Research Article | Vol. 24, No. 20 | 3 Oct 2016 | OPTICS EXPRESS 22345

Optics EXPRESS

Overwrite fabrication and tuning of long period gratings

MATTHEW PARTRIDGE,* STEPHEN W. JAMES, JAMES BARRINGTON, AND RALPH P. TATAM

Engineering Photonics, Cranfield University, Cranfield, MK43 0AL, UK
**m.c.partridge@cranfield.ac.uk*

Abstract: The central wavelengths of the resonance bands are critical aspect of the performance of long period gratings (LPGs) as sensors, particularly for devices designed to operate near the phase matching turning point (PMTP), where the sensitivity to measurements can vary rapidly. Generally, LPGs are characterized by their period, but the amplitude of the amplitude of the index modulation is also an important factor in determining the wavelengths of the resonance bands. Variations in fabrication between LPG sensors can increase or decrease the sensitivity of the LPG to strain, temperature or surrounding refractive index. Here, the technique of overwritten UV laser fabrication is demonstrated. It is shown that, on repeated overwriting, the resonance bands of an LPG exhibit significant wavelength shift, which can be monitored and which can be used to tune the resonance bands to the desired wavelengths. This technique is applied to periods in the range 100 to 200 μm, showing the cycle-to-cycle evolution of the resonance bands near the PMTPs of a number of cladding modes. The use of online monitoring is shown to reduce the resonance band sensor-to-sensor central wavelength variation from 10 nm to 3 nm.

OCIS codes: (060.2310) Fiber optics; (060.2370) Fiber optics sensors; (060.2430) Fibers, single-mode; (060.3735) Fiber Bragg gratings.

References and links

1. H. J. Patrick, C. G. Askins, R. W. McElhanon, and E. J. Friebele, "Amplitude mask patterned on an excimer laser mirror for high intensity writing of long period fibre gratings," Electron. Lett. **33**(13), 1167–1168 (1997).
2. V. Bhatia, "Applications of long-period gratings to single and multi-parameter sensing," Opt. Express **4**(11), 457–466 (1999).
3. S. W. James and R. P. Tatam, "Optical fibre long-period grating sensors: characteristics and application," Meas. Sci. Technol. **14**(5), 49–62 (2003).
4. V. Bhatia and A. M. Vengsarkar, "Optical fiber long-period grating sensors," Opt. Lett. **21**(9), 692–694 (1996).
5. X. Shu, L. Zhang, and I. Bennion, "Sensitivity Characteristics of Long-Period Fiber Gratings," J. Lightwave Technol. **20**(2), 255–266 (2002).
6. R. Y. N. Wong, E. Chehura, S. E. Staines, S. W. James, and R. P. Tatam, "Fabrication of fiber optic long period gratings operating at the phase matching turning point using an ultraviolet laser," Appl. Opt. **53**(21), 4669–4674 (2014).
7. S. A. Vasiliev, E. M. Dianov, D. Varelas, H. G. Limberger, and R. P. Salathé, "Postfabrication resonance peak positioning of long-period cladding-mode-coupled gratings," Opt. Lett. **21**(22), 1830–1832 (1996).
8. F. Abrishamian and K. Morishita, "Broadening Adjustable Range on Post-Fabrication Resonance Wavelength Trimming of Long-Period Fiber Gratings and the Mechanisms of Resonance Wavelength Shifts," IEICE Trans. **E94-C**(4), 641–647 (2011).
9. B.-O. Guan, H.-Y. Tam, H. L. W. Chan, C.-L. Choy, and M. S. Demokan, "Growth characteristics of long-period gratings in hydrogen-loaded fibre during and after 193 nm UV inscription," Meas. Sci. Technol. **12**(7), 818–823 (2001).
10. X. Shu, X. Zhu, Q. Wang, S. Jiang, W. Shi, Z. Huang, and D. Huang, "Dual resonant peaks of LP015 cladding mode in long-period gratings," Electron. Lett. **35**(8), 649 (1999).
11. K. C. Byron, P. E. Dyer, R. J. Farley, and R. Giedl, "Amplification of fibre Bragg grating reflectivity by post-writing exposure with a 193 nm ArF laser," Electron. Lett. **30**(14), 1133–1134 (1994).
12. T. W. MacDougall, S. Pilevar, C. W. Haggans, and M. A. Jackson, "Generalized expression for the growth of long period gratings," IEEE. Conf. Pub. **10**, 1449–1451 (1998).
13. T. Erdogan, T. A. Strasser, M. A. Milbrodt, E. J. Laskowski, C. H. Henry, and G. E. Kohnke, "Integrated-optical

#269663 http://dx.doi.org/10.1364/OE.24.022345
Journal © 2016 Received 30 Jun 2016; revised 1 Sep 2016; accepted 1 Sep 2016; published 19 Sep 2016
Corrected: 22 September 2016

