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Properties of length-apodized LPGs operating at the phase matching turning point

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***Abstract*— The characteristics of length-apodized phase-shifted fibre optic long period gratings with full and partial nanostructured coatings have been explored theoretically and experimentally. The twin rejection bands that are characteristic of the length-apodized phase-shifted long period gratings are studied for a long period grating (LPG) operating at the phase matching turning point. When one half of the length of the LPG is coated, complex bandgap like structure appears within the transmission spectrum, which may be of benefit to spectral filter design.**

***Index Terms*—optical fiber long period gratings, nanoscale coatings, optical filter.**

I. Introduction

Fibre optic long period gratings (LPGs) offer a controlled, repeatable method for the excitation of the cladding modes of an optical fibre, and have afforded the opportunity to develop optical fibre components such as in-fibre spectral filters [1], and sensors that exploit the properties of cladding modes [2]. The ability to tailor their transmission spectra by appropriate choice of grating parameters makes LPGs an attractive proposition for filtering applications, and they have found use in flattening the gain spectrum of erbium doped fibre amplifiers [3] and as tunable filters[4].

The transmission spectrum of a uniform-period LPG may contain a number of attenuation bands corresponding to coupling to distinct cladding modes, with the number, depth, width and separation of the bands being determined by factors such as the period, the depth of the index modulation and the length of the grating Chirping the period can broaden he spectral features [5], while apodization can eliminate side bands [6]. The introduction of phase shifts into the grating structure produces narrow pass bands within the individual attenuation bands, and the properties of these pass bands can be refined by the introduction of multiple phase steps[7]. Enhanced design opportunities are afforded if the phase steps are not uniformly spaced, as is the case for length-apodized phase shifted LPGs, as the separation of the phase steps provides an additional degree of freedom. The number of phase steps and the length of the sections of LPG between the phase steps influence the exact form of the transmission spectrum [8].

Selecting the period of the LPG such that the coupling to a selected cladding mode is effected near the turning point in the phase matching condition results in the transmission spectrum showing a high sensitivity to environmental parameters such as temperature and strain, and to the optical properties of the coating. In this regime it is possible to couple to the same cladding mode at two distinct wavelengths, producing dual resonance bands in the transmission spectrum [9]. This operating regime is of particular interest for the development of sensors [10].

In this paper the response of phase shifted and length-apodized phase shifted LPGs, designed with periods that ensure operation near the phase matching turning point, to non-uniform modulation of the refractive index of the cladding mode along the length of the LPG is explored, with the aim of identifying new opportunities for filter design and new operating regimes for LPG sensors. The effective index of the cladding modes in the different sections of the LPG are varied by the layer by layer deposition of a nanoscale coating onto the cladding of the fibre. The deposition of such coatings onto LPGs has been shown to have a strong influence on the cladding modes, and thus on the transmission spectrum [11, 12], and has been employed for chemical sensing [13, 14]

II. Long Period Gratings

An LPG is a core – cladding mode coupling device that consists of a periodic modulation of the core of the optical fiber. The period of the LPG typically lies in the range 100 µm to 1 mm and facilitates the coupling of light from the core mode to co-propagating cladding modes at wavelengths governed by the phase matching condition [15];

$$\lambda_{(x)} = \left(n_{core} - n_{clad(x)}\right)\Lambda \qquad (1)$$

where $\lambda_{(x)}$ represents the wavelength at which coupling occurs to the linear polarized (LP_{0x}) mode, n_{core} is the effective RI of the mode propagating in the core of the fibre, $n_{clad(x)}$ is the effective index of the LP_{0x} cladding mode, and Λ is the period

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of the grating. The transmission spectrum of an LPG consists of a series of resonance bands, each corresponding to coupling to a specific cladding mode. The dependence of the cladding mode effective refractive index upon the refractive index of the surrounding medium gives rise, via the phase matching condition, to the surrounding refractive index sensitivity exhibited by the resonance bands.

