Fabrication of asymmetric LPFGs using electrical arc and CO$_2$ laser

3.1 Introduction

A long period fiber grating (LPFG) is a periodic modulation of the optical characteristics of an optical fiber, obtained by either inducing a physical deformation in the fiber material or by modifying the refractive index of the core of the fiber [1,2], where the period is greater than 100 μm. Long Period Fiber Gratings or LPFG’s are classically realized by exposing the photo sensitive optical fiber to ultra-violet light (either through an amplitude mask or by using point by point technique) [2]. But with the advancement of technology over two decades since the first report[1], LPFGs have been virtually written in all kind of fibers, namely, in standard singlemode telecommunications fibers [1], in two-mode (or few-mode) fibers [3,4], polarization maintaining fibers [5], D-fibers [6], non-photosensitive fibers [7,8,9] and multimode fibers [10]. LPFGs were also fabricated in specially designed fibers like dispersion shifted [1], dispersion compensating [11], depressed inner cladding [12], dual core [13], twin core [14] and progressive three layered [15] with specific properties for optical communications and sensing. Abramov et.al. [16] reported LPFG in hybrid fibers containing silica and polymers [] while LPFG in a metal coated fiber was reported by Costantini et.al. [17]. LPFG were also fabricated in microstructured polymer fiber [18] and in photonic crystal fibers [19-22].

Regarding writing techniques, Vengsarkar et.al [1] exposed hydrogen loaded germanosilicate fibers to a 248 nm KrF laser through an amplitude mask made of chrome-plated silica. Ultra violet radiation from a frequency-doubled argon-ion continuous-wave laser ($\lambda$=244 nm) was used by Vikram Bhatia et.al [23] for fabricating the LPFG. Gratings inscription was also achieved through the radiation delivered by CW Ar ion laser [24-26]. Nanosecond pulses from an ArF excimer laser (193 nm) was used to inscribe gratings in a hydrogen loaded boron co doped germanosilicate fiber using point by point technique [27,28]. Frequency quadrupled Nd:YAG laser (266 nm) was used by several authors [29-31] of which Shu et.al. [30]
Fabrication of asymmetric LPFGs using electrical arc and CO2 laser

employed amplitude mask on non hydrogenated B–Ge codoped fiber while Visneck Costa et.al.[31] adopted point-by-point technique on hydrogen-loaded photosensitive fibers. Gratings were written in hydrogenated photosensitive fiber with the tripled output of high repetition-rate diode pumped Q-switched Nd:YAG laser (355nm) by Blows et.al.[32]. Femtosecond laser radiation at several wavelengths like 211 nm [33], 264 nm [34] 352 nm [35,36] and 400 nm [37,38] were also used for inscribing long period fiber gratings. Broadband UV sources were also used for fabrication of LPFGs in hydrogenated photosensitive fibers [39-41]. Though different laser intensities and wavelengths were used, in all cases gratings were written in photosensitive fibers and/or in hydrogenated ones.

Although the UV-based fabrication method is a well-established technology, it has problems. It requires complex and time-consuming processes, including hydrogen loading, UV writing, and annealing. Furthermore, UV-induced gratings decay and, in general, cannot stand high temperatures. Moreover it requires photosensitive fibers and the lasers used for fabrication are costly.

There are, however, several alternative techniques for grating fabrication that does not require the fiber to be photosensitive. Such methods include physical deformation of the fiber [42], core-index variation produced by thermal effects using 800 nm femtosecond laser radiation [43], 10.6 μm CO2 lasers [44-53] or electric arcs [7-9,54-64], periodic corrugation of the silica cladding of fiber through chemical etching [65-67] etc. LPFGs were reported to be written in hydrogenated Corning SMF-28 fiber using nanosecond pulses from a 157 nm F2 laser [68,69]. Among other techniques, LPFGs were fabricated by heating a heavily twisted standard fiber at high temperatures [52,70]. Gratings can also be produced by exposure of a fiber, through an amplitude mask, to a beam of He ions [71]. This method requires that the fiber cladding be reduced to ~53 μm by etching. Later, the etching process was overcome by exposure of the fiber to a focused beam of protons, which have a longer stopping distance [72]. It is known that gamma radiation can lead to considerable changes in the refractive index of optical fibers [73] and, therefore, it may be an alternative to produce long-period gratings.

LPFGs produced through exposure to CO2 laser radiation and to arc discharges share most of their properties and have been catching an increasing attention from the fiber gratings community. Comparatively, the
Fabrication of asymmetric LPFGs using electrical arc and CO2 laser

major disadvantage of the electric arc technique is the limitation in the minimum period that can be written due to the dimensions of the arc [74]. On the other hand, it is simpler, harmless and one of the most cost effective techniques.

