2.1 Introduction

The study of properties of various types of optical fibers was one of the hottest research areas in the second half of the 20th century. In late 1970s, a team led by K. O. Hill was working on non-linear properties of germanium-doped silica fibers in Canadian Communications Research Centre, Ottawa, Canada. In 1978, the group came up with an article published in Applied Physics Letters, where they reported an increase in back reflection of the fiber to a value many times higher than the Fresnel reflection (4%) from the input face of the 1-meter single mode germanium doped silica core fiber. The fiber of numerical aperture (NA) 0.2 and core diameter of 2.5µm was exposed to 488nm coherent beam of argon-ion laser of 250mW for several minutes as shown in Fig 2.1. An increase in the reflected light intensity occurred which grew until almost all the light was reflected from the fiber. Laser radiation at 488nm was reflected from the other end of the fiber producing a standing wave pattern that formed the fiber grating [1]. Such gratings are called “Hill gratings.” In this kind of gratings, reflected wavelength depends on incident wavelength (grating writing wavelength). Several years of continuous studies of Lam et al. showed that the grating strength increased as the square of the light intensity, suggesting a two-photon process as the mechanism. As per their study single photon at one-half of this wavelength i.e. at 244nm in the ultraviolet, is more effective for the grating fabrication [2, 3].

11 years after the announcement of formation of first Hill gratings, in 1989, G. Meltz with his co-workers demonstrated a new method of fiber grating fabrication known as holographic method. In this method back reflected wavelength can be tuned about the writing UV wavelength. They also showed that UV radiation of wavelength 244nm could be used to fabricate fiber gratings. The fiber grating would reflect any designed wavelength by irradiating very small length of the fiber. The UV light
Fiber Bragg Gratings

(244nm) is split into two beams and then recombined to form interference pattern. Ge doped silica fibers were exposed to that interference pattern as shown in Fig 2.2.

![Figure 2.1: Self grating writing method.](image1)

The period of the grating and the refractive index change was set by the angle between the interfering beams and the UV wavelength. Gratings fabricated with this holographic method were found to be more efficient and gratings were formed in very short time period (5minutes) [4].

![Figure 2.2: Experimental setup of holographic method.](image2)
As the periodic index modulation develops in the fiber core, a narrow peak appears in
the reflection (or a notch in transmission) spectrum. The center of the peak or notch
occurs at the wavelength that satisfy the Bragg condition, given by

$$\lambda_B = 2n_{\text{eff}} \Lambda$$

where $\Lambda$ is the grating period and $n_{\text{eff}}$ is the effective refractive index of the core
mode [4]. This type of fiber gratings are called fiber Bragg gratings (FBG). Typically
the grating period of FBGs range between submicrons to 100µm.

When broad light propagates through periodically varying regions of higher and
lower refractive index, it is partially reflected at each interference of high and low
refractive index regions as shown in the Fig. 2.3 [5]. Partial reflections those satisfy
Bragg condition will add up and grow nearly to 100% for particular wavelength. That
wavelength is known as Bragg wavelength [6, 7] given by Eq. 2.1. Other wavelengths
are transmitted through the grating with low loss. Thus the FBG selectively reflects a
very narrow range of wavelengths while transmitting others.

![Figure 2.3: FBG reflects light at high and low refractive index interface.](image)

When fiber with photosensitive core is exposed to interference pattern of UV
radiation as shown in Fig. 2.4, at the regions of constructive interference UV intensity
is high. Hence, the core refractive index increases due to photosensitivity. It may go
up to $10^{-2}$ when fiber is treated for higher photosensitivity [8]. At destructive
interference, there will be no change in the core refractive index. Hence, side
exposure of photosensitive fibers to interference pattern will result in a periodic
refractive index modulation along the length of the fiber core [9].

![Interference pattern produced on optical fiber.](image)

**Figure 2.4: Interference pattern produced on optical fiber.**

### 2.2 Photosensitivity

Photosensitivity in optical fiber refers to permanent change in refractive index induced due to exposure to light. Photosensitivity was first reported by Hill et al. in Ge-doped silica core optical fiber (discussed in the beginning of this chapter). Photosensitivity is defined as the property of photo-conductive and electro-optic material to exhibit and retain differential modulation in its refractive index due to exposure to spatial distribution of intense electromagnetic radiation. A photoconductive material absorbs photons and this results in increased conductivity due to generation of electron-hole pairs that act as free charge carriers [8]. The process of photosensitivity can be depicted as in Fig. 2.5 and can be explained as follows. Incident light generates free charge carriers (electrons or holes) by excitation of impurity energy levels at a rate proportional to optical power. These charge carriers diffuse to locations of low electromagnetic radiation intensity, leaving behind fixed charges of opposite polarity. The free charge carriers are then trapped by impurity ions leading to recombination and deposition of charges. Overall effect is the creation of an inhomogeneous space-charge distribution that can exist permanently until
stronger radiation or high temperature destroys it.

This spatial charge distribution results in an internal electric field that causes the refractive index of the material to change due to Pockels electro-optic effect. Photosensitivity is commonly used to spatially modulate the refractive index of materials and fabricate devices such as gratings [10].

