization of refractive index modulation is further emphasized by the nonlinear nature of the process. Consequently, the shape of the inscribed features does not reproduce linearly the intensity profile of the laser beam, allowing, in principle, the resolution beyond the diffraction limit. The profile of refractive index modulation in femto-inscribed gratings along the fiber axis is therefore represented by certain peaks, unlike the UV inscribed gratings which have a smooth, similar to sinusoidal, modulation profile. As a result, the, higher order components in the spectra of femto-inscribed FBGs are more pronounced than those in the UV-written devices.
Another peculiar feature of the gratings inscribed by a focused beam is the tight confinement of the modified material within a small volume with a cross section much smaller that the fiber core area. This is illustrated by Figure 3 which shows the side view and cross-section view of a second order grating obtained with a phase-sensitive microscope. It is clearly seen in the images that the grating occupies only a fraction of the core volume.

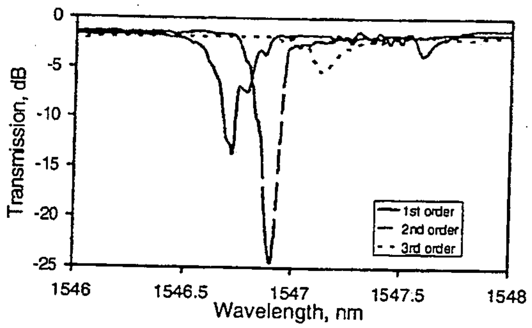

Figure 2. Transmission spectra of the first order (solid line), second order (long-dashed line) and third order (dashed line) gratings inscribed in SMF using a X100 objective. Second order gratings exhibit the strongest reflection.

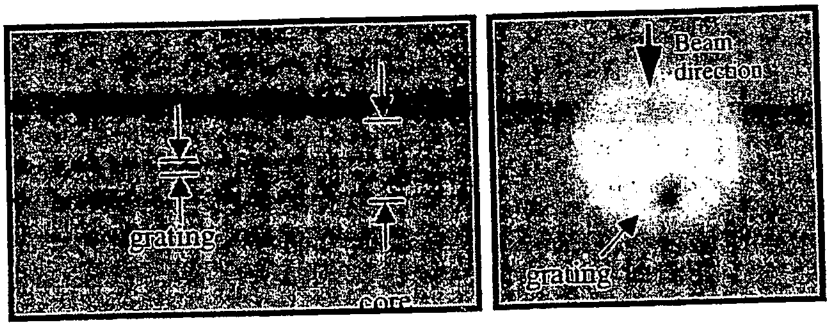

Figure 3. Microscopic images of a second order grating with the pitch size of 1.07μm pitch, inscribed in a dispersion shifted fiber (core diameter of 6μm). (a) side view; (b) cross-section view.

The FWHM linewidth of the grating resonance typically ranged between 0.1nm and 0.2nm and did not show a distinct dependence on the grating order. Nonresonant (out of band) losses were typically less than 1.0 dB.

Significant coupling to the cladding modes was observed in a broad spectral window spreading towards short wavelengths in all the gratings, as illustrated by Figure 4a. Cladding mode coupling is noticeable as far as 50nm away from the resonant frequency, coupling to the cladding modes yielded attenuations of approximately 1dB after application of index match fluid or recoating of the fibre.

The gratings also showed significant polarization dependence (Figure 4b) which can be explained by a contribution from two factors: off-center location of the grating structure and the intrinsic birefringence of the structure induced by the inscription process. The spectral separation between orthogonal polarizations was typically in range between 20pm and 40pm, corresponding to the birefringence of 3.5×10^{-5} approximately, which is much larger than that in the UV inscribed gratings. We observed that birefringence could be increased by inscribing the grating closer to the core-cladding boundary.

The strong coupling to the cladding modes can be also attributed to the tight confinement and asymmetric position of the grating within the core.

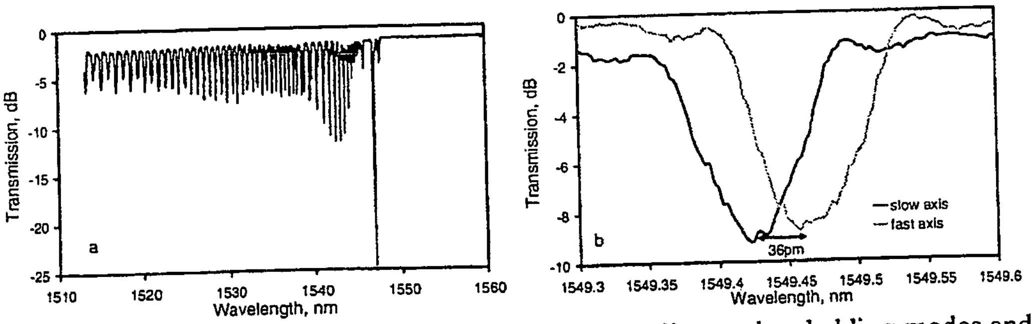

Figure 4. Transmission spectra showing (a) coupling to the cladding modes and (b) the strong birefringence of the grating.

In order to analyze the thermal properties of femto-inscribed FBGs, three similar samples with reflectivity ranging from 80% to 90% were placed in an oven and annealed at constant temperatures of 500°C, 700°C and 1000°C, respectively, for a period of 24 hours. The grating spectra were monitored every 30 minutes by an analyzer with a resolution of 5pm. After the annealing period, the oven was switched off and the gratings were allowed to cool down to room temperature. Three UV inscribed FBGs were used as control samples. These were inscribed in hydrogenated fiber by using a 90mW beam from a CW laser operating at a wavelength of 244nm. After inscription, the FBGs were post-processed by annealing at 80°C for 24 hours. The resultant reflectivity of control samples before the tests was in excess of 98%. The three control samples were subjected to the procedures of annealing and measurement identical to the ones applied to the femto-inscribed samples as described above.