3.2 Mechanism of LPFG formation

3.2.1 UV LPFG

The basis of this type of grating inscription is connected with the induction of permanent refractive index changes in fiber core by UV irradiation. The radiation has wavelength coinciding with the 5.12 eV absorption band of germanium oxygen-deficient centers which has a maximum at 242 nm. Currently there are two models which describe the mechanism for fiber photosensitivity namely the colour-centre model [75] and the densification model [76].

The colour-centre model, considers that the UV exposure of the 5.12 eV band brings about the release of photoelectrons, which become trapped in neighbouring sites, thus creating new colour centres. The following modification of the UV absorption spectrum of the germanosilicate glass leads to refractive index modification at longer wavelengths. However this model failed in the correct estimation of the induced index changes and the search for another model paved way for the densification model. In 1995 Fonjallaz et.al [77] noticed a strong increase in tension in a germanosilicate fiber core by UV laser light, which was linearly proportional to the refractive index modulation. Although it is known that an increase in tension lowers the refractive index through the photoelastic effect, an overall positive index change was only observed in the experiment. The densification model considers structural changes to more compact configurations as an important component of fiber photosensitivity. The UV-induced increase of the refractive index in fiber core, due to both colour-centre and compaction effects, is believed to exceed the decrease caused by the photoelastic effect. The amount of each contribution might vary strongly as a function of fiber content, pre-irradiation treatment and irradiation wavelength.
3.2.2 Thermal induced Gratings

Unlike in the case of UV induced LPFGs, the mechanism of grating formation is still not well understood in the case of thermal induced long period fiber gratings. Depending on the types of the employed fibers and on the fabrication techniques, possible mechanisms suggested for refractive index modulation in the thermal-induced LPFGs are residual stress relaxation [78-81], glass densification [82-84], physical deformation [9,42,85] and dopant diffusion [86].

3.2.2.1 Residual stress relaxation

A standard single mode fiber consists typically of a germanium-doped silica core and a pure silica cladding. As a result of the doping, the properties of the core, in particular, its thermal expansion coefficient increases and its viscosity decreases compared to the properties of the cladding. The elastic stress associated with the difference in thermal expansion coefficient is known as thermal stress and is present in the fiber preform itself. Another type of stress is known as draw induced, which occurs during drawing and is associated with the different viscosities of core and cladding materials. During fiber drawing the higher viscosity material, in this case the cladding, cools more rapidly than the core and bears the brunt of the drawing tension. The melted core, in turn, is surrounded by the solid cladding and cannot expand being under compressive stress during cooling. Simultaneously, due to a higher thermal expansion coefficient, the core also exerts a hydrostatic pressure on the cladding. Thus residual stress is formed in optical fibers during the drawing process, resulting mainly from a superposition of thermal stress caused by a difference in thermal expansion coefficients between core and cladding and mechanical stress caused by a difference in the viscoelastic properties of the two regions [80,81, 87]. Such residual stress can change refractive index in the fibers through the stress-optic effect and thus affect the optical properties of the fibers. Residual stresses can be released during fiber annealing, that is, the fiber is heated to a high temperature (>1000 °C) and is held for some time, followed by slow cooling to room temperature.

Residual stress relaxation usually results in a decrease in refractive index in the fibers. The efficiency of refractive-index decrease depends strongly on the types of fiber and can be enhanced linearly with the drawing
force during the drawing process of the fiber. In a Ge–B-codoped fiber the refractive-index change due to residual stress relaxation was measured as $-2.1 \times 10^{-4}$ [80] while in a Corning SMF-28 fiber it was $-7.2 \times 10^{-4}$ [81]. It has been proposed that the periodic stress relaxation caused by arc discharges or CO$_2$ laser radiation is an important mechanism of gratings formation [88,89]. In addition to residual elastic stresses and strains, conventional silica optical fibers can also exhibit inelastic, or even “stress-free,” strains. Relaxation of inelastic stress is also a possible mechanism for LPFGs formation [88].

### 3.2.2.2 Glass structure changes

Densification arises from modifications of ring structures in the silica network and is the mechanism proposed to explain the changes observed in fibers having moderate and high germanium content in the core upon exposure to UV-laser radiation [90-92].

If glass is maintained at constant temperature, the volume changes with time due to structural relaxation until it reaches certain equilibrium glass structure. The temperature that corresponds to the equilibrium glass structure is called the fictive temperature or the structural temperature. Thus the fictive temperature of a glass is defined as the temperature at which the glass is formed after melting and the glass structure at this temperature and at room temperature is the same [93]. The fictive temperature of glass depends on the cooling rate and it increases with the increase in cooling rate. Therefore, different cooling rates lead to fibers with different fictive temperatures which, in turn, results in fibers with different intrinsic properties such as viscosity, thermal expansion coefficient and refractive index [93,94].