2.2.1 Models for Photosensitivity

Photosensitivity in optical fibers is complex phenomenon. As pure silica is transparent to UV radiation, the photosensitivity effect in optical fiber is due to
dopants (most commonly Ge is doped). Due to non uniform chemical reactions and difference in the thermal expansion coefficients between the cladding and the doped core regions, fiber fabrication process will result into imperfect molecular structure of the glass waveguide. The presence of these defects causes multiple absorption bands in the UV region. During fiber fabrication process, GeO$_2$ dissociates to GeO due to its higher stability at very high temperatures. This species, when incorporated into the glass, can manifest itself into the form of oxygen vacancy Ge-Si and Ge-Ge bonds which are called as wrong bonds. Based on several independent measurements of the electron spin resonances (ESR) and optical intensity absorption of optical fibers [11, 12], germanium defect centers are recognized to be the major contributor to the photo-induced refractive index changes in the fibers that can trap electrons. Several models were developed to explain photosensitivity in optical fibers. In all the theories the germanium-oxygen vacancy defects: Ge-Si or Ge-Ge defects called “wrong bonds” are responsible for the photoinduced refractive index changes. It is believed that more than one process is involved in photoinduced refractive index change. Hence, no single model can completely explain the process of photosensitivity in optical fibers [13]. Following are the main models for the photosensitivity in silica based material.

2.2.1.1 Color Center Model

In this model the breaking of the GeO defect by the UV light results in a GeE' defect center and the released electron is free to move within the glass matrix; when this electron is trapped, an additional absorption center appear in the glass and due to the Kramers-Kronig relation, a refractive index change is observed. UV exposure changes the material properties of the glass and introduces new electronic transitions of defects (color centers). The underlying premise of this model is that the photosensitive effect arises from localized electronic excitations of defects. The
wrong-bond defects, which initially absorb the light, are transformed to defects that are more polarizable by the virtue of the fact that their electronic transitions occur at longer wavelengths or have stronger transitions. According to the color center model, the refractive index at a point is related only to the number density and orientation of defects in that region and is determined by their electronic absorption spectra [14, 15].

**2.2.1.2 Dipole Model**

The photo-excitation of defects forms built-in periodic space-charge electric fields. Each dipole will produce a static dc polarization field that extends many molecular spacings. These static electric fields induce local refractive index changes proportional to electric field of irradiated light through the dc Kerr effect. During writing process, when the fiber is exposed to UV interference pattern, free electrons from high intensity UV irradiation region will diffuse to low intensity region and will be trapped by the defects. This redistribution of charges within fiber will create periodic space charge electric fields resulting into periodic refractive index modulation [16, 17].

**2.2.1.3 Stress-relief Model**

This model is based on the hypothesis that the refractive index change arises from the alleviation of built-in thermo-elastic stresses in the core of the fiber that was created during the fiber fabrication. The fiber-optic core in a germano-silica fiber is under tension due to the difference in the thermal expansion of the core and the cladding as the glass is cooled below the fictive temperature during fiber drawing. According to stress-optic effect, it is known that tension reduces the refractive index. During UV irradiation, the wrong bonds break and promote relaxation in the tensioned glass. Due to reduced stress, the refractive index of fiber increases locally at UV constructive interference region [18, 19].
2.2.1.4 Compaction Model

The compaction model is based on laser irradiation induced density changes, which lead to refractive index change. Irradiation by laser at 248nm at intensities below the breakdown threshold has been shown to induce thermally reversible linear compaction in amorphous silica leading to refractive index changes. After annealing for an hour under high temperature and low pressure, the compaction disappears and the original thickness and pre-irradiated refractive index value will be retrieved [8, 20, 21]. Compaction model is relatively a new model.

2.2.2 Enhancing Photosensitivity in Silica Optical Fibers

Doping core of silica with germanium increases the refractive index of the fiber core which is basic need for light to guide in the optical fiber. In addition, doping with germanium brings about an excellent photosensitivity in the core of an optical fiber. The photosensitivity is highly increased by a high concentration of germanium. But this exhibits high numerical aperture (NA) and the fiber is not compatible for telecommunication devices. Hence, concentration of germanium doping is limited. Instead of germanium, core can be doped with compounds such as Al$_2$O$_3$. Absence of germanium reduces the photosensitivity [22]. Doping silica core with rare earth metals like erbium, selenium or niobium produce comparatively good photosensitivity. Inscribing gratings in rare earth doped fibers is difficult than the standard Ge doped fibers [12]. Following are some of the methods used to enhance the photosensitivity in optical fibers.

2.2.2.1 Co-doping

Photosensitivity was also observed in fibers that do not contain germanium. The evidences of photosensitivity in fibers doped with other elements such as europium [23], cerium [24], phosphorus [25], aluminum, antimony [26] suggest that the
phenomenon does not arise from the presence of a unique chemical dopant. Enhancement of photosensitivity of germanosilicate fibers due to co-doping with boron is excellent [27]. Boron co-doping increases the photosensitivity of the fiber by allowing photoinduced stress relaxation. Another benefit of boron co-doping is the compatible NA with standard telecommunication fibers. The maximum refractive index changes are higher and achieved faster than for any other kind of fiber. Other co-doping such as tin has been reported to give good results of photosensitivity [28, 29].

2.2.2.2 Hydrogen Loading

Hydrogen loading is carried out by diffusing hydrogen molecules into the optical fiber at high pressures for several hours. The reaction of hydrogen molecules at the Ge sites produces germanium-oxygen deficiency centers when exposed to UV light [30]. This is not a permanent effect. After removing form hydrogen chamber, the hydrogen diffuses out day by day and photosensitivity of the fiber decreases. If gratings fabricated in hydrogen loaded fibers are not annealed properly after fabrication, the resonance wavelength shift is observed as days pass on.

