Laser based transmission over multimode fiber is affected by differential mode delay, due to the interaction between laser spot and index profile defects. Thus single mode laser sources needs to be adapted for transmission over multimode fibers, to get guaranteed link distances. Conventionally, mode conditioning is done through offset launch method, which requires precise tools. An all-fiber mode conditioning element based on Long Period Grating is proposed and evaluated.
A growing demand for greater information bandwidth in LANs requires operation at Gbps. This has lead to the development of many techniques to increase the bandwidth of multimode fiber based local area networks [1]. In order to support gigabit speeds, the systems need laser sources such as Fabry-Perot lasers or Vertical Cavity Surface Emitting Lasers (VCSEL). When laser sources are used with multimode fibers having refractive index profile defects, it may cause excitation of far separated mode groups. Such a condition causes the laser signal to disintegrate into an uneven power distribution among the modes. The resulting degraded optical power profile, often translates into bit errors. Thus, control over modal power distribution is essential to achieve guaranteed link distances at gigabit speeds over multimode fiber [2].

This chapter discusses various methods to ensure reliable high speed transmission over existing multimode fiber installations. There are different methods reported in literature to achieve the mode conditioning which include offset splicing, offset alignment, doughnut launching and mode-field matched centre launching etc [3, 1]. Many of those techniques available today require launching condition with sophisticated launching tools or devices that are sensitive to environmental stresses. Long period fiber gratings offer coupling between co-propagating modes of a fiber are potentially useful as spectral shaping elements and mode conversion devices [4]. Mode conditioning using long period gratings, written at single mode to multimode interface is demonstrated, with comparable optical performance to other methods.

6.1 Transmission over Multimode Fiber

Fibers with large core and high numerical aperture typically allow propagation of many modes. Each mode is an independent, self-supporting, electro magnetic field that propagates axially along an optical fiber independent of other modes. Each mode will propagate with its own velocity and have a unique field distribution. The variation of the longitudinal propagation velocity with either optical frequency or path length introduces fundamental limit to fiber transmission. The dispersion in propagation velocity between different frequency components of the signal or between different modes of a multimode fiber produces a signal distortion and intersymbol interference in digital systems, which is not desirable [5]. However, multimode optical fiber has been an attractive option for cost effective premises networks offering a transmission capability up to 1Gbps and beyond [6]
Different modes traversing different optical paths in the MMF spread in time, causing pulse broadening. The parameter used to express pulse broadening due to intermodal dispersion is differential mode delay (DMD). Figure 6.1 shows the schematic representation of pulse broadening effect in multimode and single mode fibers. DMD is measured by launching a test pulse into a MMF at highly controlled radial positions across the fiber core, from the core center to the cladding region. Only a few modes are excited at each step, and their arrival times are recorded. The DMD of the fiber is the difference between the earliest and latest arrival times of all modes at all steps [7, 8]. From DMD measurements, one can calculate the effective modal bandwidth of the fiber expressed in units of MHz·km.

When light of different wavelengths propagate in a material, it does so with different velocities. VCSELs used with multimode fiber have a finite spectral width and, as a result, a pulse of light containing spectral content will be dispersed. Chromatic dispersion describes this broadening of the pulse width and has the effect of reducing signal quality, thereby degrading link performance. The velocity of light is determined by the refractive index of the medium. The refractive index profiles in modern graded index fibers used for data communication applications follow approximately a power law where the refractive index is defined as:
All-Fiber Mode Conditioner

\[ n(r) = n_1 \left( 1 - 2 \Delta \left( \frac{r}{a} \right)^g \right)^{0.5} \quad r < a \]
\[ = n_2 \quad r > a \]  

(6.1)

where \( n_1 \) is the core refractive index, \( n_2 \) is the cladding refractive index, \( r \) is the radial position, \( a \) is the core radius, \( g \) is the profile parameter and \( \Delta = \left( n_1^2 - n_2^2 \right)/2n_1^2 \) is the relative refractive index difference between the core and the cladding. The optimum profile for minimum modal dispersion is \( g \approx 2 \); the index profile becomes parabolic.

