Dispersion Compensation Using Raised Cosine Filter in Optical Fibers

Shivinder Devra and Gurmeet Kaur

Abstract—**All pass filters (APFs) are used in dispersion compensation which is the foremost requirement in an optical fiber link. All pass filters can correct any order of dispersion by the careful design of multistage all pass filters starting from very simple components with the use of N port devices. Multiple channels, as in wavelength division multiplexed (WDM) system, can be compensated with a single device since these filters are periodic in phase response. The design technique and implementation of these filters has been discussed in this paper. The simulation results obtained with raised cosine filters (RCFs) are presented in this paper. The results obtained using RCF to compensate dispersion show improvement in terms of eye diagram.**

Index Terms—**Optical communication, optical fibers, wavelength division multiplexed systems, inter-symbol interference, dispersion compensation all pass filters, raised cosine filters.**

I. Introduction

All Pass filters are used to compensate the chromatic dispersion in wavelength division multiplexed (WDM) optical fiber communication system [1]. Optical fiber communication is a way of transmitting the information from one place to another by modulating the light signal with the information signal. The light signal required for communication is generated using the spontaneous and stimulated emission occurring in light emitting diodes (LEDs) and LASERs [2]. Since the energy levels are not discrete so mono-chromaticity of the light signal is lost and it introduces chromatic dispersion. The number of compensating techniques has been reported in the literature [3], [4], [5], [6] including dispersion compensating fibers (DCFs), Fiber Bragg gratings (FBGs), Electronic Dispersion compensation (EDC) each having its own advantages and disadvantages. In WDM system where a number of frequencies are interleaved, dispersion is compensated using all pass filters [7]. All pass filters are linear systems having variable phase response and constant amplitude response. The variable phase response of the APFs makes them to be used as the phase equalizers to compensate the chromatic dispersion [8] – [17]. Since APF gives complexity and increases cost so new class of digital filters called raised cosine filters [18] – [23] are now introduced to compensate dispersion.

The need of dispersion compensation, general properties of all pass filters, the design and implementation of all pass filters along with tunable dispersion compensation all pass filters, and simulation results with raised cosine filters are discussed in this paper.

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II. Need of Dispersion Compensation

Due to the presence of chromatic dispersion the light pulse carrying the required information is spread into various components and each component travel differently along the optical fiber with different velocity and hence reach at the receiver at different times which distorts the information and can't be interpreted in the correct manner This is called group velocity dispersion (GVD) which cause the light pulses to spread in fibers, degrading signals over long distance [8-11]. In order to remove the spreading of the optical or light pulses, the dispersion compensation is the most key feature required in optical fiber communication system.

The traditional techniques like DCFs, FBGs, and EDC are not suitable for dispersion compensation in WDM system. DCFs give high insertion loss, large footprint, and non-linear distortions when the input signal is high etc. Also for the multiple channels in WDM system, the number of DCFs has to be installed making the system complex and costly. The same problem is with the FBGs which compensate the dispersion by the recompression of an optical signal. For different frequencies different architectures of the FBGs have to be introduced along the fiber link. EDC is rendered ineffective for WDM system since it is complex and also not a direct method of compensation as it involve the optical to electronic and electrical to optical conversions making the WDM communication slow which can't be tolerable in this growing world hence the need of digital filters (all pass filters or raised cosine filters) is realized by which the multiple channels can be compensated with a single device because of the periodic properties of the phase response and impulse response of these filters respectively [12-15].

III. All Pass Filters (APF)

The dispersion compensation using all pass filters is a new technique for the removal of phase distortions of an optical signal. After the various channels have been multiplexed by the wavelength interleaver over the single fiber the next step is to compensate the phase distortions due to different group delays for different channels [1], [7]. Dispersion compensating fibers [2], [3] (with opposite chromatic dispersion as that of channels) are not used these days as they introduce large footprint, high insertion loss, introduce nonlinear distortion etc, hence they have been replaced by all pass filter structure. It is a special filter with flat magnitude spectrum and non-linear phase spectrum, so it compensates phase distortion without affecting magnitude spectrum of signals [8], [9]. These all pass filters (APF's) are linear systems, which have an amplitude response that is constant over all frequencies and a phase response that varies with frequency. The period of frequency response of all pass filters is usually referred to as free spectral range (FSR). Mathematically, the frequency response of a filter is written as

$$H(\omega) = |H(\omega)| \exp[\, j\,\phi(\omega)\,] \qquad (1)$$

then for an APF $|H(\omega)| = c$ where c is a constant and $\phi(\omega)$ can be made arbitrarily close to any desired phase response. With this characteristic the nth-order dispersion is evaluated as $1/\ FSR^n$, further group delay can be enhanced by adding more number of stages [12]. However it increases loss in the system. Adding stages to the APF help in recovering group delay that is lost when the FSR is increased [12], [13].