2.2.2.3 Flame Brushing

Flame brushing is a simple technique for enhancing the photosensitivity in germanosilicate fiber. The region of the optical waveguide to be photosensitized is brushed repeatedly by a flame fueled with hydrogen-rich flame and a small amount of oxygen. The flame reaches a temperature of approximately 1700°C. The photosensitization process takes approximately 20 min to complete [31].
2.3 Principle of FBG

FBG acts as grating that reflects forward propagating modes and hence facilitates coupling of forward propagating core mode to backward propagating modes. This can be explained using ray theory. Fig. 2.6 shows forward propagating core mode of angle $\theta_1$ reflected by Bragg grating into the same mode with angle $\theta_2=-\theta_1$. Hence, the effective refractive index of both modes is same ($n_{\text{eff}}$). Grating equation can be written as [32]

$$n\sin(-\theta_1) = n\sin\theta_1 - \frac{\lambda}{\Lambda} \quad (2.2)$$

Mode propagation constants for both modes are same. $\beta_1 = \beta_2 = \beta = (2\pi/\lambda) n_{\text{eff}}$, where $n_{\text{eff}} = n \sin\theta$ [13]. Substituting the values in the above equation gives the Eq.(2.1)

$$\lambda_B = 2n_{\text{eff}} \Lambda$$

![Figure 2.6: Optical ray illustration of core mode reflection by FBG.](image)

2.4 Coupled Mode Theory of FBG

Even though we can understand working principle of FBG from ray theory, coupled mode theory provides more analytical solutions to refractive index modulation in the fiber core. It is effective method to gain information about the coupling efficiency, phase matching, overlap integral and the spectral dependence of
the gratings. In this section we are considering grating formed in single mode step index fiber with uniform refractive index modulation.

Any type of periodic perturbation (or variation) of the period $\Lambda$ in waveguides brings about the transfer of power from one mode to another which is known as coupling of modes. Coupling between two modes is possible only when the phase matching condition is satisfied. Here we consider two modes propagating in optical fiber of radius ‘a’ and refractive index profile $n(x,y)$ as $\Psi_1(x,y)$ and $\psi_2(x,y)$ in which grating is inscribed. These two modes are travelling in opposite direction. Let $\beta_1$ represent the propagation constant of the mode propagating in the +z direction and $\beta_2$ that of the mode propagating in –z direction. The periodic perturbation can couple power among these modes under certain condition. Thus the total field at any value of $z$ is given by [9],

$$\psi(x, y, z) = A(z)\Psi_1(x, y) e^{-i\beta_1 z} + B(z)\psi_1(x, y) e^{i\beta_2 z}$$  \hspace{1cm} (2.3)

$A(z)$ and $B(z)$ are amplitudes of the mode fields. In the absence of any perturbation $A$ and $B$ are constants. In fiber gratings refractive index modulation (perturbation) couples power among the modes and hence, $A$ and $B$ are $z$ dependent. The coupling between two modes is described by the following coupled mode equations [9]:

$$\frac{dA}{dz} = i\kappa Be^{-i\beta_1 z}$$  \hspace{1cm} (2.4)

$$\frac{dB}{dz} = i\kappa A e^{-i\beta_2 z}$$  \hspace{1cm} (2.5)

$$\Gamma = \beta_1 - \beta_2 - \frac{2\pi}{\Lambda}$$  \hspace{1cm} (2.6)

$$\kappa = \frac{\omega_0}{8} \int^{\text{core}} \int \nabla \nabla n \psi_1^* \psi_2 dx dy$$  \hspace{1cm} (2.7)
where, $\kappa$ is coupling coefficient proportional to $\Delta n$ and overlap integral over the core area between the coupling modes, $\Gamma$ is mode confinement factor, $\varepsilon_0$ is free space dielectric constant, $\omega$ is frequency. For uniform gratings,

$$\Gamma = 0 \quad (2.8)$$

FBG core mode is coupled to backward propagating core mode. Hence, $\beta_2 = -\beta_1 = \beta$, because $\beta_1$ represents propagation constant of mode propagating in $+z$ direction and $\beta_2$ represents mode propagating in $-z$ direction.

Now Eq. 2.6 becomes

$$2\beta_1 = \frac{2\pi}{\Lambda} \quad (2.9)$$

since,

$$\beta_1 = \frac{2\pi}{\lambda_0} n_{\text{eff}} \quad (2.10)$$

$$\lambda_0 = 2n_{\text{eff}} \Lambda \quad (2.11)$$

This Eq. 2.11 is known to be Bragg condition.

Solving Eq.2.4 & 2.5 for grating of length $L$, [9]

$$|A(z)^2 - |B(z)^2| = (\cosh^2 \kappa L)^{-1} = \text{constant} \quad (2.12)$$

This is equation for energy conservation because two waves are travelling in opposite direction. In FBG $B(z)$ corresponds to reflected amplitude. The reflection coefficient in the periodic structure is given by [9]

$$r = \frac{B(z = 0)}{A(z = 0)} = -\tanh(\kappa L) \quad (2.13)$$

The energy reflection coefficient is given by

$$R = |r|^2 = \tanh^2 (\kappa L) \quad (2.14)$$

The coupling coefficient can be written as [8, 9]
\[ \kappa = \frac{\pi \Delta n}{\lambda_B} M_{\text{Power}} \]  \hspace{1cm} (2.15)

Here, \( M_{\text{Power}} \) is fraction of core mode power confined in the fiber core.