In a graded index fiber, the modes that travel nearest the centre of the core are subject to higher refractive index than are those that travel the longer paths through the outer portion of the core. When the profile is optimized, the varying index equalizes the travel time of all mode groups and differential mode delay is minimized. All modern fiber is designed to be as close to optimum as possible but the actual range can be as much as \( 1.8 < g < 2.2 \). However, in real cases, perturbations in the refractive index can occur. Defects at the core/cladding interface, changing profile parameter \( g \) as a function of radius or a central index dip have all been reported [9].

The number of modes that propagate in a multimode fiber is given by [10]

\[ N = \left( \frac{g}{g + 2} \right)^2 \left( \frac{2m \lambda}{\lambda} \right)^2 \]

(6.2)

where \( \lambda \) is the wavelength of the light propagating in the fiber and \( M \) is the number of modes.

The modes of the square law fiber can be calculated using Hermite polynomials, \( H(p,x) \) as:

\[ H(p,x) = \sum_{m=0}^{p} (-1)^m p!(2x)^{(p-2m)} m!(p-2m)! \]

(6.3)

where \( p \) is the mode index.

The total mode field distribution may then be expressed as the product of functions of \( x \) and \( y \) coordinates (\( x \) and \( y \) in plane of the fiber end face, \( z \) along axis of the fiber) as [11]
Chapter 6

\[ \chi(p, x, \omega_0) = \left( \frac{2}{\pi} \right)^{\frac{1}{2}} \left( \frac{1}{\sqrt{2^2 \cdot p^2 \cdot w_0^2}} \right) H \left( p \cdot \sqrt{2 \cdot \frac{x}{w_0}} \right) e^{\left( \frac{x}{w_0^2} \right)} \quad (6.4) \]

and

\[ \psi(q, y, \omega_0) = \left( \frac{2}{\pi} \right)^{\frac{1}{2}} \left( \frac{1}{\sqrt{2^2 \cdot q^2 \cdot w_0^2}} \right) H \left( q \cdot \sqrt{2 \cdot \frac{y}{w_0}} \right) e^{\left( \frac{y}{w_0^2} \right)} \quad (6.5) \]

where \( p \) and \( q \) are mode indices, \( w_0 \) is the \( e^{-1} \) waist of the lowest order fiber mode given by

\[ w_0 = \left[ \frac{2R}{2\pi} \right] \times \left[ \frac{\sqrt{2\lambda}}{2\pi} \right] \quad (6.6) \]

where \( \lambda \) is the wavelength of the source.

A single transverse mode laser source may be defined as a Gaussian beam having an electric field distribution described by the following equations:

\[ F_x(x, w_x, \delta) = \frac{2}{w_x \pi} e^{-\frac{(x-\delta)^2}{w_x^2}} \quad (6.7) \]

\[ F_y(y, w_y, \varepsilon) = \frac{2}{w_y \pi} e^{-\frac{(y-\varepsilon)^2}{w_y^2}} \quad (6.8) \]

where \( w_x \) and \( w_y \) are the waists of the beam in the \( x \) and \( y \) directions. \( \delta \) and \( \varepsilon \) are the offsets in the \( x \) and \( y \) axis from the center of the fiber core.

The field excitation coefficients, \( C(p, q, w_0, w_x, w_y, \delta, \varepsilon) \), may be calculated from the overlap integral of the excitation field and the modal field distributions of the fiber:

\[ C(p, q, w_0, w_x, w_y, \delta, \varepsilon) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F_x(x, w_x, \delta) F_y(y, w_y, \varepsilon) \chi(p, x, \omega_0) \psi(q, y, \omega_0) dx \, dy \quad (6.9) \]

The double integral may be evaluated as the product of an integral over \( x \) multiplied by an integral over \( y \) so that:
All-Fiber Mode Conditioner

\[ C(p, q, w_0, w_x, w_y, \delta, \varepsilon) = C_p(p, w_0, w_x, \delta) \cdot C_q(q, w_0, w_y, \varepsilon) \quad (6.10) \]

