CHAPTER 5

APPLICATIONS OF DELAY LINE FILTERS

5.1 DISPERSION

Dispersion is the phenomenon in which the phase velocity or alternatively group velocity of a wave depends on its frequency. Dispersion induces pulse broadening and distortion of the bits, which ultimately lead to errors in a digital optical communication system. Dispersion is sometimes called Chromatic Dispersion (CD) to highlight its wavelength-dependent nature, or group-velocity dispersion (GVD) to signify the role of the group velocity. The dispersion is classified based on two different types namely Intermodal or Modal Dispersion and Intramodal or Chromatic Dispersion.

a) Intermodal or Modal Dispersion

Intermodal or modal dispersion is seen in multi-mode fibers where the optical signal propagates in different “modes”, each one following a different trajectory path inside the fiber’s core, which follows ray theory. All the modes, from a single pulse, experience different delays that result in output pulse broadening. This effect strongly depends on the refractive index profile of the fiber within and around the fiber core.

b) Intramodal or Chromatic Dispersion

An intramodal dispersion, sometimes called material dispersion, is a category of dispersion that occurs within a single-mode. This dispersion
mechanism is a result of material properties of optical fiber and applies to both single-mode and multi-mode fibers. The propagation delay differs between the different spectral components of the transmitted signal which causes intramodal dispersion. There are two distinct types of intramodal dispersion namely chromatic dispersion and polarization mode dispersion (PMD).

In single mode fiber (SMF), transmission performance is primarily limited by chromatic dispersion (also called as Group Velocity Dispersion (GVD)) which occurs due to refractive index variation of the fiber with the wavelength of the light, and the light from optical sources necessarily has non-zero spectral width. It is the fact that dispersion has become one of the major factors which affects the performance of long distance fiber-optical transmission. Therefore, it is necessary to investigate the dispersion characteristics of optical fiber transmission system for providing means and ways to reduce dispersion effects. Further, the main aim of communication systems is to increase the transmission distance by overcoming optical fiber dispersion effects.

Polarization Mode Dispersion (PMD) is another source of limitation, where refractive index of the medium depends on the frequency of the incident optical field. If the incident light has two polarization components due to refractive difference between the fast axis and slow axis, the transmit rate of the two polarization component will be different. Because of fiber birefringence changes, the group velocity of different polarization is also random resulting in Polarization Mode Dispersion (PMD)

5.2 DISPERSION COMPENSATION

The chromatic dispersion \( D \) is defined as the derivative of the group delay with respect to wavelength. The group delay \( \tau \) itself is the derivative of
the phase response with respect to the wavelength. The variation of dispersion with respect to wavelength is called the dispersion slope $S$. The constant portion of the CD is usually called dispersion $D$, whereas the linear portion is usually called dispersion slope $S$. Dispersion slope can be compensated by using a filter with an opposite slope. Therefore, $D$ is usually compensated by dispersion-compensating fibers (DCF) that have a fixed dispersion value. Dispersion-compensating fiber (DCF) provides an optical medium with a relatively large negative chromatic dispersion factor ($D(\lambda)$) at the operating wavelength. If a transmission fiber of length $L_{TF}$ is connected in series with a DCF of length $L_{DCF}$, then the total chromatic dispersion is given by

$$\Delta t = L_{TF} D_{TF}(\lambda) \Delta \lambda + L_{DCF} D_{DCF}(\lambda) \Delta \lambda$$  \hspace{1cm} (5.1)$$

where $D_{TF}(\lambda)$ is the chromatic dispersion factor for the transmission fiber, $D_{DCF}(\lambda)$ is the chromatic dispersion factor for the DCF and $\Delta \lambda$ is the transmitter spectral width. Similarly, the total attenuation loss of the two-fiber combination is given by

$$\text{Loss} = L_{TF} A_{TF} + L_{DCF} A_{DCF}$$  \hspace{1cm} (5.2)$$

Therefore, given target values for chromatic dispersion, attenuation loss, specifications of the transmitter, fiber and receiver, it is possible to determine the lengths of the transmission fiber and the DCF by solving the above two equations simultaneously.

The maximum allowable dispersion (or pulse spread) $\Delta t_{\text{max}}$ is given in terms of the transmission rate ($R$) by the following equation:

$$\Delta t_{\text{max}} = \frac{1}{4R}$$  \hspace{1cm} (5.3)$$
For standard single-mode fiber driven by a directly-modulated laser diode transmitter, the pulse spread due to chromatic dispersion is given by:

\[ \Delta t = L D(\lambda) \Delta \lambda \]  \hspace{1cm} (5.4)

where

\[ \Delta t = \text{pulse spread (ps)} \]
\[ L = \text{fiber length (km)} \]
\[ D(\lambda) = \text{chromatic dispersion factor (ps/nm-km)} \]
\[ \lambda = \text{operating wavelength (nm)} \]
\[ \Delta \lambda = \text{spectral width of the transmitter output (nm)} \]

The chromatic dispersion factor can be calculated from the formula

\[ D(\lambda) = S_0 \left( \frac{\lambda_0}{\lambda} \right)^{\frac{1}{3}} \Delta \lambda \]  \hspace{1cm} (5.5)

where

\[ S_0 = \text{zero dispersion slope (ps/nm}^2\text{-km)} \]
\[ \lambda_0 = \text{zero dispersion wavelength (nm)} \]

The dispersion-limited fiber length is the value of \( L \) such that \( \Delta t = \Delta t_{\text{max}} \).

