Review on an arc-induced long-period fiber grating and its sensor applications

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INVITED REVIEW ARTICLE

Review on an arc-induced long-period fiber grating and its sensor applications

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This paper presents a systematic review on the long-period fiber grating (LPFG) formed by the electric arcing method. The basic concept of LPFG and the background of the electric arcing method are thoroughly discussed. The paper also discussed on the methods to improve the sensitivity of LPFG towards external perturbations. The LPFG has been reported to have potential usage as sensor, thus a section of the paper has focused on some application of arc-induced LPFG as sensors.

Keywords: long-period fiber grating; electric arc-induced method; fiber optic sensors; electromagnetics theory

1. Introduction

To date, there are two types of fiber gratings that have been introduced, i.e. fiber Bragg gratings (FBGs) and long-period fiber gratings (LPFGs). The main difference between FBG and LPFG is the length of the grating period. The grating period of FBG is shorter than 100 micrometers, whereas LPFG has period of a few hundred micrometers.[1] In terms of working principle, the FBG couples forward-propagating core mode to the backward-propagating core mode, whilst LPFG couples forward-propagating core mode to several cladding modes that are co-propagating in the same direction.

The first known research on fabrication of LPFG-based device for mode conversion was reported in 1994 by Poole et al. through a two-step process.[2] However, the concept of LPFG was described in detail in 1996 by Vengsarkar et al. where the LPFG was fabricated using an ultraviolet (UV) radiation to induce a periodic index change in the fiber core.[1] Since then, the fabrication and applications of LPFGs have undergone rapid development. Even though UV-based fabrication method is a well-known method for producing LPFG, it has its shortcomings. It requires complicated and time-consuming processes. Difficulty in controlling filter parameters is also one of the problems as the resonant wavelength depends on both the grating period and the index modulation amplitude of the grating.[3] Due to these reasons, various fabrication methods have been proposed such as electric arc discharge,[4–53,64,65] CO\textsubscript{2} laser irradiation,[54–67] mechanically induced,[3,68–71] acoustically induced,[72–74] femtosecond laser exposure,[75–78] ion beam implantation [79,80], and relaxation method.[81] Although
various methods have been proposed and demonstrated in previous years, electric arc
discharge is one of the most commonly used techniques for producing the gratings.

LPFG induced by electric arcs was first demonstrated in 1994 by Poole et al. [2].
This fabrication method is simple and can be applied to various types of fibers including
single-mode fiber. Furthermore, this method allows easy control of the filter parameters
such as bandwidth and centre wavelength [3]. This paper presents a review of
LPFGs written by the electric arcing technique. The basic concept and theory of LPFGs
are first presented in Section 2. The sensitivity of LPFG to external perturbations such
as temperature, strain, bending sensitivity, and external refractive index is then
described in Section 3. Section 4 focuses on the advantages and disadvantages as well
as fabrication process of electric arc-induced LPFGs. Different sensitivity modification
methods which include the thin-film coating, etching, bending, and double-pass configuration
are discussed in Section 5. Last but not least, some sensing applications of arc-
induced LPFGs are presented in Section 6.

2. Long-period fiber grating

2.1. Basic theory

The propagation of light in a fiber can be treated as a transverse electromagnetic wave
where the propagation of light within an optical fiber is similar to the propagation of
an electromagnetic wave inside a medium. In order to simplify the analysis, the cladding
is assumed to be infinitely larger than the core.[82]

The cylindrical shape of the fiber acts as a cylindrical dielectric waveguide as
shown in Figure 1, where \( n_1 \) and \( n_2 \) represent the refractive indices of the core and
cladding of the fiber, respectively, and \( a \) is the radius of the fiber core. The coordinates
of any point in the fiber are in the form of \( (r, \theta, z) \) where \( \theta \) is the angle between the
meridional plane containing the point and the reference meridional plane. On the other
hand, \( z \) is the depth of the point into the fiber core.

The nature of the fields that exist in a fiber when light propagates through it can be
analyzed by assuming the fiber core to be a perfectly source-free dielectric material.
Maxwell’s equations for electric and magnetic fields in source-free medium can be rep-
resented as:

\[
\vec{\nabla} \cdot \vec{D} = 0 \quad (1)
\]

\[
\vec{\nabla} \cdot \vec{B} = 0; \quad (2)
\]

Figure 1. Schematic diagram of a cylindrical waveguide.
where $\vec{D} = \varepsilon \vec{E}$ is the electric displacement vector and $\vec{B} = \mu \vec{H}$ is the magnetic flux density. In order to decouple $\vec{D}$ and $\vec{B}$ from Equations (3) and (4), curls on both the equations are performed. The resulting equation can be expressed as:

$$\nabla \times \nabla \times \vec{E} = -\mu \varepsilon \frac{\partial^2}{\partial t^2} \vec{E}$$  \hspace{1cm} (5)$$

where $\varepsilon$ is the permittivity and $\mu$ is the permeability. Applying the basic vector identities,

$$\nabla \left( \nabla \cdot \vec{E} \right) - \nabla^2 \vec{E} = -\mu \varepsilon \frac{\partial^2}{\partial t^2} \vec{E}$$  \hspace{1cm} (6)

