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REVIEW ARTICLE

Optical fibre long-period grating sensors: characteristics and application

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Abstract
Recent research on fibre optic long-period gratings (LPGs) is reviewed with emphasis placed upon the characteristics of LPGs that make them attractive for applications in sensing strain, temperature, bend radius and external index of refraction. The prospect of the development of multi-parameter sensors, capable of simultaneously monitoring a number of these measurands will be discussed.

Keywords: fibre optics, fibre sensors, fibre gratings, long period gratings, strain, temperature, bend sensor, refractive index

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The development of fibre gratings has had a significant impact on research and development in telecommunications and fibre optic sensing. Fibre gratings are intrinsic devices that allow control over the properties of light propagating within the fibre—they are used as spectral filters, as dispersion compensating components and in wavelength division multiplexing systems. The sensitivity of their properties to perturbation of the fibre by the surrounding environmental conditions has led to extensive study of their use as fibre sensor elements.

Fibre gratings consist of a periodic perturbation of the properties of the optical fibre, generally of the refractive index of the core, and fall into two general classifications based upon the period of the grating. Short-period fibre gratings, or fibre Bragg gratings (FBGs), have a sub-micron period and act to couple light from the forward-propagating mode of the optical fibre to a backward, counterpropagating mode [1]. This coupling occurs at a specific wavelength, defined by the Bragg condition for the fibre grating, with the FBG acting as a narrow-band reflection filter and as a narrow-band channel-dropping filter when operated in transmission. The Bragg wavelength is governed by the period of the FBG and the effective index of the propagating mode, with the result that a change in either of these parameters, induced for example by a change in temperature or strain, changes the wavelength, forming the basis of the many reported FBG sensing schemes. Typically, FBGs deployed as sensors have lengths of the order of 5 mm, with sensitivities to temperature and strain of 13 pm K^{-1} and 1 pm $\mu\varepsilon^{-1}$ respectively, for FBGs operating at 1300 nm [2].

The long-period grating (LPG) has a period typically in the range 100 μm to 1 mm, as illustrated in figure 1. The LPG promotes coupling between the propagating core mode and co-propagating cladding modes. The high attenuation of the cladding modes results in the transmission spectrum of the fibre containing a series of attenuation bands centred at discrete wavelengths, each attenuation band corresponding to the coupling to a different cladding mode. Examples of the transmission spectra of LPGs are shown in figure 2. The exact form of the spectrum, and the centre wavelengths of the attenuation bands, are sensitive to the period of the LPG, the length of the LPG (typically of the order of 30 mm) and to the local environment: temperature, strain, bend radius and to the refractive index of the medium surrounding the fibre [3]. Changes in these parameters can modify the period of the LPG and/or the differential refractive index of the core and cladding modes. This then modifies the phase matching conditions for

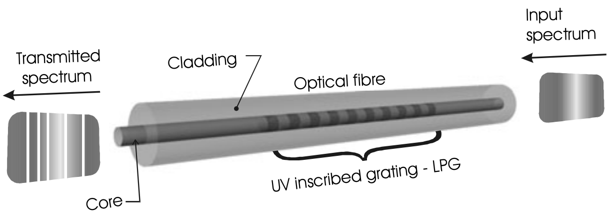

Figure 1. Schematic of an LPG.

coupling to the cladding modes, and results in a change in the central wavelengths of the attenuation bands.

The sensitivity to a particular measurand is dependent upon the composition of the fibre and upon the order of the cladding mode to which the guided optical power is coupled, and is thus different for each attenuation band. This range of responses makes them particularly attractive for sensor applications, with the prospect for multi-parameter sensing using a single sensor element [3].

This review will discuss the properties of LPGs and the methods employed in their fabrication. This will be followed by an examination of the theoretical background of LPGs, a discussion of their sensitivities to a range of measurands with a review of their implementation as sensor elements and a discussion of current trends in LPG sensor research.

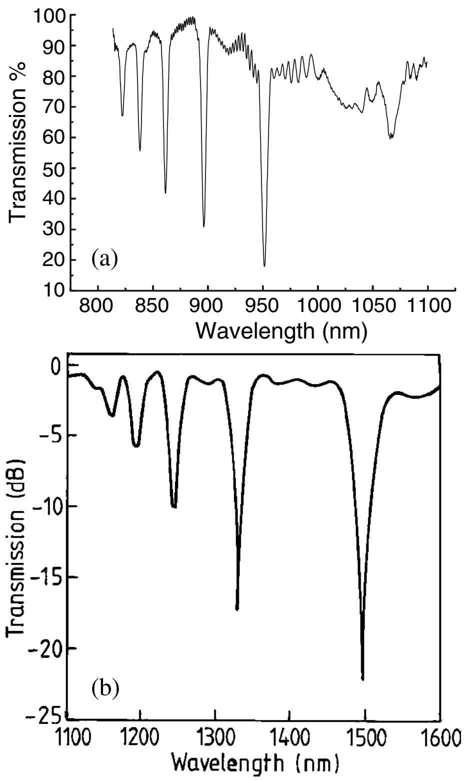

Figure 2. Transmission spectrum of (a) an LPG of length 40 mm and period 400 μm, fabricated in B–Ge co-doped photosensitive optical fibre with a cut-off wavelength of 644 nm (after [55]). (b) An LPG fabricated in Corning SMF-28 with period 320 μm (after [44]).

2. LPG fabrication

The fabrication of LPGs relies upon the introduction of a periodic modulation of the optical properties of the fibre. This may be achieved by permanent modification of the refractive index of the core of the optical fibre or by physical deformation of the fibre.

The modulation of the core refractive index has been achieved by ultraviolet (UV) irradiation [4–7], ion implantation [8], irradiation by femtosecond pulses in the infrared [9], irradiation by CO_2 lasers [10, 11], diffusion of dopants into the core [12, 13], relaxation of mechanical stress [14] and electrical discharges [15, 16]. The deformation of the fibre has been achieved mechanically [17, 18], by tapering the fibre [19] or by deformation of the core [20, 21] or cladding [22]. LPGs have been fabricated in photonic crystal fibre by periodically collapsing the holes of the fibre using CO_2 laser heat treatment [23].

The UV-induced index modulation is typically achieved in Ge-doped silica fibres using wavelengths between 193 and 266 nm [24]. This is the most widely utilized method for the fabrication of LPGs. The refractive index change is associated with the formation of Ge-related glass defects. Fibres with high photosensitivity have been developed by co-doping the core with boron and germanium [25] and by hydrogen loading [26]. The refractive index modulation may be built up on a point by point basis—a very flexible technique—or the entire length of the LPG may be formed simultaneously by exposure of the fibre though an amplitude mask [27], via a patterned mirror [28] or using a microlens array [29]—facilitating rapid and reproducible LPG fabrication.