Commonly used dispersion compensation and management techniques could be broadly classified as: Dispersion Compensating Fibers (DCF), chirped Fiber Bragg Gratings (FBG) and High-Order Mode (HOM) fiber. The idea of using dispersion compensation fiber for
dispersion compensation was proposed as early as in 1980, until after the invention of optical amplifiers, DCF began to be widespread attention and study. As products of DCF are more mature, have wide bandwidth, stable, not easily affected by temperature, DCF has become a most useful method of dispersion compensation and has been extensively used. There is positive second-order and third-order dispersion value in SMF (Single Mode Fiber), while the DCF dispersion value is negative. Hence by inserting a DCF, the average dispersion can be brought close to zero. IF Four Wave Mixing (FWM) and Cross Phase Modulation (XPM) were ignored and considering Self Phase Modulation (SPM) and dispersion alone, the signal transmission can be examined by solving the nonlinear Schrodinger equation.

\[
\frac{\partial A_j(z,t)}{\partial z} + \frac{1}{2} \beta_2 \frac{\partial^2 A_j(z,t)}{\partial t^2} - i \gamma |A_j(z,t)|^2 A_j(z,t) + \frac{1}{2} \alpha |A_j(z,t)|^4 A_j(z,t) = 0 \quad (5.6)
\]

\(A_j(z,t)\) is complex amplitude of \(j\)th channel optical pulse, \(\beta_2\) is the dispersion parameter of \(j\)th channel, \(\gamma\) is the nonlinear coefficient, and \(\alpha\) is the loss coefficient. After N-section dispersion compensation due to DCF, the channel residual dispersion can be expressed as

\[
\Delta D(\hat{\tau}_j) = N L_{\text{SMF}} \left[ \left( 1 - \mu_p \right) D_{\text{SMF}}(\hat{\tau}_p) + (j-p) \left( \frac{dD_{\text{SMF}}(\hat{\tau}_p)}{d\tau} \cdot \frac{dD_{\text{DCF}}(\hat{\tau}_p)}{d\tau} \right) \right] \quad (5.7)
\]

In the above formula, the dispersion compensation rate is given by

\[
\mu_p = \left| \frac{D_{\text{DCF}}(\hat{\tau}_p) L_{\text{DCF}}}{D_{\text{SMF}}(\hat{\tau}_p) L_{\text{SMF}}} \right| \quad (5.8)
\]
L_{SMF} and L_{DCF} are the conventional single-mode fiber length and dispersion compensation fiber length within the amplifier spacing. \( \Delta \lambda \) is the channel wavelength spacing. \( D_{DCF}(\lambda_p) \) and \( D_{SMF}(\lambda_p) \) are the dispersion coefficient of conventional single-mode fiber and dispersion compensation fiber at the \( \lambda_p \) wavelength.

### 5.3 DCF BASED DISPERSION COMPENSATION SCHEMES

#### 5.3.1 DCF for Perfect Compensation

Perfect compensation means to completely compensate the GVD effect. It is also called 100% compensation or no residual dispersion. The condition for perfect dispersion compensation is expressed in the following equation (Agrawal 2003)

\[
S_1D_1 = S_2D_2 \tag{5.9}
\]

where \( S_1 \) is the total length of the SMF in the link, \( S_2 \) is the total length of the DCF that must be used to achieve 100% compensation; while \( D_1 \) and \( D_2 \) are the dispersion values for the SMF and DCF respectively. Modern fiber optic communication systems use the 1550 nm low-loss window. In this window, most fibers have positive dispersion and therefore the compensating fibers are designed to exhibit negative dispersion.

#### 5.3.2 Pre Compensation Scheme

This approach for dispersion management modifies the characteristics of input pulses at the transmitter before they are launched into the fiber link. It consists of changing the spectral amplitude \( \tilde{A}(0, \omega) \) of the input pulse in such a way that GVD induced degradation is eliminated, or atleast reduced substantially. Clearly, if the spectral amplitude is changed as
where L is the fiber length, GVD will be compensated exactly, and the pulse will retain its shape at the fiber output. Unfortunately, it is not easy to implement Eq. (5.10) in practice. In a simple approach, the input pulse is chirped suitably to minimize the GVD-induced pulse broadening. Since the frequency chirp is applied at the transmitter before propagation of the pulse, this scheme is called the prechirp technique.

5.3.3 Post Compensation Scheme

Electronic techniques can be used for compensation of GVD within the receiver. The philosophy behind this approach is that even though the optical signal has been degraded by GVD, one may be able to equalize the effects of dispersion electronically if the fiber acts as a linear system. It is relatively easy to compensate for dispersion if a heterodyne receiver is used for signal detection. A heterodyne receiver first converts the optical signal into a microwave signal at the intermediate frequency ($\omega_{IF}$) while preserving both the amplitude and phase information. A microwave bandpass filter whose impulse response is governed by the transfer function should restore the received signal to its original form.

\[
H(\omega) = \exp \left[ -i(\omega - \omega_{IF})^2 \frac{\beta_2 L}{2} \right] \tag{5.11}
\]

5.3.4 Mix Compensation Scheme

This type of dispersion compensation is the combination of both pre and post compensation techniques. Mix compensation is realized by placing a DCF before the single mode fiber at transmitter side, whereas another DCF is provided after the fiber link at the optical receiver.
5.3.5 **DCF Orientation in Dispersion Compensation**

Based on optical transmission equation, considering the various types of nonlinear effects and the impact of Erbium Doped Fibre Amplifier (EDFA), system simulation models are established. According to relative position of DCF and single-mode fiber, post-compensation, pre-compensation, mix compensation is analyzed. DCF Pre-compensation schemes achieve dispersion compensation by placing the DCF before a certain conventional single-mode fiber. Post-compensation scheme achieve dispersion compensation by placing the DCF after a certain conventional single-mode fiber. Mix compensation scheme consist of post-compensation and pre-compensation. Different location on the system will generate different nonlinear effects.

5.4 **DELAY LINE FILTER BASED COMPENSATION**

An alternate approach to compensate dispersion is the use of either recursive Delay line filters (DLFs) or non recursive DLFs. The complex filter coefficients of non recursive DLF for dispersion and dispersion-slope compensation, can be controlled by a single parameter. The advantage of DLFs is that their behaviour can be fully controlled by their coefficients, whereas filter coefficients can be determined for both static and adaptive case. There is a need for significant computational efforts to determine and optimize the coefficients for filters of high order.