In the case of slow cooling, the glass can follow changes in temperature. As the temperature decreases, the viscosity of the glass increases, and it takes a longer time for the glass structure to reach an equilibrium state. Thus the density of the glass cooled slowly becomes larger than that of the glass cooled quickly. The refractive index is given by the Lorentz–Lorenz formula given by

$$\frac{(n^2-1)}{(n^2+2)} = \frac{N_A \alpha}{3M} \rho_m$$

3.1
where $\rho_m$ is the mass density, $\alpha$ is the mean molecular polarizability, $N_A$ the Avogadro number and $M$ is the molecular weight.

Thus refractive index increases with the density and hence the rapidly cooled glass has a lower refractive index than the slow cooled one.

In the case of arc discharges and CO$_2$ laser irradiation, the fiber is rapidly heated to a temperature which is more than that employed during the drawing process and is cooled rapidly and frozen. Because of the faster cooling rate, the fictive temperature of the quickly resoldified glass becomes higher. The viscosity and density of the molten glass thus decreases and these contribute to the reduction in the refractive index.

The change of glass structure is found to be the dominant mechanisms in the thermal-induced LPFGs written in a commercial boron-doped single-mode fiber [82-84]. Residual stress relaxation in the fiber core, which is the dominant mechanism in a conventional Ge-doped or Ge–B-codoped fiber, plays only a minor role in the boron-doped fiber that has a core with a small residual stress and a low fictive temperature. For the CO$_2$-laser-induced LPFGs in the Ge-doped or Ge–B-codoped fibers, e.g., Corning SMF-28 fiber, with large residual stress, the resonance wavelength shifts toward the shorter wavelength with the increase in the laser exposure dose due to the negative index modulation resulting from residual stress relaxation[78-80,95]. For the CO$_2$-laser-induced LPFGs in the boron-doped fibers with small residual stress, on the contrary, the resonance wavelength shifts toward the longer wavelength with the increase in the laser exposure dose due to the positive index modulation resulting from glass densification.[81-84]

### 3.2.2.3 Physical deformation

In the case of thermal induced LPFGs two types of geometric deformations can occur in a fiber namely microbending [42] and tapering [9,85]. The former, occurs when the fiber is submitted intentionally to lateral strain during heating while the latter occurs when the fiber is submitted to axial strain. The extent of the change in the fiber cross-section depends not only on the pulling tension but also on the temperature established on the fiber. During CO$_2$ laser irradiation, the fiber usually elongates or tapers based on the so-called “self-regulating” mechanism,[87] resulting from constant axial tension and the CO$_2$-laser-induced local high temperature in the fiber. Thus the fiber diameter decreases and eventually reaches a critical point at which
the fiber elongation stops because no sufficient energy is absorbed to keep the softening temperature. Moreover, the CO\textsubscript{2}-laser-induced high temperature in the fiber causes, not only the fiber elongation and the diameter decrease but also the ablation of glass on the fiber surface. Such physical deformation induces a change in effective refractive index in the fiber, and thus LPFGs are created in the periodically tapered optical fibers [49,96-98].

### 3.2.2.4 Dopant diffusion

One of the first mechanisms proposed for the formation of arc-induced LPFGs was the diffusion of core dopants [86,99]. This is a phenomenon in which the core dopant diffuses to cladding due to heating and Dianov et al [99] have fabricated LPFG in nitrogen doped fiber by utilizing this phenomenon. As the electric arc heats the fiber, owing to its small atomic weight, nitrogen diffuses to cladding and hence the core refractive index reduces. However for Ge-doped fibers, the desired modifications caused by dopant diffusions were achieved by keeping the fibers at temperatures above 1200 °C for few hours. But during LPFGs fabrication the duration of the arc discharge is only a few seconds and, therefore, the diffusion coefficients of the dopants must be high in order to have a significant influence of diffusion on the grating formation.

### 3.3 Theory of long period fiber gratings

Consider an optical fiber, as depicted in Figure 3.1, having a core radius \( r_1 \), cladding radius \( r_2 \) and different refractive indices in each layer: \( n_1 \), \( n_2 \) and \( n_3 \).

