

Tapered Fibre LPG Device as a Sensing Element for Refractive Index

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ABSTRACT

The fabrication and characterisation of Long Period Gratings in fibre tapers is presented alongside supporting theory. The devices possess a high sensitivity to the index of aqueous solutions due to an observed spectral bifurcation effect.

INTRODUCTION

Fibre Long Period Gratings (LPGs) and Tapers (adiabatic and non-adiabatic) are both devices that couple light from the fibre core into cladding modes. A LPG is an axially periodic refractive index variation inscribed in the core of a photosensitive single-mode optical fibre by ultra-violet radiation, or other means, that couples light from the core to cladding modes at discrete wavelengths^{1,2}. In a fibre taper it is the changing radius of the taper that couples the modes to each other³, producing applications in chemical/biological and strain sensing^{4,5}. The study of the LPG's attenuation bands has yielded many potential uses in the area of telecommunications, but the LPG has also found numerous applications in the field of sensing. This is because the mean wavelengths of the attenuation bands are sensitive to strain, temperature, curvature and the refractive index of the surrounding medium^{1,2,6,7}. In particular there has been strong interest in using long period gratings as chemical sensors^{6,7}, for example in the detection of organic aromatic compounds in paraffin⁷.

We report for the first time the new spectral behaviour of LPGs recorded in fibre tapers and the use of these devices as refractive index sensors. A suitable mechanism responsible for this behaviour is also proposed. These tapered fibre LPG (FTLPG) devices have a high sensitivity to refractive indices around 1.3, which suggests that they may be especially suitable for refractive index monitoring of aqueous solutions.

FABRICATION AND CHARACTERISATION

The biconical tapers are fabricated using single mode standard communications step-index optical fibre with an initial core radius of 3.5 μm and with an outer cladding radius of 62.5 μm . The tapers themselves were produced by applying a controlled tension to the fibres whilst they were subjected to a flame, generating a total taper length of 3.2cm with a minimum fibre radius of $\sim 34\mu\text{m}$. The taper profiles were measured using a microscope imaging system (Axioskop, Zeiss). Photosensitivity in the fibres was increased by hydrogenation, performed at a pressure of 120 bar over a period of 2 weeks at room temperature. LPGs were fabricated using a frequency doubled argon ion laser with a point-by-point writing technique. The total length of the LPGs fabricated was 5cm, with the central section of each LPG being inscribed into the fibre taper. A series of these LPG devices was fabricated at periods from 500 μm to 150 μm . The characterisation of the attenuation bands was carried out by observing the transmission spectrum with an optical spectrum analyser (OSA) with a resolution of 0.08 nm, when the LPG was illuminated by a broadband light source. Two typical transmission spectra of these devices are shown in figure 1.

The LPG devices with periods from 500 μm to 250 μm had similar spectral features with similar strengths. These included discrete features and Mach-Zehnder-like effects⁹. At the smaller periods used for the devices the discrete features were less pronounced and no Mach-Zehnder interferometric effects were observed over the wavelength range used. The spectral features of the LPG devices shown in figure 1 can be explained in two parts. Firstly, the phase-matching conditions of the taper's local cladding modes need to be considered. The phase matching conditions were calculated using the approach by Erdogan⁸ for various sections of the taper using the previously measured taper profiles, thus giving phase-matching conditions for the local cladding modes along the taper. The section lengths for calculating the local modes were chosen by the Slowness Criteria. From figure 2a, it can be seen that the various local modes provide phase matching in similar spectral regions (circled) to the attenuation bands displayed in figure 1 and also go some way to explaining the broadness of these features.