In general terms, the input field

\[ E_i = E_0(t)e^{j\omega t} \quad (5.12) \]

is split into (N+1) different copies that are delayed individually by multiples of the unity delay \( T_i = iT_0(0 \leq i \leq N) \). The unity delay \( T_0 \) defines the spectral
periodicity of the filter called Free Spectral Range (FSR). The filter order N is determined by the highest delay \( T_N = NT_0 \). These copies of the input field \( E_i \) are finally recombined. The splitting and combining ratios determine the complex weighting coefficients \( b_i \). The output field computes to

\[
E_0 = b_0 E_i + b_1 e^{i\varphi T_1} E_i + b_2 e^{i\varphi T_2} E_i + \ldots
\]  

(5.13)

Thus, the filter transfer function \( H(e^{i\varphi}) = E_0/E_i \) can be written as

\[
H(e^{i\varphi}) = \sum_{i=0}^{N} b_i e^{i\varphi T_0}
\]  

(5.14)

Setting \( z = e^{-j\varphi T_0} \) produces the standard description of a FIR filter in z-domain

\[
H(z) = \sum_{i=0}^{N} b_i z^{-i}
\]  

(5.15)

Unlike classical electrical FIR filters, the filter coefficients \( b_i \) are complex here. It is worth mentioning that this representation can be used regardless of the way the electrical field is manipulated, i.e. the same description applies for optical delay line filters (direct manipulation of the electric field) and for electronic filters in conjunction with coherent detection (real and imaginary part of the field are manipulated separately in butterfly finite impulse response (FIR) filter structures).

### 5.4.1 Dispersion - Slope Compensation

In digital signal processing theory, digital filters such as infinite-impulse response (IIR) and finite-impulse response filters (FIR) comprises of unit delays, weighting elements, and adders which can also be realized in optical domain. Such an optical delay line filter have periodic transfer behaviour.
The transfer function of a causal non recursive delay line filter of order N is given by

\[ H(z) = \sum_{k=0}^{N} b(k)z^{-k} \]  

(5.16)

Equivalently, transfer function can be described by filter’s zeros,

\[ H(z) = \prod_{k=1}^{N} (1 - z(k) \ast z^{-1}) \]  

(5.17)

where

\[ z(k) = a(k) \ast \exp(j \varphi(k)) \]  

(5.18)

Each zero brings an independent contribution to the phase response. As the magnitude of the zero approaches unit circle, magnitude of group delay increases. The dispersion \( D_n \) is calculated by differentiating the phase twice and hence each zero brings an independent contribution to the dispersion as well.

### 5.5 Dispersion Compensation Simulation Using DCF

A single channel SMF link is simulated for 10 Gbps and 40 Gbps data rate. The system includes the transmitter module, 120 Km SMF and a receiver. An Mach-Zehnder external modulator is used to modulate the intensity of the 193.1THz CW Laser. NRZ coding is used in this study. EDFA is used to compensate the power loss due to SMF and the DCF.
Figure 5.1(a) Post-Compensation Scheme

Figure 5.1(b) Pre-Compensation Scheme
Figure 5.1(a) and (b) show the post compensation scheme and the pre-compensation scheme respectively. The mix-compensation scheme is the combination of post and pre-compensation schemes which is shown in Figure 5.2.

A DFB Laser source operating at a frequency of 193.1THz (1550 nm) with an output power of 0dBm is taken for the analysis. A single-channel 10-Gbps Non-Return-to-Zero (NRZ) wave form, generated by a pseudorandom binary sequence (PRBS) length of 128 bits, is provided to the Mach Zehnder modulator. An optical fiber transmission channel comprising of 120 km of single mode fiber is being compensated by a negative dispersion fiber of length 24 km and an Erbium doped fiber amplifier with a Gain of 20dB, is considered for the system simulation. The entire link is simulated in optisystem software.
5.5.1 Results and Discussion

The comparison of the pre, post and mix compensation techniques with and without DCF for 10 Gbps was carried out and the results were compared. Figure 5.3 shows the eye pattern for SMF link without DCF. Figure 5.4 shows the result of pre-compensation Techniques for 10 Gbps. The eye pattern, Q-value and Min BER are shown in 5.4 (a), (b) and (c) respectively. Figure 5.5 and 5.6 shows the post and mix-compensation techniques for 10 Gbps with the corresponding eye-pattern, Q and BER value. It is observed that a Q of 4.112 and min BER of 1.958 e-5 is provided by the link.
Figure 5.4  Pre -Compensation Techniques for 10Gbps (a) eye pattern (b) Q-value and (c) Min BER

Similar analysis is repeated for post and mix compensation schemes. The Q factor and minimum BER are determined.
Figure 5.5 Post-Compensation Techniques for 10 Gbps (a) Eye pattern (b) Q-value and (c) Min BER
Figure 5.6 Mix Compensation Techniques for 10 Gbps (a) Eye pattern (b) Q-value and (c) Min BER
Table 5.1 shows the comparison between BER and Q value of pre-compensation, post-compensation, mix compensation scheme and without DCF. The same SMF length (120 km) has been considered for all the four conditions. It is found that the Q value is 3.037 and BER is about 0.0012 for the link without DCF. It is also observed that the pre and post compensation present almost similar Q values. Out of all the compensation techniques considered here, it is found that the mix compensation scheme gives high Q value (7.094) and the BER value is also the least (5.069e-013). These observations are in accordance with the reports available in the literature.

Table 5.1 Comparison of BER and Q values for DCF Compensation technique with and without DCF

<table>
<thead>
<tr>
<th>S.N O</th>
<th>SCHEME</th>
<th>DCF LENGTH (Km)</th>
<th>SMF LENGTH (Km)</th>
<th>Q</th>
<th>Min BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Without DCF</td>
<td>-</td>
<td>120</td>
<td>3.037</td>
<td>0.0012</td>
</tr>
<tr>
<td>2</td>
<td>Pre - Compensation</td>
<td>24</td>
<td>120</td>
<td>4.112</td>
<td>1.958e-005</td>
</tr>
<tr>
<td>3</td>
<td>Post - Compensation</td>
<td>24</td>
<td>120</td>
<td>4.190</td>
<td>1.395e-005</td>
</tr>
<tr>
<td>4</td>
<td>Mix - Compensation</td>
<td>24</td>
<td>120</td>
<td>7.094</td>
<td>5.069e-013</td>
</tr>
</tbody>
</table>
5.6 DISPERSION COMPENSATION USING DLF

The dispersion of each zero has a saw tooth like shape and the shape is characterized by two parameters namely extremum of the dispersion given by \( \text{Max|D}_n \) and the zero crossing (angular frequency \( \Omega \), where \( D_n=0 \)) and \( \Omega = \phi(k) \) (Duthel et al 2006).

Thus the absolute value of the extremum is given by the amplitude of zero, whereas the zero-crossing position is shifted in frequency by the phase of zero. The angular frequency versus group delay and dispersion is shown in Figure 5.7(a) and (b).