The following wave equations are then obtained:

$$\nabla^2 \vec{E} = \mu \varepsilon \frac{\partial^2}{\partial t^2} \vec{E}$$  \hspace{1cm} (7)

$$\nabla^2 \vec{H} = \mu \varepsilon \frac{\partial^2}{\partial t^2} \vec{H}$$  \hspace{1cm} (8)

In order to simplify the analysis and to solve both the wave equations, a scalar quantity is used to represent one of the two components. Thus, the wave equations can be rewritten as:

$$\nabla^2 \psi = \mu \varepsilon \frac{\partial^2}{\partial t^2} \psi$$  \hspace{1cm} (9)

$$\Rightarrow \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \psi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \theta^2} + \frac{\partial^2 \psi}{\partial z^2} = \mu \varepsilon \frac{\partial^2 \psi}{\partial t^2}$$  \hspace{1cm} (10)

Assuming the components are time-harmonic with an angular frequency of $\omega$, the following is obtained:

$$\psi = e^{j\omega t}$$  \hspace{1cm} (11)

Differentiating Equation (11) we obtain:

$$\frac{\partial \psi}{\partial t} = j \omega \psi$$  \hspace{1cm} (12)

$$\frac{\partial^2 \psi}{\partial t^2} = -\omega^2 \psi$$  \hspace{1cm} (13)

Replacing the above differentiation equation into Equation (10), we obtain:

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \theta^2} + \frac{\partial^2 \psi}{\partial z^2} = -\omega^2 \mu \varepsilon \psi$$  \hspace{1cm} (14)
Using method of separation of variables, and assuming the light is travelling along +z direction, the well-known Bessel’s equation is obtained:

\[
\frac{\partial^2 R(r)}{\partial r^2} + \frac{1}{r} \frac{\partial R(r)}{\partial r} + \left\{ \left( \omega^2 \mu \varepsilon - \beta^2 \right) - \frac{\nu^2}{r^2} \right\} R(r) = 0
\]

(15)

Let \( q^2 = \omega^2 \mu \varepsilon - \beta^2 \), radius \( r \) is smaller than \( a \), and \( q^2 > 0 \) in fiber core, on the other hand, radius \( r \) is larger than \( a \) and \( q^2 < 0 \) for fiber cladding. Therefore, the propagation constant can now be defined as:

\[
\omega \sqrt{\mu \varepsilon_2} < \beta < \omega \sqrt{\mu \varepsilon_1};
\]

(16)

The solution to the wave equation in core and cladding regions can therefore be expressed as:

\[
E_1 = AJ_v(\alpha r) e^{j\nu - j\beta z + j\omega t}; \quad r < a
\]

(17)

\[
E_2 = BK_v(\omega r) e^{j\nu - j\beta z + j\omega t}; \quad r > a
\]

(18)

2.2. Coupled-mode theory

Coupled-mode theory is the basic theory for understanding the quantitative information about the diffraction efficiency as well as the spectral dependence of fiber gratings. In single-mode fibers, energy cannot be transferred to another mode within the fiber core. Therefore, energy can only be coupled to cladding modes. In order to simplify the analysis of the mode coupling, the transverse component of the electric field is written as a superposition of the modes.[83,84] The superposition of the coupled mode where the modes are in an ideal waveguide without grating perturbation can be represented as [83]:

\[
\vec{E}_t(x, y, z, t) = \sum_j [A_j(z) \exp(i\beta_j z) + B_j(z) \exp(-i\beta_j z)] \cdot \vec{e}_n(x, y) \exp(-i\omega t)
\]

(19)

where \( A_j(z) \) and \( B_j(z) \) represent the coefficients of the slowly varying amplitudes of the \( j \)th mode traveling in +z and −z directions, respectively. The cladding modes are orthogonal in an ideal waveguide. Due to this, no energy will be exchanged between modes. The presence of a dielectric perturbation will cause the coupling between the modes. The general coupled-mode equations which describe the changes in the forward- and backward-propagating amplitudes along z-axis can be represented as:

\[
\frac{dA_j}{dz} = i \sum_k A_k(K_{kj}^l + K_{kj}^z) \exp[i(\beta_k - \beta_j)z] + i \sum_k B_k(K_{kj}^l - K_{kj}^z) \exp[-i(\beta_k + \beta_j)z]
\]

(20)

\[
\frac{dB_j}{dz} = -i \sum_k A_k(K_{kj}^l - K_{kj}^z) \exp[i(\beta_k + \beta_j)z] - i \sum_k B_k(K_{kj}^l + K_{kj}^z) \exp[-i(\beta_k - \beta_j)z]
\]

(21)

where \( K_{kj}^l(z) \) and \( K_{kj}^z(z) \) are the transverse and longitudinal coupling coefficients between modes \( j \) and \( k \). The transverse coupling coefficient between both modes can be represented as:
where $\Delta\varepsilon$ indicates the perturbation towards the permittivity and can be expressed as:

$$\Delta \in (x,y,z) = 2n_{eff} \delta n_{eff}(x,y,z)$$  \hspace{1cm} (23)

On the other hand, the longitudinal coupling coefficient between modes $j$ and $k$ is analogous to the transverse coupling coefficient.