The dispersion compensation obtained experimentally is

$$D \sim N/\ FSR^2\ \Delta^2 \qquad (2)$$

where N is number of channels and Δ is distance of poles and zeros of the unit circle. The dispersion may be increased by reducing the FSR with the introduction of more number of stages or by reducing the Δ .

IV. APF Design and Implementation

For the design of an APF, a four port device with frequency independent matrix elements can be considered. By connecting any one of the outputs through a delay to any one of the inputs a single stage APF can be realized [12]. APF may be implemented using Directional couplers, Mach-Zehnder interferometer, and thin film filter as shown below in Figures 1-4:

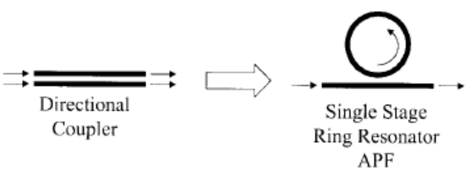


Fig. 1. Single stage APF using directional coupler [12].

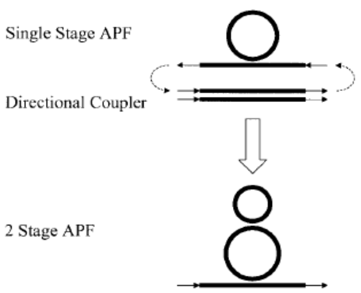


Fig. 2. Two stage APF [12].

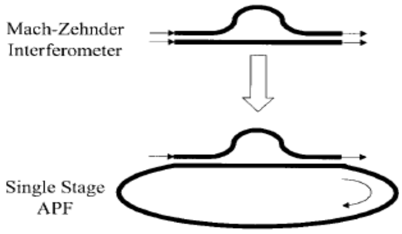


Fig. 3.Single stage APF using Mach-Zehnder interferometer [12]

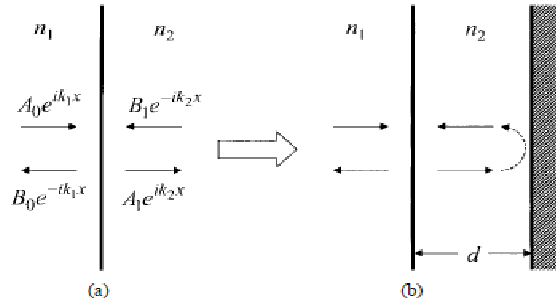


Fig. 4. Thin-film example: (a) Interface between two dielectrics. The scattering matrix relates the "input" amplitudes A0 and B1 to the "output" amplitudes A1 and B0. (b) By connecting the "output" A1 to the "input" B1 through a delay (using a 100% reflector a d istance d away), a single-stage APF is obtained. This is exactly the familiar Gires–Tournois interferometer [12].

V. Tunable Dispersion Compensation All Pass Filters

Chromatic dispersion compensation is critical for high bit rate light wave systems. Reconfigurable optical networks introduce a need for tunable dispersion compensation since different routes may have different cumulative dispersions [14]. In addition, tunable dispersion compensation is required for high bit rate nonlinear systems whose optimal dispersion depends on the channel power which may fluctuate over time [17]. Different wavelengths have different cumulative dispersions at the receiver, and a device capable of applying varying amounts of dispersion compensation to each channel is needed. Because of the large number of channels in dense wavelength-division-multiplexed (WDM) systems, periodic filters are advantageous compared to single channel devices which require a unique filter for every WDM channel [14], [15]. Tunable dispersion compensation filters are of two types:

A. Mems Compensation All Pass Filters

The tunable all-pass filter is based on the mechanical antireflection switch (MARS) device, which is a variable-thickness Fabry–Perot cavity consisting of a silicon substrate, an air gap, and a quarter-wave thick dielectric membrane. A silicon nitride layer is used for the membrane, and the gap is nominally $3\lambda_o/4$ [17]. The cavity formed by the membrane and top surface of the substrate yields a reflection of about 70%. The gap is varied from $3\lambda_o/4$ to $\lambda_o/4$ by applying a voltage to electrodes on top of the membrane as shown in Fig.5.

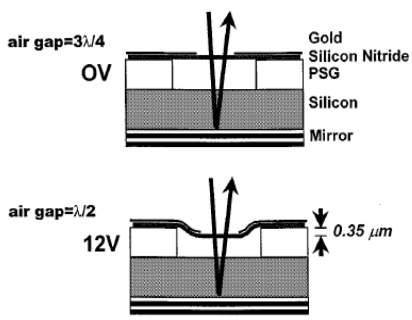


Fig. 5. MEMS all-pass filter schematic showing the change in air gap with applied voltage [14].

