Chapter

Optical Fibre Long-Period Grating Sensors Operating at and around the Phase Matching Turning Point

Rebecca Yen-Ni Wong, Dora Hu Juan Juan, Morten Ibsen and Perry Ping Shum

Abstract

Optical fibres have been exploited as sensors for many years and they provide a versatile platform with a small form factor. Long-period gratings (LPGs) operating at and around the phase matching turning point (PMTP) possess some of the highest sensitivities to external perturbations in the family of LPG-based sensor devices. This type of optical fibre grating has been demonstrated as a sensor for use in a wide range of applications. In this review chapter, an overview of PMTP LPGs is presented and the key developments, findings and applications are highlighted. The fabrication considerations and sensor limitations are also discussed.

Keywords: optical fibre, fibre optics, fibre sensors, long-period gratings, phase matching turning point, turn around point

1. Introduction

Optical fibre sensors do not only have use in telecommunications but are also extremely useful in a number of sensing applications. Many fields such as medical, oil and gas, civil, automotive as well as aerospace industries (structural health monitoring) have benefitted from optical fibre grating sensors [1–4].

In-fibre gratings are known as intrinsic sensing devices and therefore the propagation of light is guided and controlled within the fibre. Fibre gratings have a perturbation with a certain periodicity which will cause the fibre properties to change. They are also relatively easy to configure, are wavelength encoded enabling stable signals, and offer a high signal-to-noise ratio. One type of in-fibre grating is the long-period grating (LPG), which Vengsarkar et al. [5, 6] were the first to introduce. LPGs typically have periods ranging from around 100 μm to around 1 mm [7]. The principle of operation consists of the forward propagating core mode coupling with one or more of the forward propagating cladding modes [8]. The coupling involves the cladding modes, which means that the evanescent field will extend into the fibre surroundings. This will cause the LPG to be affected by its local environment. Another type of in-fibre grating is the fibre Bragg grating (FBG). The FBG promotes coupling of the propagating core mode with the counter-propagating core mode. FBGs typically have sub-micron periods and will produce a peak (in reflection) at a wavelength that is able to satisfy the Bragg condition. FBGs have also been used for numerous sensing applications [9, 10], but they will not be covered in this chapter.

By appropriately selecting the period of an LPG, it is possible to ensure the core mode will couple to a cladding mode operating at the turn around point (TAP) [11], also known as the phase matching turning point (PMTP), or dispersion turning point (DTP). A feature known as the dual resonance band can also be produced in this region. This type of LPG configuration has become increasingly popular due to its ultra-high sensitivity, a property usually desirable for a sensor. Approaches employed to improve the sensing capability of LPGs have included methods such as tapering [12] and etching [13]; however this can weaken the structure of the fibre and requires more delicate handling or complicated packaging. These sensors have been successfully used for measuring parameters such as temperature [14–16], strain [14–16] and refractive index (RI) [17–20]. The properties of LPGs at PMTP can be tailored further by adding a functional nanoscale coating for chemical and gas sensing [21]. This enables users to adapt the sensor to their own needs and applications. Chemical and bio-chemical based sensors, or those that can be applied to healthcare, are attracting increasing attention as they can have a more direct impact on the wellbeing of people. However, many are still yet to be applied in real situations outside of the laboratory [2].

This chapter aims to provide a more comprehensive coverage of LPGs which operate at and around the phase matching turning point, with respect to what can be found in existing literature [22]. The typical characteristics and fabrication considerations will be discussed. This will be followed by the different applications where PMTP LPGs have been demonstrated.

2. Long-period gratings at phase matching turning point

LPGs consist of some periodic modulation in the optical fibre which causes the core mode to couple with a number of modes in the cladding, at discrete wavelengths (**Figure 1**). The modes will propagate through the fibre with the propagation constants, β_{co} *and* β_{cl}^{M} (core and *M*-th cladding mode, respectively) and the wavelengths are dependent upon the satisfaction of the phase matching condition, which is described as [16]:

$$\lambda = [n_{co}(\lambda) - n_{cl}^{M}(\lambda)]\Lambda \quad (1)$$

Where λ is the resonant wavelength, n_{co} is the effective refractive index of the propagating core mode, n_{cl}^{M} is the effective refractive index of the *M*-th cladding mode, and the Λ is the period of the LPG.

Light that couples to the fibre cladding modes is lost rapidly through scattering and absorption at the cladding and the surrounding medium interface. This is presented as a transmission spectrum, as shown in **Figure 2**, that contains one or more resonance bands with wavelengths, λ_n.

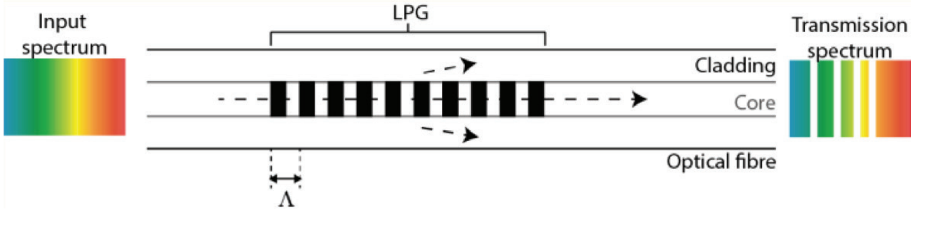

Figure 1.
Schematic diagram of an LPG.