LPFG is mainly produced by creating fiber-phase grating at the fiber core. The gratings created will induce a perturbation to the effective refractive index of the fiber guided mode; the refractive index change can be represented as equation below [83]:

$$\delta n_{eff}(z) = \delta n_{eff}(z) \left\{ 1 + v \cos \left[ \frac{2\pi}{\Lambda} z + \phi(z) \right] \right\}$$  \hspace{1cm} (24)

where $\Lambda$ is the grating period of the fiber, $v$ is the fringe visibility of the index change, $\delta n_{eff}$ is the “dc” index change spatially averaged over a grating period, whereas $\phi(z)$ represents the grating chirp. With the above two equations, the general coupling coefficient can be then expressed as:

$$K_{kj}^l(z) = \sigma_{kj}(z) + 2\kappa_{kj}(z) \cos \left[ \frac{2\pi}{\Lambda} z + \phi(z) \right]$$  \hspace{1cm} (25)

where $\sigma$ is the “dc” coupling coefficient, whereas $\kappa$ represents the “ac” coupling coefficient.

$$\sigma_{kj}(z) = \frac{\omega n_{co}}{2} \nabla n_{co}(z) \int dx \, dy \nabla \vec{e}_{kj}(x,y) \cdot \vec{e}_{kj}^*(x,y)$$  \hspace{1cm} (26)

$$\kappa_{kj}(z) = \frac{v}{2} \sigma_{kj}(z)$$  \hspace{1cm} (27)

Nonetheless, $K_{kj}^l(z)$ is generally much smaller than $K_{kj}^l(z)$ for fiber modes, hence the longitudinal coupling coefficient will usually be neglected in the analysis.

In LPFG, a forward-propagating mode of amplitude $A_1(z)$ is strongly coupled to another co-propagating mode of amplitude $A_2(z)$. Hence, Equations (20) and (21) can be replaced with the equations below which only contain terms that involve the amplitudes of both modes and making the synchronous approximation:

$$\frac{dR}{dz} = i\tilde{\sigma}R(z) + ikS(z)$$  \hspace{1cm} (28)

$$\frac{dS}{dz} = -i\tilde{\sigma}S(z) + ik^*R(z)$$  \hspace{1cm} (29)

where

$$R(z) = A_1 \exp \left[ -i(\sigma_{11} + \sigma_{22}) \frac{z}{2} \right] \exp \left( i\tilde{\sigma}z - \frac{\phi}{2} \right)$$  \hspace{1cm} (29a)

$$S(z) = A_2 \exp \left[ -i(\sigma_{11} + \sigma_{22}) \frac{z}{2} \right] \exp \left( -i\tilde{\sigma}z + \frac{\phi}{2} \right)$$  \hspace{1cm} (29b)
and \( \kappa = \kappa_{21} = \kappa_{12} \) indicate the “ac” cross-coupling coefficient, whereas \( \sigma_{11} \) and \( \sigma_{22} \) are the “dc” coupling coefficients as discussed in Equation (26). The general “dc” coupling coefficient can be expressed as:

\[
\hat{\sigma} = \delta + \frac{\sigma_{11} - \sigma_{22}}{2} - \frac{1}{2} \frac{d\phi}{dz}
\]

(30)

Assuming the detuning \( \delta \) is constant along the \( z \)-axis, hence it can be represented as:

\[
\delta = \frac{1}{2} (\beta_1 - \beta_2) - \frac{\pi}{\Lambda} = \pi \Delta n_{\text{eff}} \left[ \frac{1}{\lambda} - \frac{1}{\lambda_{d}} \right]
\]

(31)

where \( \lambda_{d} = \Delta n_{\text{eff}} \Lambda \). For a uniform forward-propagating-coupled grating, both the coupling coefficients are constants.

2.3. Phase-matching condition

The period of the LPFGs is generally in the range from 100 \( \mu \text{m} \) to 1 mm (1000 \( \mu \text{m} \)), which is much longer than FBG. A fiber grating acts as an optical diffraction grating within the fiber. Hence, LPFG can be analyzed using diffraction grating equations. The effect of the LPFG grating upon a light wave incident on the grating at an angle \( \theta_1 \) can therefore be expressed as the grating equation [83]:

\[
n \sin \theta_2 = n \sin \theta_1 + m \frac{\lambda}{\Lambda}
\]

(32)

where \( m \) is the diffraction order and \( \theta_2 \) represents the angle of the diffracted wave. The diffraction order that usually dominates in fiber grating is first-order diffraction. In other words, \( m \) is \(-1\) for fiber grating. On the other hand, the mode propagation constant, \( \beta \), can be expressed as:

\[
\beta = \left( \frac{2\pi}{\lambda} \right) n_{\text{eff}}
\]

(33)

where \( n_{\text{eff}} = n \sin \theta \). Using the equation above, Equation (32) can be rewritten as:

\[
\beta_2 = \beta_1 + m \frac{2\pi}{\Lambda}
\]

(34)

where \( \beta_2 \) represents the propagation constant in cladding mode, whereas \( \beta_1 \) is the propagation in core mode. In LPFG, \( \beta_2 \gg 0 \) as the light coupled from the fundamental core mode is travelling in the same direction as in core mode. Hence, with this condition, the resonant wavelength of the LPFG can be determined as below:

\[
\lambda_{\text{res}} = \left( n_{\text{eff}}^{co} - n_{\text{eff}}^{cl,m} \right) \Lambda
\]

(35)

where \( \lambda_{\text{res}} \) represents the resonant wavelength corresponding to the \( m \)th cladding mode, \( n_{\text{eff}}^{co} \) is the effective refractive index of the core mode, whereas \( n_{\text{eff}}^{cl,m} \) indicates the effective refractive index of the cladding modes. In summary, the basic concept in LPFG is the coupling between the fundamental core mode and several propagating cladding modes.[85,86] The core mode of LPFG couples light from the core mode into cladding modes in bands centered at wavelengths that satisfy the phase-matching condition as shown in Equation (35).
Once the light is coupled into the cladding mode, it will decay immediately due to the scattering losses, and hence leaving loss bands in the core mode observed at the output.[1] As can be predicted from the equation, a shift in the resonant wavelength can be induced by variation either in the grating period or the effective refractive indices of the core or cladding modes.