A typical LPG fabrication configuration, using UV irradiation through an amplitude mask, is shown in figure 3. The output from a UV laser source is used to illuminate the

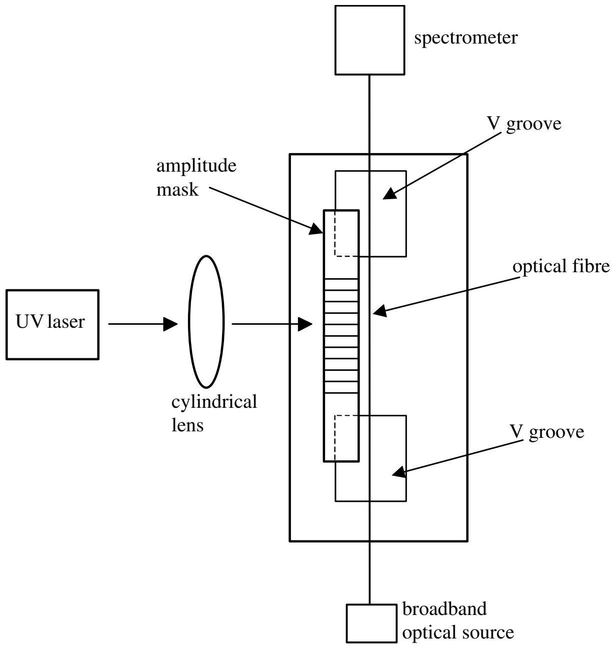

Figure 3. LPG fabrication using a UV laser.

optical fibre through an amplitude mask of appropriate period, which may be fabricated in chrome-plated silica [27] or from a metal foil, for example by milling a copper foil using a Cu vapour laser [30]. The cylindrical lens produces a line focus oriented parallel to the axis of the fibre.

The use of UV exposure is well established, due to its widespread use in the fabrication of FBGs [31]. Its use has implications for the spectral characteristics and stability of the LPG spectrum. UV exposure of optical fibres is known to induce birefringence, which can produce a polarization splitting in the attenuation bands for LPGs fabricated in non-polarization-maintaining fibres [32]. The refractive index change is known to contain an unstable component, which decays in time causing a significant change in the central wavelengths of the attenuation bands and in the coupling strength [27]. This unstable component may be removed by thermal annealing, but needs to be taken into account when designing an LPG for a particular application. The use of hydrogen loading of fibres to enhance their photosensitivity can result in further changes to the central wavelength and peak loss of the attenuation bands occurring after fabrication, as the hydrogen diffuses out of the fibre [6]. LPGs fabricated in hydrogen-loaded fibre by irradiation at 193 nm have been observed to exhibit a growth in the peak loss of up to 14 dB and an increase in central wavelength of 40 nm over the first 20 h following UV exposure, followed by a slow reduction of the peak loss and decrease in central wavelength of 50 nm over the following 450 h [6]. The effect is attributed to depletion of hydrogen in the exposed regions of the core. The diffusion of hydrogen from unexposed to exposed regions then acts to increase the amplitude of the refractive index modulation, as the refractive index increases further in the exposed regions (increasing hydrogen concentration) and decreases in the unexposed region (decreasing hydrogen concentration). Thus the strength of the LPG grows. This is followed by a slow out-diffusion whereby the refractive index of the core decreases, causing a decrease in wavelength. Similar effects have been observed for LPGs fabricated in hydrogen-loaded fibres using 248 nm irradiation [33]. These effects limit the ability to fabricate LPGs with precisely defined characteristics within hydrogen-loaded fibre. It has been shown that pre-exposure of a hydrogen-loaded fibre to a uniform UV beam locks in the photosensitivity enhancement provided by the hydrogen loading procedure [34]. The UV pre-exposure of the hydrogen-loaded fibre increases the number of defect sites believed to be responsible for photosensitivity, and these remain after the hydrogen has diffused out of the fibre. If an LPG is fabricated in pre-exposed fibre after the hydrogen has diffused out of the fibre, typically 2 weeks after removal from the hydrogen atmosphere at room temperature, the fibre maintains the photosensitivity, but does not suffer from the changes in attenuation band central wavelength and extinction [34]. Such effects have been observed using continuous-wave (CW) pre-exposure at 244 nm [34] and using pulsed irradiation at 157 nm [35] and 193 nm.

Post-fabrication tuning of the characteristics of an LPG's transmission spectrum is possible by reducing the fibre diameter by etching. The reduction in cladding diameter changes the effective index of the cladding modes, resulting in an increase in the central wavelengths of the attenuation bands. The etching also changes the electric field profile of the cladding modes, resulting in a change in the overlap integral and a concomitant change in the coupling efficiency and minimum transmission of the attenuation bands [36, 37].

Other UV wavelengths are being investigated for LPG formation, including 157 nm from F_2 lasers which offers the ability to fabricate LPGs in low-GeO_2 fibre with no hydrogen pre-treatment [38]—fibres in which LPGs would not form when exposed to other UV wavelengths. In addition, LPG formation in hydrogen-loaded fibres using this wavelength required a fluence 250 times lower than that required from a laser operating at 248 nm [5]. The frequency-doubled (266 nm) [39] and -tripled (355 nm) [7] outputs of Nd:YAG lasers have also been used to fabricate LPGs, as have femtosecond pulses from an Nd:glass laser [40].

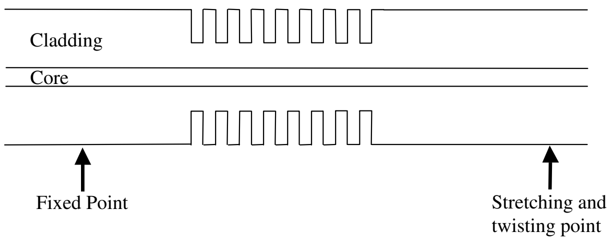

Figure 4. Corrugated fibre LPG.

LPGs have been fabricated using irradiation with femtosecond pulses in the near infrared (800 nm) [9]. The irradiation is believed to cause a densification of the glass, and the resultant index change, and LPG spectrum, is stable at temperatures up to 500 °C. CO_2 laser irradiation at 10.6 μm has been shown to produce LPGs with high temperature stability and polarization insensitivity [41], and with spectral characteristics that are unchanged even after annealing at 1200 °C [10]. The CO_2 laser exposure of the fibre was originally thought to result in the densification of the glass, and/or the relaxation of tensile stresses built into the cladding of fibres such as Corning SMF28 during fabrication [14]. However, there is evidence to suggest that the change in refractive index is a result of breakage of Si–O–Ge chains [11]. CO_2 laser irradiation has allowed LPGs to be written in both fibres that have been hydrogen loaded and in fibres with no hydrogen pre-treatment. The LPGs fabricated in hydrogen-loaded fibre were associated with few extraneous spectral features, as a result of the lower fluence required for their fabrication [11].