Optics EXPRESS

Mach-Zehnder add-drop filter fabricated by a single UV-induced grating exposure," Appl. Opt. **36**(30), 7838–7845 (1997).
14. M. Partridge, "Spectrum interrogation run time (Version 1)," figshare (2016) [retrieved 30 June 2016], https://dx.doi.org/10.17862/cranfield.rd.3759471.
15. M. Partridge and S. W. James, "Change in long period grating spectra with length," figshare (2016) [retrieved 26 August 2016], https://dx.doi.org/10.17862/cranfield.rd.3749550.
16. M. Partridge, "Repeatability of LPG fixed exposure vs tracked," figshare (2016) [retrieved 26 August 2016], https://dx.doi.org/10.17862/cranfield.rd.3749583.
17. M. Partridge and S. W. James, "Overwrite LPG fabrication data vs model," figshare (2016) [retrieved 26 August 2016], https://dx.doi.org/10.17862/cranfield.rd.3750465.
18. J. Barrington and M. Partridge, "All LPG turning points from 100 to 200um," figshare (2016) [retrieved 26 August 2016], https://dx.doi.org/10.17862/cranfield.rd.3749580.
19. M. Partridge, R. Y. N. Wong, S. W. James, F. Davis, S. P. J. Higson, and R. P. Tatam, "Sensors and Actuators B: Chemical," Sensor. Actuat. Biol. Chem. **203**, 621–625 (2014).
20. S. W. James, I. Ishaq, G. J. Ashwell, and R. P. Tatam, "Cascaded long-period gratings with nanostructured coatings," Opt. Lett. **30**(17), 2197–2199 (2005).
21. M. Partridge, "109.5um Cascade LPG formation," figshare (2016) [retrieved 26 August 2016], https://dx.doi.org/10.17862/cranfield.rd.3750564.
22. M. Partridge, "108.5 LPG with 500 overwrite 5s cycles," figshare (2016) [retrieved 26 August 2016], https://dx.doi.org/10.17862/cranfield.rd.3750567.
23. M. Kristensen, "Ultraviolet-light-induced processes in germanium-doped silica," Phys. Rev. B **64**(14), 144201 (2001).

1. Introduction

The use of optical fiber long period gratings (LPGs) as a sensing platform has stimulated considerable interest over the last two decades. Their inherent sensitivity to the refractive index of the medium surrounding the fiber [1], the ability to create highly specific chemical and bio sensors by deposition of appropriate coatings onto the cladding and the prospect for multi-parameter sensing [2] have led to the generation of a large body of literature [3].

An LPG comprises a periodic modulation of the propagation constants of the modes of the optical fiber, with periods typically in the range 100 μm to 1 mm, which acts to promote coupling of light from the core mode to co-propagating cladding modes. The coupling is characterized by the phase matching condition [4].

$$\lambda_x = (n_{core} - n_{clad(x)})\Lambda \tag{1}$$

where λ_x represents the wavelength at which light is coupled to the LP_{0x} cladding mode, n_{core} is the effective refractive index of the mode propagating in the core of the fiber, $n_{clad(x)}$ is the effective index of the LP_{0x} cladding mode and Λ is the period of the LPG.

Equation (1) can be used to generate a family of phase matching curves, which are known to contain a turning point, known as the phase matching turning point (PMTP) or turn around point [5]. A resonance band corresponding to coupling to a mode at the PMTP exhibits maximum sensitivity to environmental perturbation, initially exhibiting a significant increase in extinction with decreasing difference between core and cladding mode effective indices, before splitting into two distinct bands that show sensitivities of opposite sign to the same perturbation. The rapid variation of the gradient of the phase matching curves near the PMTP causes the sensitivity of a particular resonance band to environmental perturbation to be determined by its proximity to its PMTP [5]. This creates the possibility to tune the response and optimize the sensor for a particular application. It was shown recently that reproducible fabrication of LPGs operating at the PMPT requires careful control of the fabrication parameters and environment [6]. In addition, it has been observed that batch to batch variation in the properties of optical fibers of nominally the same cut off wavelength fiber can result in the resonance bands of LPGs of identical periods having different central wavelengths. A number of post fabrication approaches to control the spectral characteristics and sensitivity of LPGs have been demonstrated, including etching the cladding [7], heating [8], and uniform UV irradiation along the length of the fiber [9,10]. Etching reduces the diameter of the cladding, thus changing the effective index of the cladding modes and the phase matching

Optics EXPRESS

condition. The heating of the fiber was thought to cause a stress relaxation of the glass structure, resulting in a differential change in the indices of the core and cladding. Etching and heating may be impractical for larger scale production.

Trimming using uniform UV irradiation has been used with LPGs fabricated in hydrogen loaded optical fiber, where the mechanism was explained to be a result of the enhanced photosensitivity that is partially locked into the UV exposed regions of the hydrogen loaded optical fiber [9]. The difference in the photosensitivity of the exposed and unexposed regions of the fiber means that the amplitude of the index modulation would increase even when the fiber is UV irradiated uniformly [9], which, as will be discussed, will influence the resonance wavelengths and the strength of the grating and thus extinction of the resonance bands. In the case of fiber gratings written in non-hydrogen loaded fiber, uniform post fabrication UV irradiation would be expected to change the average index of the fiber, changing the resonance wavelengths but also degrading the strength of the gratings, as is the case for FBGs [11].

In [12], MacDougall *et al* discussed the evolution of the spectrum of an LPG during fabrication, considering the influence of the amplitude of the index modulation. In particular, they derived a modified expression for the phase matching condition that takes into account the influence of the increase in the refractive index of the core of the fiber;

$$\lambda_x = (n_{core} + \delta n_{core} - n_{clad(x)} - \delta n_{clad})\Lambda \qquad (2)$$

Where δn_{core} is the average index modulation in the core and δn_{clad} is the amplitude of the index modulation in the cladding, assumed to be zero here. In the modelled data that is presented in this paper, the approach reported by Erdogan [13] is exploited, with the influence of δn_{core} included within the detuning parameter.