![Figure 3.1. The structure of optical fiber](image)
Generally the cylindrical waveguide supports many modes of propagation and by adjusting the core radius and the refractive index difference between the core and the cladding ($\Delta n$) the fiber can be made to support only one mode (single mode fiber). In the case of a single mode fiber most of the energy is guided by the core, but a certain amount is also guided by the cladding. The core mode thus “sees” an effective refractive index that lies between the core and the cladding refractive indices. The other modes available in an optical fiber may be classified, according to the value of the third layer, as: cladding modes, radiation modes and leaky modes. The first occurs when the refractive index of the third layer is lower than that of the cladding, such as the case of a stripped fiber ($n_3 = 1$ air). In this case, several discrete cladding modes are guided by total internal reflection at the cladding-air interface. The effective refractive indices of those modes range between $n_2$ and $n_3$. If the cladding is infinite, ie $n_2 = n_3$, total internal reflection is not possible and, therefore, light is lost through a continuum of radiation modes. When $n_2 < n_3$, light can propagate a certain distance due to hollow waveguide and these discrete modes are called leaky-modes.

The field equations of the core and cladding modes are solutions of the wave equation that satisfy continuity conditions at the boundary. In general, the modes are TE, TM and hybrid HE/EH modes. If $\Delta n$ is small, the weakly guide approximation can be used and the modes can be treated as linearly polarized, LP. The LP modes are a superposition of TE, TM and hybrid modes. For a single mode fiber, the core mode is HE$_{11}$ or LP$_{01}$ and the field equation can be obtained considering two layers: core and cladding. For the cladding modes, a three layer geometry is required, even when $\Delta n$ is small. As far as LPFGs are concerned, the type of modes of interest depends on the symmetry of the perturbation that enables coupling from the core mode to the cladding modes. If the perturbation is axis symmetric the coupling is made to LP$_{0j}$ (or HE$_{1j}$) cladding modes ($j>1$). On the other hand,
if the perturbation is asymmetric coupling is made to LP_{ij} (or HE_{2j} + TE_{0j} + TM_{0j}) cladding modes (j>0) [100-103].

An LPFG can be represented by a sinusoidal Z dependent periodic index variation given by Δn^2(z) = Δn^2 sin(Kz), where K=2π/Λ and Λ is the grating period. The LPFG couples incident light guided by the core to the forward-propagating cladding modes of the optical fiber, which decay rapidly through radiation. The fiber supports many cladding modes and thus the LPFG induces a corresponding series of attenuation bands in the transmission spectrum of the fiber.

The light coupling from the fundamental core mode to the m\textsuperscript{th} order cladding modes occurs at wavelengths that satisfy the phase-matching condition [100]

\[ \beta_{\text{core}} - \beta_{\text{cl},m} = \frac{2\pi}{\Lambda} \]  

(3.2)

where \( \beta_{\text{core}} \) is the propagation constant of the LP\textsubscript{01} fundamental core mode, \( \beta_{\text{cl},m} \), is the propagation constant of the m\textsuperscript{th} order cladding mode and Λ is the grating period.

The effective refractive index of a medium is defined as \( n_{\text{eff}} = \frac{\beta}{k} \), where \( k \) is the wave number in vacuum. Since \( k=\frac{2\pi}{\lambda} \), the propagation constants \( \beta_{\text{co}} \) and \( \beta_{\text{cl},m} \) can be written as [100]

\[ \beta_{\text{core}} = \frac{2m_{\text{eff,core}}}{\lambda_m} \]  

(3.3)

and

\[ \beta_{\text{cl},m} = \frac{2m_{\text{eff,cl}}}{\lambda_m} \]  

(3.4)

where \( n_{\text{eff,core}} \) is the effective refractive index of the fundamental core mode (LP\textsubscript{01}) and \( n_{\text{eff,cl},m} \) is the effective refractive indexes of the phase matched cladding mode (LP\textsubscript{0m}).

If \( \lambda_m \) is the wavelength at which phase matching occurs with the m\textsuperscript{th} forward propagating cladding mode, then an attenuation band is created in the
transmission spectrum centred at the wavelength $\lambda_m$. Thus from 3.2, 3.3 and 3.4, $\lambda_m$ can be deduced as

$$\lambda_m = \left[ n_{\text{eff,core}}(\lambda, \varepsilon, T, n_i) - n_{\text{eff,cl}}^m(\lambda, \varepsilon, T, n_i) \right] \Lambda$$  \hspace{1cm} (3.5)

Both indices ($n_{\text{eff,core}}$ and $n_{\text{eff,cl}}^m$) depend on the indices of the various fiber layers, $n_i$, the wavelength $\lambda$, the temperature $T$, and the strain experienced by the fiber $\varepsilon$. Also, $n_{\text{eff,cl}}^m$ is a function of the refractive index of the surrounding medium, $n_s$.

