A Review on Optical Fiber Long Period Grating, its applications in Optical Communication System

Mr. Puneet Sehgal¹, Ms Himani Dua²

¹Department of Electronics, Assistant Professor, A.R.S.D College, University of Delhi
²Department of Instrumentation, Assistant Professor, Shaheed Rajguru College of Applied Sciences for Women, University of Delhi

Abstract: Innovations in optical fiber technology are revolutionizing world communications. As we can see that optical fiber long period grating can be used in designing of devices which are used to meet the growing demands for various ranges in the field of optical communication systems. Thus, this paper deals with the descriptive study of long period fiber grating (LPG) and its applications in emerging field of optical communication systems. LPG forms an important component of optical communication. The paper covers the analysis of long fiber grating and their fabrication. This paper also deals with the cladding mode analysis of the fiber which describes the inaccuracies of two layer model of the fiber and implementation of three layer fiber geometry to calculate the effective refractive index of the fiber so that it can effectively couple the signal for its efficient transmission. In the cladding mode analysis the whole mathematical derivation along with the requisite mathematical expressions are explained to find the effective refractive indices of the various cladding modes being supported by the fiber which are used to plot the transmission spectrum of the LPG designed for a particular frequency or wavelength used for telecommunication purposes.

Keywords: Optical Fiber Communication, long period Grating, Optical Filter, coupled mode equations, LPG fabrication.

I. INTRODUCTION

The rapid progress and development in optical fiber communication and sensing systems have impulsively speed up the exploration of researchers and scientists to improve and develop the optical devices, which could overcome the existing limitations and perform the task of precursors for future advancements in photonics technology.

Optical fiber can be used as sensors to measure strain, temperature, pressure and other quantities by modifying a fiber so that the quantity to be measured modulates the intensity, phase, polarization, wavelength or transit time of light in the fiber. Sensors that vary the intensity of light are the simplest, since only a simple source and detector are required. A particularly useful feature of such fiber optic sensors is that they can, if required, provide distributed sensing over distances of up to one meter. Optical Communication systems based on Wavelength Division Multiplexing, N signal laser beams at N different wavelengths (each carrying modulated user information) are coupled into the EDFA and propagate down the fiber along with the pump. Gain of the erbium doped fiber amplifier across the total spectrum in use, has emerged as topic of research in recent years. LPG’S have also been used as gain flattening filters for Erbium doped Fiber amplifiers [1], and as optical fiber polarizer’s[2] because of their low insertion loss and low back reflections which in addition to gain equalization; give an overall gain enhancement as well as Amplified Spontaneous Emission (ASE) noise suppression. The development of fiber gratings had a significant impact on research and development in telecommunications and fiber optic sensing. Fiber gratings are made by introducing periodic perturbation in their refractive index. Fiber gratings are intrinsic devices that allow control over the properties of light propagating within the fiber—they are used as spectral filters, as dispersion compensating components and in wavelength division multiplexing systems. The sensitivity of their properties to perturbation of the fiber by the surrounding environmental conditions has led to extensive study of their use as fiber sensor elements. Fiber gratings consist of a periodic perturbation of the properties of the optical fiber, generally of the refractive index of the core[3].

II. PHYSICAL MODEL TO ANALYSE LONG PERIOD GRATING (LPG)

The long-period grating (LPG) has a period typically in the range 100 µm to 1 mm, as illustrated in fig 1[3]. It couples light from a fundamental guided core mode into
co-propagating cladding modes at various wavelengths, was first reported by Vengsarkar and co-workers in 1996 [4]. The high attenuation of the cladding modes results in the transmission spectrum of the fiber containing a series of attenuation bands centred at discrete wavelengths, each attenuation band corresponding to the coupling to a different cladding mode and the exact form of the spectrum, and the centre wavelengths of the attenuation bands, are sensitive to the period of the LPG, the length of the LPG (typically of the order of 30 mm) and to the local environment: temperature, strain, bend radius and to the refractive index of the medium surrounding the fiber.

\[
\Delta \phi = \left( \beta_{co} - \beta_{cl}^m \right) \lambda
\]