Equation (2) indicates that the central wavelengths of the resonance bands are influenced by the amplitude of the index modulation, δn_{core}. In the case of fiber gratings formed by exploiting the photosensitivity of germanium doped optical fibers, for example via exposure of the fiber to the output from a laser operating in the ultraviolet (UV), it is known that δn is dependent upon the UV radiation dose [12]. Thus control of the dose during fabrication should allow an LPG with specific properties to be fabricated without the requirement for post fabrication trimming. Additionally, the control of the dose should produce a predictable effect allowing for the prediction of the evolution of an LPG spectrum during fabrication. Here, this is investigated in detail by repeatedly using the point-by-point technique to create an LPG and tune its properties, but similar effects will be observed when using an amplitude mask.

2. LPG fabrication system

The LPGs in this work were fabricated using an in-house designed and constructed system. The system uses a frequency-quadrupled Nd:YAG laser operating at 266 nm, a 7 ns pulse width and a rep-rate of 10 Hz, with a beam diameter of 10 mm and an average power of 200 mW. The beam is conditioned using a focusing lens before being passed through a slit placed in front of the optical fiber. The slit-width is computer controlled over a range of 1 to 1000 μm with an accuracy of +/– 0.025 μm. The focusing lens is mounted on a manually controlled stage which can be moved to alter the position of the lens relative to the optical fiber, providing control over the power density of the beam on the fiber. Unless otherwise stated the power density used in these experiments was 14 mW/mm^2 at the fiber. It was found that higher power densities caused damage to the surface of the fiber reducing their mechanical strength and making them prone to breaking when removed from the fabrication setup. The optical fiber was mounted an M150.11 (Physik Instrumente) translation stage with a range of 49 mm with an accuracy of +/– 0.025 μm, with its axis of movement oriented orthogonally to the laser. The optical fiber used in these experiments was PS750 Boron doped photosensitive fiber (Fibercore) with a cut off wavelength of 620 nm, mode field diameter of 5 μm. A schematic of the LPG fabrication system is shown in Fig. 1.

Optics EXPRESS

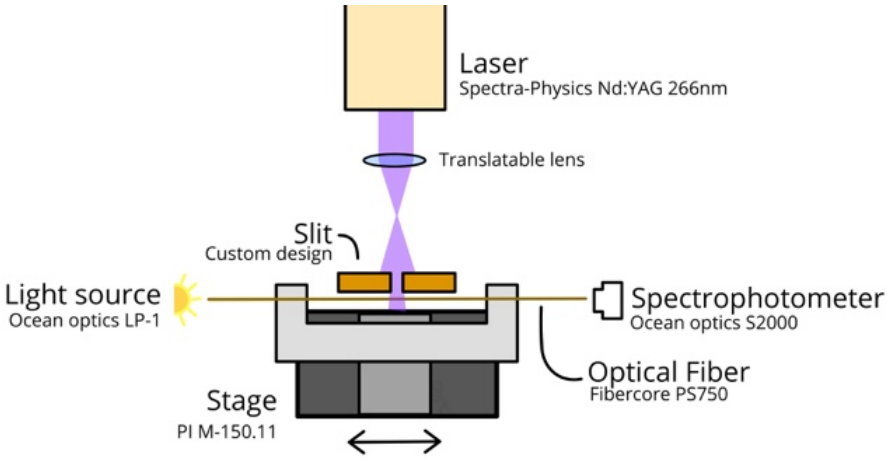

Fig. 1. LPG fabrication setup viewed from above.

The translation stage and the slit width were controlled by a custom made LPG writing program prepared in LabView, which also synchronized the data recording. The fabrication involved exposing a section of the optical fiber of length defined by the slit width for a user specified duration. The slit was then closed, the fiber translated by a distance equal to the desired period, the slit opened and the next section of fiber exposed. This was repeated until the entire length of the LPG was exposed.

The transmission spectra were recorded using an optical fiber coupled tungsten light source (Ocean Optics LP-1) and spectrophotometer with a range of 500 – 1100nm (Ocean Optics S2000). All feature tracking and post experiment processing was done using custom software, the Spectrum Interrogation Runtime (SIR) [14] in LabView. SIR has a number of feature detection methods built in. In this work the primary method used was a quadratic polynomial fit to discrete windows of the spectrum, which determines the central wavelengths of the resonance bands in the LPG's transmission spectrum. SIR also incorporates a number of feature tracking routines which link the detected features to each other so that they can be plotted throughout an experiment, even if the spectra are noisy. The tracking process is based on examining the central wavelengths of existing identified resonance bands, fitting a curve to the progression of each and estimating the central wavelengths of the resonance bands in the next spectrum to be recorded in the experiment. The resonance bands identified in a newly recorded spectrum are compared to these estimates. If a resonance in the newly recorded spectrum lies within a specified error threshold then it is appended to the data set for that resonance band, if not it is identified as a new band and is tracked separately in future iterations. Resonance bands that disappear continue to be searched for a number of iterations, as it is possible that bands may not be tracked for short periods due to errors in the feature identification caused by, for example signal to noise issues.