Electric arc fabrication of an LPG relies upon a combination of up to four effects to generate the periodic modulation of the fibre properties. The mechanisms exploited include the induction of microbends into the fibre [42], the periodic tapering of the fibre [19], the diffusion of dopants [12, 13] and the relaxation of internal stresses [15]. Such LPGs have been shown to operate at temperatures of up to 800 °C without permanent modification of their properties [43], and, if annealed appropriately, they may operate at temperatures up to 1190 °C [15]. Typically, the electrodes of a fusion-splicing machine are used, exposing a region of fibre with a length of the order of 100 μm to the arc, limiting the minimum period of LPG that may be fabricated. Chemical etching of the cladding of a fibre to produce a corrugated structure has been shown to allow the generation of an LPG [22]. The corrugated fibre is shown in figure 4. When a tensile load is applied to the fibre, the periodic variation in the diameter of the fibre results in a periodic strain variation across the corrugated structure, with a concomitant periodic refractive index induced via the photoelastic effect.

Thus the coupling strength increases with applied load, with a small change in wavelength of the attenuation bands [22].

Generally, LPGs have been fabricated to operate at telecommunications wavelengths (1300 and 1550 nm), and the spectrum is monitored by coupling light from superfluorescent fibre sources or superluminescent diodes in the fibre and recording the transmission using an optical spectrum analyser. There have been reports of the use of fibres with lower cut-off wavelengths, 650 nm, allowing the operation of the LPG within the response of silicon detectors, facilitating the use of low-cost CCD spectrometers [39].

3. LPG theory

The fibre itself consists of two waveguide structures—one being the high-index core surrounded by the lower-index cladding, the other being the cladding, surrounded by air. Phase matching between the mode propagating in the core of the fibre and a forward-propagating cladding mode is achieved at the wavelength, λ, where the expression

$$\lambda = [n_{eff}(\lambda) - n^i_{clad}(\lambda)]\Lambda \tag{1}$$

is satisfied [44], where $n_{eff}(\lambda)$ is the effective refractive index of the propagating core mode at wavelength λ, $n^i_{clad}(\lambda)$ is the refractive index of the ith cladding mode and Λ is the period of the LPG.

The minimum transmission of the attenuation bands is governed by the expression [1]

$$T_i = 1 - \sin^2(\kappa_i L) \tag{2}$$

where L is the length of the LPG and κ_i is the coupling coefficient for the ith cladding mode, which is determined by the overlap integral of the core and cladding mode and by the amplitude of the periodic modulation of the mode propagation constants.

Since the cladding generally has a large radius, it supports a large number of cladding modes. Theoretical analysis has shown that efficient coupling is possible only between core and cladding modes that have a large overlap integral, i.e. modes that have similar electric field profiles [45]. Thus coupling is observed between the core and circularly symmetric cladding modes of odd order. This is because the electric field profile of the even-order modes is such that the field amplitude is low within the core, whereas the electric field profiles of the odd modes have a peak located within the core [45].

The modelling of LPGs requires the calculation of the refractive indices of the core and cladding modes to allow the central wavelengths of the attenuation bands to be determined, and the calculation of the mode electric field profiles to facilitate determination of the coupling strength and the form of the spectrum. The refractive index of the propagating core mode of the fibre is generally determined using the weakly guided field approximation of Gloge [46]. A simple three-layer slab waveguide model to determine the cladding mode indices has been presented, allowing an approximate determination of the coupling wavelengths [27]. However, it has been shown that the effect of the core upon the effective indices and mode profiles of the cladding mode cannot be ignored for accurate simulation of LPG characteristics [45].

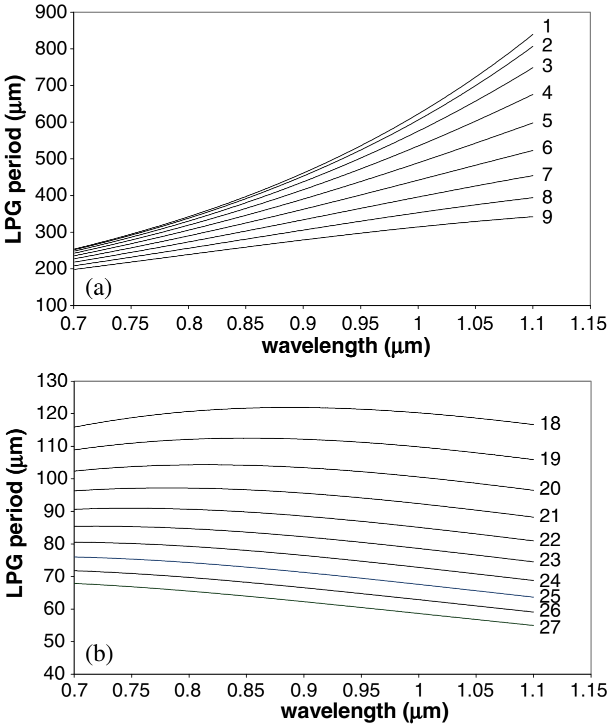

Figure 5. Plot of resonant wavelength as a function of LPG period for coupling between the guided core mode and cladding modes of order (a) 1–9 and (b) 18–29, calculated using the technique detailed in the text and assuming the fibre's cut-off wavelength is 650 nm.

Figure 5 shows the dependence of the coupling wavelength for cladding modes 1–9 (a) and 18–27 (b) upon the period of the LPG. These graphs were calculated following the method presented in [47]. The fibre modelled has a cut-off wavelength of 675 nm. The graphs indicate that coupling to lower-order modes is achieved using longer periods, while shorter periods facilitate coupling to the higher-order modes. In addition, figure 5(b) shows that, for higher-order cladding modes, coupling to one cladding mode can occur at two wavelengths, producing two attenuation bands [48]. It should be noted that small changes in the coupling conditions could result in large changes in the separation of the two attenuation bands. For LPGs fabricated such that their period coincides with the peak of the curve (for example, mode 18), it has been observed that changes in the coupling conditions result in a change in the coupling efficiency, but not in the wavelength [49].

4. LPG sensors

4.1. Temperature sensitivity

As discussed in the introduction, the sensitivity of LPGs to environmental parameters is influenced by the period of the LPG [3], by the order of the cladding mode to which coupling takes place [3] and by the composition of the optical fibre [50]. This combination of influences allows the fabrication of LPGs that have a range of responses to a particular measurand—a single LPG may have attenuation bands that have a positive sensitivity to a measurand, others that are insensitive to the measurand and others with a negative sensitivity.

This property has been widely exploited for controlling the temperature sensitivity of LPGs. For many telecommunications applications spectral stability is of prime importance, and the ability to fabricate an LPG with an inherently temperature-insensitive attenuation band is an attractive feature. This is also attractive for forming temperature-insensitive strain sensors. On the other hand, for forming temperature sensors, or thermally tuned filters, a high temperature sensitivity (of either sign) is required.

The origin of the temperature sensitivity may be understood by differentiating equation (1) [44].

$$\frac{\mathrm{d}\lambda}{\mathrm{d}T} = \frac{\mathrm{d}\lambda}{\mathrm{d}(\delta n_{eff})}\left(\frac{\mathrm{d}n_{eff}}{\mathrm{d}T} - \frac{\mathrm{d}n_{cl}}{\mathrm{d}T}\right) + \Lambda\frac{\mathrm{d}\lambda}{\mathrm{d}\Lambda}\frac{1}{L}\frac{\mathrm{d}L}{\mathrm{d}T} \quad (3)$$

where λ is the central wavelength of the attenuation band, T is the temperature, n_{eff} is the effective refractive index of the core mode, n_{cl} is the effective refractive index of the cladding mode, $\delta n_{eff} = (n_{eff} - n_{cl})$, L is the length of the LPG and Λ is the period of the LPG.