\[ M_{\text{Power}} = 1 - V^2 \]  \hspace{1cm} (2.16)

\( V \) is normalized frequency of the fiber of core radius \('a'\), cut off wavelength \('\lambda'\) and numerical aperture \(NA\) given by [9, 33, 34]

\[ V = \frac{2\pi a}{\lambda} NA \]  \hspace{1cm} (2.17)

The bandwidth (full width at half maximum) of the reflected peak is given by

\[ \Delta \lambda_B = \frac{2\lambda_B}{\pi n_{\text{eff}} L} \left( \kappa^2 L^2 + \pi^2 \right)^{1/2} \]  \hspace{1cm} (2.18)

The characteristics response from Bragg Grating can be fully described by

1. The center wavelength of Grating \(\lambda_B\)
2. Peak reflectivity \(R_{\text{max}}\) of grating which occur at \(\lambda_B\)
3. Physical length of Grating \(L\)
4. Refractive index of core of optical fiber \(n_c\)
5. Amplitude of induced core index perturbation \(\Delta n\)

From theoretical analysis for uniform gratings it is found that, as length of FBG is increased the band width of the reflected spectrum of FBG decreases (with constant refractive index modulation). Hence, reflected peak becomes narrow with increasing length. On the other hand, if length of FBG is held constant, both reflectivity and band width of reflected spectrum increases with increase in refractive index modulation \((\Delta n)\) [35]. So, in order to have FBG of narrow band and high reflectivity, length and refractive index modulation are to be optimized. If the length of FBG is increased, the effects of external environment are to be considered. Bend, strain or temperature may vary the Bragg wavelength or band width.
The reflection spectrum of a Bragg grating with uniform modulation of refractive index gives rise to a series of side lobes adjacent to Bragg wavelength. It is very important to minimize reflectivity of these side lobes. This process of removing the side lobes is known as apodization. Apodization is essential in devices where high rejection of the non-resonant light is required. An additional benefit of apodization is the improvement of the dispersion compensation characteristics of chirped Bragg gratings. Apodization is possible by varying the amplitude of the coupling coefficient along the length of the grating. One method used to apodize an FBG is, exposing the optical fiber with the interference pattern formed by two non-uniform ultraviolet light beams. In the phase mask technique, apodization can be achieved by varying the exposure time along the length of the grating - either by a double exposure or by scanning a small writing beam. In all these apodization techniques, the variation in coupling coefficient along the length of the grating comes due to local changes in the intensity of the UV light reaching the fiber [35].

2.5 Fiber Bragg Grating Types

Depending on optical fiber type and photosensitivity condition prior to inscription the growth of FBG differ with inscription condition. Different methods of grating fabrication have a significant effect on physical characteristics of the produced FBGs, particularly the temperature response and ability to withstand high temperatures. Based on the strength of gratings and thermal stability, gratings are characterized into four types as Type I, Type IA, Type IIA and Type II. Type IA gratings are the least stable and Type II gratings are the most stable gratings with increasing temperature [35]. Type I FBGs are most commonly used.
2.5.1 Type I Fiber Bragg Gratings

Type I Bragg gratings refer to gratings that are formed in normal photosensitive fibers under moderate intensities. The growth dynamics of the Type I grating is characterized by a power law with time [36]. The reflected and transmitted spectra are complementary to each other, implying that there is negligible loss due to absorption or reflection into the cladding. This is a fundamental characteristic of a Type I Bragg grating. Furthermore, due to the photosensitivity type of the Bragg grating, the grating itself has a characteristic behavior with respect to temperature erasure. Type I gratings can be erased at relatively low temperatures, approximately 200°C. Nevertheless, Type I gratings are the most utilized Bragg gratings and operate effectively from -40°C to +80°C, a temperature range that satisfactorily covers most telecommunications and some sensor applications [11].

2.5.2 Type IA Fiber Bragg Gratings

Type IA fiber Bragg gratings are subtype of Type I gratings because, the transmission and reflection spectra are complementary. Type IA gratings are always written in hydrogen loaded germanium doped silica fibers. They are typically formed after prolonged UV exposure of fiber and red shift of Bragg wavelength during inscription indicates large increase in the mean core index [37, 38]. Improvements in inscription methods have shown that they can be readily inscribed in a suitably prepared optical fiber [39]. Type IA grating appeared once the conventional type I FBG had reached saturation followed by subsequent complete or partial erasure and was therefore labeled as regenerated [11].

2.5.3 Type II Fiber Bragg Gratings

A single excimer light pulse of intensity greater than 0.5 J/cm² can photoinduce large refractive-index changes in small, localized regions at the core-cladding boundary,
resulting in the formation of the Type II grating. This change results from physical damage through localized fusion that is limited to the fiber core and it produces very large refractive-index modulations estimated to be close to $10^{-2}$. The reflection spectrum is broad and several features appear over the entire spectral profile due to non-uniformities in the excimer beam profile that are strongly magnified by the highly non-linear response mechanism of the glass core. Type II gratings pass wavelengths longer than the Bragg wavelength, whereas shorter wavelengths are strongly coupled into the cladding, as is observed for etched or relief fiber gratings, permitting their use as effective wavelength selective taps. Results of stability tests have shown Type II gratings are extremely stable at elevated temperatures [40], surviving temperatures in excess of 800$^\circ$C for several hours; this superior temperature stability can be utilized for sensing applications in hostile environments [11].

