Chapter 5

Isolation Improvement in Fused WDMs

Isolation in fused WDMs is limited by wavelength dependence of coupling ratio and deviation from ideal coupling characteristics. All-fiber methods to improve the isolation are not compact and economical. A method is proposed to improve the isolation in fused-fiber wavelength division multiplexers, through the inscription of long period gratings fabricated by electric arc technique. This method offers a simple and compact all-fiber solution with good control of isolation over the required spectral band.
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Wavelength Division Multiplexers (WDMs) are essential components in high capacity optical networks [1] and also in fiber amplifiers. WDMs are realized using various techniques like thin film filter, micro-optic and fused biconically tapered technology [2, 3]. Among these fused fiber WDMs are attractive because of the all-fiber nature, low insertion loss, stable optical performance and its compactness. Isolation is one of the key performance parameters of these devices when used as a de-multiplexer. In fused fiber devices, the wavelength dependence of the coupling ratio and deviations from ideal coupling cause the light of wrong wavelength to exit the ports of the WDM. Also, it is observed that the isolation of the fused fiber Wavelength Division De-Multiplexers (WDDM) decreases as the separation between the channel wavelengths decrease [4, 5]. These effects are undesirable, as the two wavelengths constitute two completely independent communication channels and hence contribute to the degradation in service quality.

This chapter explains the fabrication and performance parameters of fused WDMs and analyzes the factors affecting the isolation in WDMs. Different all-fiber approaches for improving the isolation in fused WDMs are discussed. Long period grating, which acts as spectrally sensitive filters are fabricated on standard single mode fibers, based on electric arc technique [6, 7]. Such long period gratings are integrated with fused WDM, demonstrating a simple and compact all-fiber method for isolation improvement.

5.1 WDM Technology: An Introduction

WDM technology enables the capacity upgradation of fiber optic links as per demand, through transmission of signals at multiple wavelengths over the same fiber as shown in Figure 5.1 [8]. At the transmitting end, a multiplexer is required to combine signals from independently modulated laser sources, to a single fiber. At the receiving end, a de-multiplexer is required to separate the optical signals into appropriate detection channels for signal processing [9]. Wavelength Division Multiplexer (WDM) / Demultiplexer is a passive component which combines / splits signals, atleast at two different wavelengths [10]. Both 1310 nm and 1550 nm wavelengths are used for long distance optical transmission. Single mode fibers available today have very low loss (typically 0.2 dB/km) and they also have very low dispersion at these wavelengths. The 1310/1550 nm WDM, with a channel spacing of 240nm is used to multiplex those telecom transmission bands. In passive optical networks, analog video signal is transmitted at 1550 nm wavelength [11], because of the low loss and the availability of erbium doped fiber amplifiers in this band.
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Figure 5.1: Implementation of a typical WDM network

Based on the channel spacing, WDMs are classified as narrow channel spacing and wide channel spacing (>100nm). The literature often uses the term dense WDM (DWDM) in contrast to regular WDM, where the channel spacing is less than 2nm, as specified by ITU-T G.692. WDMs can be realized by various methods as mentioned in Chapter 1. Wavelength multiplexers can also be made using Mach-Zehnder interferometry techniques. Such devices are configured with individual 2x2 couplers or using integrated optics. Arrayed Waveguide Grating (AWG), Fiber Bragg Grating etc is other technologies used for multiplexing [8]. Interleavers are used to separate a multiplexed stream to two different streams, with double the channel spacing [12]

The performance of WDM coupler is measured in terms of several characteristics such as insertion loss, isolation and directivity. Insertion loss and directivity are generic measurement indexes for any type of couplers, while isolation is specific to WDM. Isolation is a measure of how well light of an undesired wavelength is eliminated with respect to the desired wavelength at a particular port. Wavelength isolation is the key performance parameter of a WDM [13]. It is determined by measuring the power available at the output ports of a coupler at an operating wavelength and is a measure of the fracture of power blocked from input port to output port at the specified wavelength [14]. Mathematically,

\[
\text{Wavelength Isolation} = 10 \log_{10} \left( \frac{P_T}{P_I} \right)_{\lambda_1}
\]

(5.1)

where \( P_T \) is the power available at the throughput port and \( P_I \) is the input power, respectively at the wavelength \( \lambda_1 \).
Isolation bandwidth is another important parameter, which is a measure of the spread of wavelengths around the desired branching wavelengths. Isolation is usually quoted over a finite wavelength spread due to deviations from the specified nominal operating wavelength and finite spectral width of practical optical sources. The isolation bandwidth of a WDM is defined as the range of wavelength around the operating central wavelength, where the value of isolation is above a certain acceptable level. Passive optical components intended for use in digital systems at bit rates up to 10Gbps shall have a wavelength isolation of at least 25 dB [14]. Digital systems can operate with less isolation, but if one transmitter fails and the receive sensitivity is high or the span is short then the receiver may lock into the wrong signal. An isolation greater than 25 dB will avert this type of failure in most of the applications.

5.2 Fused Fiber WDM: Operating Principle and Fabrication

A fused WDM is a symmetric 2x2 FBT coupler, which can take two inputs at two different wavelengths, say \( \lambda_1 \) and \( \lambda_2 \), from the two input ports and combines them at one output port. Alternately, if these two wavelengths are injected into the same input port, they will get separated out at the two output ports. Such a design owes its origin to the fact that for a given coupler, the coupling coefficients and the effective length of interaction at two different wavelengths, say 1310 nm and 1550 nm, are different. Therefore the splitting ratios at these wavelengths are usually different. For a coupler to function as WDM at these two operating wavelengths, the fabrication parameters has to be optimized such that the coupling ratio at one wavelength is maximum and minimum at the other wavelength [13]. This implies that all of the input power at \( \lambda_1 \) will emerge at one output port, and all the input power at \( \lambda_2 \) will emerge at the other output, as sketched in Figure 5.2.