The first term on the right-hand side of equation (3) is the material contribution, and is related to the change in the differential refractive index of the core and cladding arising from the thermo-optic effect. This contribution is dependent upon the composition of the fibre and is strongly dependent upon the order of the cladding mode. For coupling to low-order cladding modes (accessed using longer periods, $\Lambda > 100\ \mu$m), the material effect dominates. For coupling to higher-order cladding modes (accessed using shorter periods, $\Lambda < 100\ \mu$m), the material effect for standard germanosilicate fibres can be negligible [44]. The second term is the waveguide contribution as it results from changes in the LPG's period. The magnitude and sign of the term depend upon the order of the cladding mode. For coupling to low-order cladding modes $\mathrm{d}\lambda/\mathrm{d}\Lambda$ is positive, while for the higher-order cladding modes this term is negative, as can be seen from the graphs in figures 5(a) and (b). Thus, by an appropriate choice of LPG period it is possible to balance the two contributions to the temperature sensitivity to produce a temperature-independent attenuation band and also to produce attenuation bands with temperature sensitivities (positive or negative) appropriate to specific applications. Altering the fibre composition, such that the thermo-optic coefficient of the core is either larger or smaller than that of the cladding, can also be used to obtain a required temperature sensitivity [51]. In addition to the change in central wavelength, a change in the extinction of the attenuation band may be observed for LPGs with strength $\kappa L > \pi$ [51]. At room temperature, the temperature response of the wavelengths of the attenuation bands' is linear, as illustrated in figure 6 [3]. However, it has been shown that the response becomes non-linear at cryogenic temperatures, below 77 K [52].

LPGs fabricated in standard telecommunications optical fibre exhibit temperature sensitivities in the range 3 nm/100 °C to 10 nm/100 °C [3]. This is an order of magnitude larger than the sensitivity of FBG sensors. Temperature-compensated LPGs have been demonstrated using periods $<$100 μm. In this regime, the coupling is to the higher-order modes, which have a lower material contribution to the temperature sensitivity. For example, an LPG of period 40 μm was found to have an attenuation band with sensitivity of 1.8 pm °C^{-1} [44], an order of magnitude smaller than that of a FBG.

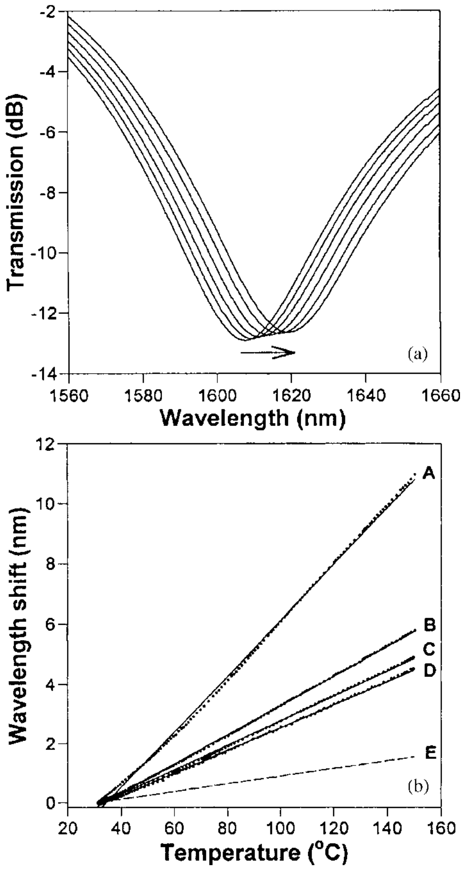

Figure 6. (a) Shift in the wavelength of an attenuation band of an LPG with temperature. The LPG was fabricated with period of 280 μm in Corning SMF-28 fibre. The spectra correspond to temperatures of 22.7, 49.1, 74.0, 100.9, 127.3 and 149.7 °C. (From [3].) (b) Shift in the wavelengths of four attenuation bands, A–D, as a function of temperature for the LPG detailed in figure 6(a). The dashed line is the shift for an FBG fabricated at 1550 nm for comparison. (From [3].)

For the fabrication of high-resolution temperature sensors, or to create widely tuneable filters, a number of techniques for further enhancing the sensitivity have been reported, including the use of fibres of different composition and different geometries and the use of polymer coatings.

By careful choice of the order of the cladding mode and operating wavelength, LPGs fabricated in photosensitive B–Ge co-doped optical fibres have been shown to offer sensitivities of up to 275 nm/100 °C [53]. Other techniques for enhancing the temperature sensitivity have been reported based upon surrounding the fibre by a material of large thermo-optic coefficient, resulting in the LPG responding to both changes in temperature and to the temperature-induced refractive index change of the surrounding medium [54–56]. These techniques will be discussed in more detail in section 4.3.

In addition to using parameters in equation (3) to design a temperature-insensitive LPG [44], there has been a report of the use of athermal packaging. The LPG was bonded to a substrate whose thermal expansion coefficient induced a strain that produced a wavelength shift of the opposite sense to that induced by the change in temperature. This temperature compensation technique reduced the thermal sensitivity of the LPG by approximately 45% by bonding the LPG in an aluminium cylinder [57]. Alternatively, recoating the fibre with a material with a negative thermo-optic coefficient has been shown to permit the temperature sensitivity to be reduced to 0.07 nm/100 °C [58]. In addition to the use of the refractive index dependence of the LPG to compensate for the thermal response, the bend sensitivity (section 4.4) has also been exploited, resulting in a reduction in the temperature sensitivity by two orders of magnitude [59].

Metal-coated LPGs have been used to develop low-power tuneable filters based upon resistive heating. The deposition of thin films of copper [60] and platinum [61] of thickness approximately 300 nm, in each case with an initial 15 nm titanium layer to give good adhesion, was found to produce a small (1 nm) wavelength shift and small reduction in coupling efficiency. The Cu-coated fibre exhibited a 4 nm wavelength shift for an electrical power of 0.5 W [60], while the Pt-based filter offered 11 nm for 0.67 W, with a linear efficiency of 16 nm W^{-1} [61]. The metal coating was observed to make the performance of the LPG insensitive to the refractive index of the medium surrounding the coating [61].

4.2. Strain sensitivity

The axial strain sensitivity of LPGs may be assessed by differentiating equation (1) [44]

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\varepsilon} = \frac{\mathrm{d}\lambda}{\mathrm{d}(\delta n_{eff})}\left(\frac{\mathrm{d}n_{eff}}{\mathrm{d}\varepsilon} - \frac{\mathrm{d}n_{cl}}{\mathrm{d}\varepsilon}\right) + \Lambda\frac{\mathrm{d}\lambda}{\mathrm{d}\Lambda}. \tag{4}$$

Again, the sensitivity comprises material and waveguide effects, the material effects being the change in dimension of the fibre and the strain-optic effect, with the waveguide effects arising from the slope of the dispersion term $\mathrm{d}\lambda/\mathrm{d}\Lambda$. For LPGs with periodicity >100 μm, the material contribution is negative, while the waveguide contribution is positive. Appropriate choice of grating period and fibre composition will thus allow the generation of attenuation bands with positive, negative or zero sensitivity to strain [44].