3. Single-exposure method

Typically, UV inscribed LPGs are written via either an amplitude mask [1] or the point-by-point method [6]. In general, in the amplitude mask approach, a cylindrical lens is used to create a line focus aligned with the axis of the optical fiber. The amplitude mask is stationary, and either the fiber is translated behind the phase mask with the laser beam stationary, or the laser is scanned across a stationary fiber. In both cases a number of periods of the LPG are fabricated simultaneously. Point-by-point systems use a slit of variable width which exposes a single half-period at a time, translating the fiber by the period of the fiber after a pre-determined exposure time, building to the required length of the LPG. In both methods each

Optics EXPRESS

period is irradiated for a single fixed length of time until the desired RI change in the core is achieved. The amplitude mask approach is well-suited to fabrication of LPGs with identical characteristics [1], while the point by point approach allows more flexibility in defining the refractive index modulation, allowing chirped and phase stepped LPGs to be fabricated.

The fabrication is monitored by observing the growth of the resonance bands that are characteristic of the transmission spectrum of an LPG. An example of this can be seen in Fig. 2. Here, each section of the LPG was exposed to the UV irradiation for a duration of 40 seconds. Figure 2(a) shows that, as the length of the LPG increases, the attenuation of the resonance bands increases. Using the approach of Erdogan [13], the coupled mode equations were solved numerically to allow the transmission spectrum of the LPG to be simulated, assuming that the amplitude of the index modulation was 1.3 x10^{-4}. The predicted evolution of the spectrum correlates well with the experimental observation Fig. 2(b).

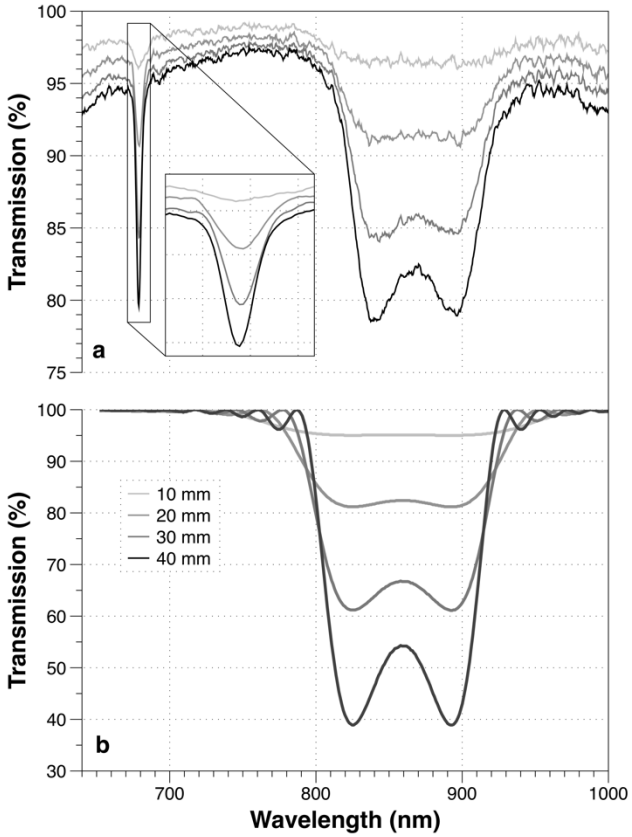

Fig. 2. (**a**) The transmission spectra of a 109.5 µm period LPG during fabrication, recorded after 10, 20, 30, and 40 mm of the LPG had been written. LP_{18} at ~680 nm is expanded for clarity. (**b**) numerical model of LPG spectra, where the value of length varies (see Ref [15]. for underlying values).

It was shown in Wong *et al.* [6] however that this approach, using a single pass of the writing beam, produces LPG spectra that are highly variable. Changes in temperature, humidity, batches of fiber or laser power can alter the final spectrum achieved and the central wavelengths of the resonance bands relative to the phase matching turning point. Figure 3 shows the measured transmission of five LPGs, each of period 174 µm prepared on five consecutive days in the same batch of optical fiber and using the same irradiation conditions. The LPG fabrication environment is controlled at 22.5 °C and has a variability of +/– 1.5 °C over a 24-hour period.

Optics EXPRESS

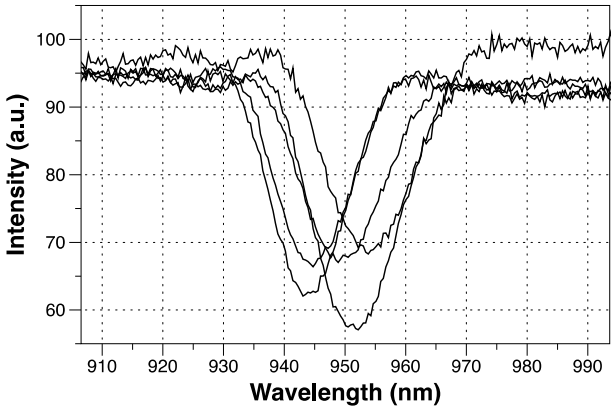

Fig. 3. Transmission spectra of 5 LPGs of period 174 μm fabricated on consecutive days using nominally identical irradiation conditions. (see Ref [16]. for underlying values).

Figure 3 shows that the central wavelength of the resonance band corresponding to coupling to the LP_{14} mode varies by as much as 10 nm when LPGs were fabricated on 5 consecutive days. Wong *et al.* [6] showed that, with temperature control to within 0.5 °C, the repeatability of the fabrication can be improved, however this can be difficult to achieve without specialist facilities. Control of the environment resolves the impact of temperature variations, but power variations in the laser system or batch variance in the fiber can still influence the spectrum.