It is seen in Chapter 2 that the coupling characteristics of fused couplers are wavelength dependent [15]. Since the coupling coefficient is wavelength dependent, the interaction length will vary with \( \lambda \) [16, 17]. The coupling behaviour in fused coupler has an oscillatory response as seen in Figure 2.9. If the interaction length of a coupler is such that it is a multiple of coupling length \( L_c \) at the desired wavelengths \( \lambda_1 \) and \( \lambda_2 \), then the entire power at one wavelength will remain in one fiber and the other wavelength will come out at the second fiber. Such a coupler will act as a WDM for these two wavelengths \( \lambda_1 \) and \( \lambda_2 \). Referring to the pull signature shown in Figure 2.9, if the process is stopped at point F, the coupling ratio is 100% for 1550 nm and 0% for 1310 nm. This is the ideal point for making the wavelength division multiplexer.
Under this condition, if $P_1$ is the power at 1550 nm and $P_2$ is the power at 1310 nm, then both the wavelengths will appear without loss at the output. i.e., they will be multiplexed onto the same fiber. As a de-multiplexer, the situation is reversed and the two wavelengths are separated by the same device.

![Figure 5.2: Schematic showing the operation of a fused WDM.](image)

For a FBT coupler to function as a WDM, two conditions shall be precisely controlled. First, the channel spacing of the required WDM must be exactly identical to the wavelength separation between a maximum and a minimum in the wavelength response curve. Secondly, the wavelength corresponding to maximum and minimum splitting ratio must be precisely located in the wavelength response curve at the desired wavelengths [18]. In the actual fabrication process, the splitting ratio curve moves to the shorter wavelength side and the wavelength period decreases in successive coupling cycles [19]. The tuning of the fabrication process may be required to position the maximum and minimum coupling ratio at the desired wavelength. The fine tuning requires the control over elongation of the FBT coupler during fabrication.

1310/1550nm WDM coupler is fabricated in the same way as that of a standard coupler. Here SMF-28 single mode fiber, made by Corning, is used. In the automated fabrication process, elongation is stopped at the precise location by monitoring the maximum and minimum of the coupling ratio at one of the required wavelengths. The important item for realizing a WDM is to determine the appropriate number of coupling cycles at the monitoring wavelength. This helps in getting a channel spacing, close to the required one around the WDM wavelength. For a specific set of fabrication parameters, the central wavelength separation can be controlled by adjusting the pull length or the gas flow. Our experiments show that both of these
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parameters have an inverse relationship with the channel wavelength separation. That is increasing either of these parameters will decrease the wavelength separation. The central wavelength can be set to the desired value by adjusting the preset coupling ratio in the control program. Figure 5.3 shows the wavelength response of 1310/1550nm WDM.

Figure 5.3: Wavelength response of a 1310/1550 WDM coupler

The same process can be extended to make WDMs such as 980/1550 and 1480/1550 etc, which are useful in the assembly of erbium doped fiber amplifiers. Corning Flexcore 1060 fiber has been used, for making 980/1550 WDMs. WDMs with narrow channel spacing (~50 nm) can be realized with fused biconical process. These couplers may exhibit a slightly higher excess loss and low sensitivity to polarization [5, 20]. To realize a narrow WDM with narrow channel spacing, large number of power coupling cycles are required. The typical half cycles observed in practice for a 1480/1550nm WDM is 20 cycles. The polarization dependence of such WDMs can be reduced by imparting a small rotation in the fused region, and devices with PDL less than 0.3dB are fabricated.

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Figure 5.4 shows the wavelength dependence of the coupling ratio for a WDM coupler fabricated with stop point at F as shown in Figure 2.9. In ideal case the coupling ratio is 100% at 1550 nm and 0% at 1310nm. As one moves away from
these wavelength, the coupling ratios are no longer ideal for a WDM. In addition, in practical, it is difficult to achieve ideal coupling even at $\lambda_1$ and $\lambda_2$ and the typical values observed in practice are 99% and 1%, respectively. These effects have a significant impact on the insertion loss and isolation made by fused taper process.

![Figure 5.4: Wavelength dependence of coupling ratio of a 1310/1550 WDM coupler](image)

For the best isolation characteristics, it is desirable that the maximum and minimum coupling ratio should occur exactly at the branching wavelengths. Isolation is of great importance, when the WDM is used as a demultiplexer. The wavelength dependence of the coupling ratio and the deviation from ideal coupling cause poor isolation performance [21]. The isolation of a WDM is shown in Figure 5.5, which shows the wavelength dependence of the isolation for a 1% deviation from the ideal. The isolation can reach 20dB near 1310nm, when the coupling ratio is ideal, but falls off rapidly as one moves away from 1310nm. Typical demultiplexers are specified at 20 dB over a $\pm10$nm bandwidth or 16dB over a $\pm20$nm bandwidth. This isolation bandwidth is significant because the central wavelength of single mode sources usually varies over a 20 to 30nm band.

The insertion loss of the WDM is the amount of light that is lost in the device and is determined by comparing the useful output light to the input light. This is a key parameter for both multiplexers and de-multiplexers, because it affects the overall system power budget. The fusion process itself contributes a small loss called excess loss. In addition, for a WDM, losses can occur because of the wavelength dependence of the coupling ratio and the non ideal coupling. Thus the total insertion loss of WDM consists of the excess loss and the wavelength dependence / non-ideal coupling.
5.4 All-Fiber Methods for High Isolation WDMs

The isolation offered by a single fused WDM is usually not sufficient for most telecommunication applications, where the requirement is as much as 30 - 35 dB isolation. One simple way to improve the isolation is to add bulk component band pass filters at the appropriate wavelengths just before the receivers, an efficient way without increasing the complexity and insertion loss. But, as data rate increase, however, it gets more difficult to insert filters and many systems now require single mode fiber right up to the detector. Also all-fiber components will have increased component stability over bulk optic counterparts.