It has been shown that the phase matching condition for each cladding mode contains a turning point [9]. The sensitivity of the central wavelength of each of the resonance bands is at its highest when the phase matching condition for a particular cladding mode is satisfied at its phase matching turning point [9]. It should be noted that this can be achieved by appropriate choice of grating period and surrounding refractive index [12].

The layer by layer deposition of coatings onto an optical fibre has been shown previously to be a useful means for changing the effective index of the cladding modes of an optical fibre in a controllable fashion [11]. The response of the LPG to the layer by layer deposition of a nanoscale coating is characterized by a transition region in which the central wavelengths of the resonance bands undergo a large change in wavelength for a small change in coating thickness. This has been shown to be a result of a rapid change in the cladding modes' effective refractive indices that accompanies a reorganization of the cladding modes that occurs when the coating thickness is such that it acts as a waveguide that is phase matched to one of the cladding modes [9]. Appropriate selection of the optical thickness of the coating and the period of the LPG can ensure that the transition region and the phase matching turning point coincide, optimizing sensitivity [12].

In general, previous studies of coated LPGs have considered LPGs with a uniform period and a uniform coating thickness along the entire length of the LPG. A study of the influence of varying the coating thickness along the length of the LPG, by locally ablating the deposited coating, revealed the introduction of structure into the LPG transmission spectrum, generating spectral features such as phase shift behaviour and multiple interference fringes [16] that can be tailored for particular applications. To date there have been no reports of the deposition of coatings onto LPGs with phase discontinuities.

III. Phase-Shifted Long Period Gratings

The fabrication of an LPG with a single π phase discontinuity located at the centre of the grating produces a bandpass response, such that each resonance feature within the transmission spectrum contains a peak at the resonance wavelength defined by equation 1, with attenuation bands located on either side [8], as shown in figure 1. At the resonance wavelength, the light coupled into the cladding mode from the sections of the grating on either side of the phase step will be in anti-phase, causing destructive interference of the cladding modes, effectively preventing core-cladding mode coupling at the resonance wavelength. As the value of the phase discontinuity is related to the period of the grating, at wavelengths other than the Bragg resonance the phase difference between the light coupled into the cladding mode from the two grating sections will not be equal to π. As a result, a narrow spectral peak is produced with the core-cladding mode coupling resonance band, with attenuation bands of equal extinction on either side. If the phase shift is not equal to π, the attenuation bands become of non equal extinction and the peak moves to a shorter/longer wavelength within the resonance feature, allowing tuning of the form of the spectrum.

This concept can be extended by incorporating a number of equidistant π phase steps within the LPG structure [17], which has been explored with the aim of manipulating the LPG transmission spectrum for filtering applications [8, 17-22]. Theoretically, the separation of the centre wavelengths of the two attenuation bands is linearly proportional to the number of phase steps, and the attenuation bands become sharper with a narrower Full-Width Half-Maximum (FWHM) bandwidth [18] as the number of phase steps increases. The spectrum can also be modified by controlling the grating length, with the FWHM of the attenuation bands showing a nearly inversely linear dependence on the grating length [18].

The design of length-adpoized LPGs is described comprehensively in [8]. The number and physical separation of the π phase steps in a length-apodized LPG to be used as a band rejection filter are influenced by the requirement for either full or zero transmission at the resonance wavelength, and in both cases are dependent upon the coupling strength of the LPG [16]. It has been shown that, for an LPG of total length L and of coupling strength $\kappa=\pi/2L$, a spectrum that has a maximum transmission at the resonance wavelength surrounded by two attenuation bands can be achieved with an even number of sections symmetrically arranged about the centre of the LPG. To ensure that there are no ripples between the bands, z_i, the length of the sections of the LPG between the π phase steps, can be arranged in a Gaussian distribution [8]

$$= \frac{}{\Sigma} \qquad (2)$$

Where f_i has the form

$$= \quad -\ln(2) \; \frac{}{} \qquad (3)$$

Where w is the full width at half-maximum of the Gaussian apodization function and m the number of sections.