An LPG of period 340 μm, written in Corning Flexcore fibre, exhibited an attenuation band with strain sensitivity of 0.04 pm $\mu\varepsilon^{-1}$ [44], which is an order of magnitude less than that of a FBG operating at 1300 nm. An LPG with period of 40 μm exhibited a larger strain sensitivity of −2.2 pm $\mu\varepsilon^{-1}$, since in this regime, $\Lambda < 100$ μm, both contributions to the strain sensitivity are negative [44]. A typical response to strain is shown in figure 7, in which the wavelength shifts in the central wavelengths of a number of the attenuation bands of an LPG of period 280 μm, written in Corning SMF 28 fibre, are plotted as a function of strain [3]. Each attenuation band exhibits a different, linear, response to the applied strain.

The ability to define the performance of an LPG by virtue of its periodicity, making the LPG (i) strain insensitive ($\Lambda > 100\,\mu$m) and (ii) temperature insensitive ($\Lambda < 100\,\mu$m), offers a convenient method for isolating the response of the LPG to one or other of the measurands, since the periodicities correspond to the regimes in which the LPG can show (i) the highest sensitivity to temperature and (ii) the highest sensitivity to strain. The dependence of the sensitivity of the LPG to strain and temperature upon the order of the cladding mode may also be used to permit the decoupling of the temperature and strain responses, while simultaneously measuring both parameters [62], which has long been an issue in fibre optic sensing schemes.

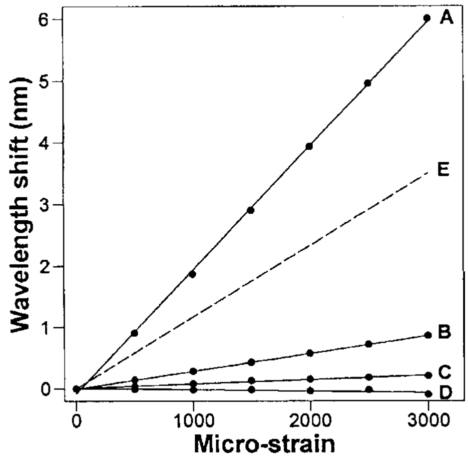

Figure 7. Shift in the wavelengths of four attenuation bands, A–D, as a function of strain for the LPG detailed in figure 6(a). The dashed line is the strain-induced wavelength shift for an FBG fabricated at 1550 nm for comparison. (From [3].)

In addition to the measurement of axial strain, the sensitivity of LPGs to transverse loads has been investigated [63, 64]. The application of a transverse load induces linear birefringence in the optical fibre, with the result that each attenuation band is split into two, the bands corresponding to the two orthogonal polarization states, as shown in figure 8. Since the wavelengths of the two components are related to the birefringence, the wavelength separation increases with applied load. A linear response was obtained, with a sensitivity of 500 nm kg^{-1} mm^{-1}, which is 800 times that of a FBG [64].

Corrugated LPGs have been used to form axial strain sensors and torsion sensors [65]. As discussed in the fabrication section, the application of axial load to a fibre that has a periodically modified diameter results in the fibre experiencing a periodic strain, which, via the photoelastic effect, causes a periodic modulation of the refractive index of the fibre. The effect of axial load is thus to increase the coupling strength of the LPG, changing the minimum transmission of the LPG attenuation bands. A corrugated fibre experiencing torsion sees different twisting rates in the etched and unetched regions as a result of the difference in diameter. This results in a stress concentration at the etched boundary. The effect of torsion is to both change the coupling strength, and induce a wavelength shift [65, 66].

4.3. Refractive index sensitivity

The refractive index sensitivity of LPGs arises from the dependence of the phase matching condition upon the effective refractive index of the cladding modes. The effective indices of the cladding modes are dependent upon the difference between the refractive index of the cladding and that of the medium surrounding the cladding. The central wavelengths of the attenuation bands thus show a dependence upon the refractive

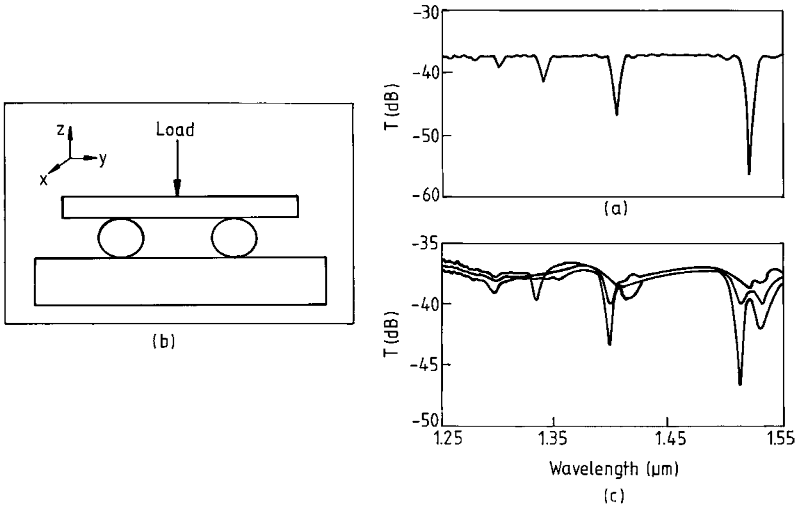

Figure 8. Loading system and transmission spectra of an LPG of period 490 μm, written in B–Ge co-doped fibre, unloaded and loaded, showing the generation of attenuation band splitting resulting from the induced birefringence. (After [64].)

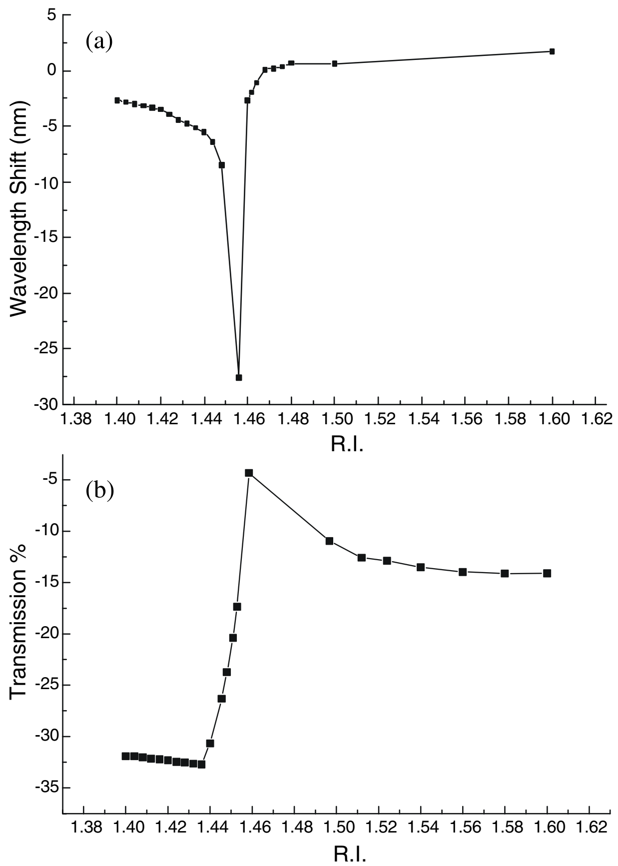

Figure 9. Plot of (a) the wavelength shift and (b) the minimum transmission value of an attenuation band against the RI of the material surrounding the LPG of period 400 μm written in boron–germanium co-doped fibre with cut off wavelength 650 nm. (From [55].)

index of the medium surrounding the cladding, provided that the cladding has the higher refractive index.