Typical isolation achieved using fused fiber technology is around 20-24 dB. For 1310/1550 nm WDM, for a coupling ratio variation of 1%, the achievable isolation is around 22 dB, more than such accuracy of 1% is very difficult to achieve in FBT process. Various methods are used to improve the isolation of fused fiber WDMs. A simple way to increase the isolation in fused WDMs is by concatenating multiple WDMs \[22\], additional WDMs serve as filters to clean up the outputs of the WDM as shown in Figure 5.6. Of course the complexity and cost of the resulting device is increased, but it offers an all-fiber method for obtaining higher isolation.

If identical WDMs centered at 1310nm is used to make the concatenated WDM, then the insertion loss will be less than 1 dB and the peak isolation will be 40 dB at the centre wavelength. But the isolation varies rapidly as one moves away from the
central wavelength. Since individual components are used to make concatenated WDM, there exists some flexibility in choosing the components and hence trade-offs can be made between peak isolation and the isolation bandwidth. Figure 5.7 shows the isolation of a device made of WDMs whose peak positions are symmetrically displaced about 1300nm by ±20nm. The upper curve shows the isolation of the concatenated WDM made from the two WDMs. Clearly, the useful bandwidth has been improved with some decrease in isolation at the centre wavelength.

Another all-fiber solution to improve isolation comes from inline spectral filters such as tapered fiber filters [23]. The tapered fiber filters are ideal where high isolation bandwidth is required and hence is not suitable for devices that operate in the Coarse Wavelength Division Multiplexing domain. Although it is possible to achieve narrow
band isolation by concatenating tapered filters, but the process gets complicated and device become very lengthy. However long period gratings, which acts as spectrally sensitive loss elements with narrow bandwidth [24], are compact and can be integrated into the same fiber [25] in which WDMs are fabricated.

5.5 Long Period Gratings: An Overview of Fabrication Methods

Fiber gratings are increasingly being used in optical networks, for variety of applications. The devices are typically fabricated by exposing photosensitive fiber to a spatially periodic pattern of UV radiation. This periodic perturbation in the fiber core causes power to couple between the modes of the fiber. Fiber gratings in general are classified according to the grating period into Fiber Bragg Grating (FBG) with grating period of about 1 µm and Long Period Grating (LPG) having a grating period of about 100 µm [24]. In FBG, the diffracted light travels contra-directionally to the light launched and in an LPG, that diffracted light is co-directional with the launched light as shown in Figure 5.8. FBGs find applications as laser diode stabilizers, mode converters, fiber lasers, band-pass filters, add-drop filters, dispersion compensators, optical sensors [26, 27, 28] etc, whereas LPGs are generally used as non-reflecting band-rejection filters and source-noise suppressors [24] and, more importantly, as gain-equalising or gain-flattening filters for erbium-doped fiber amplifiers (EDFAs) [29, 30, 31]. Other communications applications include LPGs employed as comb filters [32], wavelength-selective optical fiber polarisers [33, 34, 35, 36], add-drop couplers [37], components in wavelength division multiplexing (WDM) systems [38, 39, 40] or in all-optical switching [41], and for chromatic dispersion compensation [42].

Sensitivity of doped-glass to UV light has been reported in literature for a number of years. The use of photo-sensitivity to obtain a periodic refractive index modulation in a germano-silicate optical fiber was discovered by Hill in 1978 [43]. These fiber gratings became prominent in their application areas after the side-wring technique
was invented in 1989 [44] and till researchers increased the photo-sensitivity of telecommunication grade fiber by hydrogen-loading. When an optical fiber is irradiated by ultraviolet (UV) light the refractive index of the fiber changes permanently; a phenomena termed as photosensitivity [45]. The change in refractive index is permanent if the optical waveguide after exposure is annealed appropriately. The magnitude of refractive index change ($\Delta n$) obtained depends on several factors such as the irradiation conditions, the composition of glassy material forming the fiber core and any processing of the fiber prior to irradiation. The refractive index change can be enhanced (photosensitization) by processing the fiber prior to irradiation using techniques such as hydrogen loading or flame brushing.

Fiber gratings can be fabricated by a variety of techniques. The more versatile and widely used techniques such as interferometric, phase masks, amplitude masks, and point-by-point technique, employ UV writing procedure by single-photon absorption. In the Holographic (interferometric) technique UV light from a laser is split into two and allowed to interfere to form a standing wave pattern of periodic spatial light intensity that writes a corresponding periodic index grating in the core of the fiber [44]. This method known as the transverse holographic technique is possible because the fiber is transparent to the UV light where the fiber core is highly absorbing. In the phase mask technique, the ultraviolet light which is incident normal to a phase mask, is diffracted by its periodic corrugations [46]. The phase mask is made from flat slab of silica glass, which is transparent to ultraviolet light. On one of the flat surfaces, a one dimensional periodic surface relief structure is etched using photolithographic techniques. The shape of the periodic pattern approximates a square wave in profile. The optical fiber is placed almost in contact with the corrugations of the phase mask. A drawback of the phase mask technique is that a separate phase mask is required for each Bragg wavelength. The phase mask technique not only yields high performance devices but also flexible in that it can be used to fabricate gratings with controlled spectral response characteristics. The phase mask technique has also been extended to the fabrication of chirped or aperiodic fiber gratings.

A simple, yet efficient way of fabricating LPGs is the amplitude mask technique where an amplitude mask with variable transmittance is used to modulate the UV light falling on the optical fiber. Point-by-point technique bypasses the need of a master phase mask and fabricates the grating directly on the fiber, period by period, by exposing short sections of the fiber to a high energy pulse. The fiber is translated
by a distance before the next pulse arrives, resulting in a periodic index pattern such that only a fraction of each period has a higher refractive index. The method is referred to as point-to-point fabrication. The technique works by focusing an ultraviolet laser beam so tightly that only a short section is exposed to it.

