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LONG-PERIOD GRATING AS STRAIN SENSOR

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In this work, fabrication and demonstration of a strain sensitive long-period grating (LPG) sensor is discussed. Equally spaced inscription LPG has been fabricated in germanium doped silica (Ge-SiO$_2$) single-mode optical fibre. In the fabrication process amplitude mask approach was employed and KrF excimer laser with 248 nm wavelength has been used for inducing index modulation in the core of fibre. On a single mode fibre, uniform LPG of period 95 μm and 30 mm grating length has been inscribed and subsequently was used as a strain sensor to monitor the strain up to 7000 με. Sensitivity of this sensor is found to be 0.931 nm/1000 με whereas for standard fibre Bragg grating, it is 1.2 nm/1000 με.

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1. Introduction

Optical fibre sensors are under intensive investigation in the last two decades because of their potential applications specifically in sensing environmental parameters like temperature, strain, etc... Various ideas have been proposed and different techniques have been applied for different applications. Among these, the most important idea was given by Vengsarkar et al [1] about long period grating as a sensor. Long period grating is capable of coupling light from fundamental core mode to the forward propagating cladding mode where the phase matching condition is satisfied. One of the most remarkable characteristic of LPGs is to exhibit sensitivity to specific parameters depending on coupled cladding modes and nature of the fibre inscribed with these LPGs. This unique characteristic made feasible to differentiate among several perturbations acting on the grating at the same time besides providing an opportunity in designing devices that are very sensitive or insensitive to a particular measurand [2, 3, 4].

Though fibre Bragg gratings (FBG) have been demonstrated excellent performance in many sensor applications too, regarding strain sensitivity measurement show some limitations. Mostly FBGs also involve intricate and costly interferometer for detecting induced wavelength shifts [5]. On the other hand LPGs are simple in designing, involve simple interferometric techniques and can be easily configured for multi-parameter measurements [6]. LPGs have grating period typically in the range 100μm to 1 mm. Period of LPG play decisive role in determining cladding modes for the purpose of light coupling. When any change is made in grating period and modal, effective indices due to temperature and strain in turn produce a change in resonant wavelength [7]. Another remarkable attribute of LPGs is their sensitivity to the refractive index of the cladding modes whereas the refractive index of cladding mode displays its dependence on the material of surrounding environment in the grating area [8]. These characteristics allow us to use LPG as a strain sensitivity sensor.

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While taking into account LPGs characteristics, it is clear that sensors based on the long period gratings will respond to host of physical parameters. One of the most important parameters is strain. In a theoretical analysis, it is found that the strain sensitivity is a combined effect of the change in: the refractive index, the media and the thermal expansion of the material. It is, therefore, apparent that fibres made of different material exhibit distinct sensitivities towards strain changes. The shift in wavelength of central peaks can occur towards shorter or longer wavelengths and is usually accompanied by a variation in the intensity of the peaks, depending on the coupling modes. Thus, there is a dire need to use LPG sensor to measure the complete strain of the host material which is insensitive to other measurand particularly temperature. Therefore, there is urgent necessity and desire to discuss the variation of strain sensitivity of LPG sensor system with choice of grating periodicity. Our work is an attempt in this direction to develop a systematic approach to measure LPG strain sensitivity.

2. Theoretical analysis of strain sensitivity

For axial strain sensors using long-period gratings, there are several factors related to the grating period, fabrication conditions and refractive index of the ambient medium. The strain and temperature sensing mechanism of the long-period grating can be explained on the basis of the phase- matching condition, which results in wavelength coupling and is expressed as ;

$$\lambda = (\delta n_{eff})\Lambda \tag{1}$$

Where Λ is the period of grating and δn_{eff} is the differential effective index between the guided and a cladding mode, which can be given by

$$\delta n_{eff} = n_{eff} - n_{cl} \tag{2}$$

n_{eff} and n_{cl} are the effective indices of the forward-propagating guided and cladding modes, respectively.