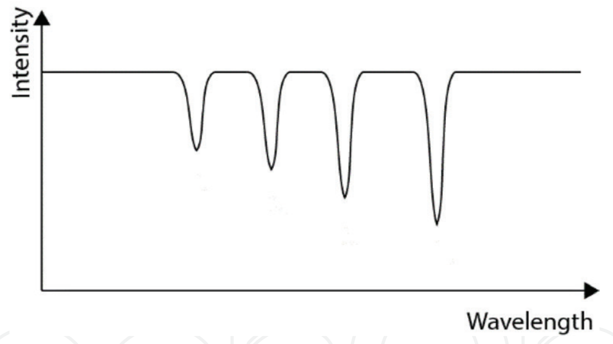

Figure 2.
Illustration of an LPG transmission spectrum with resonance bands at discrete wavelengths.

Eq. (1) shows the resonant wavelength is dependent on the effective refractive indices of the core and cladding mode of the fibre. This central resonant wavelength and the sensitivity of an LPG is affected by the order of the coupled cladding mode; choosing the grating period, the type [23] and composition of the fibre [19], and any external perturbations can alter the coupled mode.

Optical fibre LPG structures (a three layer cylindrical waveguide consisting of the core, cladding and ambient surrounding) can be modelled using coupled mode theory [24–26]. This can be used to describe the power transmitted between the modes of the waveguides. Guided modes propagating in a fibre can be treated as linearly polarised (LP), employing the weakly guided approximation [27]; this approximates the difference between the normalised core and cladding refractive index, Δ, to be very small [24, 25, 27]:

$$\Delta = \frac{n_{co} - n_{cl}}{n_{co}} \ll 1 \tag{2}$$

The coupled mode theory equations that are used to describe the LPG can be simplified to [24]:

$$\frac{dA_{co}}{dz} = i\, k_{co-co} + i \sum_{v} \frac{m}{2}\, k^{M}_{cl-co}\, A^{M}_{cl}\, e^{\left(-i\, 2\, \delta^{M}_{cl-co}\, z\right)}, \tag{3}$$

$$\sum_{v} \frac{dA^{M}_{cl}}{dz} = +i\, \frac{m}{2}\, k^{M}_{cl-co}\, A_{co}\, e^{\left(+i\, 2\, \delta^{M}_{cl-co}\, z\right)} \tag{4}$$

Where A_{co} is the amplitude of the core mode along the z-axis, A^{M}_{cl} is the amplitude of the cladding mode along the z-axis, the z-axis is along the axis of the optical fibre, k is the coupling constant, m is the induced-index fringe modulation.

The small-detuning factor for the co-propagating modes is defined as:

$$\delta^{M}_{cl-co} \equiv \frac{1}{2}\left(\beta_{co} - \beta^{M}_{cl} - \frac{2\pi}{\Lambda}\right) \tag{5}$$

Phase matching curves of resonance wavelength against grating period of an LPG can be generated by calculating the dispersion of the modes of the core and the cladding. These sets of curves are able to predict coupling from the core to the cladding mode, and that for each cladding mode there will be a turning point [28]. Around the turning point, a single mode can be coupled at two different wavelengths simultaneously [11, 28]. **Figure 3** shows an example of phase matching curves for higher order cladding modes in the 600–1150 nm wavelength range. It

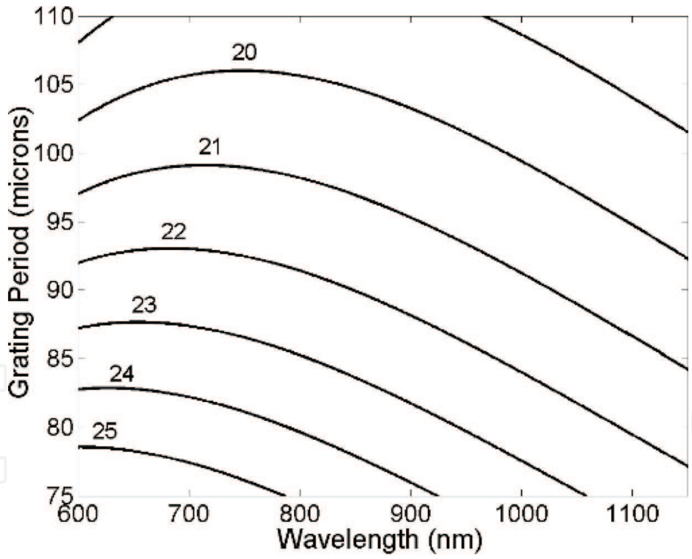

Figure 3.
Phase matching curves of the 20–25th cladding modes of an optical fibre with a cut-off wavelength of 670 nm. The relationship between the grating period and wavelength is shown. Reprinted with permission from Ref. [28], OSA.

can be observed that, at the turning point, the gradient of the curve tends to zero, $|d\Lambda/d\lambda| \to 0$ (and $|d\lambda/d\Lambda| \to \infty$). The waveguide dispersion of an LPG, expressed as $\gamma = (d\lambda/d\Lambda)$ Δn_{core} [29], will tend to infinity. As γ can be used to generalise the sensitivity of an LPG [11] it indicates that the transmission spectrum of an LPG that is fabricated with a period that closely matches a turning point, will have the highest sensitivity to external perturbations [11, 14]. The appearance of turning points will move towards shorter wavelengths when the cladding mode order is increased, as presented in **Figure 3**.