When the light is travelling within cladding modes, it experiences a high loss, which provides attenuation bands at resonant wavelength in the transmission spectrum. The minimum transmission of the attenuation bands is expressed by the equation [87]:

\[ T_m = 1 - \sin^2(\kappa_m L) \]  

(36)

where \( \kappa_m \) is the coupling coefficient for the \( m \)th mode of cladding, whereas \( L \) is the length of the LPFG. The coupling coefficient is determined by the integral overlap of the core and cladding mode, as well as the amplitude of the periodic modulation of the mode propagation constants. The number of cladding modes depends on the radius of the cladding.[88]

Generally, the radius of the cladding is large, and hence, it supports a large number of cladding modes. Theoretical analysis has shown that efficient coupling is possible only between core and cladding modes that have similar electric field, in other words, it is only possible between modes with a large overlap integral. The electric field of odd number modes has a peak located within the core, whereas modes with even number have low field amplitude within the fiber core.[88] Due to this reason, coupling is observed between the core and circularly symmetric cladding with odd number of modes.

3. Sensitivity of LPFG to external influence

Sensitivity is one of the important characteristics for LPFG to be used as a sensing device. Investigations have showed that increase in the order of the coupled cladding mode will lead to increase in the sensitivity of the LPFG. The order of the cladding mode can be changed by changing the difference in the effective mode index and grating period of the LPFG.[89]

The sensitivity of an LPFG can be characterized by the shift in the resonant wavelength. The general expression for the sensitivity is given by:

\[ \frac{\partial \lambda}{\partial X} = \gamma \left( \frac{\partial \Lambda}{\partial X} \frac{\partial \lambda_{n_{\text{eff}}}^c}{\partial n} + \frac{\partial \delta n_{\text{eff}}}{\partial n} \frac{\partial n}{\partial X} \Lambda \right) \]  

(37)

where \( \gamma \) is the general sensing parameter and can be represented by:

\[ \gamma = \frac{1}{1 - \frac{\partial \delta n_{\text{eff}}}{\partial \lambda} \Lambda} = \frac{1}{\delta n_{\text{eff}}} \frac{d\lambda}{d\Lambda} \]  

(38)

where \( \delta n_{\text{eff}} \) represents the difference in the effective mode indices and is given as \( \delta n_{\text{eff}} = n_{\text{eff}}^c - n_{\text{eff}}^l \), \( \Lambda \) is the grating period, and \( \lambda \) indicates the resonant wavelength of the fiber.

3.1. Temperature sensitivity

The temperature effect on the LPFG can be observed mainly in the changes of grating resonant wavelength. The resonant wavelength of the LPFG with grating period of \( \Lambda \) is determined by the phase-matching condition. From the phase-matching condition given
in Equation (35), the expression for the temperature sensitivity of the resonant wavelength can be derived by applying the chain rule differentiation,[90]

\[
\frac{d\Delta \lambda_{\text{res}}}{dT} = \frac{\Lambda}{1 - \Lambda} \left[ \frac{\partial n_{\text{eff}}^{\text{co}}}{\partial \lambda} - \frac{\partial n_{\text{eff}}^{\text{cl,m}}}{\partial \lambda} \right] + \frac{\lambda}{\Lambda} \frac{dA}{dT}
\]

(39)

The LPFG is inherently sensitive to changes in temperature of the surrounding. The temperature dependence of the resonant wavelengths of LPFGs enables them to become an important candidate in temperature sensing. From Equation (39), since the expansion coefficient \((\frac{\Delta V}{V})\) of silica glass is small, the temperature sensitivity of LPFG is mainly influenced by the temperature sensitivity of the refractive indices of both the core and cladding modes as well as the waveguide properties of the fiber.[90] In order to increase the temperature sensitivity of the LPFG, the waveguide term in the equation must be decreased. This can be achieved by additional outer layer with depressed refractive index or by decreasing the diameter of the cladding.[90]

Experiments have been conducted to verify the temperature sensitivities of LPFGs produced by electric arc discharge.

As shown in Figure 2, as the temperature increases, the resonant wavelength of the LPFG shifted to longer wavelength. From the results, the sensitivity of the LPFG is about 0.453 nm/°C.

### 3.2. Strain sensitivity

The axial strain, \(\varepsilon\) of the LPFG is one of the important features as well. The sensitivity of LPFGs to strain can be derived by expanding and rearranging Equation (35) [85]:

![Figure 2. Sensitivity of arc-induced LPFG towards temperature.](image-url)
The sensitivity of LPFG consists of both material and waveguide effects. The material effects consist of the relative change between the effective indices of the core and cladding modes of the fiber. On the other hand, the waveguide effect is the function of the local slope $d\lambda/d\Lambda$ for a particular cladding mode. Both of the contributions can have either polarity depending on the grating period or the order of the cladding mode.