Thus Changes in these parameters can modify the period of the LPG and differential refractive index of the core and cladding modes which modifies the phase matching conditions for coupling to the cladding modes and results in change in the central wavelength of the attenuation bands [3]. The sensitivity to a particular measure is dependent upon the composition of the fiber, order of the cladding mode to which the guided optical power is coupled and is different for each attenuation band [3]. This range of responses makes them particularly attractive for sensor applications, with the prospect for multi-parameter sensing using a single sensor element [5]

The LPG couples light from the forward propagating core mode, i.e., the mode guided by the core cladding interface of the fiber to the cladding modes, i.e., the modes guided by the cladding ambient interface of the fiber. As we know that cladding mode is essentially the mode associated with the fiber with a very large core radius (~62.5µm) with the ambient as cladding. The cladding modes can be quickly attenuated. The principle of operation of LPG is similar to that of an FBG, except that in long period grating, the incident light traveling in the core mode excites the cladding guided modes at each perturbation as shown in Fig 2. Light coupled to the \(n^{\text{th}}\) cladding mode at interface 1 travels with the propagation constant \(\beta_{cl}^m\) and interferes with the light coupled to the \(m^{\text{th}}\) cladding mode at interface 2. The light coupled at interface 2 has an additional phase due to the core mode having traversed a length \(\lambda\) with the propagation constant \(\beta_{co}\) corresponding to the core mode. Hence, the phase difference between two waves is

\[
\Delta \phi = \left( \beta_{co} - \beta_{cl}^m \right) \lambda
\]

Where:

- \(\beta_{co}\) = propagation constant of the core
- \(\beta_{cl}^m\) = propagation constant of the cladding at \(m^{\text{th}}\) order
- \(n^{co}_{\text{eff}}\) = effective index of the core
- \(n^{cl,m}_{\text{eff}}\) = effective index of the \(m^{\text{th}}\) cladding mode
- \(\Lambda\) = LPG period, which is much longer for co-propagating coupling at a given wavelength than for the counter propagating coupling.

\[
\Delta \phi = \left( \beta_{co} - \beta_{cl}^m \right) \lambda = \frac{2\pi}{\lambda_0} \left( n^{co}_{\text{eff}} - n^{cl,m}_{\text{eff}} \right) \lambda = 2\pi
\]

III. PRINCIPLE OF OPERATION

As mentioned earlier a long period fiber grating is formed typically by introducing a periodic refractive index modulation in the core of the optical fiber. LPG couples an incident fundamental core mode \((LP_{01})\) to forward propagating cladding modes \((LP_{0m})\) when the phase matching conditions are satisfied. The cladding modes are lossy and can be easily attenuated by introducing a bend.

As a result the conventional transmission spectra of an LPG consists of a series of attenuation bands, each corresponding to coupling from the propagating core mode to a particular cladding mode[6]. Defining \(\Delta \beta\) as the difference between the two propagation constants \(\beta_{co}\) and \(\beta_{cl}^m\) (where \(\beta_{co}\) denotes the propagation constant of the fundamental \(LP_{01}\) core mode and the propagation
constants of the cladding modes given by $\beta_{cl}^m$ where the superscript denotes the order of the mode, i.e., $\Delta \beta = (\beta_{co} - \beta_{cl}^m)$, the phase matching condition equation can be written as $\Delta \beta = K = \frac{2\pi}{\Lambda}$ in terms of $\Delta \beta$ and grating period $\Lambda$ where $K$ is known as the grating vector. The attenuation notches appear in the transmission spectrum of LPG at wavelength $\lambda_0$ where the core mode and a particular cladding mode is phase matched. since $\beta = \frac{2\pi}{\lambda_0} n_{eff}$, the phase matching condition in terms of the coupling wavelength $\lambda_0$ can be expressed as [3][6]

$$\lambda_0 = \left(n_{eff}^{co} - n_{eff}^{cl,m}\right) \Lambda$$

The relative positions of the propagation constants $\beta_{cl}^m$ of the cladding modes are shown with respect to the propagation constant $\beta_{co}$ of the core mode [3][6]. There is a purely sinusoidal index modulation along the fiber with the periodic index structure being perpendicular to the fiber axis. These assumptions exclude blazed gratings and as a result modal overlap conditions dictate that the fundamental guided mode can couple only to those cladding modes that are azimuthally symmetric. Thus as order of mode coupling $m$ increases grating period $\Lambda$ decreases [35].