For each individual resonance, its transmission loss can be calculated by

$$T = 10 \log \left\{ 1 - \sin^2 \left[ k_g L \left( \sqrt{1 + \left( \frac{\partial}{k_g} \right)^2} \right) \right] \right\}$$

where $\delta$ is the detuning parameter

$$\partial = \pi \left\{ \frac{n_{\text{eff,core}} - n_{\text{eff,cl}}^m}{\lambda_m} - \frac{1}{\Lambda} \right\}$$  \hspace{1cm} (3.7)

$k_g$ is the grating coupling constant and $L$ is the grating length.

Figure 3.2 shows the sample transmission spectrum of an LPFG illustrating the attenuation bands corresponds to various $\text{LP}_0^m$ cladding modes to which the fundamental guided mode couples. Since these attenuation bands are functions of applied strain, ambient temperature and refractive index, long period fiber gratings can be used as sensors, where the shift in resonance band gives the measure of ambient change.
3.4 Fabrication of Periodically tapered LPFG using fusion splicer

Long period fiber gratings were fabricated in commercially available standard telecommunication fiber (SMF-28) received from Newport using point-by-point technique. As shown in figure 3.3, a bare single mode fiber (Newport SMF-28) without its protective coating was placed between the electrodes of a fusion splice machine (Fujikura FSM-50S), while its ends were fixed on two fiber holders. The fiber holder was fixed on a computer-controlled translation stage (Newport) with a resolution of 100nm. An arc discharge with a current of 5 mA was then applied for 200 ms, which raises the temperature of the fiber section positioned in between the electrodes to its softening point. The fusion splicer was programmed to taper the fiber by a length of 50μm during each arc. The fiber was then moved by the translation stage through a distance equal to the grating period and another arc discharge along with tapering was applied. Care was taken to provide sufficient time
between arcs to allow the fiber to get cooled. The periodic tapering was continued and the optical transmission of the fiber was monitored during the LPFG fabrication process in order to obtain the desired spectral attenuation notches. The setup employed for the experiments consists of a white light source (Yokogawa AQ4305) coupled to one end of the fiber, while the other end was connected to an optical spectrum analyzer, OSA (Yokogawa AQ6319), set to a resolution of 0.05 nm. All the three writing parameters, namely discharge current, discharge time and tapering length were found out by trial and error method so that the fiber should retain its mechanical strength during the formation of grating.

The transmission spectrum was acquired and processed by a computer to determine the LPFG central dip wavelength and transmittance. The size of the arc limited the minimum grating period $\Lambda$, and we got a peak attenuation of 14 dB at 1318 nm after 34 engravings with a grating period of 500$\mu$m. The spectral evolution of the LPFG is shown in figure 3.4, illustrating the transmission spectra with various grating period numbers of 10, 21, 30 and 34. When fabrication was repeated without the tapering option, gratings were not formed even though arc current and duration were the same.
As discussed in section 3.2, the different mechanisms involved in the formation of arc induced gratings are modulation of core diameter due to fiber tapering, stress relaxation, glass structure changes and dopant diffusion. But it has been shown that the change of glass structure play the dominant role in LPFGs written in boron-doped single-mode fiber [82-84] while residual stress relaxation in the fiber core, is the dominant mechanism in a conventional Ge-doped or Ge–B-codoped fiber like SMF 28. Since we have used SMF 28 for LPFG fabrication, the effect of glass structure change on refractive index modulation can thus be omitted. Also since the temperature generated during arc cannot induce Ge diffusion to the cladding, the effective refractive index variation in the periodically tapered LPFG can be expressed as [104]

\[ \Delta n = \Delta n_{\text{residue}} + \Delta n_{\text{taper}} \]  

(3.8)
where $\Delta n_{\text{residue}}$ is the initial refractive index change induced by the residual stress relaxation as a result of the high local temperature and the constant strain during the tapering process. $\Delta n_{\text{taper}}$ is the refractive index perturbation caused by the periodic tapering of the fiber.

3.4.1 Origin of Asymmetry

Rego et al. [61] did extensive studies on the asymmetric mode coupling of arc induced LPFGs. They studied the temperature distribution in the arc that is applied to the fiber. Since the current in the arc is direct (dc), the arc is directional and it is found that the center between the electrodes is not the center of symmetry of arc glow (figure 3.5).

![Figure 3.5 Photograph of arc glow (reproduced from Rego et al. [61])](image)

The electrode at the bottom (cathode) glows only at its tip, while the electrode at the top (anode) glows over a much larger area. The arc is brighter near the lower electrode. This causes a gradient of temperature with respect to the line joining the electrodes and hence along the diameter of the fiber.