Evaluation of the integral results in the following solutions:

\[ C_p(p, w_0, w_x, \delta) = \sqrt{\frac{2}{w_x \cdot w_0}} \cdot \frac{1}{2^{\frac{p}{2}}} \cdot \sqrt{\frac{w_x \cdot w_0}{w_x^2 + w_0^2}} \cdot \frac{(w_0^2 - w_x^2)^{\frac{p}{2}}}{(w_0^2 + w_x^2)^{\frac{q}{2}}} \cdot H \left[ p, \sqrt{2 \cdot \delta} \right] \cdot e^{-\frac{\delta^2}{w_0^2 + w_x^2}} \]

(6.11)

and

\[ C_q(q, w_0, w_y, \varepsilon) = \sqrt{\frac{2}{w_y \cdot w_0}} \cdot \frac{1}{2^{\frac{q}{2}}} \cdot \sqrt{\frac{w_y \cdot w_0}{w_y^2 + w_0^2}} \cdot \frac{(w_0^2 - w_y^2)^{\frac{q}{2}}}{(w_0^2 + w_y^2)^{\frac{p}{2}}} \cdot H \left[ q, \sqrt{2 \cdot \varepsilon} \right] \cdot e^{-\frac{\varepsilon^2}{w_0^2 + w_y^2}} \]

(6.12)

The power coupling per mode, PC \((p, q, w_0, w_x, w_y, \delta, \varepsilon)\) may be calculated to be:

\[ PC(p, q, w_x, w_y, \delta, \varepsilon) = \left( C_p(p, w_0, w_x, \delta) \cdot C_q(q, w_0, w_y, \varepsilon) \right)^2 \]

(6.13)

According to the WKB method, the modal propagation time, \(\tau(g, p, q)\) for the power law fibers may be calculated as:

\[ \tau(g, p, q) = \left( \frac{n \cdot L}{c} \right) \left[ \frac{\Delta - 2 \cdot \frac{M(p, q)}{N(g)}}{\frac{M(p, q)}{N(g)}} \right]^{\frac{1}{2}} \]

(6.14)

where \(L\) is the fiber length, \(c\) is the speed of light, \(g\) the power law of the refractive index curve, \(M(p, q) = (p+q+1)^2\) and \(N(g)\) the total number of guided modes.

The RMS width of the impulse response of the fiber may then be calculated as [12]:

\[ \sqrt{\sum_p \sum_q PC(p, q, w_0, w_x, w_y, \delta, \varepsilon) \cdot \tau(g, p, q)^2 - (mean \_ \_delay)^2} \]

(6.15)
where the total power is normalized to one. Here dispersion effects are not included since modal dispersion predominates. Modal bandwidth is a measure that characterizes the effect of pulse broadening in a fiber. Typical specifications are in the range from 200 MHz to 1 GHz. This helps to determine how far a system will perform at what rate [13].

6.2 Modal Bandwidth: Launch Dependence

A simple model for the bandwidth characteristics considers the fiber consisting of a number of discrete delay lines, each of which corresponds to a particular mode [14, 15, 16]. A conceptual model is shown in Figure 6.2. Here the lower order modes correspond to the modes of rays propagating down the centre of the fiber; the higher order modes propagate near the core / clad interface and the intermediate modes propagate in between. In an ideal fiber all of the delays are tuned to be identical. Thus when a temporary narrow pulse of light is launched into the fiber, its shape is maintained at the output. However, as shown in Figure 6.2, exaggerated delay error causes the output pulse to be broadened. The higher order power arrives late relative to most of the power in the intermediate modes and the lower order modes arrive early. Thus the bandwidth is reduced and information carrying capacity is limited. The modal dispersion in multimode fibers (MMFs) is one of the main performance-limiting factors in fiber optic LANs.
**All-Fiber Mode Conditioner**