Besides illumination of the fiber by UV light, there are a number of ways to manufacture LPGs by altering the refractive index of the core. These include \[47\] irradiation from a carbon-dioxide laser, radiation with femtosecond pulses, writing by electric discharge, ion implantation, and dopant diffusion into the fiber core. Fibre deformation is less commonly used for fabricating LPGs, but various novel methods have been reported, such as: modification of the fiber core by periodic ablation and annealing \[48\], corrugation of the cladding \[49, 50\], and micro-structuring of tapered fibers \[51\].

The continued investigation of methods for LPG manufacture that do not require photosensitization and UV-irradiation has led to the use of electric arcs from a commercial fiber fusion splice machine \[52\]. The greatest advantage of this method is the simplicity of the procedure; there is also no need to use expensive laser equipment. Furthermore \[53\], any type of fiber can be used for writing gratings in this way without prior photosensitising, since it is predominantly the local heating of silica that creates the modulation in the fiber.

The fabrication process of LPGs by electrical discharge is very simple. The coating of the fiber is removed before fixing it to a translation stage controlled by a motor that allows the straightened fiber to move past the electrodes of a fusion splicer at predetermined intervals (this motion stipulates the grating period) \[54\]. An electric arc discharge is applied to the fiber situated between the electrodes, and the electric current (which determines intensity of the discharge) and duration of exposure is typically user defined. \[31, 52-54\]. Point-by-point writing occurs by advancing the fiber after each discharge has occurred, and the strength of the grating is increased to its desired level by repeating the entire process a specific number of times. Several mechanisms have been proposed as reasons for grating formation by electric arc discharge Investigations have provided evidence that it is mainly the relaxation of internal residual stresses that ensure LPGs can be manufactured with this method \[53\]. The discharges applied to specific points along the fiber cause rapid variations in temperature at these locations, which serve to anneal the fiber locally, thereby providing periodic changes in the residual stress distributions that facilitate mode
coupling. It has also been suggested that local cooling rates in excess of 1000 degrees Celsius per second can lead to a localised change in the density, viscosity and index of refraction of the glass, as well as Rayleigh scattering — all contributing to mode coupling subsequent to application of the electric discharge [53].

These gratings are also less sensitive to temperature fluctuations in the low temperature range (30-160°C) than LPGs written by UV-irradiation, as can be seen by the smaller spectral shift of the resonant wavelengths. Another advantage of gratings formed with the electric arc discharge method is that they are very stable at high temperatures. If the temperature is kept below the strain point of the fiber (i.e. the point at which residual stresses are annealed and stress relaxation begins), the spectral characteristics due to temperature are linear, but further heating may even cause plastic deformation of the fiber [53]. Fabrication methods with electric arc are attractive as they can provide a simple and flexible means of producing LPGs of relatively good performance. Such LPGs can be written on any type of optical fiber as their characteristics are mainly defined by intrinsic properties of silica glass itself. The LPGs act as a spectrally sensitive loss element by rejecting a narrow band signal and hence can be integrated with fused WDMs to improve the isolation at required ports.

5.6 Theoretical Background

A perfect dielectric waveguide can transmit optical energy by any of its guided modes without converting the energy to any other possible guided modes or to the non-guided modes which consists of a discrete set of cladding modes and a continuous spectrum of radiation modes. Any imperfection in the guide, such as a local change of its index of refractive or a deviation from perfect straightness or an imperfection of the interface between two regions with refractive indices, couples the power in a particular guided mode among other guided modes as well as unguided modes. Coupled mode theory describes the energy exchange, and serves as the primary tool for designing optical couplers and filters.

5.6.1 Coupled Mode Equation for Periodic Coupling

Consider a waveguide with a refractive index profile \( n^2(x, y) \) in which there is an \( z \)-dependent perturbation given by \( \Delta n^2(x, y, z) \). Let \( \psi_1(x, y) \) and \( \psi_2(x, y) \) be the two modes of the waveguide in the absence of perturbation. The total field at any value of \( z \) is given by:
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\[ \psi(x, y, z) = A(z)\psi_1(x, y)e^{-i\beta_1 z} + B(z)\psi_2(x, y)e^{-i\beta_2 z} \quad (5.2) \]

\( \beta_1 \) and \( \beta_2 \) are the propagation constants in the absence of perturbation and \( A(z) \) and \( B(z) \) are the corresponding amplitudes. Here, the modes with propagation constants, \( \beta_1 \) and \( \beta_2 \), are propagating in the +z direction. In the absence of perturbation \( A \) and \( B \) are constants; the perturbation, however, couples power among the modes and hence \( A \) and \( B \) are z-dependent. Since \( \psi_1 \) and \( \psi_2 \) are modes of the fiber in the absence of any perturbation, they must satisfy the following equations:

\[ \nabla_i^2 \psi_1 + \left(k_0^2 n^2(x, y) - \beta_1^2\right)\psi_2 = 0 \quad (5.3) \]
\[ \nabla_i^2 \psi_2 + \left(k_0^2 n^2(x, y) - \beta_2^2\right)\psi_1 = 0 \quad (5.4) \]

where

\[ \nabla_i^2 = \nabla^2 - \frac{\partial^2}{\partial z^2} \quad (5.5) \]

They also satisfy the orthogonality condition:

\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \psi_1^* (x, y)\psi_2 (x, y) dx dy = 0 \quad (5.6) \]

In the presence of a perturbation in refractive index, the wave equation to be satisfied by \( \psi(x, y, z) \) is

\[ \nabla_i^2 \psi + \frac{\partial^2 \psi}{\partial z^2} + k_0^2 \left[n^2(x, y) + \Delta n^2(x, y, z)\right] \psi = 0 \quad (5.7) \]

Substituting for \( \psi \) from Equation 5.2, and neglecting double derivatives of \( A \) and \( B \) w.r.t \( z \) (under slowly varying approximation),

\[ -2i\beta \frac{dA}{dz} \psi_1 - 2i\beta \frac{dB}{dz} \psi_2 e^{-i\beta z} + k_0^2 \Delta n^2(x, y, z) \left[A \psi_1 + B \psi_2 e^{-i\beta z}\right] = 0 \quad (5.8) \]

where

\[ \Delta \beta = \beta_1 - \beta_2 \quad (5.9) \]

Multiplying Equation 5.8 by \( \psi_1^* \) and integrating and then further multiplying by \( \psi_2^* \) and integrating, we get after simplifications:

\[ \frac{dA}{dz} = -iC_{11} A - iC_{12} B e^{i\Delta \beta} \quad (5.10) \]
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\[
\frac{dB}{dz} = -iC_{22}B + iC_{21}Ae^{-i\Delta \beta z},
\]

(5.11)

where

\[
C_{y}(z) = \frac{k_{0}^{2}}{2\beta_{1}} \int \int \psi^{*}_{i} \Delta n^{2} \psi_{j} \, dxdy
\]

(5.12)

Equations 5.10 and 5.11 represent the coupled mode equations and describe the $z$-dependence of $A$ and $B$.