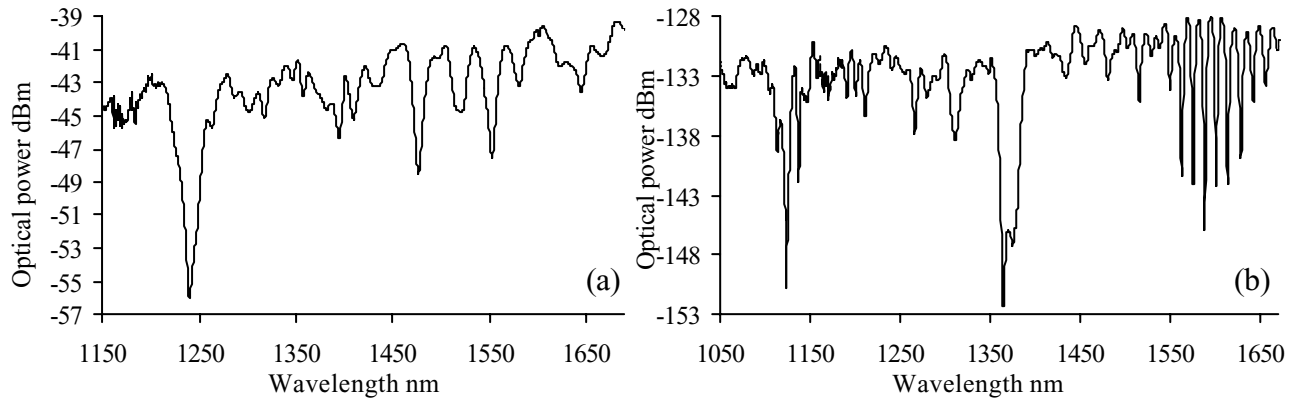


Figure 1. Transmission spectra of two 5cm long fibre taper LPG devices with 350µm period (a), and 500µm period (b).

Secondly, the discrete features present in the transmission spectra of these LPG devices can partly be explained by the core-to-cladding mode coupling constants for the local-cladding modes along the length of the tapered LPG. The coupling constants are calculated by the procedure in REF 8. As an example, figure 2b shows the variation of the coupling constant for the $HE_{1,9}$ local mode as a function of the normalised radius of the fibre. The LPG's coupling strength decreases significantly in the central section of the taper, whilst the phase-matching conditions also change along the taper length. The resultant attenuation bands broaden, but are still discrete because no significant coupling takes place in the central region where the phase matching conditions are very different from the ones at the edges of the taper.

The general behaviour exhibited arises due to the fact that the taper profile affects the coupling coefficients between the core and cladding modes as a function of the radius (in the case of the LPG) and the rate of change of the radius (for the taper) along the taper length³.

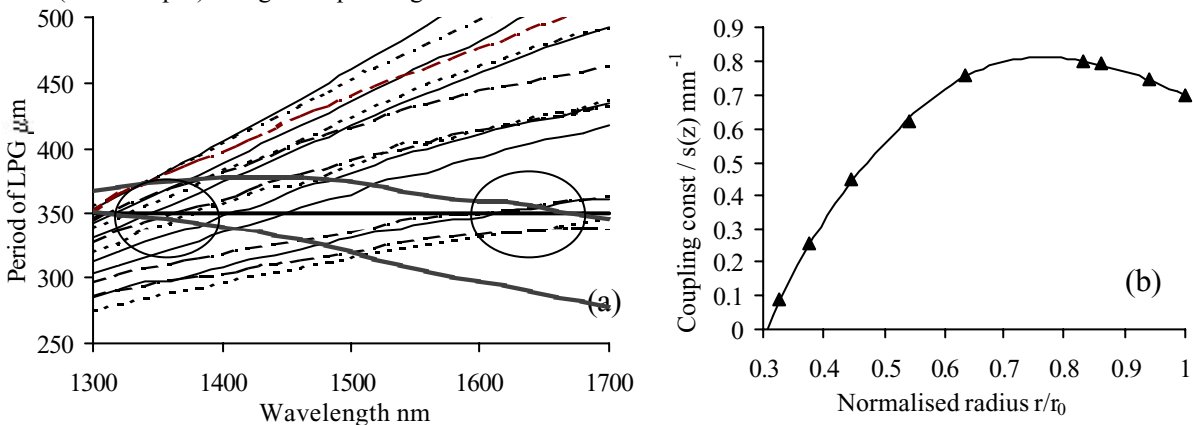


Figure 2. Λ - λ phase-matching condition for the tapers used for the LPGs, the circles indicating the phase-matching condition for a 350µm period long period grating (a), and variation of the coupling constant as a function of normalised fibre radius for the attenuation band associated with the $HE_{1,9}$ local mode (b).

A general sensitivity parameter can be calculated from reference 7, which is relevant to all the measurands and contributes to the spectral sensitivity of the different cladding mode resonances. The general sensitivity parameter is dependent on the difference between the differential effective index and the differential group index. The sensitivity parameter for each section of the LPG taper device was calculated, as shown in figure 3. This figure shows that at a given wavelength local-cladding modes and their associated attenuation bands exhibit both blue and red wavelength shifts, depending on the position in the taper. There is greater sensitivity because at some location along the taper the LPG couples to a local-cladding mode at its "turning-point" of sensitivity. In general in standard fibre the "turning-point" can exist for only one cladding mode at a given wavelength.