With increasing wavelength, the cladding mode's effective refractive index will decrease more than the effective refractive index of the core mode [15, 30]; this corresponds to the dual bands that become apparent in the LPG transmission spectrum.

Figure 4 shows how the grating period of an LPG approaching the turning point of the LP_{021} mode affects the transmission spectrum of the LP_{020} and LP_{021} cladding modes. **Figure 4(b)** shows the transmission spectrum where the period of the LPG chosen does not cut across the phase matching curve (**Figure 4(a)**) of LP_{021} at the turning point. A single resonant band develops (**Figure 4(d)**) followed by a small change in the central wavelength of the LP_{020} band as the period of the LPG hits the PMTP (**Figure 4(c)**). As the LPG crosses the turning point, the single band will split leading to the formation of two resonance bands. A much larger evolution can be seen for the LP_{021} mode when compared to the LP_{020} mode due to the much smaller gradient of the phase matching curve.

When an external perturbation is applied to the LPG, the two resonance bands of the mode around the turning point can either move towards or away from each other. This depends on the perturbation and the initial period of the LPG. The two bands respond differently to each other due to a non-symmetrical resonance [14], which may be due to modal dispersion [31]. For a 202.5 μm period LPG with dual resonance bands around the turning point, exposed to different temperatures, each band shows a sensitivity of 2.54 nm/°C (red shifted) and 3.29 nm/°C (blue shifted), respectively [14]. In the circumstance where the two bands shift towards each other, a single broad bandwidth band appears, similar to what is shown in **Figure 4(d)**. Under the influence of an external measurand, the coupling strength between the core mode and the cladding mode changes, altering only the amplitude of this single band and not the resonant wavelength [15].

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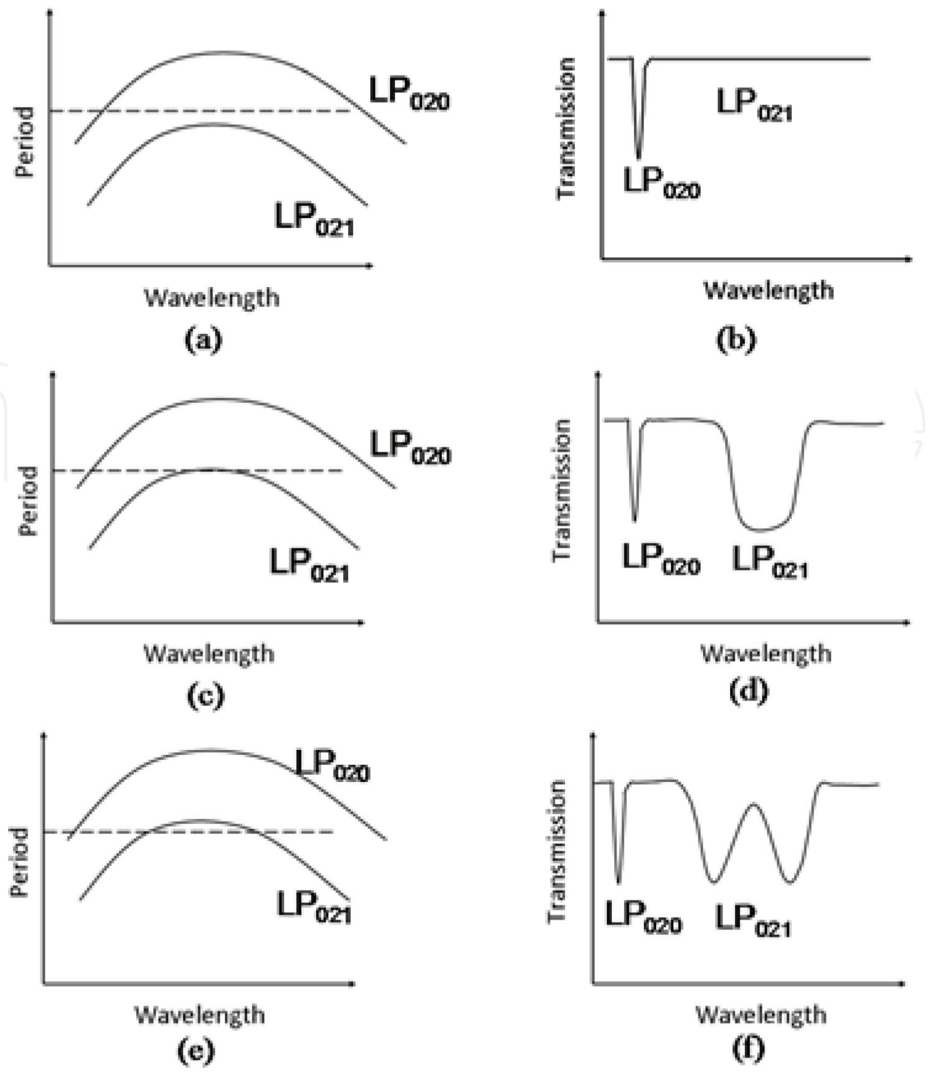