As discussed in section 3.2 glass structure change is reported to be the dominant mechanism involved in grating formation in Boron doped fibers while it has little effect in the case of normal SMF 28 fibers. It has been shown that the mode coupling is symmetric in the case of LPFGs fabricated using fusion splicer in Boron doped fibers while asymmetric in SMF 28[60]. Thus it is evident that the temperature gradient has little or no effect on glass structure changes. The origin of asymmetry in this case (SMF
28) can thus be attributed to stress relaxation and physical deformation. Two types of geometric deformation of the fiber occur in an arc discharge namely tapering and microbending. Tapering is a symmetric diameter reduction and an elongation of the fiber and it cannot induce coupling to the asymmetric cladding modes. Rego et al [61] has also shown the asymmetric geometrical microbending induced in the fiber core by the electric arc. Hence the microbending and temperature gradient can be assumed to be the possible cause for asymmetric mode coupling.

This periodic asymmetric refractive index modulation causes the LPFG to couple light guided by the core mode (LP\(_{01}\)) to the forward propagating asymmetric cladding modes (LP\(_{1m}^{\text{Clad}}\)) of the optical fiber, which decay rapidly through radiation. Since the fiber supports many cladding modes, the LPFG induces a corresponding series of attenuation bands in the transmission spectrum of the fiber. The centre wavelength \(\lambda_m\) of the attenuation bands depends on the grating period \(\Lambda\), external temperature, strain experienced by the fiber and the refractive index of the medium surrounding the fiber.

### 3.5 Fabrication of LPFG using CO\(_2\) laser

The LPFGs were fabricated in commercially available standard telecommunications fiber (SMF-28) received from Newport using the point-by-point technique. As shown in figure 3.6, a motorized translation stage with a resolution of 10nm (Newport) was used to shift the fiber. A 12 W continuous wave CO\(_2\) laser (LASY-12, 10.6μm, 12W) was used for fabrication. The optical transmission of the fiber was monitored during the LPFG fabrication process in order to obtain the desired spectral attenuation notches. The setup employed for the experiments consists of a white light source (Yokogawa AQ4305) coupled to one end of the fiber, while the other end was connected to an optical spectrum analyzer, OSA (Yokogawa AQ6319), set to a resolution of 0.05 nm. The fiber was exposed to CO\(_2\) laser radiation using a shutter for a fraction of a second and then translated by the required grating period. During the experiments the fiber was kept under constant longitudinal tension. The beam diameter of the CO\(_2\) laser limited the minimum grating period \(\Lambda\). For a grating period of 600μm, we got an attenuation of 14 dB at 1520nm after 76 periods producing a grating length
Fabrication of asymmetric LPFGs using electrical arc and CO\textsubscript{2} laser

of 4.5cm. The spectral evolution of the LPFG is shown in figure 3.7 and the photograph of the LPFG in figure 3.8.

Figure 3.6 Experimental setup for LPFG fabrication using CO\textsubscript{2} laser

Figure 3.7 Evolution of resonance peaks for CO\textsubscript{2} inscribed LPFG
The focused CO\textsubscript{2} laser beam creates a local high temperature in the fiber, which led to the vapourization of SiO\textsubscript{2} from the surface of the fiber. As a result, periodic grooves are carved on the fiber as shown in Figure 3.9. Such grooves induce periodic refractive index modulation along the fiber axis due to the photo elastic effect, thus creating an LPFG.

Since the LPFG is fabricated in SMF 28, the dominant mechanism involved in the refractive index modulation is stress relaxation. Thus the refractive index modulation in the CO2 laser carved LPFG can be expressed as

$$\Delta n = \Delta n_{\text{residual}} + \Delta n_{\text{groove}}$$ (3.9)

where $\Delta n_{\text{residual}}$ is the refractive index perturbation induced by the residual stress relaxation resulting from the heating and $\Delta n_{\text{groove}}$ is the initial refractive index perturbation induced by the periodic grooves on the fiber.
3.5.1 Origin of Asymmetry
In the case of CO₂ fabrication the laser energy is strongly absorbed on the incident side of the fiber and the non uniform absorption results in asymmetrical refractive index profile within the cross-section of the LPFGs. Thus, a larger refractive index change is induced on the incident side of the fiber compared to the opposite side which in turn causes asymmetrical mode coupling.

3.6 Temperature sensitivity of LPFG

The sensitivity of LPFGs to temperature is influenced by the period of the LPFG governed by the order of the cladding mode to which coupling takes place (105) and by the composition of the optical fiber (106). The origin of the temperature sensitivity may be understood by differentiating equation (3.5) (107)

\[
\frac{d\lambda_m}{dT} = \Lambda \left( \frac{dn_{\text{eff,core}}}{dT} - \frac{dn_{\text{eff,cl}}^m}{dT} \right) + \left( n_{\text{eff,core}} - n_{\text{eff,cl}}^m \right) \frac{d\Lambda}{dT}
\]  

(3.10)

where \( \lambda_m \) is the central wavelength of the attenuation band, \( T \) is the temperature, \( n_{\text{eff,core}} \) is the effective refractive index of the core mode, \( n_{\text{eff,cl}}^m \) is the effective refractive index of the \( m \)th cladding mode and \( \Lambda \) is the period of the LPFG.