The voltage creates an electrostatic force that pulls the membrane closer to the substrate surface, while the membrane tension provides a linear restoring force. At a gap of $\lambda_0/4$, the reflection is reduced to ~ 0% since the silicon nitride acts as an antireflection coating for the silicon substrate. To make an all-pass filter, the aim is to use Fabry–Perot cavity as a tunable, partial reflector and add a high reflectance coating to the back side of the substrate [14]. A reflectivity > 97% is obtained using a multi-layer stack. The substrate thickness L determines the free spectral range FSR = c / $2n_gL$, where n_g is the group index, c is the velocity of light. For a 100-GHz FSR, the silicon thickness is 411 m. By selecting the filter period equal the channel spacing in a WDM system, multiple channels can be compensated. For a completely tunable all-pass filter, both the partial reflector and the cavity optical length must be tunable. By varying the applied voltage, the partial reflectance of the front mirror is changed. For tuning Φ_n, the substrate is mounted on a thermo-electric cooler, and the cavity optical thickness is tuned via the thermo-optic effect. Tuning of the cavity length can also be used to compensate for variations in the fabricated cavity length from the design nominal [14].

B. Integrated All Pass Filters For Tunable Dispersion Compensation

Two parameters control its group delay response, the phase Φ and power coupling ratio k_r. By using a multistage filter where the parameters are chosen optimally for each stage, a constant dispersion (or any desired response) can be approximated over a large portion of the FSR, thus yielding a large bandwidth utilization factor [15]. It is critical to achieve the design values for these parameters, and fabrication-induced variations on the coupling ratios must be minimized. The new all-pass filter architectures are shown in Fig.6 (a), (b) and (c).

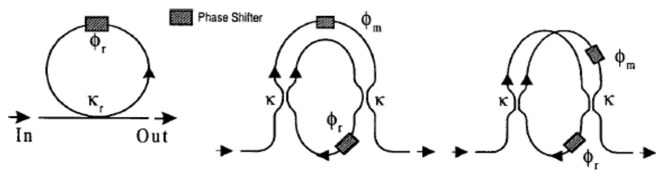


Fig. 6. (a) Ring resonator all-pass filter with a fixed coupling ratio, and fully tunable ring resonator all-pass filters with (b) an asymmetric MZI and (c) a symmetric MZI [15].

The single coupler is replaced with a Mach–Zehnder interferometer (MZI). The MZI is curved to minimize any increase in the feedback path length. The advantage is that a phase shifter can be used to tune the effective coupling k_e into the feedback path, thus a completely tunable all-pass filter is easily realized with two phase shifters, one to set k_e and one to tune the resonant wavelength. The tolerances on the couplers k composing the MZI are substantially relaxed compared to the tolerance on k_r. In Fig. (b), the MZI path lengths are different by a length $\Delta L = \pi d_{sep}$ where d_{sep} is the separation of the MZI arms. The effective coupling is given by k_e which can be set to zero at a given wavelength by choosing Φ_m appropriately [15].

$$ke = 4k(1 - k) \cos2 ([2\pi ng \Delta L/\lambda + \Phi m] /2) \quad (3)$$

In Fig. (c),

$$k_e = 1 - 4 k(1 - k) \cos^2 (\Phi_m /2) \quad (4)$$

Hence $k_e = 1$ can be achieved by the proper choice of Φ_m.

VI. Dispersion Compensation Using Raised Cosine Filters

The raised cosine filter is a pulse shaping filter used in digital modulation due to its ability to compensate chromatic dispersion and intermodal dispersion which cause inter-symbol interference (ISI) [18]. The ISI due to chromatic and intermodal dispersion is compensated by the proper design of impulse response of raised cosine filter. Its name is derived from the fact that the non-zero portion of the frequency spectrum of its simplest form (β = 1) is a cosine function raised up to sit above the horizontal i.e. frequency axis [18].

The raised-cosine filter is an implementation of a low-pass Nyquist filters i.e. one that has the property of vestigial symmetry. This means that its spectrum exhibits odd symmetry about 1/2T, where *T* is the symbol-period of the communications system [19] – [23].

Its frequency response is a piecewise function given by [18]:

$$H(f) = \begin{cases} T & |f| \le (1-\beta)/2T \\ T/2[1+\cos(\pi T\beta)[|f|-(1-\beta)/2T], & (1-\beta)<|f|\le(1+\beta)/2T \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

$$(0 \le \beta \le 1)$$

The frequency response is characterized by the two values, β, the roll-off factor, and T, the reciprocal of the symbol-rate [19].