Figure 4.
Illustration of the phase matching curve ((a), (c), (e)) with their corresponding transmission spectrum ((b), (d), (f)) for cladding modes LP_{020} and LP_{021} as coupling approaches and crosses the turning point. Korposh et al., adapted from [31]; originally published under CC BY 3.0 licence. Available from: 10.5772/52935

3. Fabrication

LPGs at PMTP can be fabricated using the same methods as those used for conventional LPGs, albeit with higher precision - the effective refractive indices of the optical fibre modes can be altered via photo-induction, or by physical deformation [7]. The refractive index can be altered using a number of different methods. Some of these include local exposure of the fibre to a UV laser [28, 32, 33, 34], CO_2 laser [35, 36], femtosecond laser [23, 37] or by electrical arc discharge [30, 38]. PMTPs have been written in conventional single mode and doped fibres [12, 11, 33, 34, 36, 39], and have been theoretically investigated using photonic crystal fibres [23]. The length of an LPG tends to range from 30 to 50 mm and have refractive index changes of around 10^{-4} [40]. Coelho et al. [41] calculated a refractive index change in the order of 2×10^{-4} and 3×10^{-4} for the core and cladding, respectively when writing an LPG in a single mode fibre using mid-infrared laser radiation. The same order of magnitude of refractive index change (4.49×10^{-4}) is also needed for femtosecond laser radiation [42].

A PMTP can also be tuned after an LPG has been fabricated, by tuning the mode coupling and effective index guiding via the means of tapering [12], UV exposure [43], with a thin film overlay [31, 28], etching [44] and radiation exposure [12].

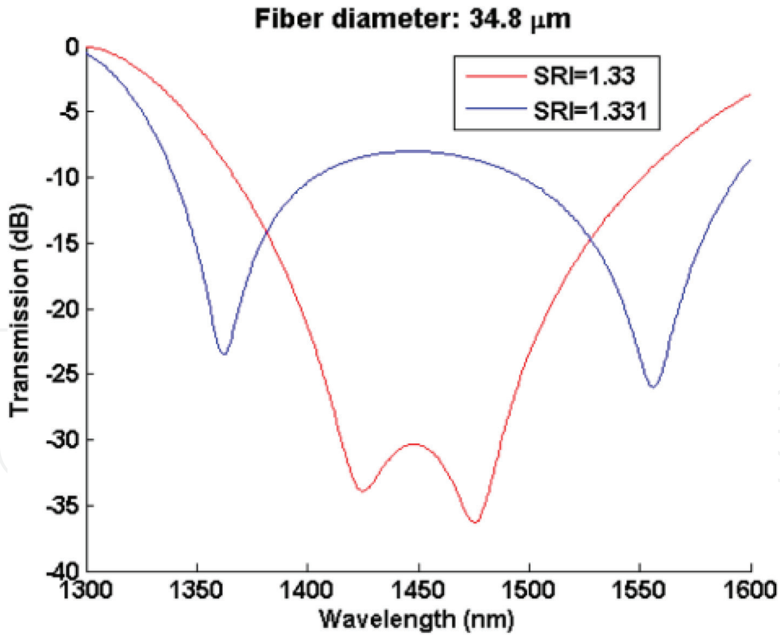


Figure 5.
Transmission spectra of a PMTP LPG with a 34.8 μm cladding diameter and 288.5 μm period, showing a large wavelength shift with a surrounding refractive index change of 0.001. SRI is surrounding refractive index. Reprinted with permission from Ref. [49], OSA.

The LPG can also been enhanced by reducing the cladding via hydrofluoric (HF) acid [13, 45–47] and plasma [48] etching to tailor the coupling strength of the cladding mode at PMTP. Using this method, Biswas et al. were able to increase the refractive index sensitivity of a hydrogen loaded PMTP LPG with a 165 μm period from 1350 to 1847 nm/RIU [45]. A refractive index sensitivity reported by Villar is 143×10^3 nm/RIU [49]. **Figure 5** shows the resonance band of the LPG splitting into two separate bands with a wavelength separation of approximately 200 nm, with a change of 0.001 RIU. This was theoretically obtained by reducing the diameter of a SMF28 single mode to 34.8 μm whilst operating at a period close to PMTP at 288.5 μm [49].

Plasma etching via ion bombardment and chemical reaction has been used to etch the fibre cladding of an LPG to bring the resonance closer to the turning point. This process assists in the precise post processing of nano-coated fibres in hard and chemically resistant films, for example, diamond-like carbon [50]. Radiation exposure has also been demonstrated to alter the refractive index of B-Ge co-doped fibres, with an equivalent increase in core refractive index of around 1×10^{-5} [12].

3.1 Fabrication considerations

Due to the nature of the LPG, they can be highly sensitive to the surrounding environment. There are stringent demands placed on the fabrication process and the system used in order to fabricate LPGs at PMTP reproducibly. The notable constraints are given by ambient temperature (**Figure 6**), duty cycle [32], power of the irradiation source [35] and amplitude of the index modulation [51]. The difference in the final outcome of LPG spectra where the ambient temperature is not controlled and allowed to fluctuate, and maintained to ±0.5°C are shown in **Figure 6**(**a**) and (**b**), respectively.