In general, the effective refractive indices of the core and the cladding at a particular temperature \( T \) can be written as

\[
n_{\text{eff,core}}(T) = n_{\text{eff,core}}(T_0) + \xi_{\text{core}} \Delta T
\]  

(3.11)

and

\[
n_{\text{eff,cl}}^m(T) = n_{\text{eff,cl}}^m(T_0) + \xi_{\text{cl}}^m \Delta T
\]  

(3.12)

where \( T_0 \) is a reference temperature, \( \Delta T = T - T_0 \), and \( \xi_{\text{core}} \) and \( \xi_{\text{cl}} \) are the thermo-optic coefficients of the core and the cladding, respectively.

The first term on the right-hand side of equation 3.10 i.e.,

\[
\Lambda \left( \frac{dn_{\text{eff,core}}}{dT} - \frac{dn_{\text{eff,cl}}^m}{dT} \right)
\]  

[105] 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 depends upon the composition of the fiber and also on the order of the cladding mode. The second term i.e., \((n_{eff, core} - n_{eff, cl}) \frac{d \Lambda}{dT}\) is the waveguide contribution as it results from changes in the LPFG’s period with respect to the changing temperature. Since the thermal expansion coefficient of silica is very small \(\sim 0.5 \times 10^{-6/0} \text{C} \) [107], the waveguide contribution due to \(d \Lambda/dT\) can be neglected for lower temperatures. However, at high temperatures, due to a much stronger dependence on temperature [107] the role of the thermal expansion coefficient becomes as important as that of the refractive index. Therefore, at low temperatures, it is the temperature dependence of the effective indices that determines mainly the temperature sensitivity of the resonance wavelength. From equation 3.10,3.11 and 3.12 it is evident that the temperature sensitivity of the resonance wavelength can be positive or negative, depending on whether the thermo-optic coefficient of the core is larger or smaller than that of the cladding.

In order to study the temperature characteristics of the fabricated LPFGs, they are kept in a setup as shown in figure 3.10. An IR lamp is used to heat the chamber and is connected through an auto transformer. The temperature is varied by changing the voltage applied to the IR lamp and measurements were taken after stabilizing the temperature. For temperature readouts, we used an electronic thermometer placed next to the probe. As usual an OSA –white light source arrangement was used to measure the spectral shift and the grating was kept at constant tension during all the investigations.

Figure 3.10 Experimental setup to find temperature sensitivity
The temperature response of a UV fabricated LPFG was studied first. The grating with a period of 435 μm was fabricated in Boron doped single mode fiber which had a length of 10mm. Figure 3.11 below shows the transmission spectrum of the LPFG which has attenuation peaks at 1418nm, 1473nm and 1570 nm.

![Figure 3.11 Transmission Spectrum of UV LPFG](image)

The transmission spectrum of the LPFG was recorded by varying the temperature and the figure 3.12 shows the shift in 1418nm and 1473 nm attenuation peaks as the temperature changed from 25°C to 75°C. It is evident that the resonance peak shifts to lower wavelengths as the temperature increases and the measured temperature dependence of the peak wavelengths (1418nm, 1473nm and 1570 nm) is shown in figure 3.13. The points represent the average shifts calculated while the temperature increase and decrease. A total shift of -1.3nm and -1.9nm occurs for the 1418 nm and 1473nm peaks respectively for the change in temperature from 25°C to 75°C while 1570 band shows a shift of -1.6nm for the same temperature change. Also dλ/dT is found decreasing for the 1570 nm attenuation peak.
Fabrication of asymmetric LPFGs using electrical arc and CO2 laser

Figure 3.12 UV-LPFG spectrum at temperature 25°C and 75°C

Figure 3.13 Shift in resonance peak of UV-LPFG as a function of temperature
The temperature sensitivity of the arc induced LPFG was then evaluated and the LPFG transmission spectra thus obtained for an ambient temperature of $25^\circ\text{C}$ and $80^\circ\text{C}$ are shown in figure 3.14. It is evident from the graph that the LPFG is insensitive to temperature in the range of measurements. The transmission spectrum of the CO$_2$ inscribed LPFG obtained for temperatures $25^\circ\text{C}$ and $80^\circ\text{C}$ is shown in figure 3.15. Even though small, a red shift in resonance peak with increasing temperature is observed. The shift in resonance peak with respect to rise in temperature is shown in figure 3.16.