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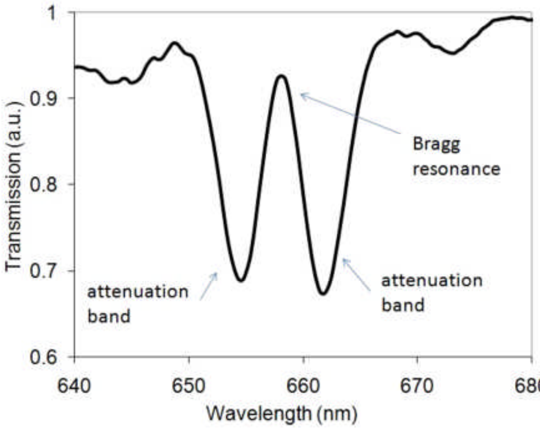

Fig. 1. Experimental transmission spectrum of a phase-shifted LPG of period 100μm and length 27mm, with a single π phase step located at the centre of the LPG. Attenuation bands located on either side of the resonance wavelength can be seen.

IV. Fabrication of Phase-Shifted Long Period Gratings

The LPGs were fabricated in hydrogen-loaded single mode fibre, SM750, which has a cut-off wavelength of 650 nm, using the point-by-point UV inscription technique [23]. The optical fibre was mounted on a translation stage and moved in a step wise fashion past a fixed aperture of appropriate width, with each step being equal to the required period. The output from a frequency quadrupled Nd:YAG laser, operating at 266nm was used to irradiate the optical fibre through the aperture. In the fabrication of the length-apodized phase-shifted LPGs, the π phase steps are introduced by programming the movement of the translation stage such that, at the appropriate locations along the length of the LPG, the translation stage was moved by an additional half a period. The translation stage used has a resolution of 1 μm. The physical locations of the phase shifts for the length-apodized phase-shifted LPG are shown in Figure 2.

The period of the LPG, 100 μm, was chosen to allow the investigation of the properties of phase-shifted, coated LPGs in the region of the phase matching turning point, which has been shown previously to offer maximum sensitivity to perturbation of the properties of the coating material [12]. During fabrication of the LPG and the subsequent deposition of the coating onto the cladding, the transmission spectrum was monitored by coupling the output from a tungsten-halogen lamp into the optical fibre and connecting the distal end of the optical fibre to an Ocean Optics CCD spectrometer of resolution 0.3nm.

Fig. 2. A schematic diagram of a length-apodized phase-shifted long period grating used in this work, adapted from [17]. This six section device has 12, 42, 81, 81, 42 and 12 periods in sections 1 – 6 respectively. Between each section is a π phase shift, indicated by the darker line.

For a length-apodized phase-shifted LPG of period 100 μm, the resonance corresponding to coupling to the $LP_{0,18}$ mode, shown in Figure 3, exhibits two attenuation bands, separated in wavelength by 20nm, with a fully resolved passband centred at 660nm. The side-lobe located to the red end of the spectrum is a by-product of length apodization [17]. These features are also present in the spectrum corresponding to coupling to the $LP_{0,17}$ mode, centered at 610nm. Note that the order of the cladding mode to which coupling occurs has been determined from a numerical model of the optical fibre, which will be discussed in section VI.

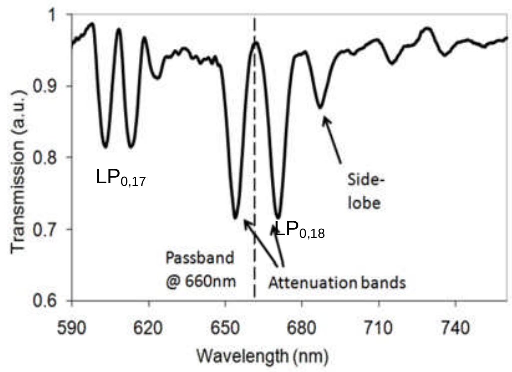

Fig. 3. The transmission spectrum obtained from a length-apodized phase-shifted LPG of period 100 μm and length 27mm. The two attenuation bands that characterize the coupling to each cladding mode are the result of the phase shifts created within the LPG. The side-lobe indicated is a known by-product of length apodization [8].