5.6.2 Co-directional Coupling

In the presence of $z$-dependent sinusoidal perturbation, we may write:

\[
\Delta n^{2}(x, y, z) = \Delta n^{2}(x, y) \sin Kz
\]

(5.13)

where $K = \frac{2\pi}{\Lambda}$, and $\Lambda$ is the spatial period of perturbation. This gives

\[
C_{y}(z) = \frac{k_{0}^{2} \sin Kz}{2\beta_{1}} \int \int \psi^{*}_{i} \Delta n^{2} \psi_{j} \, dxdy
\]

(5.14)

\[
C_{y}(z) = 2\kappa_{y} \sin Kz
\]

(5.15)

\[
\kappa_{y} = \frac{k_{0}^{2}}{4\beta_{1}} \int \int \psi^{*}_{i} \Delta n^{2}(x, y) \psi_{j} \, dxdy
\]

(5.16)

Substituting in Equation 5.10 we get

\[
\frac{dA}{dz} = -2i\kappa_{11} A \sin Kz - B\kappa_{12}e^{i(\Delta \beta + K)z} + B\kappa_{21}e^{i(\Delta \beta - K)z}
\]

(5.17)

For weak perturbations, the coupling coefficients, $\kappa_{12}$ and $\kappa_{21}$ are small and hence, the typical length scale over the modes amplitude change $\left(1/\kappa_{12}\right) \sim \left(1/\kappa_{21}\right)$, is large. It can be shown that $\Delta \beta \sim K$, the contributions from the first and second terms of the RHS Equation 5.17 are negligible as compared to the third term and hence can be neglected. However, the second term would have made significant contribution if $\Delta \beta = \beta_{1} - \beta_{2} = -K$. Thus in the presence of a periodic perturbation, coupling takes place mainly between the modes for which $\Delta \beta$ is close to either $K$ or $-K$. The
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approximation retaining either $e^{i(\Delta \beta - \kappa)z}$ term or $e^{i(\Delta \beta + \kappa)z}$ term in Equation 5.17 is called the synchronous approximation.

Hence under this approximation, Equation 5.17 can be written as

$$\frac{dA}{dz} = \kappa_{12} Be^{\beta z} \tag{5.18}$$

where

$$\Gamma = \Delta \beta - \kappa \tag{5.19}$$

Similarly,

$$\frac{dB}{dz} = -\kappa_{21} Ae^{\beta z} \tag{5.20}$$

If modes $\Psi_1$ and $\Psi_2$ are normalized to carry unit power, then under the weakly guiding approximation, we may write:

$$\frac{\beta_1}{2\omega_0 \mu_0} \int \int \psi_1^* \psi_2 dx dy = 1 \tag{5.21}$$

Using orthogonality condition, we can show that:

$$\kappa_{12} = \kappa_{21} = \kappa \tag{5.22}$$

Thus the two coupled equations become

$$\frac{dA}{dz} = \kappa Be^{\beta z} \tag{5.23}$$

$$\frac{dB}{dz} = -\kappa Ae^{\beta z} \tag{5.24}$$

These two equations describe the coupling between two modes propagating along the same direction i.e $\beta_1, \beta_2$ have the same sign. Such kind of coupling is co-directional coupling, as explained earlier also.

5.6.2.1 Co-directional Coupling under Phase Matching Condition

Phase matching condition is given by $\Gamma = 0$

$$\beta_1 - \beta_2 = \kappa \tag{5.25}$$

Thus the periodic perturbation should have period
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\[ \Lambda = \frac{2\pi}{\beta_1 - \beta_2} = \frac{\lambda_0}{(n_{s1} - n_{s2})} \]  (5.26)

where \( \beta_1 = \frac{2\pi n_{s1}}{\lambda_0} \) and \( \beta_2 = \frac{2\pi n_{s2}}{\lambda_0} \), \( n_{s1}, n_{s2} \) are the effective refractive indices of the two modes. Then equations (5.23) and (5.24) become

\[ \frac{dA}{dz} = \kappa B \]  (5.27)

\[ \frac{dB}{dz} = -\kappa A \]  (5.28)

Differentiating (5.28) and making substitution from (5.27), we obtain

\[ \frac{d^2 B}{dz^2} = -\kappa^2 B \]  (5.29)

Its solution is

\[ B = b_2 \sin \kappa z - b_1 \cos \kappa z \]  (5.30)

Similarly

\[ A = b_1 \sin \kappa z - b_2 \cos \kappa z \]  (5.31)

Initial conditions assume that \( z=0 \), the mode, \( \psi_1 \) is launched with unit power,

\[ A|_{z=0} = 1 \]  (5.32)

And initially, \( \psi_2 \) had no power in it,

\[ B|_{z=0} = 0 \]  (5.33)

Thus \( b_1 = 0 \) and \( b_2 = -1 \) and therefore

\[ A(z) = \cos \kappa z \]  (5.34)

Similarly

\[ B(z) = -\sin \kappa z \]  (5.35)