4. Overwrite method

As discussed in the introduction, for a given fiber there are 3 key variables that typify LPG resonance bands. As illustrated by the LPG spectra shown in Fig. 2, the length of the LPG influences the extinction of the resonance bands. The period of the LPG influences the central wavelength of the resonance bands [6]. Finally, the amplitude of the refractive index modulation influences both the attenuation depth and the central wavelengths of the resonance bands. It should be noted that the extinction of a resonance band and its central wavelength are also influenced by the overlap between the core mode and the corresponding cladding mode to which coupling occurs [13]. This is determined by the dimensions of the core and cladding and by their respective refractive indices.

For LPGs fabricated using a single pass of the UV illumination, the characteristics of the transmission spectrum are defined by the period, intensity of the illumination and the local exposure time. The influence of the amplitude of the refractive index modulation on the resonance bands suggest the ability to tune the properties of the LPG by repetition of the fabrication process, allowing the fabrication to be terminated once the required spectral characteristics have been attained. This is illustrated in Fig. 4(a) where the evolution of the transmission spectrum of an LPG of period 109.5 μm and length 40 mm, fabricated by repeated exposure of the fiber, is shown. Here the exposure time at each period was 5 seconds and once the entire LPG length had been exposed the fiber was translated to its original position and the process repeated. Figure 4(b) shows the numerically modelled LPG spectra, where the value of δn_{core} varies from $2\text{x}10^{-6}$ to $3\text{x}10^{-5}$ in steps of $4\text{x}10^{-6}$, showing good agreement with the form of the experimental data.

Optics EXPRESS

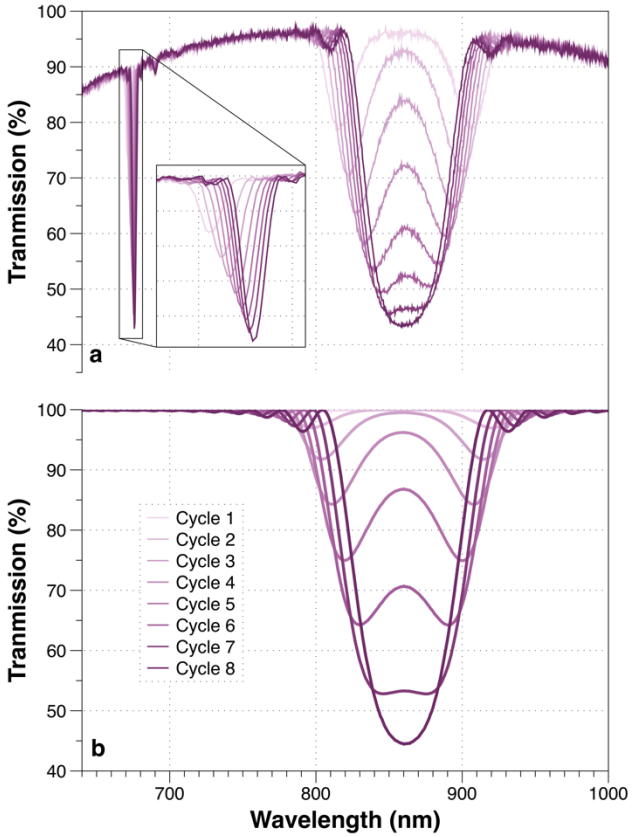

Fig. 4. (**a**) 40 mm LPG with 109.5 μm period fabricated using the overwrite method. LP_{18} at ~680 nm is expanded for clarity. (**b**) numerical model of LPG spectra, where the value of δncore varies from $2x10^{-6}$ to $3x10^{-5}$ in steps of $4x10^{-6}$. (see Ref [17]. for underlying values).

Figure 4(a) shows that each successive pass of the fiber causes the resonance bands to both increase in attenuation and also change their central wavelength, which is apparent in the insert for the band originally centered at 680nm. The period used was chosen as it was close to the PMTP for LP_{19} (~870 nm). The evolution of the coupling to this mode is characterised by the generation of the dual resonance bands, the separation of which decreases with increasing exposure, allowing the tuning of the spectrum such that the PMTP can be accessed.

Figure 4 also demonstrates that the resonance bands are visible using an exposure time of 5 seconds, with a total cycle time (time taken for 5 seconds exposure of all periods) of 30 minutes. For some applications, LPGs with relatively shallow resonance bands are sufficient.

It is interesting to note that a similar progression of the resonance bands is observed when the period of the LPG is changed as was shown in [6], where a number of LPGs of period within the range 110 μm - 111 μm were fabricated. Using experimental data presented in the visualization, the wavelength shift of the resonance band corresponding to coupling to LP_{18} (due to the merging of LP_{19} shown in Fig. 4 this is difficult to accurately track) observed over the 9 cycles of the fabrication process illustrated in Fig. 4 is equivalent to an ~0.5 μm change in the period of the grating. Analysis of the spectra, undertaken using the SIR software, yields the graphs in Fig. 5, detailing the change in the extinction and resonance wavelength for the LP_{18} band.