V. Coating The Long Period Grating

To investigate the effect of the deposition of coatings on length-apodized phase-shifted LPGs, a nanostructured coating of ω-tricosenoic acid was deposited using the Langmuir-Blodgett technique, using a Nima Technology Model 2410A Langmuir-Blodgett trough. ω-tricosenoic acid has a refractive index of 1.57 and a molecular length of 2.6nm [24], and has been used previously to investigate the influence of the layer-by-layer deposition of coatings on the transmission spectrum of the LPG [24]. A solution of ω-tricosenoic acid dissolved in chloroform at 0.14g/l was spread onto a pure water subphase of one compartment of the trough, and was compressed to a surface pressure of 26mN/m. The transfer rate was 12mm/min.

VI. Results

Figure 4 shows the evolution of the transmission spectra with increasing coating thickness of (a) an LPG of period 100μm, (b) a length-apodized LPG of period 100μm containing five π phase shifts, arranged as shown in figure 2. The multilayer ω-tricosenoic acid coating was deposited along the entire length of each LPG. Figure 4 (a) shows the mode reorganization behaviour originally reported in [12]. The resonance bands corresponding to coupling to the $LP_{0,17}$ and $LP_{0,18}$ modes undergo rapid blue shifts in wavelength in the mode transition region (for a coating thickness of order 250 nm), merging with the resonance band corresponding to coupling the adjacent lower order cladding mode at the end of the transition region, indicating that the $LP_{0,18}$ mode has taken on the characteristics of the $LP_{0,17}$ mode. The grating period

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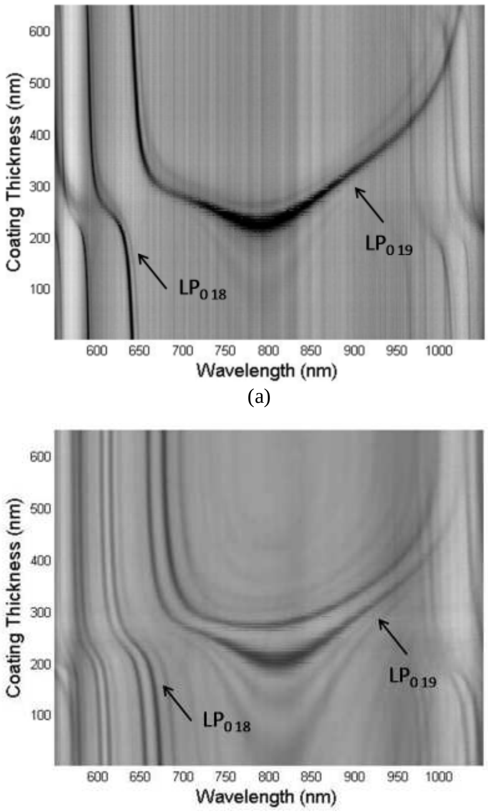
was selected such that the phase matching condition for coupling to the $LP_{0,21}$ mode was satisfied at the phase matching turning point when the coating thickness was approximately 250nm. In accord with a previous report [10], a broad resonance band develops, increasing rapidly in extinction, which splits into two bands with increasing coating thickness.



(a)

(b)

Fig. 4. The evolution of the attenuation bands of (a) a uniform-period LPG and (b) a length-apodized phase-shifted long period grating in response to increasing coating thickness. All spectra were recorded with the entire length of the LPG above the water subphase. The grey scale relates to the transmission, with black representing the lowest transmission white represents the maximum transmission.