Consider 'ξ □' is perturbation that acts on the region of a fibre that contains a grating with period (Λ). Then $d\lambda / d\xi$ representing, for the given grating, wavelength shift per unit perturbation change is obtained by differentiating equation (1) as follows;

$$\frac{d\lambda}{d\xi} = \frac{d\lambda}{d(\delta n_{eff})}\frac{d(\delta n_{eff})}{d\xi} + \frac{d\lambda}{d\Lambda}\frac{d\Lambda}{d\xi} \tag{3}$$

Theoretically, the long period grating with period Λ is assumed under the influence of axial strain $\Delta\varepsilon$. Whereas, $\Delta\varepsilon$ is a dimensionless quantity because it is the ratio of the change in length and the original length ($\Delta\varepsilon = \Delta L / L$). In the limit $\Delta\varepsilon \geq 0$, Equation (3) can be modified with $\xi = \varepsilon$, and obtained by;

$$\frac{d\lambda}{d\varepsilon} = \frac{d\lambda}{d(\delta n_{eff})}\frac{d(\delta n_{eff})}{d\varepsilon} + \frac{d\lambda}{d\Lambda}\frac{d\Lambda}{d\varepsilon} \tag{4}$$

Moreover material and waveguide contribute in the cumulative wavelength shift of LPGs. Material contribution to the strain- induced shift depends on $d(\delta n_{eff})/d\varepsilon$ and waveguide effect on the variation in the grating period with strain. Using Equation (4) and $\delta n_{eff} = n_{eff} - n_{cl}$, $\Delta\varepsilon = dL / L = d\Lambda / \Lambda$ the following equation can be obtained;

$$\frac{d\lambda}{d\varepsilon} = \frac{d\lambda}{d(\delta n_{eff})}\frac{d(\delta n_{eff})}{d\varepsilon} + \frac{d\lambda}{d\Lambda}\frac{d\Lambda}{d\varepsilon} \tag{5}$$

Axially, straining a fibre changes the core - cladding indices of refraction and the radii. The deviation in the value of these parameters from the unperturbed case will affect the differential effective index and as a result phase- matching condition will shift to a different wavelength. For a given fibre, waveguide effect shows its dependence only on the grating period and the corresponding cladding mode order. It is found that strain- induced changes in core and cladding radii contribute significantly to the material effect. The variation in the core and the cladding dimensions arises from Poisson's effect, which reduces the radii based on the following expression given by [9].

$$dq / d\varepsilon = -\nu q \tag{6}$$

where q=a, b are for core and cladding radii respectively, and ν is Poisson's ratio for the corresponding material and its value for the cladding of fused silica, is q=0.17, and for the core of fused silica with 3% GeO_2, q=0.165. It is assumed that the core and the cladding are homogeneous and ignore the spectral dependence of Poisson's ratios (ν). The strain-induced change in the material refractive index is given by [9].

$$\frac{dn}{d\varepsilon} = \frac{n^3}{2}[p_{12} - \nu(p_{11} + p_{12})] \tag{7}$$

Where $n = n_1, n_2$ and, n_1 represents the refractive index of core and n_2 for cladding, and p_{ij} are the strain-optic coefficients. For fused silica, $p_{11} = 0.12$ and $p_{12} = 0.27$. By assuming $n = 1.458$, we get $dn_2/d\varepsilon = -0.316$ for the cladding. It is found that small changes in the values of $dn_1/d\varepsilon$ and $dn_2/d\varepsilon$ significantly alter the strain-induced shift, implying that the axial strain sensitivity is a strong function of the nature and concentration of the dopants. It could be assumed that the change in the material refractive indices with strain is not a function of the operating wavelength. Moreover, any non-linearity in the values of $da/d\varepsilon$, $db/d\varepsilon$, $dn_1/d\varepsilon$ and $dn_2/d\varepsilon$ are also neglected. To model long-period grating-based strain sensors analytically, there is basic procedure to opt. For such sensors material contribution is negative since the overall changes in the core & the cladding indices and radii produce an overall reduction in the differential effective index.

3. Method and materials

LPGs fabrication is done by a number of methods [10] which belong to either the UV exposure or non-UV exposure. In the UV exposure, there is either the point-by-point direct writing method or amplitude mask technique. The former method is flexible for fabricating long-period gratings with different spectral characteristics but not suitable for the mass production, whereas the amplitude mask techniques could be used for the mass production of long-period gratings. There are three types of amplitude masks including the chrome mask, the dielectric mask, and the metal mask. In the non-UV exposure, the facilities of CO_2 laser are inexpensive, whereas the cladding etching method and ion implantation technique is still in the experimental stage.