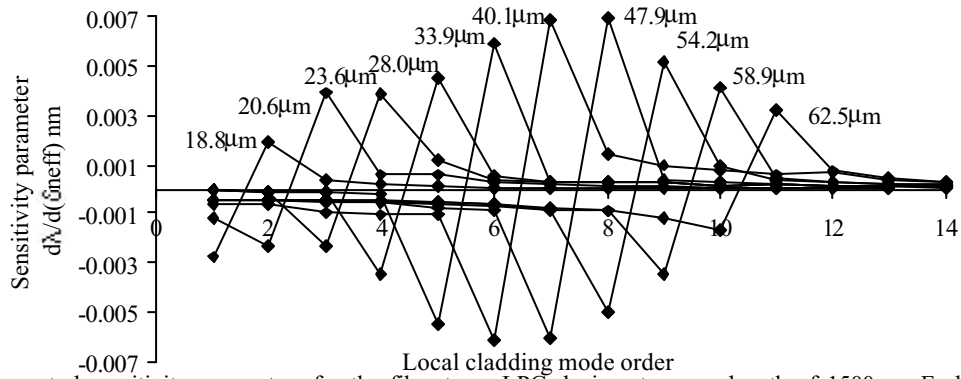


Figure 3. The spectral sensitivity parameters for the fibre taper LPG device at a wavelength of 1500nm. Each curve represents a section of the LPG fibre taper with different fibre radii (shown in figure).

REFRACTIVE INDEX SENSITIVITY OF LPG-TAPER FIBRE DEVICE

For refractive index sensitivity measurements the LPG device was placed in a V-groove and immersed in certified refractive index (CRI) liquids (supplied by Cargille laboratories Inc.) which have a quoted accuracy of ± 0.0002 . The LPG device and V-groove were carefully cleaned, washed in methanol, then in deionised water and finally dried before the immersion of the LPG device into the next CRI liquid. The V-groove was made in an aluminium plate, machined flat to minimise bending of the fibre. The plate was placed on an optical table, which acted as a heat sink to maintain a constant temperature. An example of the spectral response of a tapered LPG (period $350\mu\text{m}$, length 5cm) as a function of the surrounding medium's refractive index is shown in figure 4, along with the measured wavelength shift of a couple of individual spectral features.

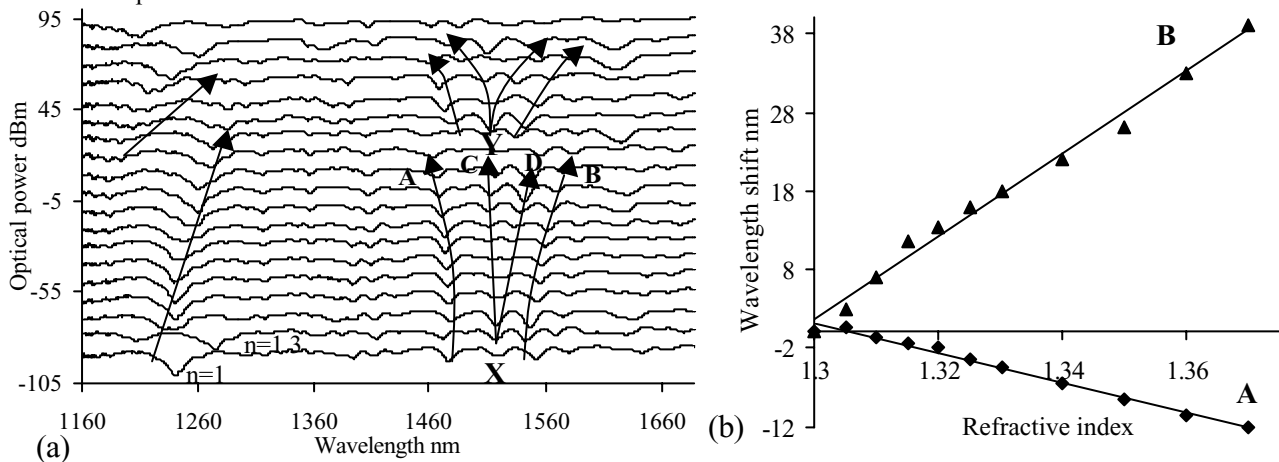


Figure 4. Transmission response of a fibre taper LPG device (period $350\mu\text{m}$, length 5cm, radius $\sim 34\mu\text{m}$), (a), and the spectral sensitivity of features A and B as a function of the surrounding medium's refractive index (b).

The bifurcation effect (e.g. at points X and Y) in the transmission spectrum of the LPG device gives some experimental evidence for the overlapping phase-matching (Fig. 2) along with the blue and red shifts predicted by the sensitivity parameter (Fig. 3). A general observation of this type of LPG sensor is that it exhibits higher spectral sensitivity to the surrounding medium's refractive index in the range of 1.3 to 1.34 than either a single LPG in standard optical fibre or a Mach-Zehnder LPG (MZLPG)⁹. The maximum measured spectral sensitivity of the tapered LPG devices was obtained with a period of $350\mu\text{m}$, achieving $d\lambda/dn = +1500.1$ nm in the region between $n=1.3$ and 1.331, which is greater than reported values in other fibre LPG devices such as those recorded in step-index fibre, where $d\lambda/dn = +320$ nm has been measured, or in W-index-profile fibre, where $d\lambda/dn = -310$ nm has been reported².