### 3.3. External index sensitivity

One of the unique features of LPFGs compared to FBGs is the high sensitivity to changes in the external refractive index. The influence of the external refractive index on the cladding of the LPFG can be expressed as,[91]:

$$\frac{d\lambda_{res}}{dn_3} = \frac{d\lambda}{dn_{cl}} \frac{dn_{cl}}{dn_3}$$

The propagation constant of the LPFG cladding mode depends not only on the fiber parameters, but also on the refractive index of the surrounding medium, $n_3$, as well. The term $dn_{cl}/dn_3$ is different for each cladding mode within the LPFG. The index $n_3$ represents the refractive index of the external medium. Hence, it can be concluded that the response of LPFG highly depends on the order of the coupled cladding mode due to the refractive index changes.[91–93] In general, the sensitivity increases when the external refractive index increases. However, it will reach a maximum point where the mode becomes unguided.[94]

Interaction of cladding modes with that of the external ambient occurs because the evanescent fields of these modes penetrate beyond the cladding surround interface.[91] If the refractive index of the external medium is lower than that of the cladding ($n_3 < n_2$), LPFG sensitivity to increasing external index of refraction is observed as both shifting in central wavelength of the attenuation band in the gratings transmission spectrum, as well as a decrease in its peak depth.[95] The latter effect is caused by successively smaller coupling coefficients due to the decrease in overlap integral between the core and cladding modes. When the value of external refractive index approaches that of the cladding $n_3 \cong n_2$, discrete cladding modes are no longer guided along the fiber. The LPFG is most sensitive to the external refractive index changes in this region where index matching occurs between the cladding and the surrounding medium.[96] In the event of $n_3 > n_2$, where the external refractive index exceeds the cladding refractive index, attenuated cladding modes are present in the cladding. The attenuation bands reappear at slightly higher wavelength values than for the case where air is the ambient medium.[97,98]

Experiments have been conducted to investigate the effect of refractive index change on the spectrum of LPFGs produced by electric arc discharge. Mediums with different refractive indexes were used in the experiment, which include air (RI = 1.00), water (RI = 1.33) as well as standard Cargille oil with RI ranging from 1.40 to 1.50.

Figure 3 shows the response of the LPFG towards changes in refractive index. As the refractive index increases from 1.00 to 1.45, the resonant wavelength of the LPFG shifted towards lower wavelengths. At index of 1.46, there is a sudden shift of the notch wavelength towards a longer wavelength. The transmission notch started to shift towards shorter when the RI increased from 1.47 to 1.50.
4. Electric arc discharge technique

Among the techniques that have been proposed in fabricating LPFGs, electric arc discharge technique is probably the one that offers more advantages than the others. Electric arc discharge technique was first introduced in 1994 by Poole et al. in a two steps LPFG fabrication process.[2] Since then, various electric arc discharge methods have been established and improved in order to fabricate LPFGs with better quality. There are a few methods that have been proposed in electric arc discharge techniques which include the use of fusion splicer [99] and ignition coil.[100]

4.1. Advantages

The LPFGs produced by electric arc-induced technique possess several unique and crucial properties which differentiates them from LPFG gratings that are produced by other techniques. First and foremost, the gratings produced using electric arc discharge have very high thermal stability due to their formation mechanisms which rely on thermal effects.[35] This enables them to become the best candidate to be used as high-temperature sensors. Experiment has showed that the gratings produced by electric arc discharge can withstand temperature up to 800 °C without degradation of the performance.[68] On the other hand, in another experiment, it was demonstrated that arc-induced gratings can stand temperatures as high as 1000 °C for several days without significant degradation in their spectrum.[21] This thermal stability is an advantage over other techniques such as UV radiation, in which high temperature will erase the gratings produced.[64]

Furthermore, the electric arc technique is much simpler than other technique such as UV radiation.[43,101] It does not require expensive device such as laser equipment and therefore the fabrication cost is lower as well. It enables the writing of LPFGs in any kind of fibers including non-photosensitive fibers and photonic crystal fibers.

Figure 3. Sensitivity of arc-induced LPFG towards index change (→ wavelength shift when RI increases from 1.00 to 1.45) (← → wavelength shift when RI increases from 1.46 to 1.50).
without the need for fiber hydrogenation or post-fabrication annealing. These make electric arc discharge technique to become a widely used method in fabricating LPFGs since its introduction.

4.2. Disadvantages

One of the main drawbacks of the LPFGs produced by arc discharge is the lack of reproducibility and duplicability.[22] This is due to the asymmetric changes induced by the electric arc that may vary for every single discharge. This can cause a significant influence to the coupling strength of the LPFG produced. Another disadvantage of the arc-induced LPFG is the limit imposed on the shortest grating period that can be produced.[22] This limitation is mainly due to the width of the arc. If the period is too short, it will produce overlapping of the refractive-index modulations.