Thus the powers carried by the two modes vary with \( z \) as;

\[ P_1 = |A(z)|^2 = \cos^2 \kappa z \]  (5.36)
5.6.3 Contra-directional Coupling

When coupling takes place between the two modes propagating in opposite directions, it is known as contra-directional coupling. In such a case, we have to choose

$$\psi(x, y, z) = A(z)\psi_1(x, y)e^{-i\beta_1 z} + B(z)\psi_2(x, y)e^{i\beta_2 z} \quad (5.38)$$

Here the mode with propagation constant $\beta_1$ is propagating in the $+z$ direction and the mode with propagation constant $\beta_2$ is propagating in the $-z$ direction. Following an exactly similar procedure, one obtains coupled mode equations for contra-directional coupling as:

$$\frac{dA}{dz} = \kappa Be^{i\beta z} \quad (5.39)$$
$$\frac{dB}{dz} = \kappa Ae^{-i\beta z} \quad (5.40)$$

The signs on the RHS of Equations 5.39 and 5.40 are same unlike that in co-directional coupling, therefore the solution in this case are not oscillatory.

5.6.4 Long Period Gratings

The pattern of refractive index modulation in the fiber core acts as a perturbation that serves to couple power between the “matched” modes of the optical waveguide. Figure 5.9 depicts the propagation constant of various spatial modes in the fiber. The forward propagating guided modes have their propagation constants $\beta$ that lie in the range $\frac{2\pi n_1}{\lambda} < \beta < \frac{2\pi n_2}{\lambda}$ where $n_1$ and $n_2$ are indices of refraction of the core and cladding respectively.

For a single-mode fiber, the propagation constant of the guided mode can be represented by $\beta_{c} = \frac{2\pi n_{ce}}{\lambda}$, where $n_{ce}$ is the effective index of the mode. For mode coupling to occur between two modes, the propagation constant difference between
these modes $\Delta \beta$ (represented as $\Delta \beta_{FBG}$ in Figure 5.9) should match the “phase vector” of the grating:

$$\Delta \beta = \frac{2\pi}{\Lambda} \tag{5.41}$$

where $\Lambda$ is the periodicity of the grating. For coupling to occur from the forward to the reverse propagating guide mode ($\beta = -\beta_{co}$), $\Delta \beta$ needs to be relatively large and thus the periodicity of the required grating is small. Such short-period gratings, commonly called as Bragg grating, have typical periodicity around 0.5 $\mu$m for coupling in the 1550 nm window. The overlap interval between the two coupling modes over the grating cross-section determines the magnitude of the power coupled. Long-period gratings are utilized to couple the forward-propagating guided mode to one or more forward-propagating guided or cladding modes [24]. Since the required propagation constant difference $\Delta \beta$ (depicted as $\Delta \beta_{LPG}$ in Figure 5.9) between the coupled modes is relatively small, Equation 5.41 predicts that the required grating periodicity is fairly large.

![Figure 5.9 Depiction of mode-coupling in short- and long-period fiber gratings based on the difference between propagation constants of the coupling modes.](image)

The optical power transmitted through the fiber as core modes at a wavelength $\lambda_c$ is coupled between core modes and cladding modes at the grating region. In one approach this coupling process may be expressed as

$$\lambda = \frac{(n_{co} - n_{cl}(p))}{\Lambda} \tag{5.42}$$

where $\Lambda$, $n_{co}$, $n_{cl}(p)$ are the period of the grating, the effective refractive index of any of the core modes and the effective refractive index of the $p^{th}$ cladding mode respectively. This equation is similar to Equation 5.26. Since, in single mode fibers
there exists only one core mode (LP_{01}) and many cladding modes (LP_{1p}), the core-cladding coupling occurs at certain specific wavelengths. These wavelengths can be found out by calculating the various values of \( n_{cl}(p) \) which in turn is determined by assuming a step index profile for the cladding and ignoring the presence of the core. The light in the cladding quickly decays due to losses at the cladding / air interface, leaving a series of loss bands or resonance in the guided modes.

Another method of calculating the wavelength separation between the different cladding modes makes use of the cut-off wavelength \( \lambda_{\text{cut}} \), which is the wavelength at which a given mode switches from a cladding mode to radiation mode or vice versa. Consider the transverse component of the propagation constant of the cladding mode \( \kappa \). This component satisfies the condition

\[
\beta_{cl}^2 + \kappa^2 = \frac{\omega^2 n_{cl}^2}{c^2}
\]  

(5.43)

where \( \beta_{cl} \) is the propagation constant of the cladding mode, \( \omega \) is the angular frequency of the radiation and \( c \) is the velocity of light. The separation in wavelength between the \( p^{th} \) cladding mode and \( \lambda_{\text{cut}} \), is found by using the above two equations,

\[
\delta \lambda_{p\rightarrow p+1} \approx \frac{\lambda_{\text{cut}}^2}{8n_{cl}(n_{co} - n_{cl})} \frac{a_{cl}^2}{p^2}
\]  

(5.44)

where \( n_{co} \) is the effective refractive index of the guided LP_{01} mode and \( a_{cl} \) is the cladding radius. For the first few cladding modes one can further simplify the expression by assuming that \( \lambda_{p} \) and \( \lambda_{\text{cut}} \) are in close proximity. The wavelength separation between the \( p^{th} \) and the \( (p+1)^{th} \) mode can then be approximated by

\[
\delta \lambda_{p\rightarrow p+1} \approx \frac{\lambda_{\text{cut}}^2}{8n_{cl}(n_{co} - n_{cl})} \frac{2p+1}{a_{cl}^2}
\]  

(5.45)

The ratio of power coupled into the \( n^{th} \) cladding mode to the initial power contained in the guided LP_{01} mode is then given by

\[
\frac{P_{cl}(n)}{P_{01}(0)} = \frac{\sin^2 \left[ \kappa_g L \sqrt{1 + \left( \frac{\delta}{\kappa_g} \right)^2} \right]}{1 + \left( \frac{\delta}{\kappa_g} \right)^2}
\]  