A period change of less than 1 μm can also influence transmission spectrum significantly and high resolution control has to be taken into account when deciding on the grating period [32, 35]. UV exposure time may also play a part in the sensitivity of LPGs at turning point; the spectrum of a 168.7 μm period PMTP LPG written in

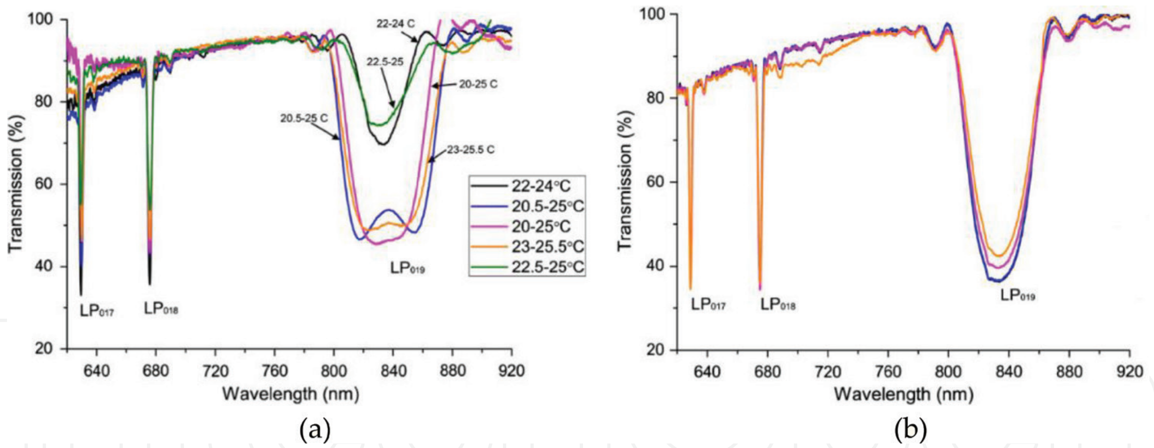


Figure 6.
Transmission spectra of a 110.9 μm PMTP LPG. The temperature is (a) not controlled (5 spectra) and (b) controlled to ±0.5°C (4 spectra). Reprinted with permission from Ref. [32], OSA.

boron co-doped fibre had a greater variation with pressure when fabricated with a longer exposure time [34]. Other factors that can affect the grating include the size of the fibre. By changing the diameter of the cladding, but maintaining the same period, the dual resonance bands will also change accordingly [44].

Hydrogen loading can induce or increase the photosensitivity in a fibre by increasing the effective refractive index difference between the core and cladding [52]. However, hydrogen will diffuse from the fibre gradually over time, causing the LPG spectrum to drift [52, 53]. Annealing a hydrogen loaded fibre at a temperature above the desired operating temperature can help overcome this problem [54]. This rapid removal of hydrogen will still cause the resonance wavelengths to shift, due to the changing effective indices, but will remain stable and permanent after the annealing process has been completed. This has to be taken into consideration when choosing a period to fabricate an LPG, at or around turning point, using a hydrogen loaded fibre [33, 43].

4. Applications

For an LPG to function at its optimum sensitivity when exposed to an external perturbation, its period should be chosen such that it is able to operate at a turning point. Optical LPGs operating at the turning point provide the potential for low cost sensors with fast response time [21, 55, 56] and can provide a simpler detection method as some are able to work as intensity-based sensors [15, 17, 55].

LPGs operating at the PMTP have been used for temperature, strain, refractive index sensing [11, 35] and as filters. PMTP LPGs, when modified with a functional film can be adapted for potential uses as enhanced gas and chemical sensors [28].

4.1 Filters

By employing the broadband characteristics, PMTP LPGs can make successful bandpass and rejection filters [57, 58]. A coated PMTP LPG with a π phase shift is simulated to provide tuneable broadband characteristics for rejection filtering applications [58]. By introducing multiple π phase shifts, it is possible to adjust the separation between the dual resonant bands. On the other hand, by partially coating a phase shifted PMTP LPG, bandgaps appear over a narrow wavelength band which could be useful for designing spectral filters [59].

4.2 Temperature sensing

By careful choice of the grating period to allow coupling close to or at the turning point, it is possible to improve the temperature sensitivity of an LPG [14, 15, 33, 60]. Shu et al. [14] showed that for an LPG with a 175 μm period, the dual resonance band had a temperature sensitivity of 3.2 nm/°C whereas the single band away from the PMTP had a much lower sensitivity of -0.31 nm/°C. The response of the dual resonant bands to changing temperature is non-linear, with a reduction in the rate of separation as the resonance moves away from the phase matching turning point. A band operating away from the turning point has a linear response to changing temperatures [60], which may make it easier to characterise temperature sensitivity. When comparing the sensitivities of LPGs with periods of 110.8, 111 and 111.5 μm the highest sensitivity was seen when the LPG was chosen to operate near the PMTP (111.5 μm period), just as the single broad resonance band would begin to appear. A sensitivity of 0.99 nm/°C was achieved for the sensor at turning point, which was more than five times greater when compared to the sensitivity of a band away from turning point (0.17 nm/°C). As the temperature response changes depending on the surrounding environment, it may also be possible for the thermo-optic coefficients of a surrounding medium to be characterised [60].