To assess their performance with aqueous solutions, the sensitivity of the tapered LPGs was further investigated using saline (NaCl) solutions. A MZLPG was used to calibrate the index of the solutions in the spectral region of interest. First a MZLPG was calibrated with the CRI liquids and then placed in a bath of deionised water (volume 500cc), to which successively 10cc increments of 2 Molar NaCl-solution were added and stirred into. The water used for this investigation came from a single container, which had the same ambient temperature as the room where the experiment was carried

out. The temperature of the solution was monitored and held constant to 0.1°C. Comparing these wavelength shifts with the wavelength shifts obtained from the CRI liquids and assuming linearity, allowed us to determine the average increase in the refractive index per increment of 10cc of 2 Molar NaCl-solution to the 500cc of deionised water; this figure was $(3.2 \pm 0.7) \times 10^{-4}$. The experiment of adding increments of 10cc of 2 Molar solution of NaCl was repeated with the tapered LPG device (period 350µm, length 5cm), the results being shown in figures 5a and 5b.

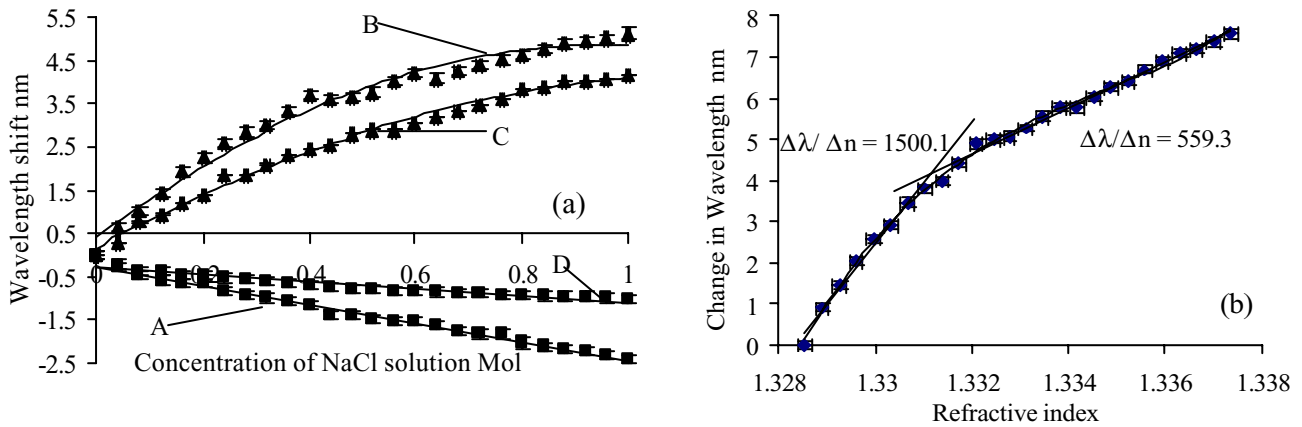


Figure 5. Spectral sensitivity as a function of Molar concentration showing slopes of opposite sign (a), and the variation of the wavelength separation of the spectral features A and B as a function of the refractive index (b).

We considered two ranges around 1.330 and 1.335, the first range gave a sensitivity of $d\lambda/dn = 1500 \pm 36$ nm, which leads to a limiting resolution of $\pm 8.5 \times 10^{-5}$. The second range (near 1.335) gave a sensitivity of $d\lambda/dn = 560 \pm 55$ nm, which leads to a limiting resolution of $\pm 3.3 \times 10^{-4}$. The uncertainty in the CRI liquids limits the present accuracy to that of the calibration liquids themselves.

The comparison of these experimental results against other index measuring systems is favourable. Firstly, Abbe refractometers have a resolution of 10^{-4} - 2×10^{-5} (1.33 to 1.58) and are relatively expensive, whereas this system has comparable or better resolution, can be used remotely and has the potential for being low cost. Secondly, sensors have been demonstrated based on FBG evanescent field interactions¹⁰ that yields an index resolution of around 10^{-3} (1.3) and have a more complex optical arrangement. Thirdly, LPG-based systems such as that in reference 7 are best used to investigate refractive indices greater than 1.4, where the spectral sensitivity of the LPG is intrinsically greater.

CONCLUSION

For the first time to the authors' knowledge, LPGs have been inscribed into fibre tapers. A new spectral bifurcation effect in fibre LPGs has been observed and a suitable mechanism for its origin has been proposed, which is supported by experimental results. These devices have a greater spectral sensitivity with respect to refractive index in the 1.333 range than other fibre grating sensors, which suggests that this device may be suitable for refractive index monitoring of aqueous solutions.

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