(5.46)

where \( \delta \) is the detuning parameter given by
\[ \delta = \frac{1}{2} \left\{ \beta_{01} - \beta_{11}^{(n)} - \frac{2\pi}{\lambda} \right\} \]  

(5.47)

\( \kappa_g \) is the coupling constant for the grating and \( L \) is the grating length. The coupling constant \( \kappa_g \) is proportional to the index change and is typically to maximize the power transfer to the cladding mode. Thus \( \Delta n \) (and hence, \( \kappa_g \)) is increased until the condition \( \kappa_g = \frac{\pi}{2} \) is met. Thus the intensity of the perturbation and the length of the grating determine the isolation of the filter. An approximate expression of the full width at half maximum (FWHM) \( \Delta \lambda \), for a resonance band, at the complete power transfer condition is [24]:

\[ \Delta \lambda = \frac{0.8\lambda^2}{L(n_{co} - n_{cl})} \]  

(5.48)

Thus the FWHM of the resonance is inversely proportional to the length of the grating, \( L \). The spectral response of the LPG depends on the period, the intensity of the perturbation and the grating length.

### 5.7 Fabrication of LPGs with Electric Arc Technique

Our experimental setup for long period grating fabrication consists of an arc generator, fiber holder mounted on a translational cum rotational stage, optical spectrum analyzer and a white light source, as shown schematically in Figure 5.10. This is similar to the setup described in [54,55,56]. The grating fabrication consists of positioning the uncoated fiber between the electrodes of the arc generator, based on a commercially available fiber optic splicing machine from Furukawa. One end of the fiber is clamped in a fiber holder attached to a motorized translation stage, which moves with a precision of 0.1 \( \mu \)m. At the other end the fiber is attached to a mass (~4 gm) through a pulley to provide constant axial tension. An electric discharge is then produced with a current less than 10mA, for a duration of ~1s. Afterwards the fiber is moved by grating period followed by a new electric discharge. The displacement discharge process is then repeated 15-40 times, giving rise to periodic perturbations along the fiber due to its local heating. A broadband light is launched to the fiber and the transmitted power is monitored using an optical spectrum analyser in order to analyse the evolution of the grating characteristics.

Local section of the normal fiber heated by application of electric arc at periodic intervals is deformed as decreasing core and cladding diameter, due to the
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longitudinal tension. The change in the diameter depends on the arc condition and tension applied [56]. The core and cladding diameter reduces with arc time. Decreasing the core and cladding diameter cause increasing of mode coupling coefficients and decreasing core and cladding effective indices. The mode coupling in these gratings can be explained due to the change of glass properties by fast local heating-cooling process. The fast local heating – cooling process anneals periodically residual stresses and create new stresses, and results in mode coupling [53]

Certain experimental setups suggest constant tension applied along the length of the fiber using a mass piece attached to the one end of the fiber [50, 51], whereas minimal or no axial strain is exerted in other cases [52, 54]. The effect of this tension is to cause periodic tapering (i.e. narrowing of fiber diameter) where discharges have occurred, but this phenomenon plays a minor role in the grating quality and is not necessary for LPG manufacture [53]. Adding tension to the fiber does tend to increase insertion loss, but it was also found to be beneficial – fewer discharges are required for a greater isolation loss in LPGs where axial stress was applied during manufacture.

Unlike UV-induced LPGs, gratings manufactured with this method do not undergo changes in their resonant wavelengths (observed in transmission) as the grating strength is increased. Thus the spectral characteristics only depend on the length and the grating period, providing a method to manufacture LPGs whose mode coupling characteristics are quite predictable. There may be an anisotropy introduced in the fiber, because of the asymmetry of the electric discharge [55]. This anisotropy changes the polarization of the excitation signal. Also, resonance wavelength of LPGs induced by single arc per grating is difficult to reproduce, because of irregularity in fiber deforming. So for more stable fabrication, we generate not just one arc, but several weak ones periodically in a single grating.
Long Period Fiber Gratings are fabricated with a period of 610 µm on standard Corning SMF-28 fiber (Corning), having dimensions of 9/125 µm. The transmission characteristic of LPG is shown in Figure 5.11. The response shows three resonance wavelengths corresponding to the coupling from the core mode to a particular cladding mode. During the fabrication the spectral response of the grating is monitored after each step. Figure 5.12 shows the growth of LPG at different grating lengths with a constant period of 610 µm. The optical power transfer increases with the grating length. Figure 5.12 shows the evolution of isolation during the fabrication at 15, 25 and 35 arcs respectively. The isolation increases after each arcs, while the loss at non-resonant wavelengths remains almost unaltered. The insertion loss is evaluated to be less than 0.3 dB. The process is stopped at the required isolation. It is observed that both the arc power and arc time has a role in determining the loss and isolation of the grating. The intensity of perturbation and length of the grating
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determines the isolation. The peak loss of the resonance wavelength becomes larger as the grating length increases, the lower resonance wavelengths change more slowly than those of the higher modes.

Gratings with different periods have been fabricated, the peak resonance wavelength changes linearly to higher wavelengths, for a specific set of other fabrication parameters (keeping arc current, arc duration and number of grating as constant). Gratings were fabricated with different arc time, while keeping all other parameters as constant. The arc time is varied from 500 ms to 1000 ms. A shift in resonance wavelength is observed for lower wavelength resonance peaks to shorter wavelengths, while that of the higher wavelength resonance peak remains as the same.

![Figure 5.12: Isolation Evolution of the LPG](image)

The local temperature of the fiber during the arc exposure is more than silica glass softening temperature. So for moderate applied tension, a tapering of the fiber is observed, which increases as the axial tension is increased. As the tension on the fiber increases the degree of tapering increases, the insertion loss and isolation also increases. Decreasing the core and cladding diameter cause increasing of mode coupling coefficients at the expense of higher polarization sensitivity and less mechanical strength. Hence it is better to reduce the diameter modulation to the minimum level to reduce the polarization sensitivity. Also, it is observed that the asymmetry of the electric discharge contributes to the polarization sensitivity. Intentional rotation during the grating fabrication is also incorporated. The fabricated
LPG show isolation up to 14 dB while keeping the insertion loss at the non-resonant wavelengths to below 0.3 dB. By optimizing the process the isolation can be improved up to 25 dB, without compromising the polarization performance. The polarization dependent loss of the device is measured by varying the polarization of the input light over all possible states and by observing the variation in insertion loss. With normal process the PDL was around 1.5 dB, but with rotation incorporated, the PDL could be controlled to below 0.3 dB.