4.3. Fabrication methods of arc-induced LPFG

The fabrication of gratings by electric arc discharge technique was first demonstrated in 1994 in a two-step point-by-point LPFG fabricating process.[2] A focused CO₂ laser beam was used to create periodic cuts on the surface of the fiber followed by point-to-point annealing of the individual cuts via electric arc discharge. The purpose of using electric arc in this fabrication process was to use the surface tension of the silica to transform the fiber surface into sinusoidal deformation. The same process has been demonstrated in 1997 to produce a band rejection fiber filter.[63]

In the same year, Dianov et al. proposed a new methodology in fabricating LPFG which only required either of the former two steps demonstrated.[64] In this experiment, a step-index nitrogen-doped silica fiber was used and a fusion splicer was used to heat the fiber up to the temperature in which the nitrogen diffuses efficiently. The grating produced has a period of more than 200 μm. In 1998, arc discharge is also used to fabricate LPFGs in pure silica core optical fiber.[102]

The setup of the LPFG fabrication was then improved by Kosinski and Vengsarkar using a commercial splicer.[103] In this grating fabrication as shown in Figure 4, a pair of electrodes were used to produce electric arc in order to periodically modify the physical structure of the optical fiber. The fiber holding mechanism in the splicer was replaced by a motorized stage, which allowed the translation of the fiber in between both the electrodes. Three different types of gratings have been fabricated using this setup of fabrication, including the physical deformation gratings, mode-field modified gratings as well as the index-modulated gratings.

In 1999, Hwang et al. proposed and demonstrated a new type of LPFG induced by electric arc and producing periodic microbends.[3,68] An unjacketed fiber was held straight in between two fiber holders. One of the holders was then displaced in the direction orthogonal to the fiber axis that induced a lateral stress on the fiber section between both the holders. The electric arc was then used to heat the fiber to create deformation in the form of a microbend. The electrodes were then translated along the fiber and the arcing process repeated at specified points on the fiber. Successive microbends were created without movement of the fiber holders which prevented misalignment of the fiber during the fabrication process.

In 2002, Kim et al. made improvements to the arc discharge fabrication method proposed by Hwang et al. [43]. The schematic of the fabrication setup is shown in Figure 5. The setup involved using of a mass at one end of the fiber. The fiber is held
straight between the electrodes, so that the fiber can be moved by the motorized translation stage. The purpose of attaching a mass at one end of the fiber is to provide a constant tension to the fiber. The fiber was tapered when it is heated by the electric arc discharge due to the longitudinal tension. The stability of the electric arc produced was maintained using a 20-kHz arc generator.

In the fabrication setups that have been discussed, the gratings are formed by thinning or tapering of the fiber diameter. Chavez et al. introduced a new arc discharge method [104] in which the gratings of the LPFGs are produced by the fattening of the fiber. The fiber is heated to the softening point by the arc and hot pushed to a predetermined distance. The hot push is repeated until the section of the fiber reaches the desired diameter. The fattening process is then repeated at different points on the fiber. The advantage of this fattening fabrication technique is that it does not require any special equipment such as motorized translation stages and external weight that applies tension to the fiber.

Another promising technique was proposed and demonstrated in 2014.[105] High-quality LPFGs are fabricated by periodically tapering a standard single-mode fiber. The fabrication setup consists of a typical fusion splicer with ZL and ZR motors fixed with fiber holders as well as a SWEEP motor. The function of the SWEEP motor is to move the ZL and ZR motors which are positioned on a translation stage driven by the SWEEP motor. The fabrication process consists of heating the fiber via the electric arc discharge and synchronously stretching the two ends of the fiber by both the ZR and
ZL motors. This resulted in the formation of a taper on the fiber. Next, the fiber is moved to the next point along the fiber axis by the SWEEP motor and the arcing process repeated. The problems of alignment and effect of mass on the tapers can be overcome in this fabrication setup.

Majority of the electric arc induced LPFGs are fabricated using fusion splicer. In the work by Zulkifly et al. [42] and Lee et al. [100], a simple electric arc-induced LPFG fabrication system was developed, as shown in Figure 6, which consists of an ignition coil with an arcing circuit, a tension meter with weight, a pair of electrodes mounted on the motorized stage, and a pair of fiber clamps (with and without sliders).

During the fabrication process, a constant force is applied to the fiber to create a constant axial tension. Tapers were formed at each of the arcing point. The motorized stage is used to move the electrodes to the next point of the fiber to create the periodic gratings. The structure of the tapers produced depends on the tension applied to the fiber and arcing discharge time. Figure 7 shows the transmission power spectrum during the formation on of an arc-induced LPFG (with grating length $L = 26$ mm).

![Figure 6. Setup for fabricating arc-induced LPFG with ignition coil.](image)

![Figure 7. Transmission spectra formation of an arc-induced LPFG.](image)
5. Sensitivity modifications

Sensitivity to external perturbations is one of the crucial properties of LPFG. There are many research works reported on the modification and enhancement of the LPFGs sensitivity. The techniques proposed include thin-film coating,[39,106–116] etching, [7,38,42,90,117], bending [118,119] as well as double-pass configuration.[120,121]

5.1. Thin-film coating

Film coating is a method used to modify and enhance the sensitivity of LPFGs. As the film thickness on the LPFG surface increases, the average external refractive index of the LPFG increases leading to a down shift of the resonant wavelengths. There will be a point where the resonant disappear due to the similarity in the refractive indices of both the cladding and the average index of external medium. The higher the refractive index of the film, the thickness required to achieve higher sensitivity is lower compared to the film with lower refractive index. The thin-film that has higher refractive index than the glass cladding can help to improve the sensitivity of the LPFGs. According to the phase-matching condition, the refractive index sensitivity of the resonant wavelength arises from the dependence of the effective index of cladding modes on the refractive index of the surrounding material.

