Highly refractive index sensitive femtosecond laser inscribed long period gratings

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ABSTRACT

The distinct behaviour of femtosecond laser inscribed long period gratings, with a non-uniform index perturbation within the optical fibre core, has been studied experimentally. The non-uniform laser-induced perturbation results in light coupling from the core mode to a greater number of cladding modes than is the case with their UV laser inscribed counterparts, and this is made evident from the surrounding refractive index (SRI) grating response. Femtosecond inscribed long period gratings are shown to simultaneously couple to multiple sets of cladding modes. A 400µm LPG is shown to result in attenuation peaks that have both blue and red wavelength shifts over a 1250nm to 1700nm wavelength range. This gives rise to SRI sensitivities far greater than anything achievable by monitoring a single attenuation peak. The maximum sensitivity produced by monitoring a single attenuation peak was 1106nm/RIU, whereas monitoring opposing wavelength shifts resulted in a significantly improved sensitivity of 1680nm/RIU.

Keywords: Femtosecond laser, Long period grating, Refractive index

1 INTRODUCTION

UV inscribed long period gratings (LPGs) have been extensively used for measuring multiple sensing parameters. The foremost inscription method has relied on focused UV laser irradiation into a germanium doped and hydrogen loaded optical fibre core. This method, although efficient, is limiting since only germanium doped fibre can be utilized, and also time consuming, because the fibre needs hydrogen loading to increase its photosensitivity. There is also the problem of long-term stability, as even below 100°C there is grating quality degradation[1]. Femtosecond inscription does not require any special fibre pre-treatment relying on a different method for the refractive index change. The induced index change has the possibility of being far more thermally stable over a broader temperature range, compared to UV induced gratings. Also, with the inscription procedure being focused at a location in the core rather than the entire core (as with UV inscription) femtosecond LPGs have a far greater polarisation response and the ability to couple to further sets of cladding modes, compared to the LP_{0m} which the UV inscription technique is essentially bound. Various periods of LPG were inscribed in the core of SMF-28 optical fibre and their SRI and polarisation response were investigated.

2 THEORY

Typically, an UV LPG grating is inscribed into the fibre core using a point by point inscription method. Doing so produces a uniform periodic index perturbation throughout the core of the photosensitive fibre. In coupled mode theory, the light travelling through the fibre core is assumed to be linearly polarised thus simplifying the calculations, whilst maintaining the key results. Bound by this approximation, as there is no azimuthal dependence within the fibre core, the UV LPG will only couple to cladding modes of azimuthal order 1 [2]. Femtosecond inscribed gratings have a far smaller focal point compared with UV inscribed gratings, and induce a local index change in a small section of the fibre core. Much as small and large angle tilted gratings there is now angular and polarisation dependence on the femtosecond laser inscribed gratings. Mathematically, the coupling efficiency between two modes has an extra term, when coupling between all azimuthal modes becomes possible[2].

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$$\int_{0}^{2\pi} e^{j(l-1)\phi} d\phi = 2\pi\delta_{l1} \tag{1}$$

As a result, the small containment of femtosecond inscribed grating and the localised refractive index (RI) change associated with it has two different properties compared to the uniform RI change throughout the core of UV laser inscribed gratings. Firstly, a polarisation dependency arises as different polarisations of light will see the RI perturbation differently. Secondly, the azimuthal dependence now means that the cladding mode coupling is not limited to LP_{1l} but can now couple to multiple sets of cladding modes LP_{ml}. For sensing, this opens up the possibility of coupling to more sensitive cladding modes than are possible compared with standard UV inscribed grating devices.

3 INSCRIPTION AND CHARACTERISATION METHOD

The LPGs were inscribed into the core of standard SMF-28 using a femtosecond laser system with a repetition rate of 100kHz, emitting 300fs pulses at a wavelength of 1035nm. A Mitutoyo microscope objective (with a magnification of 50 and a numerical aperture of 0.40) was used to focus the laser beam into the fibre. To focus the laser energy into the fibre core we optimize the characteristic plasma signal that is generated. A pulse picker selected pulses for a 1 kHz repetition rate and producing laser energies < 3.5µJ/pulse at the laser exit, of which 10% reaches the fibre. A computer controlled stage and synchronised shutter were used to produce the typical LPG stepped RI perturbation. Several LPG periods were investigated and a period of 400µm gave the highest sensitivity, as reported here. The LPGs were then, in turn, connected to a broadband light source, via a polariser, polarisation controller and then to an OSA. Due to the polarisation response of the gratings, all fibre patch cords were fixed to minimise polarisation drift. The grating section was placed on a metal 'v'-grooved plate that acted as both a heat sink and way of ensuring the fixed location of the grating during interrogation. The polarisation response was optimised for transmission through changing the input light polarisation and the wavelength spectrum was recorded in air. The LPG was then immersed in several certified RI liquids, from Cargille, ranging from 1.33 to 1.444. Once immersed, the transmission spectrum was recorded and the fibre was subsequently cleaned thoroughly using ethanol and the spectrum in air was compared to before and after oil immersion. The process was then repeated to evaluate the response to different RI liquids up to a RI-value of 1.444.