In figure 4 (b), the attenuation bands within each of the resonance features corresponding to coupling to the $LP_{0,17}$ and $LP_{0,18}$ modes of the phase-shifted LPG show similar behaviour to that in figure 4 (a). The development of the resonance feature corresponding to coupling to the $LP_{0,21}$ mode shows that the attenuation bands form at different coating thicknesses, the first at approximately 200nm, and the second at 300nm. The first band to form shows the same behaviour as the resonance band in figure 4 (a), splitting into two with the wavelength separation increasing with increasing coating thickness. When the coating thickness is such that the phase matching condition is satisfied for the $LP_{0,19}$ mode (approximately 250 nm) the transmission at the Bragg resonance wavelength is at a maximum. The second attenuation band then forms and splits into two. For coating thicknesses > 300 nm, it is possible to couple to the same cladding mode at 4 different wavelengths. For coating thickness of order 290 nm the attenuation bands show different sensitivities to changes in the optical thickness of the coating, which may be of use in compensating for temperature induced effects in chemical sensing schemes.

The effect has been modeled numerically, using the approach presented in [11] to calculate the effective indices of the core and cladding modes of the multilayer cylindrical waveguide formed by the core, cladding and coating. These values were then used to determine the transmission spectrum using the matrix method reported in [25]. The values of the core and cladding indices used were 1.449 and 1.4432, respectively, and the core and cladding radii were 2 μm and 62.5 μm respectively. The product of the coupling strength and the grating length was unity in all cases. Assuming values for the period, phase step locations and coating refractive index (1.57) that were used in the experiment, the predicted evolution of the spectrum in response to increasing coating thickness is shown in figure 5. The figure shows qualitative agreement with the experimental observations. Uncertainties in the fibre parameters prevent quantitative comparison.

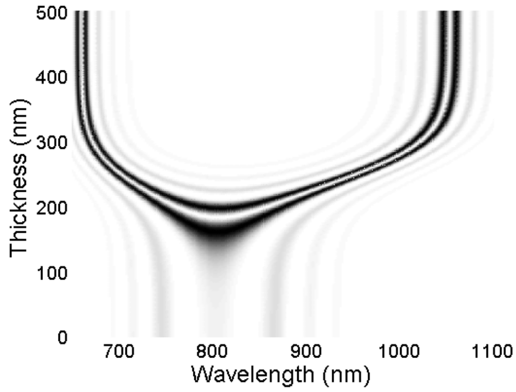


Fig. 5. Output from a numerical model of the response of the LP_{019} cladding mode resonance of a length-apodized phase-shifted LPG to the deposition of a coating of ω tricosenoic acid onto the cladding. The grey scale relates to the transmission, with black representing the lowest transmission white represents the maximum transmission.

The effect of partial coating on the transmission spectra of a standard LPG and a length-apodized phase-shifted LPG were studied experimentally. The results are presented in Figure 6. The standard LPG was coated along half its length, and the length-apodized phase-shifted LPG was coated over sections 4, 5 and 6 (defined in figure2). The response of the standard LPG shows that the resonance bands corresponding to coupling within the coated sections exhibit the expected behaviour, showing large wavelength shifts in the mode transition region and with the resonance bands subsequently merging with the resonance band corresponding to coupling the adjacent lower order cladding mode of the uncoated section of the fibre.

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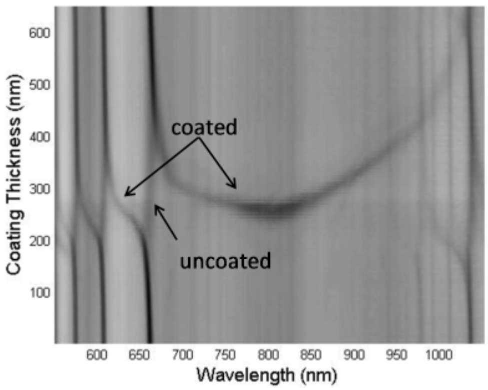
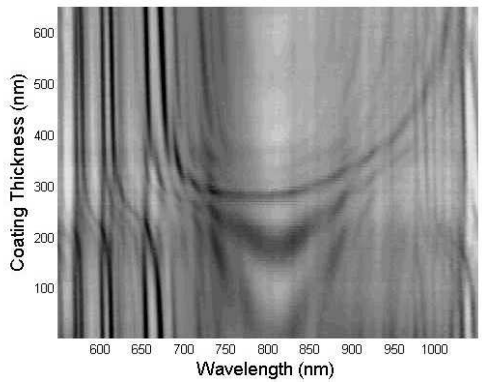