2.5.4 Type IIA Fiber Bragg Gratings

Type IIA fiber Bragg gratings appear to have the same spectral characteristics as Type I gratings. The transmission and reflection spectra are again complementary, also rendering this type of grating indistinguishable from Type I in a static situation. However, due to the different mechanisms involved in fabricating these gratings, there are some distinguishable features that are noticeable under dynamic conditions either in the initial fabrication or in the temperature erasure of the gratings. Type IIA gratings are inscribed through a long process, following Type I grating inscription [41]. After approximately 30min of exposure (depending on the fiber type and exposure intensity), the Type IIA grating is fully developed. However, when the grating is exposed to high ambient temperature, a noticeable erasure is observed only at temperatures as high as 500$^\circ$C. The advantage of the Type IIA gratings over the
Type I is the improved temperature stability of the grating, which may prove very useful in developing temperature sensor in higher temperature ranges [11].

2.6 FBG Fabrication Methods

Based on exposure of fiber to laser in order to develop refractive index modulation, two types of FBG fabrication methods can be labeled as internal writing method and external writing method. First fiber gratings were written using internal writing method by Hill et al. [1], where the laser radiation was launched directly into fiber (refer 2.1 Introduction, Fig. 2.1). In external writing method, the fiber is exposed to laser beam such that the fiber axis is perpendicular to the beam. External writing method was first introduced by Meltz et al. in 1989 and this method is known as holographic method [4]. After this, grating fabrication methods have been a subject of serious research as driving force arising from communication and sensing applications. Very few fabrication methods came out successfully giving stable fiber Bragg gratings. These are - interferometric method, image projection method, point by point method, direct writing method and phase mask method.

2.6.1 Interferometric Method

Interferometric method also known as holographic method was first demonstrated by Meltz et al. in 1989 [4]. In this method interferometer was used to split UV radiation into two equal beams and then recombined to interfere on the optical fiber using systematic optics. The fiber grating period is dependent on writing laser wavelength and angle of incidence of two interfering beams [8, 12]. In turn, interferometers are of two types – amplitude splitting and wave-front splitting interferometer.
(a) Amplitude splitting interferometer: The experimental setup is as shown in the Fig. 2.7. The UV laser is split into two equal beams and made to interfere on optical fiber through two cylindrical lenses at mutual angle \( \theta \). The grating period \( \Lambda \) is given by [8, 12],

\[
\Lambda = \frac{\lambda_{uv}}{2 \sin(\theta / 2)} \tag{2.19}
\]

Substituting this value in Eq. 2.1, the reflected Bragg wavelength of FBG is

\[
\lambda_B = \frac{n_{eff} \lambda_{uv}}{\sin(\theta / 2)} \tag{2.20}
\]

![Interferometric method of FBG fabrication.](image)

From the above Eq. 2.20, Bragg wavelength can be designed by varying wavelength of UV laser or angle between the two beams. One should keep in mind that wavelength range of UV laser is restricted by photosensitivity region of the fiber core. This method allows fabrication of wavelength narrowed or broadened gratings. Chirped gratings can also be fabricated using suitable materials like curved mirrors. Very high spatial & temporal coherent UV laser source with excellent output power stability is the basic requirement of amplitude splitting interferometric fabrication.
method. This method is highly susceptible to mechanical vibrations. Submicron disturbance in beam splitter or mirror or fiber or any other mountings can spoil the gratings. Even air turbulence can drift the path of beams [8, 12].

(b) Wave-front splitting interferometer: Wave-front splitting interferometer is modified method of amplitude splitting method. This method has some advantages over the amplitude splitting interferometers. In wave-front splitting interferometer single optical component is used to produce interference. This greatly reduces the sensitivity to mechanical vibrations and wave-front distortion induced by air currents. Different optical components are used in demonstrating wavelength splitting interferometers. The wave-front splitting interferometer is also known as Lloyd interferometer. It consists of a dielectric mirror, which directs half of the UV beam to a fiber that is perpendicular to the mirror. The UV beam is centered at the intersection of the mirror surface and fiber. The overlap of the direct and deviated portions of UV beam creates interference fringes normal to the fiber axis [42]. In another method, Lloyd mirror is replaced by high homogeneity ultraviolet-grade fused silica prism. The interference pattern is produced at output face of the prism, where fiber is exposed to this pattern to fabricate Bragg gratings [43, 44]. In both the above methods, a cylindrical lens can be placed in front of the system to focus the fringe pattern along the core of the fiber. In this method grating length is restricted to half of the beam width. The beam coherence length limits the Bragg wavelength tunability. Wave-front splitting interferometers are not as popular as the amplitude splitting interferometers for grating fabrication [8].

2.6.2 Point by Point Method

This is the simplest method of FBG fabrication. In point by point method refractive index perturbations of the fiber grating are produced by focusing single
pulse of excimer laser. Fiber mounted on precise translation stage is irradiated with single pulse of UV laser directly (optical components may be used if necessary) and refractive index of the core increases locally. Schematic setup of point by point method is shown in the Fig. 2.8. The fiber is translated through desired grating period ($\Lambda$), in direction parallel to fiber axis using translation stage. It is important to control the translation stage movements accurately. Precise and submicron translation stage is basic requirement of this method. Resolution of translation stage and beam width of UV laser limits the fabrication of submicron FBGs. Alternatively laser beam can be swift along the fiber axis with desired grating period. Point by point method is useful in writing gratings of period greater than 10µm. In this method grating pitch can be easily altered. Hence, this method is most useful in fabrication of chirped gratings. High quality and high order gratings were fabricated using this method [45, 46]. Also this method is most useful for making coarse gratings with pitches of the order of 100µm that are required for LP$_{01}$ to LP$_{11}$ mode converters [47].