launch is referred as over filled launch [17], where 100 percent of the optical power is launched to the full area of the fiber core. If the launch power distribution is reduced only the lower and intermediate modes are excited, the pulse width decreases and the bandwidth goes up. When the launch is restricted to only lower order modes, the output pulse will become very narrow. Such a type of excitation will occur when a laser is launched to a multimode fiber. Laser light fills only a portion of the core due to the smaller, focused light pattern that lasers emit, such condition is referred as restricted launch. The key aspect in determining the bandwidth of a multimode fiber communications link is the number and distribution of modes within the multimode fiber, which are excited, and therefore carry optical energy. If only low order mode is launched, and there is no mode mixing, the bandwidth will be high. But often, mode mixing occurs, due to fiber profile irregularities, or mechanical perturbations of the fiber, energy will be coupled to higher order modes, and additional pulse dispersion will inevitably result.

### 6.3 Laser Launch and Differential Mode Delay

The small spot size of lasers concentrate energy near the center of the multimode fibers and hence are sensitive to any central irregularity in the refractive index profile. When an unconditioned laser source, designed for operation on a single mode fiber, is directly coupled to a multimode fiber, differential mode delay will occur. Thus a combination of the restricted launch and a flaw in the index of refraction leads to a reduction in the multimode fiber modal bandwidth [18]. The central index dip is probably the most severe defect and can occur during in the manufacture of the fiber. The central dip can occur due to the evaporation of dopant from the inner surface of the fiber perform when the perform is collapsed during the fabrication of the fiber [19]. This dip in the refractive index profile is schematically shown in Figure 6.3. The better the fiber manufacturing process and the tighter the control of process parameters, the better the quality and the more consistent the optical fiber.

In addition to the modal dispersion, the signal also broadens due to chromatic dispersion. Chromatic dispersion occurs because the index of refraction of glass changes with wavelength, and therefore the various spectral components of the signal travel at different velocities. The modal and chromatic bandwidths combine quadratically to give the fiber’s total system bandwidth as given below:
Modal Bandwidth, \(BW_m\) is inversely proportional to the differences in propagation time, or modal delays, that exist between multimode fiber modes. Also, for short-distance links, the bandwidth is dependent on the launch conditions. For multimode fiber (whether step-index or gradient-index) the excitation conditions are particularly important. Due to the constitution of the core, the laser beam can be split into two or more modes (or paths) of light. The different modes can be subject to different propagation delays and arrive at the receiver with a time skew, which causes jitter. Fiber bandwidth is a sensitive function of the index profile and is wavelength dependent, and the scaling with length depends on whether there is mode mixing [20]. DMD is the result of beam splitting caused by structural constitution of the core. Both dispersion and DMD produce the same effect - jitter that builds-up as a function of fiber length. Thus the launch dependent modal power distribution of multimode fiber combined with Differential Mode Delay (DMD) can cause serious problems in Gigabit Ethernet LANs. Worst case DMD occurs when equal power is launched into the fastest and slowest fiber mode groups appearing as pulse splitting in the impulse response [21]. Also, the use of a laser to launch a small number of low order modes into a multimode fiber is known to give rise to modal noise [22].
6.4 Mode Conditioning for Gigabit Networks

To achieve useful link distances at Gigabit speeds, the signal from the single mode must be adapted to the multimode fiber. Theoretical studies confirmed that an offset single mode to multimode fiber launch could solve the problem by maintaining a high bandwidth due to mode conditioning effect, where only mid order modes of the multimode fiber are strongly excited. The mid order modes excited is predominately within a small number of mode groups and thus have similar propagation constants. This leads to a reduction in modal dispersion and thus to a significant increase in bandwidth where the enhancement results from the selection of launched modes [2]. Also, the offset launch is tolerant both to the launch conditions and to any imperfections in the fiber refractive index profile.
This adaption is conventionally done using an optical mode conditioning patch cable (MCP), which is an optical mode conditioner for efficiently conditioning a single mode optical signal propagating in a single mode optical fiber for propagation within a multimode optical fiber. It is based on the principle of enhancement of bandwidth of a multimode fiber by launching optical signals with a deliberate, predetermined offset between the central axis of the single-mode fiber and the multimode fiber. The desired optical intensity profile is a Gaussian mode distribution, similar to that obtained when a multimode light source is used with multimode fiber. This offset launch condition, represents a significant advancement because it has the potential to extend the bandwidth of multimode optical fiber already installed in existing network configurations, such as in a LAN. This is implemented by connecting the GbE electronics to the cable plant using a special patch cord called a "Mode Conditioning Patch Cord". It contains a single-mode fiber (for attaching to the transmitter) connected precisely off-center to a multimode fiber [13] as shown in Figure 6.4. This offset creates a launch that performs very well on multimode fiber. The GbE specification requires the offset launch positioning for LX 1300 nm long-wavelength systems operating on both 62.5\(\mu\)m and 50\(\mu\)m multimode fiber [13].