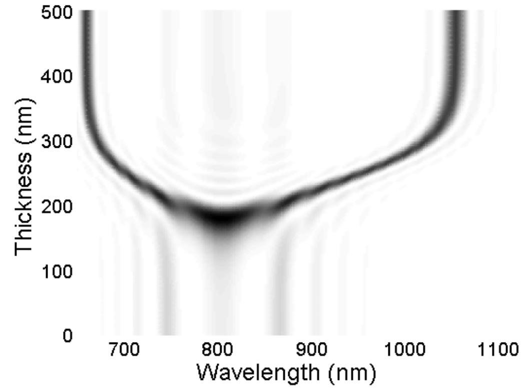
(a)



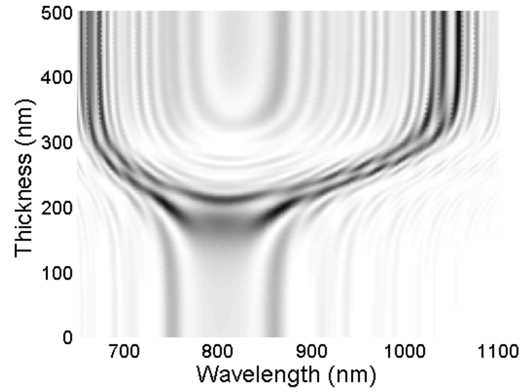
(b)

Fig. 6. The evolution of the spectrum of (a) a uniform-period LPG and (b) a length-apodized phase-shifted LPG with increasing thickness of a coating of ω-tricosenoic acid deposited on one half of the LPG (sections 4, 5 and 6 for the length-apodized phase-shifted long period grating). The LPGs both had a period of 100 μm and were both of length 28 mm. The grey scale relates to the transmission, with black representing the lowest transmission white represents the maximum transmission.

Coating half the length of the length-apodized phase-shifted LPG (i.e sections 4, 5 and 6, as identified in figure 2) reveals complex behaviour for the resonance features corresponding to coupling to the $LP_{0,19}$ mode. In the mode transition region, where the effective refractive indices of the cladding modes are changing rapidly, “Bandgaps” appear in the spectrum, where coupling is prevented from the core to the cladding mode over a narrow wavelength band. It is suggested that these arise as a result of interference between the light coupled into the cladding from the different sections of the length-apodized phase-shifted LPG.



(a)



(b)

Fig. 7. Output from numerical model of the response of the $\mathbf{LP_{019}}$ resonance of (a) an LPG containing a single phase shift located at its centre the deposition of a coating over one half of the length of the LPG and (b) a length-apodized phase-shifted LPG to the deposition of a coating over sections 4,5 and 6 (as defined in figure 2). The period of the LPG, 100 μm, is such that the resonance is at its phase matching turning point. The grey scale relates to the transmission, with black representing the lowest transmission white represents the maximum transmission.