![Figure 2.8: FBG fabrication of point by point method.](image)

2.6.3 Image Projection

High-resolution mask projection method was demonstrated by Mihailov et al. in 1994. The mask projection system consists of excimer laser source generating an UV
beam, which is incident on a transmission mask. The transmission mask consisted of a series of UV opaque line spaces. The transmitted beam was imaged onto the fiber core by a multi-component fused silica high-resolution system having a demagnification of 10:1. Experimental set up is shown in Fig. 2.9. Because of the simplicity of the source and setup, the recording of coarse period gratings by mask-imaging exposures may be more flexible than other techniques in some cases. Complicated grating structures such as blazed, chirped, etc. can be readily fabricated with this method by implementing a simple change of mask [8, 48].

![Image projection method of FBG fabrication.](image)

**Figure 2.9: Image projection method of FBG fabrication.**

### 2.4.4 Direct Writing Method

During fiber grating fabrication, it requires to strip off the protective polymer coating of the fiber which is opaque to short wavelengths of UV light. This reduces mechanical stability of the optical fibers. To avoid this problem, grating inscription on the fiber drawing tower enables the fiber grating to be coated immediately after fabrication. In direct writing method, the fiber is exposed to interference pattern of UV radiation while drawing the fiber as shown in the Fig. 2.10. The short duration pulses have the potential to be used to write fiber gratings into the fiber as it is being drawn [49]. The quality and repeatability is poor in this method of fabrication because
of problems of beam uniformity, stability and repeatability of mechanical alignment [12]. If necessary precautions are taken, this method will be very useful fabrication method for FBGs used in telecommunication fields. As protective polymer coating is done after the grating is written in the fiber, the mechanical strength of the grating is retained. The drawback of this process is it is expensive.

![Figure 2.10: FBG direct writing method.](image)

### 2.6.5 Phase Mask Method

All methods discussed above have been superseded by phase mask method because of several advantages over the above methods. This method first demonstrated by Hill et al. and Anderson et al. separately in 1993 [50, 51]. In Phase mask method, fiber is exposed to interference pattern of UV laser beam produced by phase mask. In this method phase mask plays very important role. Experimental setup for fabrication of FBG using phase mask method is shown in the Fig. 2.11. Phase mask is illuminated by UV radiation (cylindrical lens is used to produce broad field
for grating of long length). Fiber is placed on other side of the phase mask with fiber axis parallel to phase mask length.

**Inset of Phase mask**

![Phase mask method diagram](image)

**Figure 2.11: Phase mask method.**

Normally phase mask is designed so that, it diffracts UV beam so that 0-order beam is suppressed to less than 5% and most of the energy is concentrated in +1 and -1 order beams. These two beams of order +1 and -1 interfere to produce the interference pattern. Fiber is placed exactly at the position of interference pattern, but not touching the mask which may damage the fiber. The low spatial coherence of UV laser requires the fiber to be placed in near contact to the phase mask corrugations in order to induce maximum refractive index modulation. The fiber Bragg grating period fabricated is one half of the grating period of the phase mask [8]. Using high spatial coherent UV beam will produce high quality FBGs and relax the requirement that the fiber has to be in contact with the phase mask. [52]. Spatial coherence of UV laser is important in phase mask method than the temporal coherence. One can take little leniency in temporal coherence of the laser. With small modification in the above experimental setup, chirped gratings can also be fabricated.
Apart from the above mentioned methods, different experimental setups were proposed where the interference between 0 and +1 order diffracted beams are used [53]. Talbot method was another method used to fabricate FBGs. But these methods involve various optical components and require highly coherent laser source [54].

Compared with the two-beam interferometer method, the phase-mask method has many advantages. Some are as follow:

(1) The Bragg wavelength of an FBG is determined by the pitch of the phase-mask and is independent of the wavelength of the UV laser.

(2) Length of FBG is independent of the beam size of the UV laser beam.

(3) The phase-mask method offers a high probability of mass production with good repeatability at low cost.

(4) Single-beam writing method improves the mechanical stability of the FBG writing apparatus and hence, it is easy to use in practice.

(5) The requirement for the coherence of the UV laser is reduced and hence, low spatial and temporal coherence lasers can be used to replace very expensive highly coherent UV lasers [8].

Phase Mask: The phase mask consists of high quality, thin fused silica slab with grooves etched on one surface. Phase mask is transparent to the UV excimer laser radiation. The important features of the phase mask are the grooves etched with a carefully controlled mark-space ratio as well as etch depth. Generally the shape of the periodic surface-relief pattern of the phase mask approximates a square wave in profile, as shown in the Fig.2.12. The principle of operation is based on the diffraction of an incident UV beam into several orders. Generally for normal incidence of UV radiation, the most of intensity is distributed in 0 and ±1 orders. In phase mask, the depth of surface-relief (grooves) structure is maintained so that, zero-order diffracted
beam is suppressed. In practice, the zero-order beam can be suppressed to less than 5% of the light diffracted by the mask. The principal beams exiting from the mask are the diverging into +1 and -1 orders, each of which contain typically more than 35% of the diffracted light. These two beams diffracted at +1 and -1 orders interfere and produce fiber gratings \[50\]. Other than square wave shaped phase masks, sine wave shape also produce stable and reliable FBGs. G. W. Goodman discussed zero-order nulled surface relief phase mask of sinusoidal shape for grating fabrication in his article \[55\]. Phase masks are fabricated either by holographically or by electron-beam lithography. Highly uniform phase mask may be fabricated by holographic method without error but length is limitation. Complicated patterns (like quadratic chirps, Moire patterns) of phase mask can be written using electron beam lithography. But it may have stitch errors because using lithography method small phase masks are fabricated and then stitched together to form long phase masks. Random variation in absolute positioning of electron beam is fundamental limitation in electron beam lithography \[8, 12\].