Optics EXPRESS

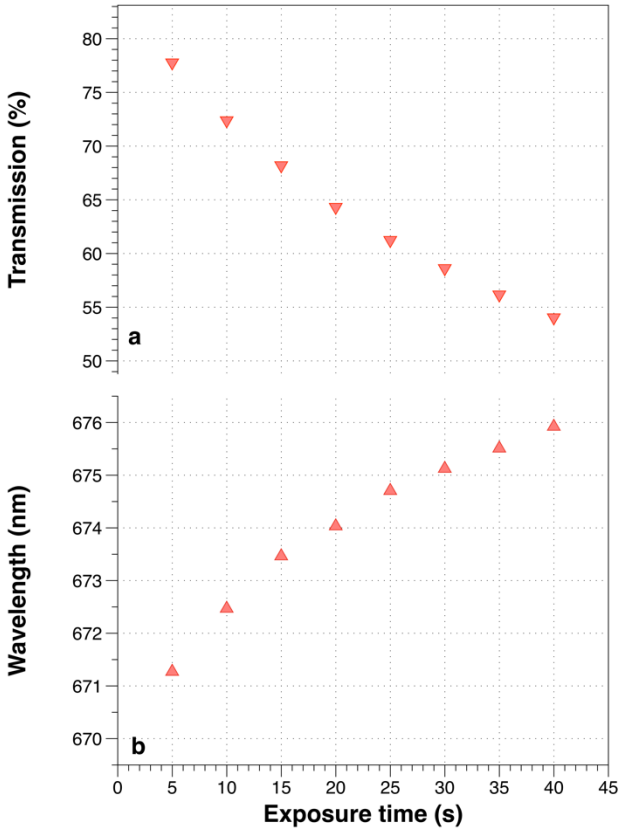

Fig. 5. Intensity (**a**) and wavelength position (**b**) of LP_{18} during the fabrication of a 109.5 µm period LPG. (see Ref [17]. for underlying values).

Figure 5 shows that, after 40 seconds, the changes in both wavelength and intensity have not plateaued. The final writing cycle shows a rate of 0.1 nm and 0.8% per second of exposure, respectively. This trend in attenuation and wavelength change is consistent across a wide range of resonance bands and LPG periods. A number of LPGs were fabricated with periods in the range 100 µm to 200 µm, chosen to be around the phase matching turning point for the LP modes between 13 and 20. These LPGs were fabricated using the overwrite method, each with 6 cycles and with a 5 second exposure for each period. In total, 60 LPGs were fabricated. The data is shown in Visualization 1 which shows a series of 6 intensity plots. Each plot represents a cycle of the exposure of the LPG during fabrication. From cycles 1 to 6 it can be seen that the resonance bands develop in the same way as that shown in Fig. 4, both in wavelength and intensity. See Ref [18]. for the underlying values.

5. Overwrite tuning of LPG characteristics

The key advantage of the technique of overwriting for making LPGs lies in the control of the position of the central wavelength and the attenuation of the resonance bands, as shown in Fig. 3. For any large scale LPG sensor fabrication one of the key requirements would be to ensure that the central wavelength and the depth of the attenuation band match a specific application requirement and therefore that the characteristics of the LPGs are repeatable. As the central wavelengths of the resonance bands move closer to, or further away from, the PMTP their sensitivity to environmental perturbation changes, therefore well controlled, repeatable fabrication with low device to device variability is essential.

Optics EXPRESS

The overwrite method allows the fabrication of LPGs with low device to device variability by enabling tracking of the resonance bands during fabrication. By monitoring the central wavelengths of the resonance bands during fabrication, the exposure can be stopped when they match the desired specification and any changes due to batch to batch variability in the central wavelength positon or experimental variation can be corrected. Figure 6 shows 5 LPGs, all fabricated on different days, with the fabrication process stopped when their resonance band corresponding to coupling to LP_{14} was within 1.5 nm of 945 nm. All 5 LPGs were fabricated using a 174 μm period and a 5s exposure time per cycle.

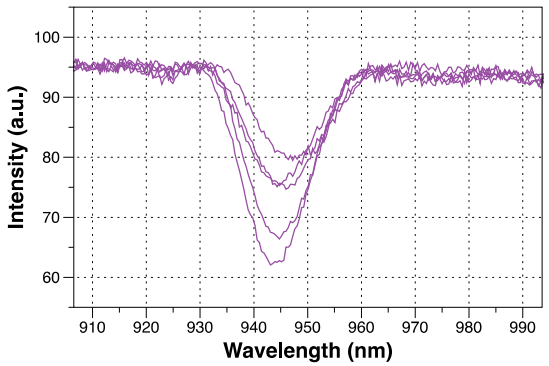

Fig. 6. Spectral response of 5 LPGs with a period of 174 μm fabricated with the overwrite method using varying exposure times. (see Ref [16]. for underlying values).

Figure 6 shows that the bands are closely aligned in wavelength with a range of 3 nm. There is a higher variation for the intensity values with a range of 20% between the peaks. This compares to 12% in Fig. 3. This difference in attenuation is likely to be linked to the variation in laser power which during a 6 cycle exposure can change by as much as +/– 10%. Variations in the dopant concentration within the fiber may also contribute to this effect.

The ability to tune the wavelength of the LP resonance band is crucial for sensor development, whether for simple refractive index sensing, for specific sensing based upon functional coatings deposited onto the fiber [19], or in the production of more complex interferometric sensors based on cascaded LPGs [20]. A cascaded LPG interferometer consists of two LPGs of the same period separated by a short distance along a single optical fiber. The first LPG (LPG-L) acts to couple a portion of the light propagating in the core into the cladding. The 2nd LPG (LPG-R) recombines the core and cladding modes (as shown in Fig. 7). This creates a path-length imbalanced Mach-Zhender interferometer, the transmission spectrum of which consists of a channeled spectrum within the envelopes of the resonance bands.