4.3 Strain sensing

Previous studies have shown that the dual resonance bands will move together, when increasing strain is applied, with a near linear trend [14]. The separation of the dual bands was calculated to be -33.6 nm/1000 μm whereas the sensitivity of an LPG can be more than an order of magnitude less [16]. Using the single broad band resonant mode at PMTP, Grubsky et al. [15] were able to obtain a sensor resolution of 1 μm by changing the coupling strength using different strengths of strain; the band would show an appreciable decrease in amplitude as strain increased, whilst the wavelength remained fixed as shown in **Figure 7**. The fixed wavelength allows for a simpler detection method as spectrometers or post processing can be bypassed for a simple photodetector [15].

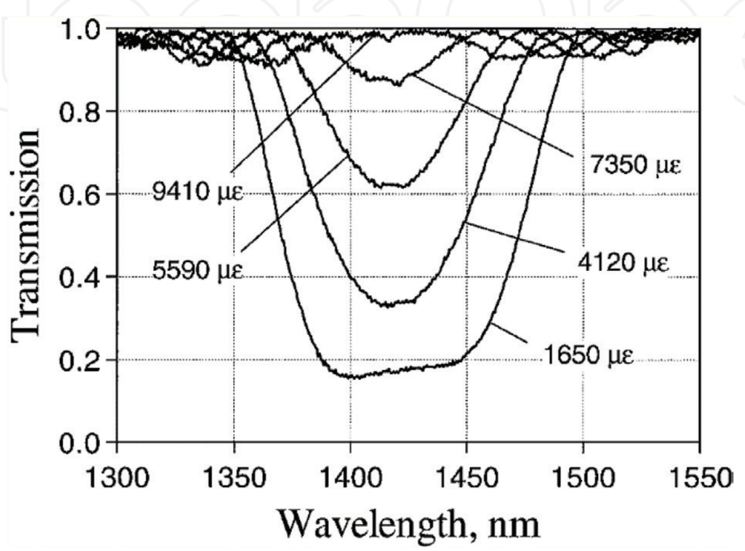


Figure 7.
Transmission spectrum of a 50.1 μm period LPG with increasing strain. The wavelength of the band remains fixed at 1420 nm but the coupling efficiency decreases. Reprinted with permission from Ref. [15], OSA.

4.4 Refractive index sensing

The optical intensities of the guided cladding modes will likely dissipate out of the fibre after a short distance. This could be due the fibre being bent, of from scattering or absorption due to the protective jacket of the fibre. By removing the jacket, the cladding mode evanescent field extends into the immediate surroundings, which will influence the fibre mode properties. The refractive index of the local environment will affect the effective refractive indices of the cladding modes propagating in the fibre. These effective refractive indices determine the sensitivity of the PMTP LPG.

A refractive index PMTP LPG sensor based on intensity as opposed to wavelength shift provides high sensitivity with a linear response for different refractive indices. A linear correlation coefficient, of more than 0.98 and sensitivity of 59.88/RIU for the refractive index range of 1.410–1.420 was achieved using a PMTP LPG with a period of 231.5 μm [17]. This allows for simple calibration and linear interpolation to determine the sensitivity of the sensor within this refractive index range.

By coating a PMTP LPG, such that it coincides with the mode transition region, it can be possible to enhance the refractive index sensitivity of a sensor [18, 31]. Mode transition describes the reorganisation of cladding modes caused when a higher refractive index material of a certain optical thickness surrounds the LPG [61–63]. After a certain thickness, the surrounding material is able to guide the outer most cladding mode, causing large shifts in the resonance wavelengths. The sensitivity of the LPG can also be optimised by controlling the optical thickness of the overlay so that the turning point coincides with the mode transition region, and has been proven theoretically and experimentally [28, 64]. Pilla et al. [18] were able to achieve a sensitivity exceeding 9000 nm/RIU in solutions with RIs similar to water, using an LPG with a single resonance band close to 1.55 μm. By increasing the refractive index, the dual bands appear and eventually split as shown in **Figure 8**. A mesoporous coating consisting of silica nanospheres was able to improve the refractive index sensitivity of a 100 μm period LPG operating near turning point, with a maximum sensitivity of 1927 ± 59 nm/RIU, as well as increase the detection range of the LPG [19]. The refractive index sensitivity of the first electric arc induced LPG at turning point was increased from 400 to 700 nm/RIU to 887–2146 nm/RIU