Advanced fabrication techniques are essential for obtaining high quality and low cost FBG in sensor technology. Considerable efforts are being made by laboratories
Fiber Bragg Gratings

around the world to improve the manufacturing methods of fiber gratings as they have various potential applications in optical communication as well in sensing technology.

An ideal FBG fabrication technique should have the following features [56].

(1) Flexibility: Reflectivity and central wavelength of FBGs produced should be independent as much as possible from writing parameters.

(2) Economical: Low-cost FBGs would be available if produced in large quantity and production should be fast (should not be time consuming).

(3) Good qualities: The method should produce FBGs of good mechanical grade and should not degrade with time. A narrow spectral linewidth and a low excess loss are normally required to achieve high-resolution measurement.

(4) Good repeatability: Repeatability of both the central wavelength and the reflectivity of an FBG should be good enough in order to make it standard device under the condition of mass production and interchangeable without calibration.

Number of schemes have been demonstrated to match the requirements mentioned above. Now, FBGs are produced in large quantity and available in market which has led to successful commercialization of the FBG. Of the above discussed methods, phase mask method is more flexible, reliable and fulfills the above conditions in the present scenario.

2.7 Fabrication of FBG

FBG was fabricated in single mode fiber using phase mask method. KrF laser of output wavelength 248nm was used for writing FBG. Details of KrF laser and phase mask are given in Table 2.1. It is better to use low repetition rate lasers to avoid heat accumulation. Thus refractive index modulation is restricted to the high density region and an optimum contrast for refractive index modulation can be obtained [57]. The
experimental set up of phase mask method is shown in the Fig 2.11 which is already discussed in section 2.6.5. Fig. 2.13 is FBG fabrication unit at Central Scientific Instrumentation Organization (CSIO), Chandigarh.

Table 2.1 Specifications of KrF laser and phase mask

<table>
<thead>
<tr>
<th>Grating writing source: KrF excimer laser</th>
<th>Phase mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength : 248nm</td>
<td>Material used : Silica glass</td>
</tr>
<tr>
<td>Pulse Energy : 6mJ/cm²</td>
<td>Length of mask : 1.8cm</td>
</tr>
<tr>
<td>Pulse rate : 10Hz</td>
<td>Thickness : &lt;5mm</td>
</tr>
<tr>
<td>Exposure time : 20sec</td>
<td>Period $\Lambda_{PM}$ : 1.064µm</td>
</tr>
</tbody>
</table>

Figure 2.13: FBG fabrication Unit at CSIO, Chandigarh.

Table 2.2 F-SBG-15 Fiber Details

<table>
<thead>
<tr>
<th>Refractive Index Profile : Step Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical Aperture : 0.12-0.14</td>
</tr>
<tr>
<td>Mode Field Diameter : 9.6µm</td>
</tr>
<tr>
<td>Core Material : Boron co-doped Germano Silicate</td>
</tr>
<tr>
<td>Cladding Diameter : 125±1µm</td>
</tr>
<tr>
<td>Cladding material : Pure silica</td>
</tr>
<tr>
<td>Buffer Coating diameter : 245±1µm</td>
</tr>
<tr>
<td>Buffer Coating : Acrylate</td>
</tr>
<tr>
<td>Supplier : Newport Corporation</td>
</tr>
<tr>
<td>Operating Wavelength : 1550nm</td>
</tr>
<tr>
<td>Cut off wavelength : 1100-1260nm</td>
</tr>
</tbody>
</table>
Acrylate buffer coating surrounding cladding (about 5 to 6cm) where the grating to be written was stripped off and placed in-front of the phase mask as shown in Fig. 2.11. Positioning fiber next to phase mask is very important. Fiber was fixed in position where the +1 and -1 diffracted beams from phase mask interfere. UV beam from KrF laser was made incident on the fiber through the phase mask for 20sec. The grating formation can be monitored online through optical spectrum analyzer by observing the reflected spectrum of FBG.

FBG was fabricated in single mode fiber F-SBG-15 (Newport Corporation), with Germanium and Boron doped silica core. The period of grating inscribed is 0.532µm. The fabricated FBG is characterized.

Germanium doping in silica increases the refractive index. This also brings about the photosensitivity to UV radiation in the material. Hence, most of the single mode optical fibers are fabricated with germanium doped silica core and pure silica cladding, as core refractive index should be greater than the cladding refractive index for light to propagate in optical fiber. In order to increase the photosensitivity, Boron is co-doped with Ge doped silica core. Co-doping with Boron greatly reduces the fabrication time and increases the efficiency of the grating.