![Transmission spectrum of arc induced LPFG (25°C and 80°C)](image)

Figure 3.14 Spectrum of arc induced LPFG at temperatures $25^\circ\text{C}$ and $80^\circ\text{C}$
Figure 3.15 Spectrum of CO$_2$ induced LPFG at temperatures 25$^\circ$C and 80$^\circ$C

Figure 3.16 Shift in resonance peak of CO$_2$ induced LPFG as a function of temperature
The temperature response of all the LPFGs and an FBG are combined in one graph and is shown in figure 3.17. While the arc induced LPFG shows no sensitivity, the CO$_2$ inscribed LPFG has a temperature sensitivity of 11 pm/°C and UV LPFG has -24 pm/°C. Hence the following conclusions can be deducted. Even though the LPFG are formed by thermal method in similar SMF 28 fiber, the arc induced LPFG was found insensitive to temperature while the 1417 nm peak of CO$_2$ inscribed LPFG shows a red shift of 1 nm for a temperature change from 25 °C to 80 °C. The UV fabricated LPFG in Ge doped fiber shows a blue shift for temperature rise and has shown a maximum sensitivity of -24 pm/°C.

![Figure 3.17 Temperature response of different LPFGs and FBG](image)

The difference in temperature sensitivity between the SMF-28 and Boron doped silica fibers ie. red shift and blue shift, can be explained on the basis of the thermo-optic coefficients of the core and the cladding materials [107,108]. As per equation 3.10, 3.11 and 3.12, if the thermo optic coefficient of core is higher than that of cladding, the peak shift will be positive. Since the addition of boron to the core brings down the thermo optic coefficient of core below that of the cladding, blue shift occurs for the
Fabrication of asymmetric LPFGs using electrical arc and CO2 laser

attenuation peak with respect to increasing temperature. Thus the presence of Boron alters the temperature dependence of the effective refractive index [56] and hence the UV fabricated LPFG has a negative wavelength shift with increasing temperature. In the case of SMF-28, thermo optic coefficient of core is higher than that of cladding and hence the CO2 inscribed LPFG in SMF 28 has a positive shift.

There are contradictory reports comparing the temperature sensitivity of LPFGs written by the arc and that with UV technology. Humbert et al [55] fabricated LPFG with a period of 600μm in SMF 28 fiber using electric arc and got temperature sensitivities around 70 pm/°C. Almost similar sensitivity was reported by Hwang et al [42] for the LPFG based on arc induced microbends in standard single mode telecommunication fiber with 620 μm period. Temperature sensitivity as high as 154pm/°C in single mode fibers fabricated using UV were reported [109]. Allsop et al have found arc inscription a better method to achieve high temperature sensitivity [110]. In contrast Smietana et al [109] have observed that the thermal sensitivity of LPFGs fabricated in boron co-doped fiber is independent of the writing method.

Since LPFG fabricated in SMF 28 using CO2 laser irradiation has shown sensitivity to temperature, the temperature insensitivity of the periodically tapered arc induced LPFGs in similar fiber can thus be attributed to the fabrication method. It has been shown by Rego et al [54] that the thermal sensitivity of arc induced LPFGs depends on the arc current and pulling tension. Hence it can be concluded that the fabrication method makes the arc induced LPFG temperature insensitive.

Conclusions

In this chapter the basic theory related to long-period fiber gratings is presented. Afterwards, the different mechanisms proposed in the literature for the formation of thermal induced gratings are discussed. The fabrication process of asymmetric LPFGs in SMF 28 using fusion splicer and CO2 laser is also elaborated. Compared with the UV laser exposure technique, the fabrication methods discussed in the chapter based on electric arc and CO2 laser are much more flexible and cost effective because neither photosensitivity nor any other pretreated processes are required to induce a grating in the glass fibers. Moreover, the writing process can be controlled to
Fabrication of asymmetric LPFGs using electrical arc and CO2 laser

generate complicated grating profiles via point-by-point technique without any expensive masks. Possible mechanisms of refractive index modulations in the fabricated asymmetric LPFGs are due to residual stress relaxation and physical deformation. The periodically tapered LPFG fabricated using electric arc from fusion splicer is found to be insensitive to temperature in the temperature range 25°C to 80°C. For telecommunication and sensing applications spectral stability is of prime importance, and an LPFG with temperature insensitive attenuation band is an attractive feature. The fabricated LPFGs have been employed for sensor development and are discussed in the next chapter.

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Fabrication of asymmetric LPFGs using electrical arc and CO2 laser


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Fabrication of asymmetric LPFGs using electrical arc and CO2 laser


Fabrication of asymmetric LPFGs using electrical arc and CO2 laser