![Figure 5.7 (a) Normalized Angular frequency Vs group delay](image-url)
The dispersion-slope compensator is used to obtain a saw tooth-shaped dispersion behaviour with arbitrary slope. Considering even symmetry for amplitude response means the filter coefficients have to be real valued. This leads to the following relations for the filter’s zeros:

\[ a(N+1-k) = a(k) \] \hspace{1cm} (5.19)

\[ \varphi(N+1-k) = -\varphi(k) \] \hspace{1cm} (5.20)

where \( 1 \leq k \leq N/2 \) for \( N \) even

and \( 1 \leq k \leq (N/2-1/2) \) for \( N \) odd

It is empirically found that a saw tooth like dispersion requires zeros with zero-crossings equally spaced over a determined range \( \Delta \varphi \). It is necessary that the dispersion extrema of the zeros are increasing linearly. Therefore, the amplitudes and phases of filter’s zeros are distributed as:
For $1 \leq k \leq (N/2+1/2)$ and $0 \leq C \leq 1$, the distribution of zeros amplitudes and phase are shown in Figure 5.8(a) and (b).

Figure 5.8 (a) Distribution of amplitudes of zeros of DLF
Filter Implementation Algorithm

The algorithm used in the filter implementation is given in the form of steps as follows:

Step 1: Let the desired response be $H_n(z)$

Step 2: Assume $A_n(z) = H_n(z)$

Step 3: Determine $B_n(z)$ from the equation.

Step 4: $B_n(z)B_n^R(z) = -A_n(z)A_n^R(z) + z^{-n}[2]$

Step 5: Find the roots of $B_n(z)B_n^R(z)$

where $B_n^R(z)$ is the reverse polynomial of $B_n(z)$

Step 6: Calculate $B_n(z)$ and multiply it by scale factor $\alpha[2]$
Step 7: Calculate coupling ratio solutions \((k_n)\) and phase solutions \((\varphi_n)\)

Step 8: Step-Down recursion \(A_{n-1}, B_{n-1}\)

Step 9: If \(n>0\), then \(n=n-1\) and go to step 3, else Output \(k\)’s and \(\varphi\)’s

Table 5.2 shown below gives the filter coefficients calculated using the synthesis algorithm

**Table 5.2 Filter coefficients**

<table>
<thead>
<tr>
<th>Design step</th>
<th>Number of stages</th>
<th>degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_Z(Z))</td>
<td></td>
<td>-0.250 + 0.433(Z^{-1}) - 0.250(Z^{-2})</td>
</tr>
<tr>
<td>(A_Z(Z)A_R^R(Z)-Z^N)</td>
<td></td>
<td>0.0625 - 0.2165(Z^{-1}) - 0.6875(Z^{-2})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.2165(Z^{-1}) + 0.0625(Z^{-4})</td>
</tr>
<tr>
<td>Roots of (B_Z(Z)B_R^R(Z))</td>
<td>1</td>
<td>0.1801, -0.5993</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5.5519, -0.5993</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.1801, -1.6687</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.5519, -1.6687</td>
</tr>
<tr>
<td>(B_z(z))</td>
<td>1</td>
<td>0.7609 + 0.3189(Z^{-1}) - 0.0821(Z^{-2})</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.1371 - 0.6788(Z^{-1}) - 0.4560(Z^{-2})</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.4560 + 0.6788(Z^{-1}) - 0.1371(Z^{-2})</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.0821 - 0.3189(Z^{-1}), 0.7609(Z^{-2})</td>
</tr>
<tr>
<td>Coupling ratio function</td>
<td>1</td>
<td>0.9026, 0.6483, 0.0974</td>
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<tr>
<td></td>
<td>2</td>
<td>0.2311, 0.2892, 0.7689</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.7689, 0.2892, 0.2311</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.0974, 0.6483, 0.9026</td>
</tr>
</tbody>
</table>
5.6.2 Digital Optical Link Simulation Incorporating DLF

The simulation setup of digital optical link is shown in Fig. 5.6. The optical transmission system consists of transmitter, fiber transmission channel and an optical DLF for dispersion compensation and a receiver. A Continuous Wave (CW) Laser source operating at a frequency of 193.1THz (1550 nm) with an output power of 0dBm is taken for the analysis. A single-channel 10-Gbps Non-Return-to-Zero (NRZ) wave form, generated by a pseudorandom binary sequence (PRBS) of length 128 bits, is provided to the Mach Zehnder modulator. An optical fiber transmission channel comprising of 120 km of single mode fiber and an Erbium doped fiber amplifier with a gain of 20dB is considered for the study.

Figure 5.9 Digital optical link for system simulation

The receiver consists of a PIN photodiode and a low pass filter with a cut-off frequency of 75% of the data rate. BER Analyzer is used to analyze the performance measure of the link in terms of BER, Q factor and an Eye-Opening Penalty (EOP). The entire link is simulated in OptiSystem simulation environment and the link parameters are evaluated.
5.6.3 Comparison Between DLF and DCF for 10 Gbps

In this section, the various simulation results based on DLF implementation using transfer function and DCF are discussed. A fifth order filter is used for simulation with the transfer function, \( H(z) = 0.0625 + 0.2165z^{-1} - 0.6875z^{-2} - 0.2165z^{-3} + 0.0625z^{-4} \). Comparison of DLF with DCF is performed in terms of Q value, min BER and eye pattern.

(a) Q factor (DLF)

(a) Q factor (DCF)

Figure 5.10 (Continued)
Figure 5.10 (Continued)
Figure 5.10 Comparison of Q factor, min BER and eye pattern for DLF and DCF techniques

The comparison between DLF and DCF techniques in terms of various performance measures such as Q-factor, min BER and eye pattern are shown in figure 5.10 a, b and c. It is found that DLF compensation gives better performance than DCF. It is observed that the Q-factor is high (6.421)
for DLF compared to DCF (4.112) technique. The BER value is also found to be less (6.524e-011) in the case of DLF, whereas in the case of DCF it is found to be 1.958e-005.

5.7 IMPLEMENTATION OF DLF USING 2 X 2 COUPLER

In the previous section, the transfer function of DLF is used for performance comparison with DCF. However in practice the transfer function is realized using optical components. We study some cases of transfer function implementation for dispersion compensation.