Measured evolution of the grating reflection is presented in Figure 5. Femto-inscribed gratings showed a significantly improved thermal stability compared to the hydrogenated, UV inscribed ones. The UV inscribed sample experienced a significant degradation at 500°C and was rapidly erased at 700°C, whilst the femto-inscribed FBG did not show any signs of rapid decay up to 1000°C. Comparison with the similar studies from literature shows that the thermal stability of the femto-inscribed FBGs is better than that of common Type I and Type IIA gratings and is similar to the stability of the Type II gratings, based on optical damage [10].

The grating reflectivity after cooling down to the room temperature was greater than that at the corresponding high temperature. This could be explained by relaxation of mechanical stress created in the outer regions of the modified area. Similar annealing behavior has been previously observed femto-inscribed photonic crystals [11]. At lower temperature levels of 500°C and 700°C, this effect dominated in femto-inscribed gratings and the resulting reflectivity actually increased after the annealing-cooling cycle in those gratings.

The range of specific applications for these devices is not yet defined; potential applications of the femto-inscribed FBG can emerge from some of their exclusive characteristics described above as well as from the possibility to perform laser inscription in materials or situations where the UV processing is not possible. Currently, inscription in wide range of materials is being studied. High thermal stability can be used to develop thermal sensors suitable for exploitation at temperatures inaccessible to the UV inscribed gratings.

Since the grating structure is significantly smaller than the core, we have recently demonstrated the possibility to fabricate superimposed, but physically non-overlapping grating structures by using inscription in different segments of the fiber core. The technique is in principle suitable for inscription of as many as several tens of gratings in the same length of fiber without effects of blurring of the grating pitch caused by overwriting.

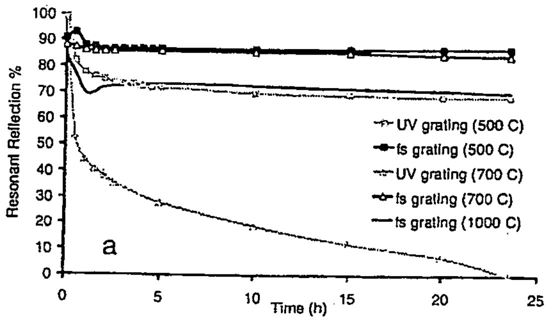

Figure 5. Isothermal evolution of femto-inscribed (grey) and UV-inscribed (black) gratings during a 24-hour annealing period at given temperatures.

CONCLUSIONS.

Fabrication of highly reflective FBG by using direct, point-by-point femtosecond laser inscription has been demonstrated. Non-photosensitive single mode fiber was used in this experiment. First, second and third order gratings have been produced. The inscribed structures possess several peculiar properties, such as tight confinement of the structure in a fraction of the core volume, increased birefringence and thermal stability at temperatures up to 1000°C.

REFERENCES.

1. KM Davies, K Miura, N Sugimoto and K Hirao, Writing waveguides in glass with a femtosecond laser, Optics Letters, 1729, Vol. 21, no.21 (1996).
2. AM Streltsov and NF Borrelli, Fabrication and analysis of a directional coupler written in a glass by nanojoule femtosecond laser pulses, Optics Letters, 42 Vol. 26, no. 1 (2001).
3. S. Juodkazis, S Matsuo, H Misawa, V Mizeikis, A Marcinkevicius, HB Sun, Y Tokuda, M Takahashi, T Yoko, J Nishii. Application of femtosecond laser pulses for microfabrication of transparent media. Applied Surface Science, 8095, 1-5, (2002).
4. E. N. Glezer, M. Milosavljevic, L. Huang, R. J. Finlay, T.-H. Her, J. P. Callan, E. Mazur, Three-dimensional optical storage inside transparent materials, Optics Letters, Volume 21, Issue 24, 2023, (1996).
5. Mihailov, S. J., Smelser C.W., Grobnic, D, Walker, R.B., Lu, P., Ding, H. and Unruh, J.: "Bragg gratings written in All-SiO2 and Ge-Doped core fibers with 800 nm femtosecond radiation and a phase mask" J. Lightwave Techn., 22, pp. 94-100, (2004).
6. Dragomir, A., Nikogosyan, D.N., Zagorulko, K.A., Kryukov, P.G., Dianov, E.M.: "Inscription of fiber Bragg gratings by ultraviolet femtosecond radiation", Opt. Lett., 28, pp 2171-2173, (2003) .
7. A Martinez, M. Dubov, I.Y. Khrushchev, I. Bennion, "Direct writing of fibre Bragg gratings by femtosecond laser", Electron. Lett. 40, 1170-1172, (2004).
8. A. M. Strelsov and N. F. Borrelli, "Study of femtosecond laser written waveguides in glasses", J. Opt. Soc. Am. B, 19, 2496-2504, (2002).
9. Malo B., Hill K.O., Bilodeau F., Johnson D.C. and Albert J.: "Point-by-point fabrication of micro-Bragg gratings in photosensitive fibre using single excimer pulse refractive index modification techniques", Electron Lett., 29, pp.1668-1669, (1993).
10. A. Othonos and K. Kalli "Fibre Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensors", Artech House Books, (1999).
11. H.B. Sun, Y. Xu, S. Juodkazis, K. Sun, M. Watanabe, S. Matsuo, H. Misawa and J. Nishii, "Arbitrary-lattice photonic crystals created by multiphoton microfabrication" Opt. Lett. 26, 325-327, (2001).