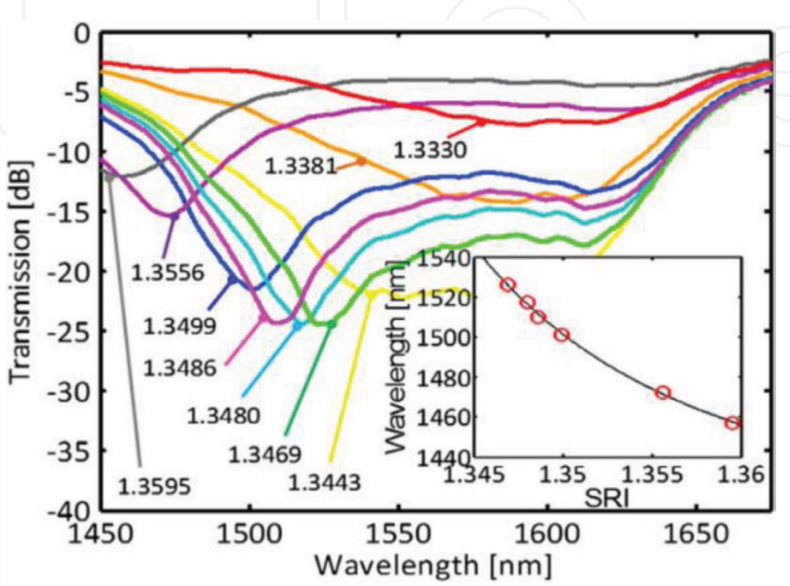


Figure 8.
Transmission spectra showing the response to different refractive indices of ethanol solutions. SRI is surrounding refractive index. Reprinted with permission from Ref. [18], OSA.

by operating close to the turning point and by coating a thin film overlay of silicon nitride [20]. By combining these phenomena with a reduced diameter fibre, it can be possible to further enhance the sensitivity of the LPG, which can help improve the resolution of biochemical sensing applications.

4.5 Chemical and gas sensing

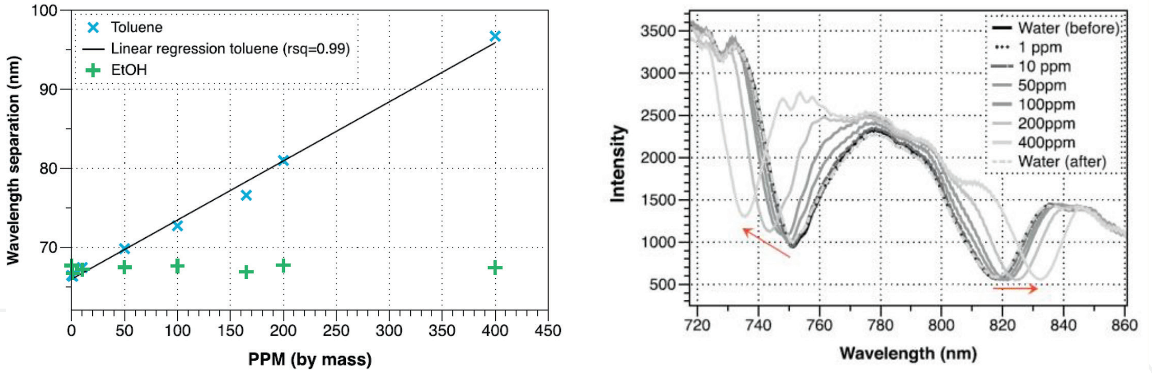
Their small dimensions, suitability in harsh environments and versatility make fibres ideal sensing platforms. The high sensitivity property of the PMTP allows for detection of low quantities and concentrations of different chemicals. For example, a PMTP is able to detect a 0.01% aqueous solution of cane sugar [65].

Optical fibre sensors with functional thin film coatings have become of interest due to the large pool of possible applications, especially in the chemical and biosensing fields. These sensors have the potential to measure concentrations of chemicals or for detecting gaseous species. These thin films can improve the sensing ability of the fibre and allow them to have different responses to different stimuli, such as concentrations of chemicals in the surrounding environment [19, 66, 67]. Functional materials can also be used to enhance the sensitivity for detection of a particular analyte. The thickness of the film on the LPG sensor is usually in the region of a few 100 nm as the transmission spectrum can be greatly affected [28, 61, 68, 69].

The following techniques allow for nanoscale thickness deposition control of the coating. These include the Langmuir–Blodgett deposition [28, 59, 70], self-assembly [21, 55, 71], layer-by-layer deposition [19], atomic layer deposition [72], sol-gel [73] and liquid phase deposition [67].

Functionalised LPGs operating around the PMTP have been tested for volatile organic compound (VOC) detection [70, 74, 75]. VOCs can be generated from a variety of processes. These include, but are not limited to, fuels and combustion processes, petroleum products, paints, and in nature and farming [76]. PMTP LPGs have been used for toluene [70, 74] and benzene [74] detection. By applying a functional overlay, particular compounds will affect the refractive index of the overlay and therefore influence the fibre modes, which will be shown as changes in transmission spectrum [74]. Providing clean water is an integral part of life, therefore monitoring water quality is critical. Partridge et al. demonstrated a proof-of-concept sensor for detecting toluene contamination in water. A 97 μm period LPG at turning point coated with calix [4]res C11 and was shown to be specific to toluene when compared to another potential contaminant, ethanol as shown in **Figure 9(a)**. The sensor was able to achieve a minimum detection limit of 100 ppm (see **Figure 9(b)**) which is the approximate limit of oil weep sampling and leaking oil plumes [70]. Some gases, such as hydrogen, are odourless and colourless, and have a low ignition energy. Means of detecting leaks in small quantities are therefore an important safety tool. A sensor coated with a 70 nm thick palladium overlay, when exposed to 4% hydrogen, experienced a dual band wavelength shift apart of 7.5 nm [77]. A thin film PMTP LPG with a functional material of poly(acrylic acid) PAA was successfully used to selectively bind to ammonia with lower detection levels when compared to other devices such as colorimetric and absorption spectroscopic devices [71].