Fiber Optic couplers have the same functionality as electronic couplers. They split the signal to multiple points (devices). They are needed for tapping (monitoring the signal quality) for more complex telecommunication systems which require more than simple point-to-point connections such as bus, ring and star architectures. Fiber optic couplers can be either active or passive devices. The difference between active and passive couplers is that a passive coupler redistributes the optical signal without optical-to-electrical conversion. Active couplers are electronic devices that split or combine the signal electrically and use fiber optic detectors and sources for input and output.

A 2 x 2 waveguide directional coupler in its simplest form consists of two closely placed parallel single-mode optical waveguides. The basic operation of such a device involves a partial or complete transfer of power between the two waveguides. The exchange of power occurs due to optical coupling between the evanescent tail of the guided mode of one waveguide, in which light is launched and that of the natural mode of the second waveguide. This optical interaction can also be viewed as the beating between the symmetric and the anti-symmetric super modes of the composite structure. The uniformly spaced parallel interaction region plays the key role in the
coupling process. The interaction region has a longitudinally invariant structure and the optical coupling that takes place in this region can be understood through the coupled mode analysis.

Figure 5.11 (a) The symmetric and antisymmetric mode fields of the composite structure formed by a pair of identical single mode waveguides

In the coupled mode analysis across the interaction region, the two uniform waveguides lying parallel to each other are assumed as a composite
structure. The composite system formed by the two single-mode waveguides can be shown to support two modes, a symmetric (even) mode and an anti-symmetric (odd) mode. These two modes called the normal modes or supermodes of the composite structure have different propagation constants. When light is coupled into one of the waveguides, it excites a linear combination of the symmetric and the anti-symmetric supermodes as shown in Figure 5.11 (a). Due to the unequal propagation constants of the two modes, the fields propagating down the system develop a relative phase difference with the distance of propagation. For a certain length of interaction, if the accumulated phase difference between these two modes becomes \(\pi\), the superposition of these two modal fields will result in the cancellation of the field amplitudes in the input waveguide and an addition in the second waveguide. Such a situation is referred to as coupled state, and the corresponding interaction length as the coupling length, \(L_C\). If the interaction length extends beyond \(L_C\), reverse coupling takes place from the second waveguide at the input waveguide. Thus, for propagation over a length of \(2L_C\) will result in accumulation of a phase difference of \(2\pi\) and hence power will be restored back in the input waveguide. Thus a periodic exchange of power between the two waveguides takes place with propagation. If the two waveguides are identical, complete power can be transferred from one waveguide to the other and vice-versa, while for non-identical waveguides, only a certain maximum power transfer takes place Rahim et al (2012).

For unit power launched in waveguide-1 at \(z = 0\), the power distribution between the throughput (PT) and coupled (PC) waveguides at any \(z\) is given by

\[
P_T(z) = 1 - \frac{k^2}{\gamma^2} \sin^2 \gamma z
\]  
(5.23)
\[ P_c(z) = \frac{k^2}{\gamma^2} \sin^2 \gamma z \]  \hspace{1cm} (5.24)

where

\[ \gamma^2 = k^2 + \frac{(\Delta \beta)^2}{4} \]

\[ \Delta \beta = \beta_1 - \beta_2 \]

Here \( \beta_1 \) and \( \beta_2 \) are the propagation constants of the fundamental modes of the individual waveguides, and \( \kappa \) is called the coupling coefficient. \( \kappa \) is a measure of the strength of the coupling. It can be shown that:

\[ k = \frac{1}{\sqrt{1 - \frac{\Delta \beta^2}{4}} \left[ \frac{\beta_s - \beta_a}{2} \right]} \]  \hspace{1cm} (5.25)

where \( A = \frac{\Delta \beta}{2k} \) is the asymmetry parameter, \( \beta_s \) and \( \beta_a \) represent the propagation constants of the symmetric and antisymmetric supermodes and they are given by

\[ \beta_s = \frac{\beta_1 + \beta_2}{2} + \sqrt{\frac{\Delta \beta^2}{4} + k^2} \]  \hspace{1cm} (5.26)

\[ \beta_a = \frac{\beta_1 + \beta_2}{2} - \sqrt{\frac{\Delta \beta^2}{4} + k^2} \]  \hspace{1cm} (5.27)

For a symmetric coupler formed with two identical waveguides, \( \Delta \beta = 0 \) and hence

\[ k = \left[ \frac{\beta_s - \beta_a}{2} \right] \]  \hspace{1cm} (5.28)
\[ \beta_{\pm a} = \beta \pm k \]  

(5.29)

Thus, the power distributions in a symmetric coupler are given by

\[ P_T(z) = \cos^2 kz \]  

(5.30)

\[ P_C(z) = \sin^2 kz \]  

(5.31)

These equations clearly demonstrate that input power can be completely transferred to the coupled waveguide. The power remains in the input waveguide when the interaction length \( z = 0, \pi/\kappa, 2\pi/\kappa, \ldots m\pi/\kappa \); where \( m = 0,1,2,3,\ldots \) whereas the entire power is coupled to the second waveguide at \( z = \left( m + \frac{1}{2}\right)\pi/\kappa; \ m = 0,1,2,3,\ldots \). This suggests that by choosing a suitable interaction length, any arbitrary power distribution between the two interacting waveguides can be achieved. For a 50\% distribution of power, the required interaction length is \( z = \pi/4\kappa \). This is the basic principle underlying the operation of a 3dB coupler, used as signal splitters or combiners.

For an asymmetric coupler consisting of two non-identical waveguides, since \( \Delta\beta \neq 0 \), 100\% transfer of power from one waveguide to the other is not possible. The efficiency (\( \eta_{\text{max}} \)) for maximum power transfer depends on the asymmetry parameter, as

\[ \eta_{\text{max}} = \left\{ \frac{k^2}{\gamma^2 \sin^2 \gamma} \right\}_{\text{max}} \]  

(5.32)

If \( \Delta\beta/2\kappa = 1 \), then \( \eta_{\text{max}} = 1/2 \), i.e., a maximum of 50\% power transfer is possible. The coupling coefficient, \( \kappa \) quantifies the strength of coupling, which is the amount of power transfer that takes place per unit length of the coupler. \( \kappa \) is proportional to the difference between the propagation constants of the even and odd supermodes. Hence, the value of \( \kappa \)
is governed by the geometry and refractive index profile of the composite waveguide. Since the mode propagation constants vary with wavelength, \( \kappa \) is wavelength sensitive and also polarization dependent.