The axis of the figure represents the $\beta$-axis in Fig 3. The open circle represents the core guided fundamental mode for $n_2 < n_{eff} < n_1$; filled circles represent cladding modes for which $n_a < n_{eff} < n_2$. The hatched region represents the continuum of radiation modes for which $n_{eff} < n_a$. Hence, the guided core mode is phase matched to a co-propagating LP02 cladding mode, for a grating of period $\Lambda = \frac{2\pi}{\Delta \beta_{02}}$. Similarly, the guided core mode becomes phase matched to a co-propagating LP03 cladding mode for a grating of period $\Lambda = \frac{2\pi}{\Delta \beta_{03}}$. The pictorial description implies that for a given $\lambda_0$, depending on the periodicity $\Lambda$ one can induce mode coupling between the fundamental core mode and several different cladding modes. Since in LPG $\Delta \beta = (\beta_{co} - \beta_{cl}^m)$ decreases as modes increase [6].

IV. EFFECT OF GRATING PERIOD AND RESONANCE WAVELENGTHS

To generate phase matching curves one requires the propagation constants of the guided core mode and a given cladding mode of the fiber at different wavelengths. From these we obtain periodicities $\Lambda$ that meet the phase matching condition given by equation,

$$\Lambda = \frac{\lambda_0}{\left(n_{eff}^{co} - n_{eff}^{cl,m}\right)}$$

[3][6]

The choice of grating period, $\Lambda$ also allows the designer to vary the separation between the resonance wavelengths, $\delta \lambda$. We now try to estimate the wavelength spacing between resonance wavelengths corresponding to coupling to the two adjacent cladding modes for a given periodicity $\Lambda$ thus phase matching conditions for $m^{th}$ and $(m+1)^{th}$ cladding mode can be expressed as

$$\Delta \beta_1$$

$$\Delta \beta_2$$

Fig3: $\beta$-plot for mode-coupling mechanism in long period grating.
The deformation of the fiber has been achieved mechanically[17] and electrical discharges[18] or using a micro lens array[32]—facilitating rapid and reproducible LPG fabrication.

The use of UV exposure is well established, due to its widespread use in the fabrication of FBGs. Its use has implications for the spectral characteristics and stability of the LPG spectrum. The diffusion of hydrogen from unexposed to exposed regions then acts to increase the amplitude of the refractive index modulation, as the refractive index increases further in the exposed regions (increasing hydrogen concentration) and decreases in the unexposed region (decreasing hydrogen concentration). Thus the strength of the LPG grows. This is followed by a slow out diffusion whereby the refractive index of the core decreases, causing a decrease in wavelength.

The technique of UV exposure is widely used in the fabrication of LPG’S, as it stabilizes the spectrum of LPG. To increase the modulation in the refractive index, the hydrogen gas is diffused from unexposed UV region to exposed UV area. Hence the refractive index increases in the exposed region while decreases at the other. Then slow diffusion process is carried out to decrease the refractive index of the core as the wavelength decreases.

For telecommunication areas use, LPG’S are fabricated at wavelengths 1300nm and 1550nm and the spectrum is monitored by coupling light from super fluorescent fiber sources or super luminescent diodes in the fiber and recording the transmission using an optical spectrum analyzer. There have been reports of the use of fibers with lower cutoff wavelengths, 650 nm, allowing the operation of the LPG within the response of silicon detectors, facilitating the use of low-cost CCD spectrometers [33].

VII. CLADDING (COUPLED) MODE ANALYSIS

Cladding modes

Cladding modes are those modes which are propagated by total internal reflection at the cladding air interface. Calculation of cladding modes uses the approximation that the fiber can be considered as a multimode step index structure ignoring the presence of core, an approach that has commonly been used to simplify cladding mode analysis[34].

Two Layer Model

The two-layer model basically treats the cladding and core as one multimode fiber and the surrounding environment as the new cladding only in the LPG region[34].

Three layer model

To calculate \(n^\text{eff}_m\) the three layer model is used to overcome the design inaccuracies of two layer model. In three layer model the variation of effective refractive
index can be calculated correctly up to fourth decimal point whereas this is not possible in two layer model[34].