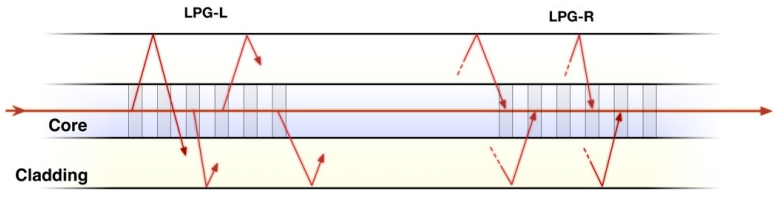

Fig. 7. Schematic of a cascaded LPG sensor showing the left (LPG-L) and right LPGs (LPG-R) and the coupling of the core propagating modes, represented by the arrows, into and out of the cladding.

Optics EXPRESS

It is important to ensure that the two spectra of the LPGs are matched to ensure the presence of a high visibility channeled spectrum within the LPG attenuation bands. Using the UV laser overwriting method reported here it is possible to tune the second grating to match the first and stop the fabrication when the visibility is optimum. This was demonstrated by fabricating a cascaded LPG pair where the LPGs were of period 109.5 µm. The cascaded LPG is formed of two 2 cm long LPGs, left (LPG-L) and right (LPG-R), separated by a 3 cm gap of optical fiber with the buffer jacket removed. LPG-L was fabricated first, with 60 cycles of 5 second exposures, followed by the fabrication of LPG-R using 60 cycles. A selection of the spectra recorded during the fabrication of LPG-R, showing the evolution of the channeled spectrum, is shown in Fig. 8.

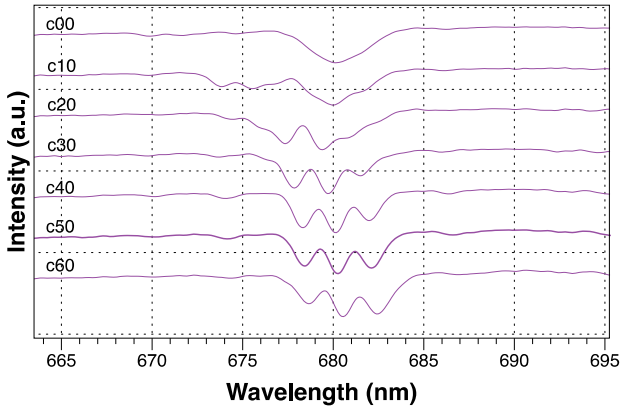

Fig. 8. Formation of a cascade LPG during the writing of LPG-R. The spectra are offset in intensity to show the progression of LP_{18} every ten cycles (denoted as cxx). (see Ref [21]. for underlying values).

Figure 8 shows that, as LPG-R is fabricated by the overwrite method, the center wavelength of the resonance band corresponding to coupling to LP_{18} moves into coincidence with that of LPG-L between cycles 0 and 50. This is typified by the growth of the channeled spectrum features which move in to a symmetrical phase by cycle 50. Further cycles of the fabrication of LPG-R cause the wavelength of the resonance band to move out of coincidence and, with the channeled becoming asymmetrical in the opposite direction. In this case, in order to optimize the cascaded LPG pair, it would be preferable to stop the fabrication at cycle 50.

For both single and cascaded LPGs, the wavelength encoded nature of the information returned by the LPG means that the central wavelength of the resonance band, rather that it's attenuation, is the most important feature for sensing applications. In the data sets reported here, the tuning of the LPG required a difference of as much as 50 seconds of exposure time between the LPG-L and LPG-R. For large differences in fiber parameters or writing conditions, this difference would increase to compensate and maintain the matched resonance band wavelengths. In order to examine the typical range of 'tuning' that is possible using the overwrite technique, a single fiber was exposed to a large number of cycles of 5 seconds exposures. The data shown in Fig. 9 is a selection of spectra taken after a number of cycles during the exposure of a 2 cm long LPG of period 108.5 µm. In total, the fiber was exposed for 500 cycles of 5 seconds exposures, giving each grating period a total exposure time of 2500 seconds (41.5 minutes).

Optics EXPRESS

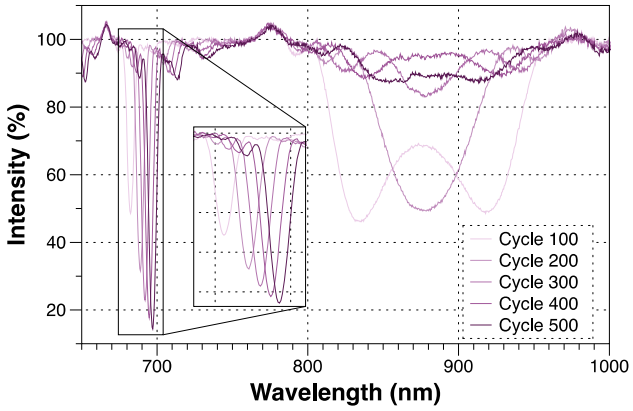

Fig. 9. Spectra from 100 to 500 cycle overwrite exposure of a 108.5 μm period LPG. LP_{18} at ~680 nm is expanded for clarity. (see Ref [22]. for underlying values).