In optical FIR filters, the transmission characteristics is expressed by polynomials whereas in optical IIR filters, they are expressed by rational functions. Optical delay line filter have several configurations i.e., transversal form and lattice form based on its application. In order to realize the inverse channel characteristic, the filter coefficients is to be determined, which iteratively optimizes the filter coefficients to minimize dispersion and thereby reduce the bit error rate. Fiber capacity is specified in terms of the bit rate-distance product \( BL \) which is given by,

\[
BL < \frac{n_2c}{n_1\Delta}
\]  \hspace{1cm} (5.33)

where \( n_1 \) is refractive index of the core, \( n_2 \) is refractive index of the cladding, \( \Delta \) is refractive index difference and \( c \) is the velocity of light in vacuum, \( B \) is the bit rate and \( L \) is the repeater spacing. Optic couplers either split optical signals into multiple paths or combine multiple signals on one path. The number of input (N)/ output (M) ports, (i.e., N x M size) characterizes a coupler. Coupling the fiber to sources and detectors creates losses as well, especially when it involves mismatches in numerical aperture or in the size of optical fibers. Considering coupling coefficient of 0.5, we analyze BER and Q factor of optical delay line filter using 2x2 coupler based on eye opening penalty (EOP) with BER analyzer for dispersion compensation application.
5.7.1 DLF Implemented Using 2x2 Coupler

The link simulation of delay line filter using 2x2 Coupler is shown in figure 5.12 (a) and (b).

![Diagram of DLF implemented using 2x2 Coupler](image)

**Figure 5.12 (a) Link simulation of Delay Line Filter using 2x2 Coupler**

![Diagram of DLF implemented using 2x2 Coupler in Optisystem](image)

**Figure 5.12 (b) Link simulation of Delay Line Filter using 2x2 Coupler in Optisystem**
The simulation results of the DLF implementation using a 2x2 coupler is shown in Figure 5.13. The results are evaluated in terms of the Q-factor, BER and the eye pattern as shown in figure 5.12 a, b and c. The value of the Q-factor obtained using this technique is found to be 5.963 and the BER value is about 1.235e-009.

![Simulation results for DLF implemented using 2 x 2 Coupler](image)

(a) Q factor  
(b) Min BER  
(c) Eye pattern

**Figure 5.13** Simulation results for DLF implemented using 2 x 2 Coupler  
(a) Q-factor (b) BER and (c) Eye pattern
Table 5.3 shows the comparison of the BER and Q of two different DLF implementation techniques and DCF at 10 Gbps. From the table, the Q-factor is found to be high for DLF using transfer function and the BER value is also very less. It is also observed that the performance (on comparing Q and BER) of DLF is better when compared to that of DCF. DLF implemented with 2x2 coupler shows a reduced value due to losses and variations arising in practical situation.

![Figure 5.14 Comparison of Q factor for DCF and DLF](image-url)
Figure 5.14 shows the comparison of the Q-factor with respect to different lengths for the DCF and DLF implemented by transfer function. The performance of DCF and DLF are compared for different lengths of SMF link and it is found that the DLF with transfer function shows better performance than DCF at all lengths.

5.8 DISPERSION ESTIMATION

Vestigial sideband filtering can be used for chromatic dispersion measurements. An optical delay line filter providing upper sideband (USB), lower sideband (LSB), and passband was designed for that application. The straightforward utilization is to measure the time delay between the USB and the LSB. (Neumann et al 2011).

Figure 5.15 Second order delay line filter structure (Neumann et al (2011))
A second order fiber optical delay line filter (Figure 5.15) can be used to pass the signal through and couple out the USB and LSB at the same time. This delay line filter consists of two 3 x 3 fiber couplers and delay lines of lengths $T$ and $2T$. It can be tuned by adjusting the phase shifters in the interferometer arms ($\varphi_1$, $\varphi_2$ and $\varphi_3$). The coupling coefficients and the delay time difference between the delay lines define the range of operation. The scattering parameter matrix of the 3 x 3 fiber coupler with the amplitude coupling ratio ($k$) is derived as follows:

$$S_{3 \times 3} = \begin{bmatrix}
0 & 0 & 0 & \kappa & \kappa' & \kappa' \\
0 & 0 & 0 & \kappa' & \kappa & \kappa' \\
0 & 0 & 0 & \kappa' & \kappa' & \kappa \\
\kappa & \kappa' & \kappa' & 0 & 0 & 0 \\
\kappa' & \kappa & \kappa' & 0 & 0 & 0 \\
\kappa' & \kappa' & \kappa & 0 & 0 & 0
\end{bmatrix}.$$ 

Assuming unitarity (i.e., a lossless coupler) it can be written

$$1 = |k|^2 + 2|k'|^2 \quad (5.37)$$

and from

$$0 = |k|^2 + kk'^* + k^*k \quad (5.38)$$

the phase difference

$$\Delta \sigma = \arg(k) - \arg(k') = \pi - \arccos\left(\sqrt{\frac{1-|k|^2}{8|k|^2}}\right) \quad (5.39)$$

as well as

$$k' = \sqrt{1 - k^2}/2 \ e^{i\Delta \sigma} \quad (5.40)$$
follow. In the z domain, transfer functions of the optical delay line filters without feedback are defined by the complex coefficients $b_i$ or by the zeros $z_0 = e^{j\omega}$. Taking into account that the general transfer function for a dispersion compensator is

$$H_F(z) = C(1 + b_1 z^{-1} + z^{-2})$$

(5.41)

for the symmetry of the setup identical couplers have to be used and $\varphi_1 = \varphi_3$ has to be set. Thus, for a fixed free spectral range (FSR) only the phase difference $d\varphi_1 - \varphi_1 - \varphi_2$ of the path with unity delay is relevant. Hence, the transfer function with optical components (couplers, phase shifters) is

$$H_F(z) = k' k e^{j\varphi_1} (1 + \frac{k}{k'} e^{j\varphi_1} z^{-1} + z^{-2})$$

(5.42)

The transfer functions for the other ports follow accordingly:

$$H_{LSB}(z) = k' e^{j\varphi_1} (1 + e^{j\varphi_1} z^{-1} + k' z^{-2})$$

(5.43)

$$H_{USB}(z) = k' e^{j\varphi_1} (\frac{k'}{k} + e^{j\varphi_1} z^{-1} + z^{-2})$$

(5.44)

To optimize the USB, LSB, and passband functions for a 10 Gbps NRZ signal, this analytic description of the three ports was used to find the power splitting ratio of the 3 x 3 couplers (20%/40%/40%). This filter provides low passband attenuation and sufficient optical bandwidth for the LSB, USB, and passband ports. The three fiber paths with delays were set in such a way that the FSR of the filter was 25 GHz. The filter can be thermally fine-tuned by adjusting the phases $\varphi_1 \ldots \varphi_3$. The optical bandwidth of the pass-through signal is about 10 GHz so that the signal quality is not affected. The USB and LSB output port filter functions have their maximum at 15 GHz.
away from the channel centre. The transfer functions are shown in Figure 5.16.