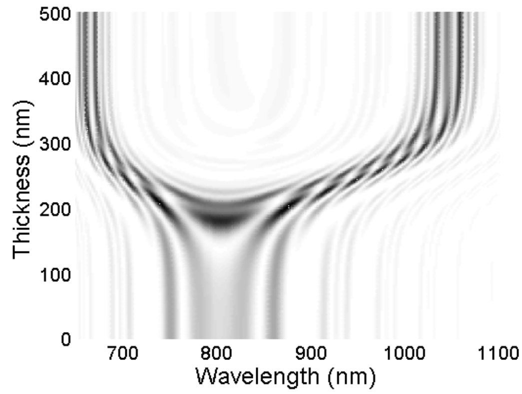


Fig. 8. Output from a numerical model of the response of the LP_{019} resonance of a length-apodized phase-shifted LPG to the deposition of a coating onto sections 2, 4, 5 and 6 (as identified in figure 2). The period of the LPG, 100 μm, is such that the resonance is at its phase matching turning point. The grey scale relates to the transmission, with black representing the lowest transmission white represents the maximum transmission

Figure 7 shows the numerically modeled response of an LPG with a single centrally located π phase shift (a) and that of a length-apodized phase-shifted LPG (b) in response to increasing coating thickness deposited on half the length and

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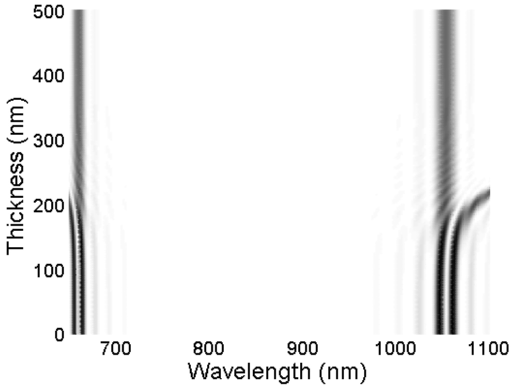
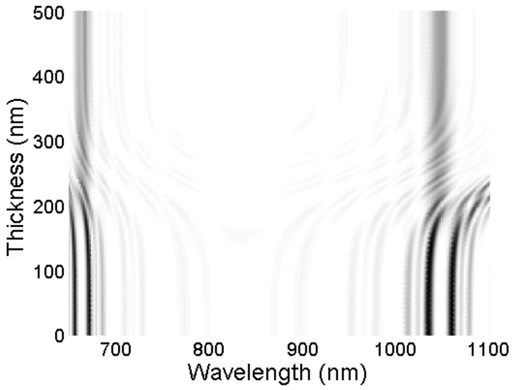
over sections 4, 5 and 6 (as identified in figure 2), respectively. There is evidence of banding in the spectrum of the single π phase-shifted LPG, which is more pronounced in the spectrum of the length-apodized phase-shifted LPG. The model shows qualitative agreement with the experimental results.

The visibility of the bands is improved when section 2 of the length-apodized phase-shifted LPG is coated in addition to sections 4, 5 and 6, as shown in figure 8. These spectral features are under investigation for exploitation in chemical sensing configurations, and may offer opportunities for synthesizing complex filter functions. These effects are also seen for resonance features not at the phase matching turning point, as shown for the $LP_{0,18}$ resonance band in figure 9



(a)



(b)

Fig. 9. Numerically modeled response of the $LP_{0,18}$ mode resonance feature of (a) a half coated single phase shift LPG and (b) a half coated length-apodized phase-shifted LPG (coating deposited on sections 4,5,6). The period of the LPG, 100 μm, is such that the $LP_{0,18}$ mode is not at its phase matching turning point. The grey scale relates to the transmission, with black representing the lowest transmission white represents the maximum transmission.

It should be noted that the coating of the LPG allows the observation of this effect, but may not prove to be the best means to control the spectrum for filtering applications, as the extinction of the attenuation bands for coating thicknesses within the mode transition region reduces for coatings of lossy materials whose refractive index is close to that of the cladding [26], while when the coating-cladding refractive index contrast is large the transmission spectrum exhibits complex behaviour in the mode transition region [11]. Any method for changing the effective refractive index of the cladding, e.g. thermally or by changing the surrounding refractive index, could be used to modify the spectrum. Figure 10 shows a plot of the response of a resonance feature of a length-apodized phase-shifted LPG to a linear change in effective refractive index of the cladding mode in regions (4, 5 and 6) of the LPG.