The sensitivity to refractive index manifests itself as a change in the central wavelengths and in the minimum transmission value of the attenuation bands, as is illustrated in figure 9(a). The highest sensitivity is shown by the higher-order modes, and occurs at refractive indices approaching that of the cladding [67]. When the refractive index is equal to that of the cladding, the cladding appears to be of infinite extent and thus supports no discrete modes. Broadband radiation-mode coupling losses are then observed, with no distinct attenuation bands. For surrounding refractive indices higher than that of the cladding, the centre wavelengths of the attenuation bands show a considerably reduced sensitivity [67–69], but a change in the form of the transmission spectrum is observed, in that the extinction of the attenuation bands is reduced [70], as is illustrated in figure 9(b). The presence of attenuation bands in this situation, where the cladding is no longer acting as a waveguide, is attributed to the existence of attenuated cladding modes arising from Fresnel reflection, rather than total internal reflection from the cladding/air interface [70].

Clearly, for some applications where well-controlled spectral characteristics are required, the refractive index sensitivity has a number of practical implications for the packaging and protection of an LPG. Care has to be taken to ensure that the properties of an adhesive used to attach an LPG to a substrate, or the properties of materials used to protect the LPG from mechanical damage or humidity, do not change the wavelengths of the attenuation bands from their original value, and that any changes in the refractive index of the surrounding material do not cause a change in the transmission spectrum of the LPG.

With this in mind, LPGs have been fabricated in fibres with complex structures to desensitize the LPG spectrum to the surrounding refractive index. LPGs fabricated in dual shaped core (DSC) dispersion-shifted fibre exhibit an attenuation band that is insensitive to external refractive index and to mechanical damage of the fibre surface [71]. The DSC fibre contains an inner cladding region that has a higher refractive index than the remaining cladding layer. The refractive-index-insensitive attenuation band is believed to correspond to coupling to a mode of this inner cladding.

LPGs have been fabricated in an air-clad optical fibre, in which the cladding of the fibre is surrounded by a capillary tube, supported by thin silica webs [72]. The evanescent field of the cladding modes does not extend beyond the capillary, with the result that all of the attenuation bands are insensitive to the external refractive index. A similar fibre structure, but in which the space between the capillary and the inner cladding is filled with a liquid crystal material, has been used to create a tuneable filter. In this case, the refractive index of a dye doped nematic liquid crystal was controlled by realignment of the molecules using polarized laser illumination [73]. Similar systems could be controlled using electrical or thermal techniques.

The refractive index sensitivity of LPGs has been exploited to form refractive index sensors, chemical concentration sensors [74–76], a liquid level sensor [77] and as a means of forming a tuneable spectral filter [73]. While LPGs are sensitive over only a limited refractive index range, and their response is not species specific, it has been shown that LPGs may be used for on-line monitoring of the concentration of aqueous solutions of materials or of materials in inaccessible locations for industrial production quality control [76]. Concentrations of solutions of sodium chloride [76], calcium chloride [76] and ethylene glycol [67, 76] have been measured, with sensitivities equal to, or better than, that of conventional Abbe refractometry [76]. The use of LPGs to monitor the refining of kerosene, which requires that the concentration of organic aromatics such as benzene and xylene is measured, has been proposed. To demonstrate the feasibility, the concentration of a binary solution of xylene in heptane was measured with a minimum detectable volumetric concentration of 0.04%, corresponding to a refractive index change of 6×10^{-5} [75]. This is comparable to the accuracy of the standard technique of liquid chromatography and UV spectroscopy. The use of two cascaded LPGs, with periods chosen such that one LPG had an attenuation band that was insensitive to temperature while the other had a band that was insensitive to refractive index, has been shown to allow simultaneous, independent measurement of these two parameters. This potentially allows the temperature-independent monitoring of chemical solutions with temperature-dependent refractive indices [78].

The majority of studies to date have concentrated upon the bulk immersion of the LPG into a solution. It is attractive to consider the prospect of depositing overlay materials that exhibit changes in their refractive index in response to their local environment. In this way, the LPG may be used to form, for example, a tuneable loss filter [61], a temperature-insensitive filter [58] or a species-specific chemical sensor [79].

LPG-based biosensors have been investigated by immobilizing antibodies on the surface of the fibre and monitoring the change in refractive index that occurs when an antigen bonds with the antibody [79]. This is the first reported example of the use of an LPG to form a species-specific chemical sensor, again offering comparable performance to other techniques including surface plasmon resonance and interferometry, but with the prospect for on-line monitoring.

The effect of the thickness of the overlay material upon the LPG response has also been investigated [80]. A thin film of organic material was deposited upon an LPG using the Langmuir–Blodgett technique, which allows high-resolution control (≈3 nm) over the thickness of the film by depositing one molecular layer at a time. It was observed that, for films of refractive index *higher* than that of the cladding, the wavelength and amplitudes of the attenuation bands exhibited a very high sensitivity to the optical thickness of the overlay when the thickness of the films was of the order of a few hundred nanometres. For materials of index lower than that of the cladding, the sensitivity to thickness of the overlay is considerably reduced. This is quite distinct from the behaviour under bulk immersion, in which the highest sensitivity is observed for indices lower than that of the cladding, as shown in figure 9(a). An example of this response is shown in figure 10. Materials suitable for deposition by the LB technique have been previously shown to be chemically sensitive [81, 82], offering the prospect for the development of a range of new species-specific chemical sensors.

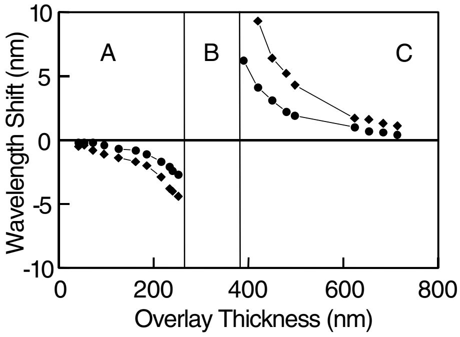

Figure 10. Experimentally determined response of two of the attenuation bands of an LPG to the deposition of a thin film of material of refractive index 1.57. (From [80].)