![Figure 5.16 Transfer functions of the passband, LSB, and USB filter output ports](image)

The chromatic dispersion adds a frequency-dependent delay to the optical signal. If the upper sideband and the lower sideband are detected separately, the delay ($\Delta t$) can be seen in the electrical domain. The dispersion $D$ can be estimated from this delay Neumann et al (2011)

$$D = \frac{\Delta t}{\lambda_0 \left(1 - \frac{1}{1 + \frac{\Delta f}{c}}\right)}$$  \hspace{1cm} (5.45)$$

where $\lambda_0$ is the operating wavelength, $\Delta f$ is the frequency offset between the two sidebands, and $c$ is the speed of light in vacuum.
Table 5.4 shows the parameters for simulation for dispersion estimation in optisystem environment.

**Table 5.4 Parameters for simulation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRBS signal Bit rate</td>
<td>10 Gbps</td>
</tr>
<tr>
<td>Laser $\lambda_0$</td>
<td>1550 nm</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>15 GHZ</td>
</tr>
<tr>
<td>Length of the fiber</td>
<td>25 Kms</td>
</tr>
<tr>
<td>FSR</td>
<td>25 GHz</td>
</tr>
<tr>
<td>$D_{\text{theory}}$</td>
<td>418.75 ps/nm</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>50 ps</td>
</tr>
<tr>
<td>$D_{\text{practical}}$</td>
<td>416.25 ps/nm</td>
</tr>
</tbody>
</table>
Figure 5.17 shows the measurement setup using Optisystem Software. An optical source was externally modulated (NRZ) with a 10 Gbit/s PRBS signal. The signal is sent through SMF fiber of 25 kms length that produces dispersion. The delay (Δt) between the upper and lower sidebands was estimated from the eye diagrams of the received LSB and USB signals.

Figure 5.18 (a) Eye diagram of the LSB signal after 25 km SMF dispersion
Figure 5.18 (b) Eye diagram of the USB signal after 25 km SMF dispersion

Figure 5.18(a) and (b) shows the eye diagrams for the LSB and USB Signals of the filter under the presence of 418.75 ps/nm of chromatic dispersion. The delay between the LSB and USB signals is 50 ps. For the wavelength of 1550 nm and with a sideband separation of $\Delta f = 15$ GHz, using Eq. (5.45), this computes to 416.25 ps/nm dispersion, matching perfectly with the fiber characteristics.

5.9 DISPERSION COMPENSATION USING DLF

In the previous discussion, the dispersion present in the fiber of length 25 kms was estimated using delay line filter. It is known that delay lines can be used to compensate the dispersion present in the optical fiber. Here a dispersion compensating delay line is placed before the delay line filter as shown in figure 5.19. The eye diagram of the lower side band and upper side band is shown in figure 5.20 (a) and 5.20 (b). Comparing the results
obtained after compensation of the dispersion in the 25 kms fiber, the estimated delay between the LSB and USB has been very much reduced from 50 ps to 2 ps. i.e., the delay line could compensate the dispersion in the fiber. The dispersion was compensated from 416.75ps/nm to 16.65ps/nm.

Table 5.5 shows the link simulations parameters for dispersion compensation using DLF (transfer function $H(z) = -0.25+0.433z^{-1}-0.25z^{-2}$).

**Table 5.5 Simulation parameters for dispersion compensation using DLF**

<table>
<thead>
<tr>
<th>PRBS signal Bit rate</th>
<th>10 Gbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser frequency</td>
<td>193.1THz</td>
</tr>
<tr>
<td>Sequence length</td>
<td>128</td>
</tr>
<tr>
<td>Samples per bit</td>
<td>64</td>
</tr>
<tr>
<td>Numerator co-efficient (0)</td>
<td>-0.25</td>
</tr>
<tr>
<td>Numerator co-efficient (1)</td>
<td>0.433</td>
</tr>
<tr>
<td>Numerator co-efficient (2)</td>
<td>-0.25</td>
</tr>
<tr>
<td>Denominator co-efficient (0)</td>
<td>1</td>
</tr>
<tr>
<td>Denominator co-efficient (1)</td>
<td>-0.928983</td>
</tr>
<tr>
<td>Length of the fiber</td>
<td>25 kms</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>10 ps/nm</td>
</tr>
</tbody>
</table>
Figure 5.20 (a) Eye diagram of LSB after DLF compensation

Figure 5.20 (b) Eye diagram of USB after DLF compensation
5.10 DISPERSION COMPENSATION USING DCF

The same system simulation was repeated using DCF based compensation and the eye diagrams are obtained as shown in Figure 5.22 (a) and (b).

![Simulation link for dispersion compensation using DCF](image)

**Figure 5.21 Simulation link for dispersion compensation using DCF**

![Eye diagram of LSB after DCF Compensation](image)

**Figure 5.22(a) Eye diagram of LSB after DCF Compensation**
From the eye diagrams of LSB and USB signals, it is found that there is 6ps time delay in the electrical domain. This corresponds to the Dispersion of 49.95ps/nm. The Dispersion before compensation is 416.25 ps/nm ($\Delta t= 50$ps shift in electrical domain and dispersion after compensation is 49.95 ps/nm ($\Delta t= 6$ps).