4 RESULTS

The location of the femtosecond induced index perturbation was examined using a microscope and the recorded images are shown in Figure 1. The images show that the index perturbation is ~ 2µm from the core cladding interface and the measured period is close to that of the design. Through changing the input polarisation of light, the transmission spectrum could be optimised for multiple attenuation peaks for this 400µm LPG. The transmission spectra for the LPG in air and immersed in a RI liquid 1.444 were recorded and are plotted in Figure 2(a) (b), respectively.

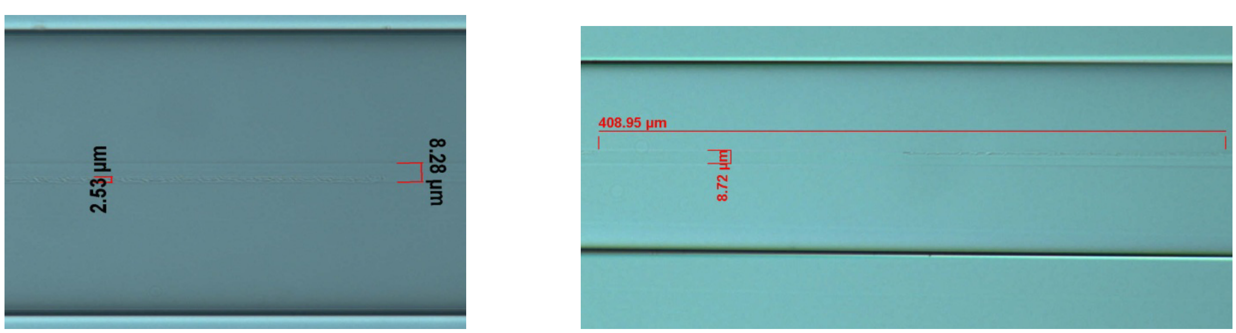


Figure 1. Showing the location femtosecond index perturbation within the core of the period of the inscribed LPG

In air there are approximately 2 strong and 3 weak attenuation peaks exhibited, whereas when the LPG is immersed in RI liquid 1.444, two strong peaks remain with two weak ones. This suggests that the effective indexes of the cladding modes associated with them are higher than 1.444, and that the modes being coupled to are lower order. If the LPG was UV inscribed the attenuation peaks would all experience the same wavelength shift with increasing surrounding refractive index (SRI). However, this is not the case for femtosecond LPG's as they couple to multiple sets of cladding modes simultaneously.

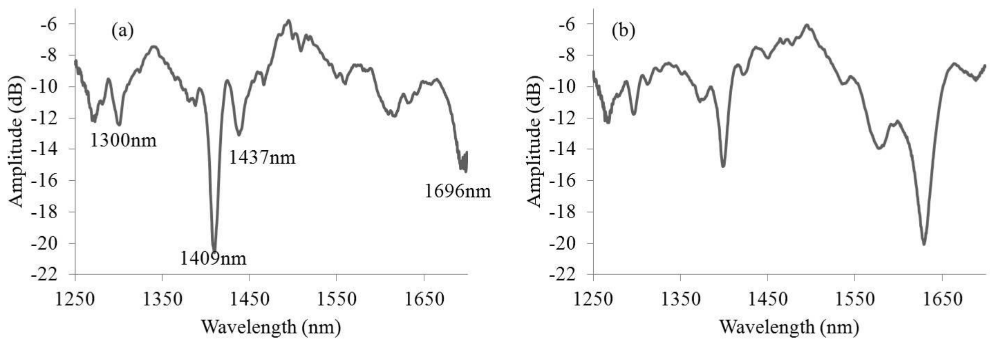


Figure 2. The transmission spectra of the femtosecond induced LPG of period 400μm in (a) air and (b) a liquid of SRI 1.444

The multiple attenuation peaks responses of the 400μm LPG to increasing SRI were monitored and calculated for the four labelled attenuation peaks shown in Figure 2(a) and the results are plotted Figure 3. The spread of sensitivities is very large with the maximum wavelength shift from air to a SRI 1.424 being 69.3nm for the attenuation peak at 1409nm in air, with the minimum being 1.7nm. With standard UV induced gratings, coupled modes that produce attenuation peaks in the wavelength range from 1250nm to 1700nm for a fixed period of LPG have sensitivities that are similar to one another; in contrast to the femtosecond inscribed LPGs. This offers evidence that the femtosecond LPG is coupling to different sets of cladding modes, explaining the large variation in sensitivities between attenuation peaks. The 400μm femtosecond LPG produces attenuation peaks that mostly blue shift, with a single attenuation peak red shifting. This may suggest that between these two LPGs there could be a turning point for a given set of cladding modes.