6.5 Offset Launch Methods

There are different approaches to implement the mode conditioning: offset splicing, offset alignment, special ceramic ferrules and dough-nut launching. In offset splicing technique, a single mode fiber and multi-mode fiber are joined by fusion splicing.
Fusion splicing is accomplished by applying sufficient heat to the fiber ends to fuse the fibers together, thereby creating a single continuous fiber optic path [23]. The fibers are aligned in the fusion splicing process in such a manner as to provide the mode conditioning function. This can be accomplished using commercially available fusion splice device. During the fusion splicing process, the thinner core of the single mode fiber is aligned such that it is slightly offset from the center of the thicker core of the multi-mode fiber as shown in Figure 6.5. The amount of offset is calculated prior to splicing; thus, the fibers do not need to be tuned during the splicing process. Preferably, the two fiber core center offset required for 50/125μm fiber is 10-16μm and that for 62.5/125μm fiber is 17-23μm [13]. This slight offset causes the light of the lowest order propagation mode exiting the single mode fiber to avoid entering the center of the core of the multi-mode fiber. This enable the optical path to avoid the imperfections and obstructions that exist throughout the core centers of older, lower quality multi-mode fibers used in many existing infrastructures. Fibers joined using a fusion splice form a monolithic mode conditioner, that is not susceptible to alignment shifting after installation. In addition, fused fibers do not introduce modal noise [23]. Splice method also do not use epoxy in the optical path, the use of which lowers thermal stability. A tolerance analysis of this approach revealed that some installations could experience unacceptable variability in the splice elements, resulting in poor alignment and ineffective mode conditioning. Also it is very difficult to protect the offseted splice region. A small perturbation can cause break or change in the mode conditioning.

![Figure 6.5: Illustration of offset launching technique](image-url)
Other methods use special ceramic ferrules or active alignment to achieve the mode conditioning. Special ceramic ferrules are costly; while active alignment is time consuming and complex. In another approach, ferrules with different dimensions are used to achieve the required offset. The concept of this approach is illustrated in Figure 6.6, where ferrules of diameters 125 µm and 144 µm is used for a 50/125 µm fiber. A simple and cost effective method has been proposed based on differentially changing the fiber geometry and then coupling the light from single mode to multimode fiber, through a connector type mechanism [3]. Here in this process the fibers are etched to suitable dimensions to get the offset and the fibers are placed in ferrules with same dimension (125 µm ferrule). Only single mode fiber is etched. The required dimensions of the etched single mode fiber is 85 µm with a 62.5/125 µm fiber and 99 µm with a 50/125 µm fiber. This method is attractive because it uses only standard ferrules. This avoids the need for costly offsetted ferrules and also causes significant reduction in the manufacturing time. This mode conditioner does not require as precise an alignment as current methods using ceramic ferrules, which will also contribute to lower manufacturing costs. Recently an angular offset launching
technique for bandwidth improvement has been reported [24]. Bandwidth enhancements based on mode filtering [25] and mode field matched centre launch method [26] also have been reported. Most of these methods are sensitive to environmental stresses and suffer long term performance degradation.