Optical sensors have become more popular and valuable in the biomedical field. They have the potential to be used for diagnosis and monitoring and can be cost effective, portable and easy to use. This has also contributed to the increase in interest in label-free sensing using LPGs, especially at the PMTP where there is high RI sensitivity, rapid response and adaptability by choice of overlay [18, 72, 78, 79]. LPGs at PMTP have been used for real time monitoring of phage-bacteria interactions [80, 81] where a 1.3 nm wavelength shift was detected as bacteria binding



(a) (b)

Figure 9.
(a) Plots showing the response of a calix [4]red C11 coated LPG sensor to toluene and ethanol concentrations. Exposure to ethanol shows negligible response compared to toluene. (b) Transmission spectra showing the response of the dual resonance bands of a calix [4]red C11 coated LPG to different concentrations of toluene. Partridge et al.,. Reprinted from [70]; originally published under CC BY 3.0 licence. Available from: 10.1016/j.snb.2014.06.121

occurred [80], and target-probe DNA hybridisation [82, 83]. The well-known properties of the streptavidin-biotin interaction, as well as its use for studying biological processes, have encouraged its use as a means of understanding the characteristics of thin film PMTP sensors [21, 55]. Korposh et al. showed a mesoporous SiO_2 film coated sensor with an additional functional material could detect a specific chemical species. In this case the species was a porphyrin compound, with a 10 μM concentration being detected in under 10s [56].

Selectivity is an important indicator for a sensor as it can potentially prevent false readings, which is especially helpful at the highly sensitive turning point region [66, 67, 84]. Molecular imprinting provides a versatile platform as the properties of the receptor can be modified to detect a desired molecular compound [66, 67]. An LPG coated with a molecularly imprinted polymer (MIP) was prepared, for the detection of antibiotics [66]. In the presence of different commonly prescribed antibiotics, the sensor showed selectivity to the target antibiotic vancomycin. The target compound can also be removed and the sensor reused. Removal methods used include organic solvents, and photodecomposition have also been investigated [67]. Reusing an LPG or sensor also increases the versatility of a biosensor [81, 82, 84] and can therefore be more time and cost effective.

Choosing a particular fibre type can also contribute to the final characteristics of the fabricated sensor. For instance, PMTP LPGs written in boron co-doped fibres have been demonstrated as radiation dose sensors [36], pressure sensors [34] (boron co-doping can increase the pressure-optic coefficient of a material [85]), and for fuel adulteration detection [39].

4.6 Sensor limitations

The inherent high sensitivity of the PMTP LPG also leads to its limitations. For instance, cross-talk or unwanted interference, such as from varying temperature, have to be limited in order to ensure the shift in the wavelengths is only due to the desired parameter. By fabricating cascaded PMTP LPGs, based on a Mach-Zehnder interferometer, it is possible to eliminate interference [86] and make simultaneous measurements for parameter compensated sensing [87]. James et al. demonstrated that coating a cascaded PMTP LPG device with mesoporous silica nanoparticles, and subsequently infusing a functional material to the central of the region (between the two gratings) enables measuring of only the desired analyte [86].

The broad spectral width of the resonance bands can also limit the multiplexing capabilities of the PMTP LPG. By utilising the double resonance bands, simultaneous measurements of surrounding refractive index and temperature were carried out for temperature ranges limited to ±3°C if the refractive index range is ±0.004 RIU [87]. This information enables temperature calibrated sensing.

5. Summary

PMTP LPGs as versatile sensing platforms have become increasingly popular. The ultra-high sensitivity and quick response, as compared to other configurations of LPGs, proposes promising capabilities for use in many sensing applications. PMTP LPGs can be achieved by the precise choice of period or by post processing methods. However, the nature of their high sensitivity can also pose as limitations and sensors need to be optimised in order to avoid interference. By applying functional nanoscale coatings, it has been possible to tailor PMTP LPGs to have a preferred sensitivity to particular parameters. This opens the doors for a number of applications in the medical field for portable, real time monitoring. The sensors have potential deployment into the biochemical industry for measuring chemical concentrations and can also be applied to sense different gases in the environment. Specially designed sensors can also be used for monitoring food quality. However, calibration must be carried out first as the period and thickness of coating will affect the sensitivity of the sensor. More vigorous and consistent testing needs to be carried out before adoption in the healthcare and food safety industry [2]. Sensor packaging, ease of use and reusability are some aspects that need to be taken into consideration. As many chemical sensing applications take place in a solution, it may be beneficial to fabricate an LPG such that the appearance of the dual resonance bands will appear when the fibre is placed in solution. The fibre cladding size can greatly affect the sensitivity allowing a greater flexibility when designing an LPG at PMTP [49].

Author details

Rebecca Yen-Ni Wong[1]*, Dora Hu Juan Juan[1], Morten Ibsen[2] and Perry Ping Shum[3,4]

1 Institute for Infocomm Research, Agency for Science, Technology and Research (A*STAR), Singapore

2 Optoelectronics Research Centre, University of Southampton, Southampton, United Kingdom

3 Centre for Optical Fibre Technology, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore

4 CINTRA CNRS/NTU/THALES, UMI 3288, Research Techno Plaza, Singapore

*Address all correspondence to: rebecca-wong@i2r.a-star.edu.sg

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