In 2002, Rees et al. has proposed and demonstrated the use of Langmuir–Blodgett (LB) thin-film deposition technique to allow the deposition of a thin film over the gratings of LPFG, in which the refractive index of the thin-film material exceeding that of the cladding.[114] Another technique that was proposed for the deposition of the thin film is based on the ionically self-assembled monolayer (ISAM).[110,111,122–126] ISAM is a layer-by-layer deposition technique where the deposition of the thin film involves the dipping of a charged substrate into an aqueous solution of cation followed by an aqueous solution of anion alternately.

5.2. Etching

Etching is one of the methods used to modify the sensitivity of LPFG to ambient refractive index. Cladding etching has been used as a post-fabrication method for repositioning the resonant wavelength of LPFG to enhance and improve their sensitivity to external refractive index.[38,42,90] The effect of etching of the LPFG cladding resulted in the resonant peak of the LPFG to shift to a higher wavelength as well as an increase in notch depth. The shift in the cladding mode resonances is due to the change in the effective index difference between the core and cladding modes. A reduced cladding diameter results in an increase in the effective refractive index difference between the core mode and the cladding modes. Based on the phase-matching condition, a higher effective refractive index difference will lead to larger wavelength shift. A larger resonant wavelength shift will lead to higher sensitivity of LPFG towards external refractive index variation. Investigation has been carried out to compare the numerical and experimental results of etching effect on LPFG in which results showed that the sensitivity of LPFG to the external index increases with decreasing cladding radius.[127]

5.3. Bending

Bending is also one of the techniques that has been proposed for the purpose of improving LPFG sensitivity. When the sensing zone in fiber is having a flat and smooth
surface, the sensitivity will be low. On the contrary, if the sensing surface is not smooth, surface scattering loss will occur due to the distorted waveguide.\[119\]

When the LPFG is bent, the surface between the fiber core and surrounding air is no longer smooth, hence the waveguide is distorted and the light transmission mode will be changed. This will then lead to the change in the surface scattering loss and causes the output light loss to change. The transmission of light in a bending fiber is shown in Figure 8. Assume that the left side of the fiber is fixed, whereas the right side of the fiber is being bent from the dashed line to real line as shown in the figure. This will increase the incident angle, from $\theta_i$ to $\theta_i'$, and lead to the transformation of high-order modes to lower order modes. This will then cause the surface scattering loss to decrease, and thus the output intensity will increase.

In 2005, Frazao et al. has investigated the effect of bending on the performance of LPFG.\[118\] The fiber used in the experiment was single-mode fiber with gratings period of 540 $\mu$m. Investigations showed that the transmission loss will increase with the increasing in the curvature of the fiber bending. In other words, bending of the fiber will sensitize the performance of LPFG.

5.4. Double-pass LPFG configuration

In 2014, a double-pass configuration was introduced by Yong et al. to enhance the sensitivity of an arc-induced LPFG.\[120\] The double-pass LPFG configuration was applied in a hybrid LPFG-FBG system, where two circulators are used to enable the signal to be recirculated back to the LPFG. The purpose of using the double-pass configuration is to increase the notch depth of the LPFG resonant wavelength and thus, the response of the LPFG towards external perturbation. The double-pass configuration provides longer propagation path for the light to pass through and hence enables better coupling between the core and cladding modes of the LPFG. As a result, better transmission attenuation can be obtained when there are changes in the surrounding medium. The double-pass hybrid system demonstrated has been used for monitoring RI changes. Results showed that the sensitivity of the double-pass system is approximately twice the sensitivity of single-pass system.

In addition, the double-pass configuration has been demonstrated by Loh et al. in order to sensitize the arc-induced LPFG-based sensor.\[121\] The double-pass configuration demonstrated has been used to monitor the avidin–biotin interaction. Results obtained showed that the transmission attenuation of the LPFG with double-pass
configuration is higher compared to the single-pass configuration. This translated to an improved sensitivity of the LPFG utilizing the double-pass configuration. The advantage of using the double-pass technique is that it does not require any physical change or modification to the LPFG structure. The double-pass configuration is shown as Figure 9.

6. Some applications of arc-induced LPFGs

One of the interesting properties of arc-induced LPFGs is their sensitivity to external perturbations caused by pressure, temperature, strain as well as changes in surrounding refractive index. Due to these, arc-induced LPFGs have been used in many sensing applications especially for pressure,[4] temperature and strain,[27,29,30,36,95] refractive index sensing,[7,25,39] biosensors [121,128], and chemicals.[73,129]

6.1. Pressure sensor

The resonant wavelength of LPFGs usually shifts linearly when a pressure is applied. The output notch of the LPFG is easily shifted by changes in its inner stress and physical shape that are caused by bending. Due to this sensitivity towards pressure, various grating-based sensors have been developed for the measurement of applied pressure. In 2007, arc-induced LPFGs have been fabricated using a computer-assisted precision arc-discharge apparatus.[4] The LPFGs fabricated were used for measurement of hydrostatic pressure up to 450 bar in a special housing shown in Figure 10. From the experiment, the LPFG responded linearly as a function of pressure. The resonant wavelength of the arc-induced LPFG shifted to higher wavelength when the applied pressure increased.