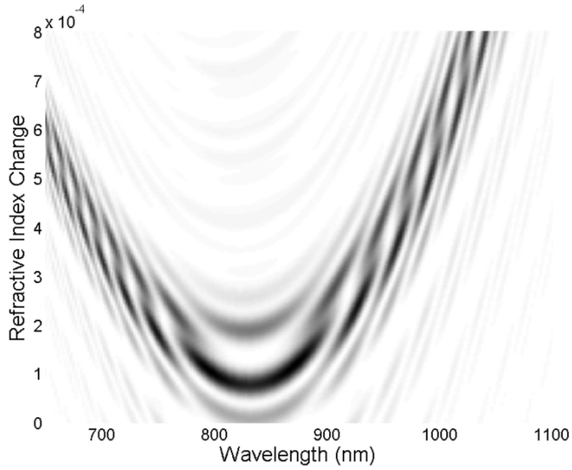


Fig. 10. Numerically modeled response of the $LP_{0,19}$ mode resonance feature of a length-apodized phase-shifted LPG to changes in the effective refractive index of the cladding mode in regions (4,5,6). The period of the LPG, 100 μm, is such that the $LP_{0,19}$ mode is at its phase matching turning point. The grey scale relates to the transmission, with black representing the lowest transmission white represents the maximum transmission

Figures 11 (a) and (b) provide examples of the predicted spectra, for cladding effective index changes of $8x10^{-5}$ and $1.2x10^{-4}$, respectively.

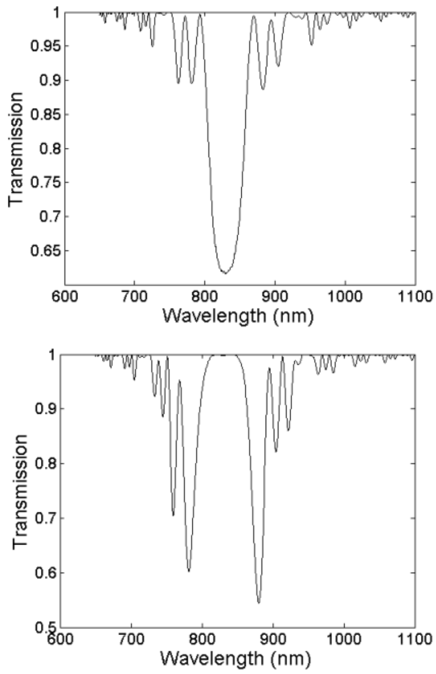


Fig. 11. Numerically modeled transmission spectra of the $LP_{0,19}$ mode resonance feature of a length-apodized phase-shifted LPG. The effective index of the cladding mode in regions (4,5,6) has been changed by $8x10^{-5}$ (a) and $1.2x10^{-4}$ (b). The period of the LPG, 100 μm, is such that the $LP_{0,19}$ mode is at its phase matching turning point.

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VII. Conclusion

The response of the transmission spectrum of length-apodized LPGs operating at the phase matching turning point to changes in the effective index of the cladding modes has been investigated. The changes in cladding modes' effective indices were induced by the layer-by-layer deposition of nanoscale coatings onto the fibre and the experimental results were compared to a model of the composite waveguide structure. Coating the entire length of a length-apodized phase-shifted LPG reveals that the attenuation bands within the resonance features for the coupling to modes at the phase matching turning point develop at different coating thicknesses and that when the coupling is fully developed, it is possible to couple to the cladding mode at 4 different wavelengths. For coating thickness corresponding to the mode transition region, the attenuation bands show different sensitivities to changes in the optical thickness of the coating, which may be of use in compensating for temperature induced effects in chemical sensing schemes. Partially coating a length-apodized phase-shifted LPG operating at the phase matching turning point has revealed bandgaps where coupling is prevented from the core to the cladding mode over a narrow wavelength band. This may offer benefits for the design of spectral filters.

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