### 6.6 Coupled Power Ratio

Knowledge about the modal power distribution is desirable to predict the performance of high-speed systems. A wide-field charge-coupled-device camera can be used to measure the two-dimensional spatial distribution of optical power at the output of the multimode fiber [27]. It is possible to characterize the modal distribution by measuring its near field and calculating the Modal Power distribution. The simple method to get a measure of this Modal Power Distribution is the Coupled Power Ratio Measurement. Coupled Power Ratio (CPR) is a qualitative measurement that is commonly used to describe the mode power distribution in multimode fibers. It is the ratio of the total power out of a multimode fiber to the power measured when a single mode fiber is coupled to the multimode fiber [28]. The coupled power ratio is often used to evaluate the launch conditions of transmitters and light sources into multimode fibers and is used in some standards for establishing attenuation measurements criteria for installed fiber plants [29].

The coupled power per mode observed at the output of a multimode fiber that has been excited by a single transverse mode source can be calculated as:

$$\text{CP}(p, q, w_0, w_x, w_y, \delta_x, \delta_y, \epsilon_x, \epsilon_y) =$$

$$\left( C(p, q, w_0, w_x, w_y, \delta_x, \epsilon_x) \cdot C(p, q, w_0, w_x, w_y, \delta_y, \epsilon_y) \right)^2$$

(6.17)

where $\delta_x$, $\epsilon_x$ and $\delta_y$, $\epsilon_y$ are the offsets of the input single mode source and the sampling single mode fiber in the x and y directions respectively.

If $\epsilon_x$ and $\epsilon_y$ are set to zero, the CPR in dB is then:

$$\text{CPR}(w_0, w_x, w_y, \delta_x, \delta_y) = 10\log \sum_p \sum_q \text{CP}(p, q, w_0, w_x, w_y, \delta_x, \delta_y, 0, 0)$$

(6.18)

The schematic of the CPR measurement set up is shown in Figure 6.7. The power out of the multimode fiber in the CPR test represents all modes launched into it by the light source. The single mode fiber captures only the lowest order modes. The difference in coupled power between the multimode and single mode fibers (the
Chapter 6

CPR) provides a simplified measure of the launched MPD. In the case of an under fill, the single mode fiber captures a greater percentage of light exiting the multimode fiber. The result is a smaller numerical CPR value for the under fill case. The measurement is easily done and gives quantitative and repeatable results. A higher CPR means that there is a high loss when coupled in to the single mode fiber and indicates a more fully filled launch. A low CPR indicates restricted launch conditions corresponding to under filling of the fiber. When measuring CPR, it is important to use single mode fibers at 850nm and 1300nm [29].

![Figure 6.7: Schematic of CPR measurement](image)

The coupled power ratio is measured in two steps. In the first step, the mode conditioner is directly connected to a power meter and the absolute power is recorded as $P_1$ (dBm). In the second step, a single mode fiber is connected to the multimode fiber and the power coupled to the single mode fiber is recorded as $P_2$ (dBm). Now, CPR is calculated as, $P_1 - P_2$ (dB). A higher order mode filter is incorporated in the measurement path, by making a mandrel of diameter 30 mm in the single mode launch. The number of turns is five or six. In cases where mechanical instability causes variations $>0.5$ dB in the successive power readings follow the averaging procedure is followed by taking reading for five times. All the individual readings must be within the acceptable range. For 50/125 $\mu$m fiber the CPR should be in the range of 12-20 dB, while that for 62.5/125 $\mu$m is 28-40 dB [13].

6.7 Long Period Gratings

Long Period Grating helps to achieve coupling between co-propagating modes of a fiber. LPGs are designed to couple light between two guided modes of a few-mode fiber [30] and also between the guided mode and the cladding modes of a single mode fiber [31]. The fabrication of an LPG relies on the introduction of a periodic

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151
modulation of the optical properties of the fiber, which can be in the form of index modulation along the fiber core [31] or physical deformation along the fiber [32]. The most widely used method of introducing an index modulation is by exposing a photosensitive fiber to UV irradiation. Index modulation has also been achieved by ion implantation, near infrared femto-second pulse irradiation, \text{CO}_2\text{-laser irradiation and electrical discharges. The fabrication method of LPGs on standard single mode fiber is detailed in Chapter 5.}