2.8 Characterization of FBG

Fabricated FBG was characterized in our laboratory. Reflected spectrum of FBG was recorded with optical spectrum analyzer (OSA) (Make: Wistom) using PROXIMION software. Schematic diagram for observation is shown in Fig. 2.14. The FBG was illuminated with broad band laser source (JDS Uniphase, 1530-1600nm) of output power 17mW through 2X2 (3dB) coupler. This 2X2 coupler is used to collect the reflected spectrum of the FBG.
The fabricated FBG reflects sharp narrow band spectrum of 0.2nm, centered at 1546.96nm and with reflectivity of 72%. The reflected spectrum of FBG is shown in the Fig.2.15. This kind of FBGs are useful in FBG sensor fabrication and WDM systems.

Figure 2.14: Experimental setup to observe the reflected spectrum of FBG.

Fig. 2.15: Reflected spectrum of FBG of grating period 0.532µm.

Other two FBGs fabricated in Nuferm GF1 fiber are also characterized in our laboratory. The fiber details are given in Table 2.3 as given by the company.
FBGs were fabricated by irradiating Nufern GF1 fiber through phase mask by KrF laser (248nm) emitting 5mJ pulses at 200Hz for 60seconds. The length of FBGs is roughly 3cm. FBGs were fabricated using phase mask of period $1.068\mu$m and $1.072\mu$m. The reflected spectra are recorded using EXFO optical spectrum analyzer.

FBG with $\lambda_B = 1551.845\text{nm}$ was fabricated with phase mask of $1.068\mu$m and grating period of FBG is $0.534\mu$m. Fig. 2.16 shows reflected and transmitted spectra of the FBG. Reflectivity is 80%. The reflected spectrum shows the principal peak centered at 1551.845nm with full width at half maxima (FWHM) of 0.435nm, with two prominent side lobes. Third side lobe is just evolving.

**Table 2.3: GF1 Fiber Details**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive Index Profile</td>
<td>Step Index</td>
</tr>
<tr>
<td>Numerical Aperture</td>
<td>0.13</td>
</tr>
<tr>
<td>Mode Field Diameter</td>
<td>$10.5\pm1.0\mu$m @ 1550nm</td>
</tr>
<tr>
<td>Core Material</td>
<td>Germanium doped Silica</td>
</tr>
<tr>
<td>Cladding Diameter</td>
<td>$125\pm1\mu$m</td>
</tr>
<tr>
<td>Cladding material</td>
<td>Pure silica</td>
</tr>
<tr>
<td>Buffer Coating diameter</td>
<td>$245\pm1\mu$m</td>
</tr>
<tr>
<td>Buffer Coating</td>
<td>Acrylate</td>
</tr>
<tr>
<td>Supplier</td>
<td>Nufern</td>
</tr>
<tr>
<td>Operating Wavelength</td>
<td>1500nm-1600nm</td>
</tr>
<tr>
<td>Cut off wavelength</td>
<td>1260$\pm$75nm</td>
</tr>
</tbody>
</table>

Figure 2.16: Reflected and transmitted spectra of FBG of period $0.534\mu$m.
Grating period of FBG with \( \lambda_B = 1558.363 \text{nm} \) is 0.536\( \mu \text{m} \). This FBG was fabricated with phase mask of period 1.072\( \mu \text{m} \). Reflected and transmitted spectra of the FBG are shown in the Fig. 2.17. Reflected spectrum shows one principal peak centered at 1558.363nm with FWHM=0.474nm and peak power 7.526\( \mu \text{W} \). Reflected spectrum also shows three side lobes on lower wavelength side. Although, the reflected spectrum of third lobe is small, it is clearly visible. Complete details of the FBG spectra are given in the Table 2.4.

FBG fabricated in boron co-doped fiber shows a single narrow band of reflected spectrum. Hence, it is useful in sensing applications. Both the FBGs fabricated in GF1 fiber show side lobes on lower wavelength side and reflected spectrum is broad. Side lobes appear in reflected and transmitted spectra.

So, these side lobes arise due to coupling of backward propagating core mode to backward propagating cladding modes. If side lobes appear only in transmitted spectrum and not in reflected spectrum of FBG, then the reason would be coupling of core mode to some forward propagating cladding modes. If the strength of the index modulation in a grating is constant over some length and suddenly drops to zero outside that range, the reflection spectrum exhibits side lobes.

![Reflected Spectrum](image1)

**Figure 2.17:** Reflected and transmitted spectra of FBG of period 0.536\( \mu \text{m} \).
Sometimes these side lobes are probably due to multiple reflections to and from opposite ends of the grating region. These side lobes can be reduced by apodization technique [8].

Table 2.4 Characteristic properties of fiber Bragg gratings

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Fiber</th>
<th>Grating period</th>
<th>Bragg wavelength &amp; Reflectivity</th>
<th>Reflected peak power in µW</th>
<th>FWHM in nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F-SBG-15 (Newport)</td>
<td>0.532µm</td>
<td>1548.96nm 72%</td>
<td>30.36</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>GF-1 (Nufern)</td>
<td>0.534µm</td>
<td>1551.845nm 79%</td>
<td>7.56</td>
<td>0.435</td>
</tr>
<tr>
<td>3</td>
<td>GF-1 (Nufern)</td>
<td>0.538µm</td>
<td>1558.363nm 82%</td>
<td>9.29</td>
<td>0.474</td>
</tr>
</tbody>
</table>
References:

10. Vikram Bhatia, “Properties and Sensing Applications of Long Period Gratings” Thesis submitted to Virginia Polytechnic and State University, USA.


57. Thesis by Elodie Wikszak “Inscription of fiber Bragg gratings in non-photosensitive and rare-earth doped fibers using ultrafast laser,” Jena University, Germany