The changes in central wavelength and extinction of the resonance bands corresponding to coupling to the LP_{19}, LP_{18}, LP_{17}, and LP_{16} bands are plotted in Fig. 10. The plot shows that, even after an exposure time of 2500 seconds, the resonance bands still exhibit measurable changes.

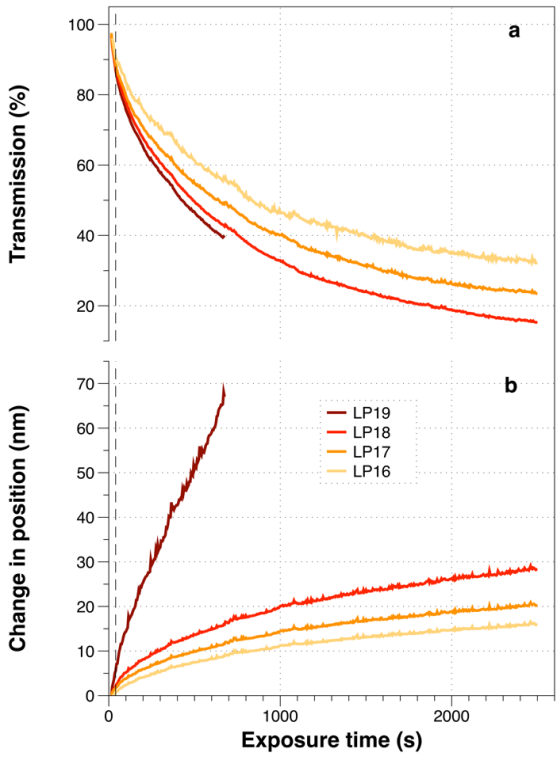

Fig. 10. Intensity (**a**) and wavelength position (**b**) of LP_{16}, LP_{17}, LP_{18}, and LP_{19} during the fabrication of a 109.5 μm LPG. The dashed line is to highlight a 40 second exposure. (see Ref [22]. for underlying values).

The rate of wavelength shift is dependent upon the cladding mode to which coupling occurs, which is expected due to the different modal slopes. For example, for LP_{18} after a 2500 second exposure the wavelength shift was 30 nm, which from previous data and the data

Optics EXPRESS

presented in supplementary data is equivalent to a ~3 μm change in period. The LP_{19} resonance band, the band nearest the PMTP, shifts further (67 nm) as expected, however as after 135 cycles the dual resonance bands merge at ~870 nm the broad band characteristic of the PMTP reduces in attenuation. Side lobes associated with this band are still visible and can be seen in the wavelength range 800 - 900nm in subsequent cycles.

The extinctions of the resonance bands vary similarly in slope due to their position within the non-linear spectra produced by the spectrophotometer and tungsten light source which has a non-linear intensity over the wavelength range. However, all fit an exponential decay which is indicative of the conversion of the germanium doped fiber core. The UV exposure to germanium doped silica causes the buildup of localized refractive index altering defects around the germanium [23]. However once the defects have been catalyzed no further change in the silica takes place and so further exposure to UV should show reduced change, as demonstrated in Fig. 10. The dotted lines on Fig. 10(a) and (b) denote the 40 seconds exposure time (intensity of 14 mW/mm^2) that was previously typically used in single exposure LPG fabrication in the laboratory at Cranfield. Using an exponential fit to the change in the transmission of the LP modes the data presented indicates that an exposure of 10,000 seconds is required before the change in extinction of the resonance band would be below the signal to noise ratio of the spectrophotometer. This indicates that a 40 second exposure is equivalent to 7.5% of the total possible change from UV inscription.

In single-exposure LPG fabrication, one of the constraining factors in exposure time is the damage to the fiber by the inscription process. With a power density of 14 mW/mm^2, 40 seconds has been found to be the longest single exposure possible without causing the fiber to become brittle. Longer exposures, of up to 60 seconds, can lead to the fiber breaking during fabrication. However, as is evident from the data presented in Fig. 9 and Fig. 10 the overwrite method appears to not suffer from this same problem as the fiber withstood a total of 42 minutes of exposure without breaking. It also didn't have the same issues of brittleness that single exposure fibers had, and has been used in a number of subsequent experiments for related work.

6. Conclusions

The use and viability of a modified writing method for LPG sensors systems has been demonstrated. Often in the literature LPGs are characterized by their period and length, but it has been shown that the amplitude of the index modulation plays a significant role in the depth and central wavelength of the resonance bands. The use of the overwrite method facilitates control over the exact characteristics of the LPG's transmission spectrum, of considerable importance when fabricating LPGs to operate near the PMPT. We also demonstrated the use of this overwrite method at a wide range of LPG periods and LP modes.

Using this method, the error on LPG sensor production can be reduced to just 3 nm range between central wavelength positions and this can be applied to both single LPG sensors and to more complex multi-LPG sensor systems. There is also some evidence that using this method reduces the physical damage to the fiber caused by UV exposure however this evidence is subjective and needs further work to quantify and fully understand.

While we have focused on the application of this method to point by point fabrication this could also be applied to the exposure of short scanned sections of LPGs by amplitude mask. In addition, while the work concerns LPGs fabricated in short cut-off wavelength fibre, which allows the resonance bands to be observed using a low cost system comprising a tungsten halogen light bulb and silicon CCD spectrometer, the principles apply within any wavelength band.

Funding

The authors acknowledge funding from the Engineering and Physical Sciences Research Council (EPSRC) UK, via grants EP/L010437 and EP/H02252X.