From the above simulations it is found that the delay line filter compensation is better than that of DCF based dispersion compensation technique.
5.11 EXPERIMENTAL DEMONSTRATION OF A SIMPLE OPTICAL FILTER

Optical filters are completely described by their frequency response, which specifies how the magnitude and phase of each frequency component of an incoming signal is modified by the filter. The response of the filter can be written in terms of exponential functions with complex arguments as follows:

\[ H(\nu) = \sum_{n=0}^{N} \left[ C_n e^{-j(2\pi \nu n - \phi_n)} \right] \]  

(5.46)

where \( H(\nu) \) is the frequency response of the filter, \( N \) is the filter order, and the \( C_n e^{j\phi_n} \) terms are the complex weighting coefficients. An incoming signal is split into a number of parts that are individually weighted and then recombined. Mach Zehnder interferometers are preferred for optical implementation of delay line filters.

In MZI, an incoming signal is split equally into two paths. One path is delayed with respect to the other by a time \( T = \Delta L n / c \) where \( n \) is the refractive index of the paths, \( c \) is the velocity of light in vacuum, and \( L \) is the path length difference. The effective group index is used for waveguide delay paths. The signals in the two paths are then recombined.

In waveguide version, directional couplers are used for the splitter and combiner. The implementation has two outputs that are power complementary. The power coupling ratios for the couplers are designated by \( k_1 \) and \( k_2 \).
Coherent interference at the combiner leads to a sinusoidal frequency response whose period is inversely proportional to the path length difference.

The transfer function of an MZI can be obtained by cascading the transfer functions of two optical couplers and that of the optical delay line, suppose the optical length of the delay line in arm1 and arm2 are $n_1L_1$ and $n_2L_2$, respectively the transfer matrix of the two delay lines is simply

$$\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} \exp(-j\phi_1) & 0 \\ 0 & \exp(-j\phi_2) \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

(5.47)

where $\phi_1 = (2\pi/\lambda)n_1L_1$ and $\phi_2 = (2\pi/\lambda)n_2L_2$ are the phase delays of the two delay lines. If we further assume that the two optical couplers are identical with power splitting ratio of $\varepsilon$,

$$\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} \sqrt{1-\varepsilon} & j\sqrt{\varepsilon} \\ j\sqrt{\varepsilon} & \sqrt{1-\varepsilon} \end{bmatrix} \begin{bmatrix} e^{-j\phi_1} & 0 \\ 0 & e^{-j\phi_2} \end{bmatrix} \begin{bmatrix} \sqrt{1-\varepsilon} & j\sqrt{\varepsilon} \\ j\sqrt{\varepsilon} & \sqrt{1-\varepsilon} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

(5.48)

$$\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} (e^{-j\phi_1} - e^{-j\phi_2}) & j(e^{-j\phi_1} + e^{-j\phi_2}) \\ j(e^{-j\phi_1} + e^{-j\phi_2}) & -(e^{-j\phi_1} - e^{-j\phi_2}) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

(5.49)

If the input optical signal is only at the input port 1 and input port 2 is disconnected ($a_2=0$) the optical field at the two output ports will be

$$d_1 = \frac{1}{2}(e^{-j\phi_1} - e^{-j\phi_2})a_1 = -e^{-j\phi_0} \sin \left( \frac{\Delta \phi}{2} \right) a_1$$

(5.50)

$$d_2 = \frac{j(e^{-j\phi_1} + e^{-j\phi_2})a_1}{2} = j e^{-j\phi_0} \cos \left( \frac{\Delta \phi}{2} \right) a_1$$

(5.51)
where $\phi_0 = (\phi_1 + \phi_2)/2$ is the average phase delay and $\Delta \phi = (\phi_1 - \phi_2)$ is the differential phase shift of the two MZI arms. Then the optical power reflected from input port 1 is

$$T_{11} = \left[ \frac{d_1}{d_2} \right] \text{ for } a_2 = 0 = \sin^2 \left[ \frac{\pi f}{c} (n_2 L_2 - n_1 L_1) \right]$$

(5.52)

The optical power transfer function from input port 1 to output port 2 is

$$T_{12} = \left[ \frac{d_2}{d_1} \right] \text{ for } a_2 = 0 = \cos^2 \left[ \frac{\pi f}{c} (n_2 L_2 - n_1 L_1) \right]$$

(5.53)

where $f = c/\lambda$ is the signal optical frequency and $c$ is the speed of light. Obviously the optical powers coming out of the 2 output ports are complementary such that $T_{11} + T_{12} = 1$, which results from energy conservation since it is assumed that there is no loss.

The transmission coefficient $T_{11}$ and $T_{12}$ of an MZI are the functions of both the wavelength $\lambda$ and the differential optical length $\Delta L = n_2 L_2 - n_1 L_1$ between the two arms.

The theoretical simulation of transmission response is normalized between 0 and 1 and is shown in Figure 5.23.

The transmission response was studied for a filter having FSR of 50 MHz.

$$FSR = \frac{c}{\Delta L \cdot n}$$

(5.54)
From equation 5.54, the differential optical length $\Delta L$ can be found. Having velocity of light $c = 3 \times 10^8$, refractive index of fiber $n=1.46$, $\Delta L$ is calculated as 4m. The length of one fiber is 1 m and the second fiber is 5 m are used in the filter design of 50 MHz. The frequency is swept from 200 MHz to 300 MHz and the response is studied.

![Figure 5.23 Simulation response of MZI](image)

**Figure 5.23 Simulation response of MZI**
The experimental consists of network analyzer which generates RF sweep signal from 10 KHz to 1.5 GHz and the output from network analyzer is given to laser transmitter. The delay line filter configuration of optical filter is shown in Figure 5.24. The optical signal generated by optical transmitter is passed through variable attenuator and then to delay line filter. The delay line filter consists of two 50-50 splitter/combiner and fibers of length 1m and 5m. One of the outputs of the 50/50 splitter/combiner is given directly to the coupler through 1m fiber and the other output is connected to the 5 m fiber and then to other 50-50 splitter/combiner. The output of the optical coupler is given to the pin photo detector, whose output is viewed in the network analyzer.
The practical transmission response for frequency range of 200 MHz and 300 MHz is shown in Figure 5.25.

This approach is useful in filtering out a particular RF band, in a subcarrier multiplexed optical transmission systems. Further, this scheme does not involve optical to RF conversion. The required RF band can be filtered out and transmitted along with the optical carrier for the intended destination. The filter has been implemented as a Mach Zehnder interferometer scheme, using single mode optical fibers.