In general, index modulation is accomplished in LPGs fabrication using UV laser light of wavelengths lying in the range from 193 to 266 nm in Germanium doped silica fibre [11]. The use of UV light in LPGs fabrication displays its impact directly on the gratings spectral characteristics and stability [12]. When the Ge doped glass (e.g. Ge-SiO_2) is irradiated to UV laser light, spectral change takes place due to point defects which in turn changes refractive index [13]. Fig. **1** illustrates the experimental set-up for LPG writing using the amplitude mask. It is mainly composed of a 248 nm KrF excimer laser, beam focusing optics and cylindrical lens, an electronic shutter, a fibre aligner, amplitude mask, tunable laser source, optical spectrum analyzer, and a fibre translation stage. Amplitude masks with a rectangular transmittance function are imprinted on chrome-plated glass and have a 100 mJ/cm^2/pulse optical damage threshold level [14]. The KrF excimer laser produced a pulsed beam of area 2.6×1.1cm^2, energy 250-300mJ/pulse, repetition frequency 20 pulses/s, and pulse duration 10ns at a wavelength of 248nm. The acrylic jacket was removed from about 3 to 4cm length in a hot (>200°C) sulphuric acid bath and the fibre is subsequently cleaned with acetone. The two ends of the fibre are clamped for connection with the optical spectrum analyzer and the tunable laser source. The fibre was aligned behind the amplitude mask of appropriate period and was supported on both sides of the bare region to prevent bends from influencing the coupling to clad Amplitude masks with a rectangular transmittance function are imprinted on chrome-plated glass and have a 100 mJ/cm^2/pulse optical threshold damage level [14].

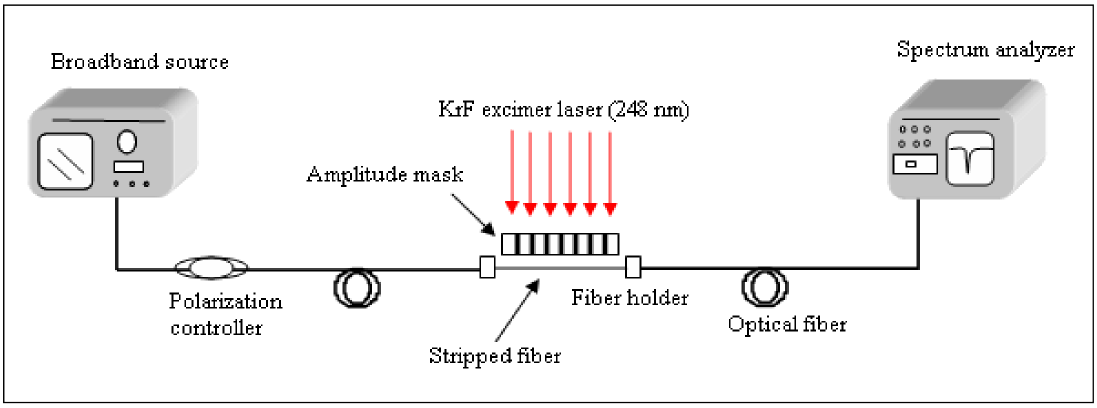

Fig. 1. Schematic diagram of the LPG fabrication system.

Light from a broadband source such as tunable laser source was launched from one end of the fibre while the normalized transmission spectrum was obtained on the optical spectrum analyzer display. The long-period gratings are then written in this chemically stripped photosensitive fibre by using UV light at 248 nm. The transmission spectra of long-period gratings are measured in-sit. To avoid blazing the grating, it was ensured that the fibre was exactly parallel to the axis of the mask. A blazed grating couples the fundamental guided mode to cladding modes that lack azimuthally symmetry [15]. The grating transmission spectrum is monitored in real time as the bare fibre exposed to UV radiation and resonance bands corresponding to different cladding modes coupling could be observed. The LPG was fabricated with period of 95 μm in Corning SMF-28 fibre.

4. Results and discussions

Experimental set-up is shown in fig. 2 for strain sensitivity measurement of LPGs. In our experiments, the long-period grating was written into the photosensitive fibre (PS–1500–Y3 made by Stocker Yale Co.; cut-off wavelength: 1360 nm; NA: 0.17) by using the stainless steel amplitude mask (scan start: 26 mm; scan length: 30 mm; step: 10; number of pulses: 500/step; KrF excimer laser: Lambda Physik – COMPex- 102; energy: 300 mJ/pulse). The grating being tested is pre-annealed to temperatures in excess of the highest operating temperature to ensure that all unstable defected sides are removed prior to the measurement process. If this procedure is not followed, the resonance bands will be shifted to shorter wavelengths as the grating ambient temperature approaches the annealing temperature. As a general precaution, the long period gratings are annealed at a temperature 50°C higher than the maximum expected test temperature for duration of 10 to 20 hours. Fibre containing long-period grating (centre wavelength: 1550.351 nm) is clamped to two longitudinally separated translation stages after removing a length of jacket on either side of the grating region. The separation between the two clamped regions is termed the gauge-length (L_0=100 cm in our experiments) of the sensor.