The complete refractive index profile for evaluating the propagation characteristics of both core and cladding modes is given by [34]

\[ n = n_1 \quad r < a_{co} \]
\[ = n_2 \quad a_{co} < r < a_{cl} \]
\[ = n_a \quad r > a_{cl} \]

(1)

Where symbols have their usual meanings. The cross-section view can be shown as

![Complete Three-Layer Fiber Geometry for calculation of propagation constants of different modes](image)

Fig 4: Complete Three-Layer Fiber Geometry for calculation of propagation constants of different modes

The differential equations for determining the radial variation of field \( R(r) \) are of the form given in equations. For the symmetric \( (l = 0) \) core guided mode \( n_1 > \beta / k_0 > n_2 \) the equations reduce to

\[
\frac{d^2 R}{dr^2} + \frac{1}{r} \frac{dR}{dr} + \left( \frac{U^2}{a_{co}^2} \right) R = 0 \quad r < a_{co} \\
\frac{d^2 R}{dr^2} + \frac{1}{r} \frac{dR}{dr} - \left( \frac{W^2}{a_{co}^2} \right) R = 0 \quad a_{co} < r < a_{cl} \\
\frac{d^2 R}{dr^2} + \frac{1}{r} \frac{dR}{dr} - \left( \frac{W_{1}^2}{a_{co}^2} \right) R = 0 \quad r > a_{cl}
\]

(2)

and leads to the following solutions

\[
R(r) = A J_0(Ur/a_{co}) + B Y_0(Ur/a_{co}) + C I_0(Ur/a_{co}) + D K_0(Wr/a_{co})
\]

(3)

where \( U_1 = a_{co}k_0 \sqrt{(n_2^2 - n_{eff}^2)} \). \( J_0 \) and \( I_0 \) are the Bessel functions and modified Bessel functions of the first kind, while \( Y_0 \) and \( K_0 \) are the Bessel functions and modified Bessel functions of the second kind.

(4) Using the continuity of \( R(r) \) at \( r = a_{co} \) and \( r = a_{cl} \) and that of \( \frac{dR}{dr} \) at \( r = a_{co} \) and \( r = a_{cl} \) for the solutions in

where \( U = a_{co}k_0 \sqrt{(n_1^2 - n_{eff}^2)} \),

\[ W = a_{co}k_0 \sqrt{(n_{eff}^2 - n_2^2)} \] and

\[ W_1 = a_{co}k_0 \sqrt{(n_{eff}^2 - n_a^2)} \]
equation (9), the constants \( B, C \) and \( D \) can be expressed in terms of \( A \) and one obtains an eigenvalue for the propagation constant of the core guided mode as

\[
\left[ J_0(U) - K_0(Wc) \right] \left[ I_0(Wc) + K_0(Wc) \right] = K_1(W) I_1(Wc) K_1(Wc)
\]

where \( c = \frac{a_{cl}}{a_{co}} \). The constant \( A \) is obtained from the normalization condition

\[
\int_0^\infty \psi^2 r dr = 1
\]

Similarly, \( B \) and \( C \) can be expressed in terms of \( A \) as

\[
B = A(UJ_1(U)I_0(W) + WJ_0(U)I_1(W))
\]

and

\[
C = A(WJ_0(U)K_1(W) - UJ_1(U)K_0(W))
\]

Using the continuity at \( r = a_{cl} \) gives \( D_1 \) in terms of \( B_1 \) and \( C_1 \) as

\[
D_1 = \frac{B_1 J_0(Uc) + C_1 I_0(Uc)}{K_0(Wc)}
\]

Thus we can calculate the \( n_{eff} \) of the fiber provided the refractive indices of the core, cladding and their respective radii are given to us. Hence we can verify the refractive index of cladding modes from above equations for a given fiber by this three layer model analysis. This analysis is further used to plot the transmission spectrum of the LPG studied at a particular wavelength, let say at 1550nm.
which is the most common wavelength used for telecommunication purposes.

VIII. CONCLUSION

Thus we have discussed about the long period grating, its fabrication and analysis of cladding modes which are propagating in it, this analysis is used to find the effective refractive indices of the various cladding modes being supported by the fiber which are used to plot the transmission spectrum of the LPG designed for a particular frequency or wavelength used for telecommunication purposes.

ACKNOWLEDGEMENT

The authors are thankful to University of Delhi, Department of Electronic Science, South Campus and their respective colleges. Thanks are also due to our colleagues, for their constant guidance and unconditional support.

REFERENCES