6.2. Temperature and strain sensor

Temperature and strain sensitivity are important properties of arc-induced LPFGs that make them suitable device to be used in systems to monitor temperature and strain variations. Rego et al. investigated the characteristic of arc-induced LPFGs towards temperature as well as strain.[30] It was demonstrated that the response of arc-induced LPFGs towards temperature and strain could be altered by different fabrication parameters. Different LPFGs were fabricated with three different electric currents, which were 9, 10, and 12 mA. The LPFGs were then tested to compare their sensitivities towards...
temperature as well strain. Results obtained showed that the LPFG strain sensitivity changed from $-0.14$ to $-0.86 \text{ pm/με}$ as the electric currents used for fabrication increased. On the other hand, the temperature sensitivities of LPFGs decreased from 68 to 60 pm/°C when the electric current used for fabrication increased.

In another research conducted to investigate the temperature sensitivities of an arc-induced LPFG,[95] showed that the wavelength of the LPFG shifted to longer wavelength as the temperature was increased. This might be due to the increase in the difference between effective refractive indices of the modes caused by the heating. In 2007, Petrovic et al. conducted a research to investigate the effect of strain on LPFG performances as well.[36] As expected, the resonant wavelength of the LPFG was shifted to lower wavelength as the applied strain increased. All these investigations showed that the arc-induced LPFG is a suitable candidate to be used as temperature and strain sensors.

6.3. Refractive index sensor

As discussed in previous subsections, LPFGs are sensitive to external pertubations such as presssure, temperature, and strain. Refractive index sensitivity of LPFG is another important property that makes it suitable to be used as refractometer. The sensitivity of LPFG towards external refractive index has been widely exploited with one of the researches conducted by Rios et al. [7]. In the research, the LPFG with 40 gratings and grating period of 500 μm was produced using a fusion splicer. The cladding of the LPFG was etched with a hydrofluoric acid solution to enhance its sensitivity. In medium with refractive index value of 1.3, the wavelength shift of the LPFG was larger compared with non-etched arc-induced LPFG. This was due to the higher order cladding modes which existed in etched LPFG. The coupling between fundamental core mode to higher order cladding modes leads to a higher sensitivity. Hence, it can be concluded that a reduction in cladding diameter will increase the LPFG refractive index sensitivity.

In 2013, Smietana et al. have also used an electric arc-induced LPFG as refractive index sensor.[39] In the experiment, the LPFG was coated with a thin nanothick layer of silicon nitride. Results showed that the resonant wavelength of the LPFG shifted to lower wavelength as the external refractive index increased with an enhanced sensitivity.
6.3.1. Biosensor

Due to the sensitivity of the resonant peaks of the LPFG towards changes of the surrounding refractive index, LPFG has the potential to be used as a biosensor. One of the examples of potential usage of arc-induced LPFG as biosensor is its application as a dengue detection device. The results obtained indicated that the resonant wavelength shift of the LPFG in serum of positive dengue patient was greater compared to the serum from a healthy person. This might be caused by the higher refractive index of the serum positive due to the presence of antibody. When an infection occurs in human body, the antibody is responsible to control the spread of the virus. Hence, in the serum obtained from a positive dengue patient, the antibody increased the refractive index of the serum and therefore causing the LPFG resonant wavelength to shift.

Loh et al. extended the use of LPFG in biosensor field to monitor the avidin–biotin interaction. In this research, the LPFG used was fabricated using arc-induced method. The LPFG was having grating period of 675 μm and was coated with gold nanoparticles and subsequently avidin by self-assembly method. From the results obtained, a shift of resonant wavelength was observed during the avidin–biotin interactions. Besides, the transmission attenuation of the LPFG increased compared to the reference LPFG spectra.

In 2010, LPFG has been used as an immunosensor as well. In the research, LPFG was used to measure the interaction between immobilized IgG and the corresponding antigen. The gratings section of the fiber was coated with a thin layer of nano-thick precursor polymer using the layer-by-layer technique. The precoated LPFG was immersed into a IgG solution of 0.05 mg/mL concentration for an hour, followed by a standard binding block solution for another hour. Experimental results showed that the immunosensing was able to detect specific antigen–antibody binding. On the other hand, with a standard binding block, it is possible to eliminate cross-sensitivity to undesired agents.

6.3.2. Chemical sensor

In 2011, Linesh et al. carried out experiments in order to test the performance of LPFG in different ethanol concentrations in gasoline. In the research, the LPFGs were fabricated using point-by-point arc-induced method by fusion splicer machine. Different samples of ethanol-blended gasoline were prepared by mixing pure gasoline with different percentages of ethanol, i.e. 0, 10, 20, 50, 80 as well as 100%. Results showed that the shift of the LPFG resonant peak was not obvious when the concentration of ethanol increased from 0 to 10%. However, the notch shift became prominent when the ethanol concentration increased from 10% to 100%.

7. Conclusion

We presented a review on arc-induced LPFGs, covering the basic theory of LPFG, the various arc-discharge fabrication methods, the sensitivity, and methods to enhance sensitivity towards external perturbation. The arc-induced LPFG has many advantages and has the potential to be used as optical sensors. However, one of the main drawbacks of the LPFGs produced by arc discharge is the lack of reproducibility and duplicability due to the asymmetric changes induced by the electric arc. Some sensing applications had been reported, i.e. as pressure, strain and temperature, refractive index, and chemical sensors.
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