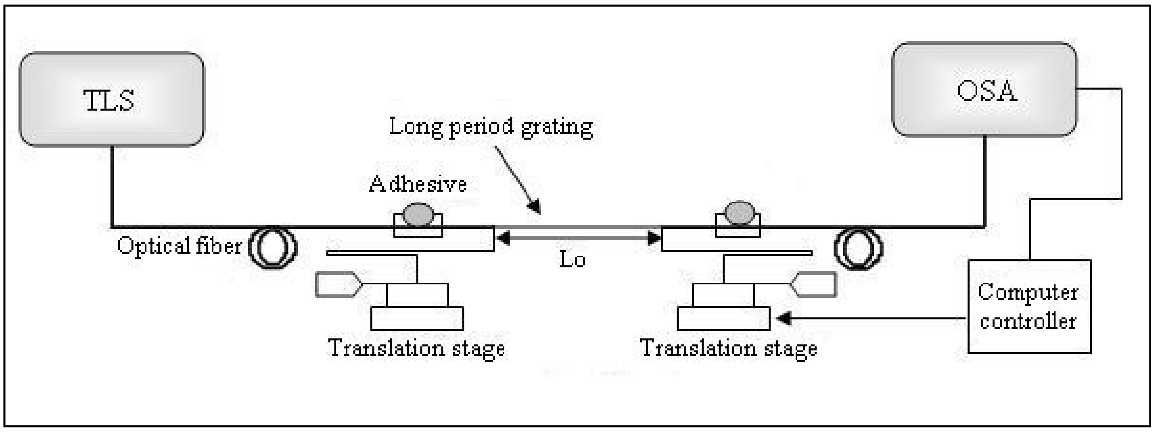

Fig. 2. Experimental set-up used to determine the axial strain-induced spectral shift in the resonance bands of a Long-period Grating.

Typically, only one of the translation stages is used to strain the fibre while the other is held stationary. The increase ΔL_0 in the length of the fibre between the clamped regions is read from the scale of the translation stage and the strain is calculated by using the equation ($\Delta\varepsilon = \Delta L_0/L_0$). The translation stage is moved manually, although this process can be automated by using a motorized stage. For the majority of experiments, the strain is limited to 7000 με although the fibre can survive much higher strain magnitudes. The strength of the fibre is not expected to degrade much after UV exposure and the long-period grating can be strained to 15,000–20,000 με (for conventional fibre: 1.5% - 2%, which is a high strain range). The process of mechanically stripping the coating before exposure can damage the fibre by initiating the propagation of small cracks in the fibre surface. This degradation can be avoided by using chemical stripping (some kind of acid), which also serves to dissolve any residual coating completely. For the strain experiment, the long-period gratings can be interrogated by using broadband sources such as tunable laser source (MG – 9638A; resolution: 0.1 nm) centered at required wavelength depending on the location of the resonance bands. The grating throughput is coupled into the optical spectrum analyzer (MS – 9710B; resolution: 0.07 nm), which is interfaced to a computer controller. The resonant wavelength are displayed on the computer monitor and saved in a file for post-processing. For the optical spectrum analyzer that detects the shift in the resonance bands, a larger wavelength displacement implies increased sensitivity. The resolution of a sensor using the optical spectrum analyzer for demodulation depends on the minimum detectable wavelength shift. Modern optical spectrum analyzers are available with resolutions ranging from 0.01 to 0.5 *nm*, depending on the cost of the system. Fig. **3** shows the examples of transmission spectra of the long-period grating with different applied load. Wavelength change in the LPG attenuated band is noted apparently with applied load. The spectra correspond to applied load through moving the micrometer of 0, 1, 2, 3 and 4 mm.

Fig. 3 reveals characteristic attenuated bands of LPG transmission spectrum. It clearly indicates the dependence of right shape of transmission spectrum and central wavelengths of corresponding attenuated bands of LPGs on surrounding parameters like strain, temperature etc. It means, effect of any change in these parameters appears in the modification of LPG period or/and differential refractive index of core and cladding modes which then materialize in the form of change in phase matching coupling conditions and ultimately display as a result in shifting the central wavelength of attenuated bands [11].