Fiber-to-fiber coupling via the cladding mode of the fiber can relax the alignment tolerances substantially [33,34]. A lens-free fiber-to-fiber connector that has a long working distance and a wide alignment tolerance has been implemented by using two matched LPGs written in a double-cladding fiber [35]. Lateral alignment tolerances of ~450 \(\mu\)m and ~3 mm for coupling losses less than 1 dB and 3 dB respectively have been achieved. Laser-to-fiber coupling based on an LPG and a lens has also been demonstrated [36]. A working distance longer than 100 \(\mu\)m and a lateral tolerance of 2.5 \(\mu\)m have been obtained [36]. Fiber-to-waveguide coupling has also been demonstrated with a \text{CO}_2\text{-laser-induced} LPG [37], which does not require access to the fiber and waveguide end faces. Long period gratings written on the single mode to multimode fiber interface to control the modal power distribution is explored in the following sections. The concept is to couple the power from the guided mode of the first fiber, which is single mode, to the guided modes of the second multimode fiber that is permanently joined to the first fiber. The power coupled is controlled through the long period gratings written on the fibers.

### 6.8 Mode Conditioner based on LPGs

All-fiber mode conditioning device is realized by fusion splicing a single mode fiber to a multimode fiber and then inscribing a long period grating at the single mode to multimode fiber interface. The long period grating helps to couple power from the core mode of the single mode fiber to the guided modes of the multimode fiber. Long period fiber gratings are fabricated using electric arc discharge method, using a commercially available splicing machine. A setup as described in Chapter 5 is used for the fabrication of the long period grating.

#### 6.8.1 Fabrication

The setup consists of a source at 1310nm, precision translation stages and a power meter. A small weight (~10gm) is attached to one end of the fiber to keep it under
tension. The power coming out of the multimode fiber is captured using a single mode fiber to monitor the CPR value. After exposing the fiber to one arc, the fiber is moved by a distance equal to the grating period, using the precision translation stages. The period of the grating is optimized at 450µm. The single mode fiber used is Corning SMF-28 with a mode field diameter of ~10µm at 1310nm. The multimode fiber used is a graded index fiber from Corning with a core radius of 62.5µm. The single mode fiber is spliced to the multimode fiber, through cladding alignment method. The coupled power ratio is recorded after every five arcs from the splicing machine.

The modal power distribution is characterized by measuring the CPR value as described in section 6.6. The variation in CPR at 1310nm with the length of the grating is shown in Figure 6.8. The CPR value increases almost in a linear fashion with the grating length. It can be seen that a grating length of 10mm is sufficient to get the required CPR value >28dB. The long period grating at the single mode fiber to multimode fiber interface converts the forward propagating core modes to forward propagating cladding modes. These cladding modes are guided by the multimode fiber as its core modes. The insertion loss is below 0.2 dB when the grating length is 10mm, indicating that the power is coupled to the forward propagating core mode of the multimode fiber. However increase in insertion loss (above 0.5 dB) is observed after a grating length of 15mm, which may be due to the coupling to the lossy cladding modes of the multimode fiber. The splice and grating is protected in the conventional way a splice is protected, using a metal rod assisted package. The length of the package is 40mm, and hence offers a compact all-fiber solution, for mode conditioning.

![Figure 6.8: Variation of CPR with grating length](image-url)
A 62.5/125 multimode fiber link is characterized by measuring the bit error. Signal at 1GHz is launched into a 500m MM fiber through LPG based mode conditioning element. The signal is detected using a high speed photo-detector and the bit error rate is monitored. A data pattern of PRBS $2^{31}-1$ is used. The Figure 6.9 shows the BER measurement data of the system when mode conditioners with different grating lengths are used. It is found that with grating inscription, the performance of the link is improved.