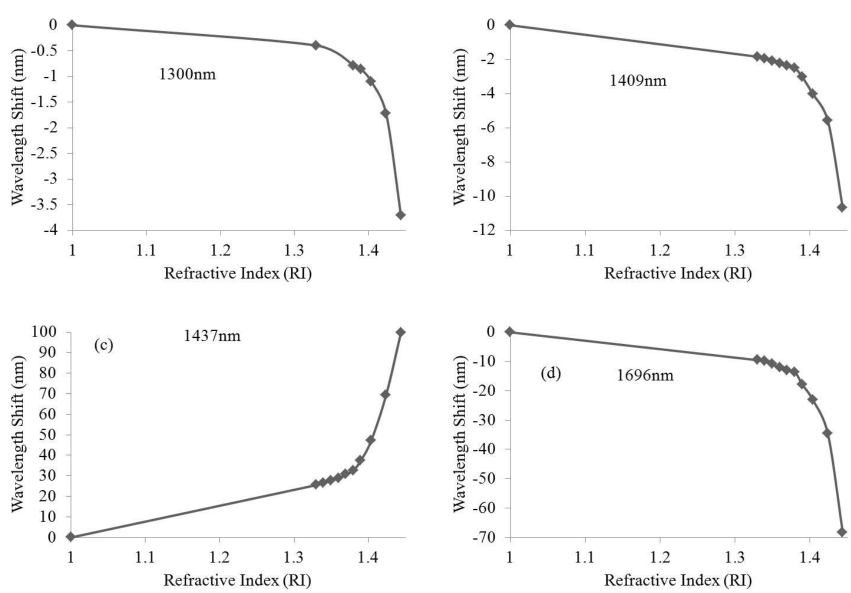
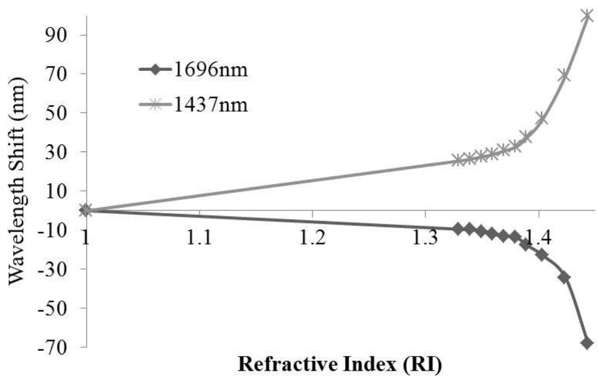


Figure 3 The SRI response of 4 attenuation peaks for the 400μm period femtosecond inscribed LPG

Since we also see oppositely shifting peaks for the 400µm LPG, the maximum sensitivity can be achieved by combining the opposite shifts of the 1437nm and 1696nm attenuation peak and this is shown in Figure 4.
Using the data shown in Figure 4, the SRI sensitivity for the individual and combined attenuation peaks for various SRI regions can be calculated and the results are displayed in Figure 4's Table 1. The maximum sensitivity achieved for a single peak is 1106nm/RIU for SRI ranging from 1.404 to 1.424. The maximum sensitivity possible through combining the opposite shifts is 1680nm/RIU, which is approximately a 1.5 fold increase compared to the sensitivity of the 1696nm attenuation peak. As for all LPGs, the SRI response is non-linear and the highest sensitivity is in the high SRI range, however, using the combined peaks the sensitivity enhancement will be seen across the entire SRI range.



	1 to 1.33 nm/RIU	1.33 to 1.38 nm/RIU	1.38 to 1.424 nm/RIU	1.404 to 1.424 nm/RIU
Single 1696nm	77.3	142.7	834.4	1106.8
Single 1437nm	28.9	81.0	477.3	573.8
Combined	106.1	223.7	1311.6	1680.5

Figure 4 The peak sensitivity of the LPG grating and the numerically calculated values

5 CONCLUSION

A series of femtosecond laser inscribed LPGs were characterised as refractive index sensors in SMF-28 fibre. A LPG with a period 400µm was found to be the most sensitive to changes in SRI. The grating was found to simultaneously couple to multiple sets of cladding modes, and this behaviour gave rise to multiple attenuation peaks that had both blue and red wavelength shifts with increasing surrounding refractive index. By using the combined shift of two opposing attenuation peaks a greater RI sensitivity could be achieved than monitoring a single attenuation peak wavelength shift. The maximum RI sensitivity produced was 1680nm/RIU.

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