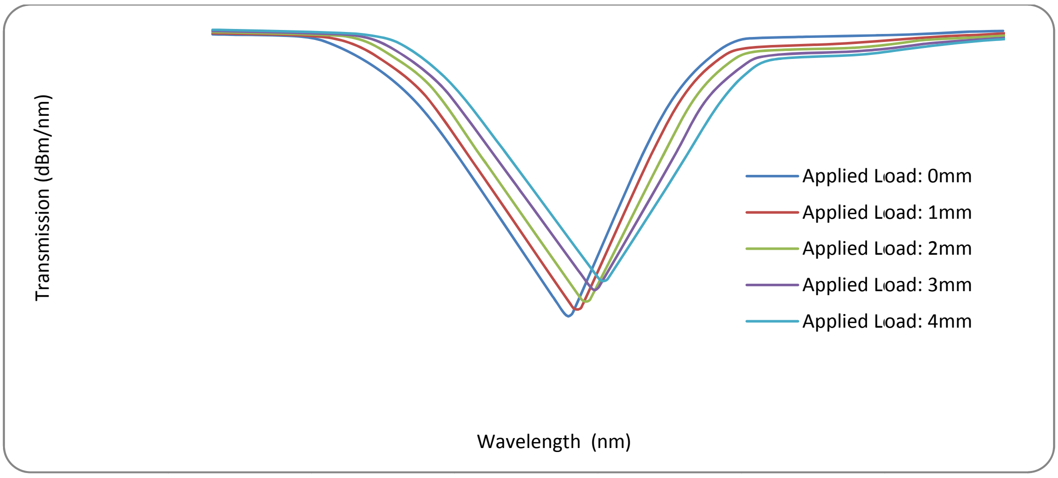

Fig. 3. Transmission Spectra of the long-period grating with different applied loads.

Although effectiveness of a sensor to measure strain is a strong function of its temperature cross- sensitivity, for particular measurand dependence of the sensitivity of LPG on the period and coupling cladding mode order made them attractive matter of choice in multi parameter sensing applications as a single sensor element [16]. Two approaches are commonly adopted for efficient use of LPGs as a strain sensor: One method to obtain strain measurements in environments with extensive temperature fluctuations is to use temperature-insensitive long-period gratings whereas another technique is to propose a scheme to separate the effects of strain and temperature perturbations. Period dependence LPG performance (temperature insensitive for a period Λ<100 µm and strain insensitive in the range Λ>100 µm) provides a handy approach to separate response to temperature and strain [11]. In our study, performance of LPG has been demonstrated in the temperature insensitive periods <100 µm because coupling in this regime takes place with higher order cladding modes where the material contribution is lower one. Fig. **4** shows the strain induced wavelength shift of LPG. Based on experimental data of strain testing for the long-period grating, a linear response has been observed between applied load and Bragg wavelength shift throughout the measured region.

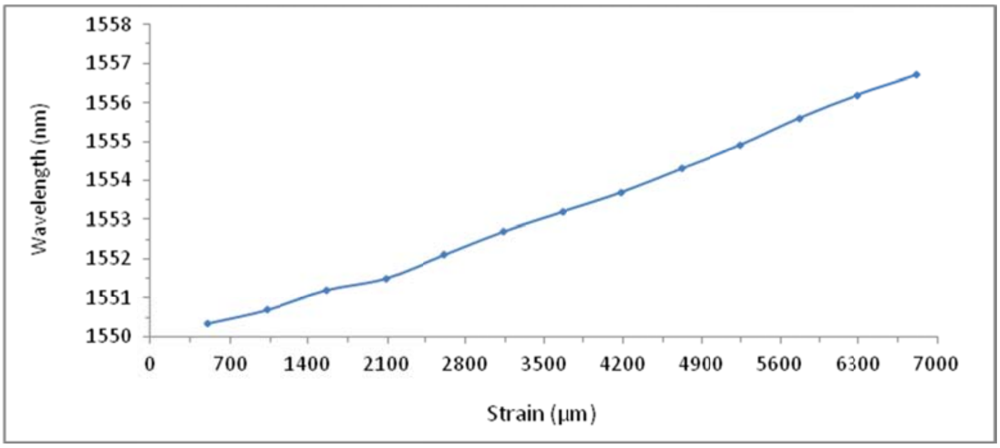

Fig. 4. Wavelength shift of the long-period grating with different axial strains.