![Figure 6.9: Plot of BER versus grating length at 1310nm for 62.5\(\mu m\) link](image)

The CPR distribution of 15 samples of 62.5/125\(\mu m\) mode conditioning samples fabricated is shown in Figure 6.10. It is seen that the CPR values of 75% samples falls in the category of 28-31 dB, which is fairly good value of mode conditioning. More than 95% samples made with the current process confirm to the CPR values as specified by the IEEE requirement, which proves the consistency of the developed method. The CPR values conform to the IEEE 802.3z standard, industry standard which specifically provides for operation of single mode transceivers over multimode fiber optic cables. Though the standard allows an insertion loss value of 0.5 dB, our typical loss is around 0.3dB. The typical back reflection values are greater than 45 dB, in the mode conditioned channel. LPG based mode conditioning offers better back reflection performance, since the long period gratings couple power only to the forward propagating modes and there is no optical discontinuity in the path.
6.8.2 Sensitivity Studies

The mode conditioning depends on the coupling of power between the modes of the fiber. Here the sensitivity of the position of the grating at the single mode-multimode interface is analyzed. Figure 6.11 shows the variation in CPR and insertion loss of the LPG based mode conditioning element written on a 62.5/125µm fiber. Here a grating of fixed length (10mm) is considered. The centre of the grating is taken as the origin of the grating. It is observed that the CPR value is almost stable when the grating is close to the interface. As the grating centre shifts to the single mode side, both CPR and IL become high. This is attributed to the coupling of power from the guide modes of the single mode fiber to the leaky modes of the multimode fiber. On the other hand, if the grating lies on the multimode fiber, its CPR value is not well controlled. This can be due to the difference in behaviour of grating formed on multimode fibers and needs more analysis.

The effect of combinational effect of misalignment between the single mode fiber and multimode fiber introduced during the splicing and the grating length written on the interface is studied. Figure 6.12 shows the evolution of CPR values with for different lateral mis-alignment between the single mode and multimode fiber combined with the strength of LPGs. The misalignment helps to achieve CPR with less grating strength. However, the insertion loss increases slightly. The insertion loss measurement before the grating inscription shows that the insertion loss increase is not due to the lateral misalignment. Thus the loss increase can be attributed to coupling to some of the leaky modes of the multimode fiber.
6.8.3 Stability Analysis

Even though the products meet performance specifications, they could still suffer from performance degradation and even failure in the field. Hence product samples are subjected to accelerated test conditions to ensure the field operability. Our studies indicate that most field problems can be attributed to: a. Fiber fracture, b. High Insertion Loss due to fiber misalignment or bending caused by the stress induced effects. Optical microscopic technique can be used to identify the cause and location of the failure, if any. Fiber fracture occurs when the fiber inside the assembly were
subjected to stress induced effects. This factor is taken care in our packaging and assembling process.

Figure 6.13: Variation in CPR values with temperature cycling

Figure 6.14: Variation in BR values with temperature cycling

To analyze the effect of severe environmental conditions the devices are subjected to the following tests, viz Humidity Aging (HA), Low Temperature, Temperature Life, Impact Test and Vibration Test as per the relevant standards [38]. Variation of the Insertion Loss, Coupled Power Ratio and Back Reflection of the device are measured after each tests. The parameters were measured both before and after the tests. Also online monitoring is done during temperature cycling and humidity aging. A sample size of 11 is chosen, with no failure as the reliability criteria. A device is judged fail if any specification item is not met, during or after the test. With the new method the
CPR stability is within 2dB of the initial value, for a period of 500 thermal cycles from -40 to +85°C. The BR value is highly stable compared to the offset launch technique. The insertion loss during the temperature cycling is stable within ±0.1 dB.

6.9 Conclusions

An all-fiber solution for the mode conditioning, based on LPG has been proposed, fabricated and evaluated. The coupled power ratio increases almost linearly with the grating strength. The device offers good control on modal excitation and improves the performance of the link. The positional sensitivity of LPG has been studied and found to be best close to the splice point. The thermal stability and back reflection have been compared with existing solution and found to be far better. The back reflection performance of the device is better, since LPGs couple power to the forward propagating modes. This offers the technique to build a compact and stable mode-conditioning device for Gigabit Ethernet LANs. All the 11 samples passed reliability tests, with out any failure, thus proving the process stability and less sensitivity to environmental variations.

References


158
All-Fiber Mode Conditioner