The transmission spectrum of LPG is susceptible to both bending and twisting and the resonance peak may shift or split due to these effects. Hence the packaging of these devices needs care for repetitive spectral performance. Packaging of these devices is done by fixing the grating on a quartz substrate with the same tension and bonding it to the substrate with suitable epoxy, as done for the fused couplers. As the thermal expansion of quartz is identical to the fiber, it does not create any additional strain on the grating region, due to temperature variations or external perturbations. A Kovar tube protects this preliminary package.

5.8 Integration of LPGs in Fused WDM

WDMs are fabricated using the fused fiber coupler station as described in Chapter 2, where the fibers are biconically tapered until the desired coupling characteristics are achieved, by online monitoring the CR. Long period gratings are then fabricated on the respective ports of these WDMs, using a setup as described in section 5.7. As the LPGs couple power from guided mode to forward propagating cladding modes – propagating in the same direction, until being completely attenuated by scattering in air-cladding interface and in fiber coating – these devices have excellent back reflection. The process is stopped at the required isolation by real-time monitoring the values. The packaging of this integrated WDM is done in a similar fashion of the FBT devices, to make it less sensitive to environmental variations. The fiber is bonded to a quartz substrate whose thermal variation is matched to that of the fiber, with a suitable adhesive. The substrate is then encapsulated with in an Invar tube for overall protection.

5.9 Results and Discussions
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LPGs have been integrated with 1310/1550 nm WDM. Long Period Fiber Gratings are fabricated with a period of 610 µm on standard Corning SMF-28 Fiber. The isolation of fused WDMs at 1310 nm port and that of the LPG integrated WDM are shown in the Figure 5.13. The isolation of the single fused WDM is around 22-24 dB and that of the LPG integrated fused WDM is 32-35 dB. Hence it is obvious that the isolation is improved while keeping the insertion loss in the pass wavelength band well below 0.6 dB. This insertion loss value is comparable to the concatenated WDM solution. As LPGs couple the undesired wavelength power to the forward propagating cladding modes, it does not contribute to the back reflection or directivity performance of the LPG integrated WDMs. The back reflection of the combined device is found to be better than -55 dB, which is same as the concatenated WDMs.
The polarization dependence of the device is plotted in Figure 5.14. The polarization dependent loss of the device is measured by varying the polarization of the input light over all possible states using the Lefevre’s loop controller and by observing the variation in insertion loss. Though the isolation increases with grating strength, polarization dependent loss also increases as discussed in the previous section. Thus there exists a trade off between the achievable isolation and the PDL of the device. The PDL of the device is function of the grating strength. This polarization dependence comes mostly from the fiber asymmetry of the electric arc discharge during the grating fabrication and the contribution of the same from WDM is limited. To reduce the effects of polarization states to the minimum level, intentional rotation is provided during fabrication.

![Figure 5.15: Isolation Bandwidth of WDM](image-url)
Defining Isolation bandwidth as the wavelength range over, which the isolation is greater than, or equal to some value, it is observed that the isolation increases while the isolation bandwidth decreases with grating strength. The variation of isolation bandwidth and isolation with grating length is shown in Figure 5.15 and 5.16 respectively. The typical isolation bandwidth achieved is in the range of 10-30 nm, which makes use of this application novel, especially in Coarse Wavelength Division Multiplexing applications. Typically the isolation bandwidth provided by the short taper fiber filter is in the range of more than 100nm. Isolation bandwidth in the case of cascaded WDMs depends on the similarity of the spectral shapes of the individual WDMs used, thus making the performance requirements of individual WDMs very stringent. From Figure 5.16, it is evident that the isolation has reached the level of 35 dB, where the 3 dB bandwidth is around 20 nm. The isolation improvement with grating length owes to greater amount of optical power transfer at the resonant wavelength, but the loss at the non-resonant wavelengths remains the same thus not contributing to the insertion loss at the ports.

To validate the packaging technique and to ensure the optical performance over various environmental conditions, 11 samples have been subjected to various accelerated tests. The effect of temperature variation on the spectral performance is studied by subjecting the packaged grating to temperature variations from 0 to +70°C. The resonance wavelength shift of LPG was measured to be around 0.04 nm/°C. The resonance wavelength shift of the device does not make appreciable changes in the
performance, over the temperature range. Comparison of the typical performance of a standard WDM and High Isolation WDM is summarized in Table 5.1.

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<th>Parameters</th>
<th>Standard WDM</th>
<th>High Isolation WDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
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<td>1310 &amp; 1550</td>
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<tr>
<td>Insertion Loss (dB)</td>
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<td>Peak Isolation (dB)</td>
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<td>SMF-28</td>
</tr>
<tr>
<td>Dimension (L)</td>
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<td>70-75 mm</td>
</tr>
</tbody>
</table>

Table 5.1: Comparison of the performance of standard WDM and a grating integrated WDM

5.10 Conclusions

A novel method has been suggested to improve the isolation of fused wavelength division multiplexers using inline spectral filters based on Long Period Grating. The gratings are fabricated on the same SMF28 fiber used to fabricate WDM couplers, using electric arc technique. The performance of the device is also analyzed in detail. This technique finds application in improving the adjacent channel isolation in fused CWDM devices. The advantage of this process comes from three points: 1. LPGs are fabricated on the standard fiber 2. Narrow isolation bandwidth makes this suitable for CWDM applications 3. Easy and flexible fabrication technique. This technique also offers the possibility of integrating the Gain Flattening Filter into the WDM module for EDFA applications.

References

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