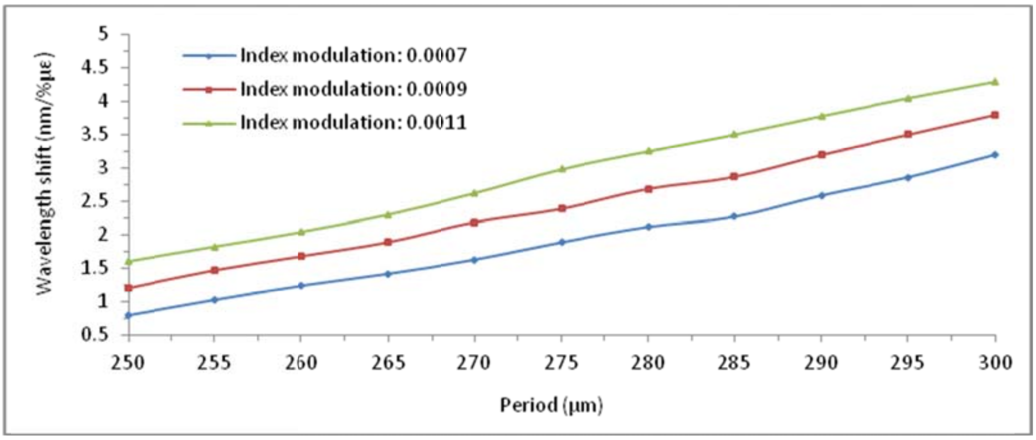

Fig. 5. Wavelength shift as a function of grating period.

It is also observed, when axial load is applied to a fibre having periodically modified diameter results into the periodic strain along fibre which in turn causes to modulate the refractive index periodically through photo-elastic effect. Thus axial load simply increases LPG coupling strength without changing the appreciable transmission of their attenuation bands. Results of transmission spectrum and reflectivity of light in LPGs based sensor have shown a relationship with wavelength during the monitoring of strain effect on LPGs. This corresponds to change in the grating spacing and the refractive index of a fibre. Any change in the grating spacing or refractive index leads to shift in the peak of central wavelength. Besides, the linear characteristic of the graph between wavelengths versus strain shows that the wavelength shifting is proportional to the strain difference. However, this linearity has a threshold level where at this point the long-period grating will break. This experiment was only done below the threshold point to avoid this effect. The good linear relationship between axial strain and wavelength shows the potential of using device (LPG) sensing applications for metallic and steel structure monitoring. Fig**. 5** shows the strain sensitivity of LPG as a function of the peak index change induced during the writing process and three curves correspond to different peak index changes in the core, which are $\Delta n = 7\times10^{-4}$ (lower), $\Delta n = 9\times10^{-4}$ (middle) and $\Delta n = 11\times10^{-4}$ upper.

The strain sensitivity of the resonance band is found to increase with the peak index change and can be attributed to the large waveguide contribution on increasing Δn which serves to shift the band to longer wavelengths. The enhancement in the sensitivity is larger for higher values of grating periods since the shift due to the same change in Δn increases with the period, also due to the fact that the waveguide contribution is non-linear. It is also shown that the writing conditions can be varied to manipulate the strain sensitivity of long-period gratings. For example, if a band is found to have a very small strain coefficient for a particular period, another grating with the same period can potentially be made strain-insensitive by changing the value of the peak index change till the waveguide contribution balances the material contribution. Similarly, the strain sensitivity of the gratings can be tuned following fabrication by annealing and serve to reduce the peak index change. Hence by using certain annealing temperatures and durations, the strain coefficients of long-period gratings may be selectively tuned. The waveguide effect has a significant contribution due to the strain-induced change in the grating period. The waveguide contribution increases with the period since gratings with large periods have higher slopes ($d\lambda/d\Lambda$) of the corresponding characteristic curves. The effect is more pronounced for higher order modes and introduces a non-linearity in the wavelength shift. It is predicted that the shift for 1% strain varies from 0.9 *nm* for Λ=240 μ*m* to 8.4 *nm* for Λ=320 μ*m,* which reveals the versatility of using long-period gratings for strain measurement since the sensitivity can be tailored to a particular application.

5. Conclusions

In this study, an approach to fabricate systematic and uniformly written long period gratings (LPG) has been demonstrated based on the amplitude mask technique by UV laser light. This methodology ensures that with the increase of power grid there is no change in the wave length of resonance peak. Evenly written LPGs have been used to fabricate strain sensor over a wide range and corresponding sensitivity was found to be 0·93 nm/1000 με. Our obtained experimental results from LPG sensor were satisfactory, and give assurance about the reliability of LPGs based sensor for other applications of future.

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