The refractive index sensitivity of LPGs has been exploited to form other types of physical sensor. LPGs have been proposed to form a flow sensor to monitor the arrival of resin within a liquid composite moulding system [83, 84]. The measurement relies upon the reduction in the extinction ratio of the attenuation band that occurs when the LPG is surrounded by a material of higher refractive index. An LPG-based liquid-level sensor has been reported [77]. Partial immersion of the LPG within a liquid results in each attenuation band splitting into two. One of the split attenuation bands has a central wavelength corresponding to coupling to the cladding mode with an air surround (B), while the other has a central wavelength corresponding to coupling to the same cladding mode, but with its effective refractive index modified by having the liquid surround (A), as illustrated in figure 11. As the minimum transmission value of an attenuation band is dependent on the length of the LPG (according to equation (2)) then the relative depth of the split attenuation bands will change in response to a change in the liquid level. The sensor has a linear response, as shown in figure 12.

The refractive index sensitivity has also been used to enhance and reduce the temperature sensitivity of LPGs. Surrounding the LPG by a liquid with a large thermo-optic coefficient results in the LPG responding to both changes in temperature and to the temperature-induced refractive index change of the surrounding medium [54–56]. If the material has a negative thermal expansion coefficient then, for increasing temperature, the wavelength shift induced by the change in refractive index of the coating causes a red shift in the wavelength of the attenuation band. If the attenuation band itself has positive temperature sensitivity, then the two

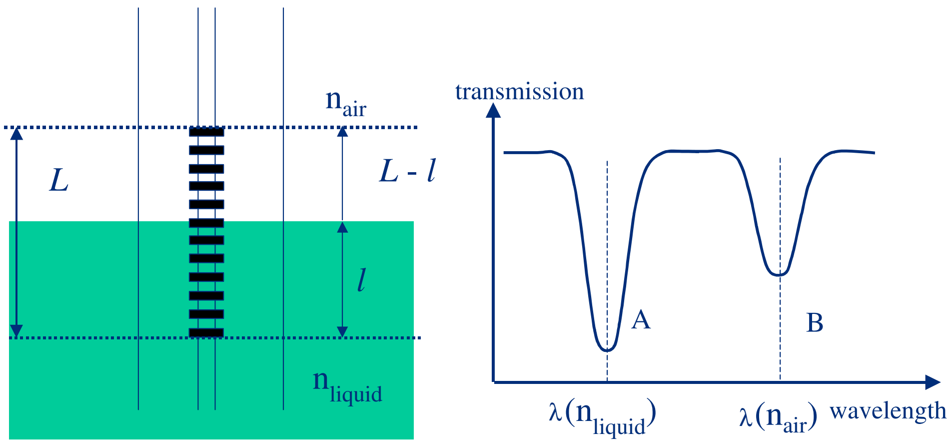

Figure 11. Principle of operation of the liquid-level sensor: (a) deployment of the LPG; (b) schematic of the expected split in the attenuation band.

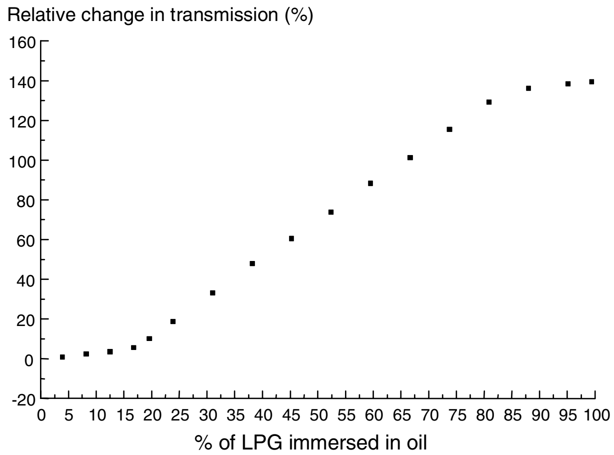

Figure 12. Relative change in the extinction of the attenuation bands of the liquid-level sensors, exhibiting a linear response over 60% of the LPG's length. (From [77].)

effects add to increase the temperature response. If, however the material has a positive thermo-optic coefficient, then an increase in temperature causes a blue shift of the attenuation band, reducing the temperature response of the attenuation band.

Recoating the LPG with a UV-curable acrylate-based polymer of refractive index approximately equal to that of the cladding, and with a negative thermo-optic coefficient, increased the sensitivity of an LPG fabricated in a conventional dispersion-shifted fibre from 5 nm/100 °C to 80 nm/100 °C [55]. This, however, was accompanied by a change in the coupling strength. Using an air-clad optical fibre, described previously in this section, in which the air regions were filled by the same polymer, produced a similar sensitivity but with no change in the minimum transmission of the attenuation bands [56]. In addition, it was noted that the novel fibre structure allowed the polymer to be protected from environmental effects, such as humidity, that may degrade its performance. A similar system using a liquid crystal material produced a sensitivity of 210 nm/100 °C [54]. For an LPG recoated with a material of positive thermo-optic coefficient, a temperature response as low as 0.07 nm/100 °C was obtained [58].

Ultra high sensitivity of up to 1900 nm/100 °C, over a limited temperature range of 1 °C, has been obtained by surrounding the fibre with a Cargille oil of refractive index that was approximately equal to that of the cladding. The sensor could be designed to operate at a range of temperatures by choosing an oil whose thermo-optic coefficient was such that, at the required operating temperature, the refractive index was approximately equal to that of the cladding [55].

4.4. Bend sensitivity

The bend sensitivity of an LPG manifests itself in one of two ways: as a shift in the central wavelength of the attenuation bands or as a splitting in two of each attenuation band, with the wavelength separation of the split components increasing with increasing curvature.

The first observation of the influence of bending upon the transmission spectrum of an LPG noted that the shift in the central wavelength of the attenuation bands was accompanied by a reduction in the loss and a broadening of the spectral dropout [85]. The magnitude of the bend-induced wavelength shift was subsequently observed to depend upon the orientation of the optical fibre with respect to the plane in which the bend is applied, with the maximum and minimum sensitivities separated by 180° [86]. The origin of the orientation dependence is believed to be an eccentricity of the fibre core, with the core no longer at the neutral axis of the fibre. Fibres with eccentricities of up to 14 μm have been used to form bipolar bend sensors [87].

