Annealing Properties of Femtosecond Laser Inscribed Point-by-point Fiber Bragg Gratings

Graham D. Marshall and Michael J. Withford

Centre for Ultrahigh bandwidth Devices for Optical Systems, Centre for Lasers and Applications, Department of Physics, Macquarie University, North Ryde, Sydney, NSW 2109, Australia
graham@ics.mq.edu.au

Abstract: The annealing properties of point-by-point inscribed fiber Bragg gratings written at different pulse energies is examined. Three annealing modes are observed due to the complex interaction of regions modified by different writing laser beam intensities.

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1. Introduction

The point-by-point method of Bragg grating inscription has become a versatile technique applicable to both optical fibers [1] and embedded waveguides [2]. By rapidly translating a sample through a tightly focused femtosecond laser beam grating periods can be individually inscribed on a point-wise basis. There are several advantages of this technique over the more common phase mask methods; firstly the period of the grating can be continuously adjusted since it is simply determined by the ratio of the translation speed to the laser pulse frequency but most importantly the process does not require any native photosensitivity of the optical medium. The high intensity generated by a focused femtosecond laser is sufficient to enable light-matter interactions to take place though a range of non-linear processes. These processes result in highly localized changes in material refractive index and morphology to the extent that first, second and higher order Bragg grating structures (with periods of approximately 500 nm, 1 µm and greater) can be written in fibers using IR (800 nm) laser sources. Another important property of these gratings is their behavior at significantly elevated temperatures where, following suitable writing conditions, they may remain stable beyond the point at which Type-I UV inscribed gratings will erase. This is of particular importance in temperature sensor and high power fiber-laser applications [3] where FBGs are required to endure long periods of time at elevated temperatures.

In this article we examine the intensity dependence and annealing behavior of point-by-point (PbP) written FBGs in a parametric study. We establish that there are threshold processes leading to grating formation that are analogous to phase mask written IR femtosecond laser gratings [4], however because of the complexity of the PbP case there exists a further anomalous annealing property of PbP written gratings. Finally we use these results to elucidate some of the morphology of the grating structures and draw comparisons with previous work.

2. Experiment

Fiber Bragg gratings were inscribed in un-sensitized Corning SMF-28e optical fiber using an 800 nm 120 fs transform limited laser operating at 1 kHz. The fiber was stripped of its polymer jacket and the center of the fiber core was aligned with the focus of a 0.8 NA 20× oil immersion microscope objective. The fiber was translated by an air-bearing stage. In a single piece of fiber several C-band 2nd-order gratings of length 10 mm were written with a distance of 2 mm separating each grating. Each grating was written at a different wavelength and laser intensity. The gratings were arranged in wavelength such that a C-band source and detector could probe all the gratings at room temperature. Once the grating array was written it was
inserted into a tube furnace whereupon it was exposed to an isothermal annealing process. The fiber was heated to 1000°C in 50°C steps with a step interval of 30 minutes. Throughout the fabrication and annealing process the insertion loss of each grating was analyzed using a swept wavelength source.

3. Results

The dependence of grating depth versus writing laser energy observed during grating manufacture is shown in Fig. 1. The on-resonance grating loss exhibits a monotonic increase with writing laser energy. There exists a clear threshold in the writing pulse energy at 120 nJ; above this value significantly stronger gratings are written and the gradient of the trend line increases approximately 20 fold. The dependence of the out of resonance insertion loss of the gratings follows exactly the same relationship.

![Fig. 1. Dependence of the depth of 10 mm long 2nd-order PbP written grating on the writing laser power. The laser power is measured at 1 kHz repetition rate therefore 100 µW corresponds to a pulse energy of 100 nJ. The arrows on the data points indicate the trend in grating strength change during the annealing process as shown in Fig. 2.](image)

The threshold in pulse energy of 120 nJ corresponds to an approximate peak intensity of $2 \times 10^{14}$ W cm$^{-2}$.

Following manufacture the grating array was isothermally annealed to 1000°C. At the end of each 30 minute period following a 50°C increase in temperature the strength of the gratings produced with laser energies above 100 nJ was recorded. These results are presented in Fig. 2. At 110 nJ and all lower pulse energies the gratings erase rapidly with increasing temperature in much the same manner of UV laser inscribed Type-I gratings. At 800°C the 110 nJ grating has completely been erased. However the 120 nJ and 130 nJ gratings monotonically increase in strength with temperature up to the maximum temperature of 1000°C. The strength of the gratings written with pulse energies of 140 nJ to 160 nJ show a net decrease with increasing temperature. These trends are indicated in Fig. 1 in the arrows added to each data point. An interesting observation of the data in Fig. 2 is that the strength of all the gratings written with pulse energies of 120 nJ and above all tend towards the same value of approximately 7.5 dB. This may be key in understanding the microscopic structure of the gratings as will be discussed in the following section.
4. Discussion and Conclusions

There exist three distinct annealing behaviors belonging to the gratings studied here. In the first, the low pulse energy regime, gratings are written that can be erased with moderate temperatures (with complete erasure at 800°C) and are akin to Type-I UV written gratings. This is in accordance with previous reports [4] on the thermal stability of IR femtosecond gratings written using a phase mask. In a narrow band of pulse energies, the moderate pulse energy regime, grating strength is observed to increase with annealing up to 1000°C. This is caused by an increase in the refractive index contrast of the grating periods and could be attributed to the existence of a central localized and temperature hardy region of increased refractive index surrounded by a region of a Type-I like material. As the annealing temperature increases so this Type-I like region erases thereby increasing the contrast in the grating and thus its strength. We postulate that in the higher pulse energy regime, at pulse energies of 140 nJ and above, the region of Type-I modified material (both in between periods and now in the surrounding region) contributes significantly to the grating strength and dominates over the grating’s periods’ central regions. As these regions of Type-I refractive index change anneal out so the grating’s strength is determined by the effect of the periods’ central regions only. This structure accounts for the tendency of the gratings to gravitate under annealing (and erasure of Type-I change) to the same strength regardless of writing pulse energy. Isolated aspects of these behaviors have been alluded to in previous reports however this parametric study provides evidence of a complex combination of the various processes and resulting material changes that exist in PbP written gratings. Further experimental results including long term lifetime studies, SEM and optical microscopy images will be presented.

5. References