The second manifestation—the splitting of the attenuation bands—is attributed to a breaking of the symmetry of the system that results in two degenerate spatial modes of the cladding becoming non-degenerate. The effect on the spectrum is shown in figure 13. This effect has been observed in B–Ge co-doped photosensitive fibre [39, 88] and in fibres with large core eccentricities [89]. This effect also has been observed to exhibit a dependence upon the orientation of the fibre [39, 89]. In this case the reference plane is defined by the orientation of the fibre during fabrication of the LPG, with the largest sensitivity corresponding to the surface of the fibre oriented towards the UV source on the outer surface of the bend [39]. This is thought to be a result of an asymmetry

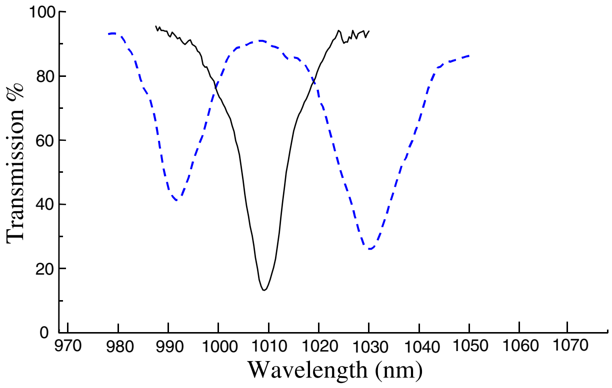

Figure 13. A plot of the transmission spectrum of an attenuation band in the spectrum of an LPG experiencing different bend curvatures. Solid curve, curvature 0.00 m^{-1}; dashed curve, curvature 1.55 m^{-1}. The LPG of period 400 μm and length 40 mm was fabricated in B–Ge co-doped optical fibre with cut-off wavelength 650 nm. (From [39].)

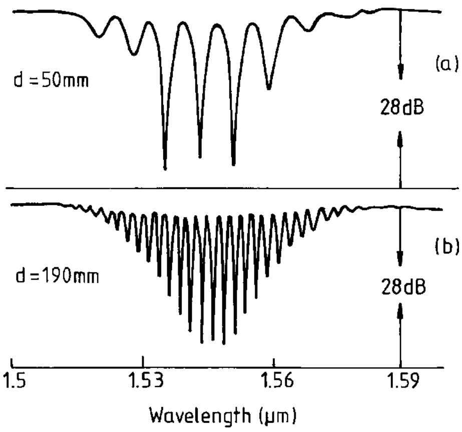

Figure 14. Transmission spectrum of a pair of in-series LPGs: (a) with a 50 mm spacing; (b) with a 190 mm spacing. (From [64].)

introduced by a radially non-symmetric UV-induced refractive index modulation. Such asymmetries have been used to account for similar effects in LPGs formed by CO_2 laser irradiation, where the asymmetry is more pronounced due to heating of the surface facing the laser beam [90].

As discussed in the theory section, for higher-order cladding modes it is possible to couple to the same cladding mode at two different wavelengths. The wavelength separation of the two resulting attenuation bands shows high sensitivity to external measurands, and has been exploited to perform bend sensing, offering sensitivities of up to 50 times that offered by the previously reported LPG bend sensors [48].

4.5. In-series LPGs

There has been some interest in the use of concatenated LPGs for sensing applications. When a pair of identical LPGs is fabricated in series within an optical fibre, separated by up to 10 cm, a set of fringes are observed within the attenuation bands, as seen in figure 14. The formation of the fringes may be understood with reference to figure 15. The first LPG couples light to the cladding mode. Light then propagates to the second LPG via two routes: in the core and in the cladding.

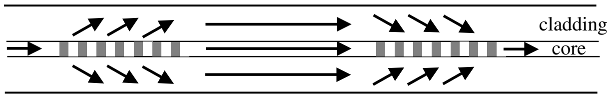

Figure 15. Principle of operation of in-series LPGs. (From [92].)

By virtue of the difference in the effective refractive indices of the core and cladding modes, the light coupled into the core by the second LPG is phase shifted with respect to the light propagating in the core, giving rise to the interference pattern. The narrower bandwidth of the fringe facilitates greater resolution in the measurement of the wavelength than is possible with conventional LPGs.

In-series LPGs have been used to sense bending [91], external index of refraction [92, 93], temperature and transverse load [93]. Bending the fibre results in an increase in the attenuation of the cladding modes, with a concomitant reduction in the fringe visibility, along with a shift in the central wavelength of the band [91]. Transverse loading was observed to reduce the fringe visibility linearly until, at a threshold load, the fringe pattern disappeared [93]. Further increase of the load causes the pattern to reappear with a π phase shift [93]. The response of the in-series LPGs to refractive index is a decrease in fringe visibility and a change in the central wavelengths, of similar form to that observed for single LPGs [93]. For refractive indices higher than that of the cladding, the fringes reappear, but with considerably reduced visibility. If, however, only the section of fibre between the LPGs is surrounded by the material of high refractive index, the minimum transmission of the attenuation bands can show up to twice the sensitivity of a conventional LPG, for refractive indices in the range 1.5–1.55 [92].

Coating the end of a fibre containing an LPG with a metal film results in the double pass of the light through the LPG, allowing the generation of the interference fringes characteristic of in-series LPGs [94]. This also allows the monitoring of the performance of the LPG in reflection, and avoids the need to fabricate identical LPGs. This has been used to form a temperature sensor [94].

4.6. Multi-parameter sensing using LPGs

As has been discussed previously, the sensitivity of LPGs to the various measurands is dependent on the composition of the fibre, the period of the LPG and the order of the cladding mode to which coupling takes place. Appropriate choice of fibre composition and grating period allows the generation of attenuation bands that are insensitive to temperature or strain, facilitating independent measurement of these measurands [44]. Alternatively, the differential shifts in two or more resonance bands of a single LPG may be used to measure simultaneously and independently the temperature and strain, by virtue of the difference in their sensitivities to the measurands [62]. The observation of the bend-induced splitting of the attenuation bands has allowed the simultaneous measurement of bend radius and temperature, where the wavelength separation of the split components of the attenuation band gave a measurement of bend radius, while the average wavelength was dependent upon temperature [39].

LPGs have been used in conjunction with FBGs to separate their temperature and strain responses [95], and also to demodulate the return from the FBG [96]. Two FBGs were fabricated such that their Bragg wavelengths sat on either side of the spectrum of an attenuation band of an LPG physically located on the source side of the two FBGs. Thus the LPG acted to attenuate the reflections from the FBGs, the attenuation being dependent upon their relative central wavelengths. By virtue of the difference between the sensitivities of the FBGs and LPGs to strain and temperature, a small decrease in the measured reflection of the low-wavelength FBG, accompanied by a small increase in the reflection from the higher-wavelength FBG, indicated a change in strain, while a large increase in the reflection from the low-wavelength FBG, accompanied by a large decrease in the reflection from the longer-wavelength FBG indicated a change in temperature. Measurement of the relative intensities of the reflections allowed independent measurement of temperature and strain [95]. An LPG was also used as an edge filter to facilitate an intensity based method to demodulate the reflection from an FBG [96].

5. Summary

The sensitivity of LPGs to strain, temperature, bending and external refractive index, the ability to tune the sensitivity by virtue of fibre composition and LPG period, and the presence of features with the transmission spectrum that show differing sensitivities to the various measurands offer the prospect for the development of sensor elements capable of simultaneously and independently monitoring a number of measurands. This paper has discussed the properties of LPGs, techniques for their fabrication and the origin of their sensitivity to the various measurands. The means for optimizing the performance of the LPG for particular applications has been outlined, along with a review of the uses to which they have been put.

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