The impulse response of RCF is [18]

$$h(t) = \text{sinc}(t/T) \cos(\pi\beta t/T) / (1 - (4\beta^2t^2 / T^2)) \quad (6)$$

Since RCF has impulse response zero at all *nT* (where *n* is an integer), except n = 0, so it has the property of eliminating ISI when used to filter a symbol stream. Therefore, if the transmitted waveform is correctly sampled at the receiver, the original symbol values can be recovered completely [18].

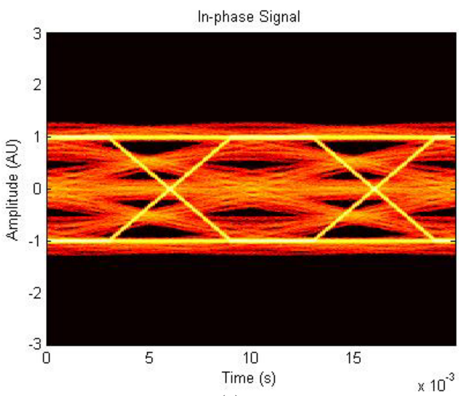
The comparison of various dispersion compensation techniques is given in table I.

VII. Simulation Results and Discussion

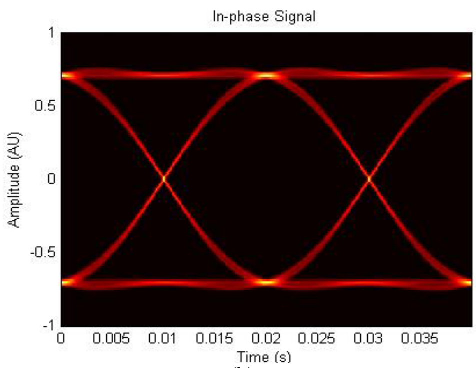
The results have been simulated for the non-return to zero data with sampling frequency of 10000 Hz and symbol rate of 50 symbols per second launched into an optical fiber. The message data gets corrupted with additive white Gaussian noise, various jitters and dispersion effects which cause intersymbol interference as it travels along the optical fiber. The dispersion compensation by the use of raised cosine filters is shown in terms of eye diagrams which depicts that more the vertical opening of the eye diagram the best would be the signal quality i.e more it would be free from dispersion effects. Fig. 7a shows the eye diagram of the dispersion affected optical signal at the receiver. Fig. 7b shows the eye diagram of the same signal filtered with raised cosine filter. It has been observed from the following figures that eye diagram in fig. 7a has the very low vertical opening but eye diagram in fig. 7b opens widest hence the dispersion effects are compensated with raised cosine filtering maintaining a high optical signal to noise ratio (OSNR).

TABLE I: COMPARISON OF ISI COMPENSATION TECHNIQUES

Dispersion Compensation Method	Technique Used	Results
Dispersion compensating fibers	DCFs have dispersion characteristics that negate the dispersion characteristics of the main fiber.	DCFs give high insertion loss, large footprint, and non-linear distortions when the input signal is high. Also for the multiple channels in WDM system, the number of DCFs has to be installed making the system complex and costly [1] – [3].
Electronic dispersion compensation	The compensation is done in the electrical domain using optoelectronic devices.	EDC is rendered ineffective for WDM system since it is complex and also not a direct method of compensation as it involves the optical to electronic and electrical to optical conversions making the WDM communication slow [6], [16].
Dispersion compensation using fiber Bragg gratings	The ISI affected pulses are recompressed after passing through the gratings.	FBGs compensate the dispersion by the recompression of an optical signal. For different frequencies different architectures of the FBGs have to be introduced along the fiber link [4].
All Pass Filters	The phase response is made variable to correct any order of dispersion.	These all pass filters (APF's) are linear systems, which have an amplitude response that is constant over all frequencies and a variable phase response that can be made arbitrarily close to any desired phase response [12] – [15]. Hence they can correct all order of dispersion but with highest complexity which increases the cost of WDM system making it less practical.
Raised Cosine Filters	The ISI compensation is based on the appropriate design of the impulse response of the filter.	When used to filter a symbol stream, a Nyquist filter has the property of eliminating ISI, as its impulse response is zero at all nT (where n is an integer), except $n = 0$. These filters are cheaper, easy to implement and realize. So it is the best method of compensating ISI with the same advantages as offered by APF.



(a)



(b)

Fig. 7 (a) Eye diagram of the dispersion affected signal (b) Eye diagram of same diagram compensated with RCF

VIII. CONCLUSION

There are number of techniques to compensate the chromatic dispersion of an optical signal travelling along the optical fiber. The dispersion compensation using digital filters is the most effective way of compensating it. All pass filters are lossless filters which offer the flexibility to tune a desired phase response arbitrarily close by increasing the number of stages keeping magnitude response of a system unchanged. The fully tunable all pass filters having 100 GHz FSR and negligible polarization dependence have been fabricated with tuning range of $\pm$ 100 ps/nm, a pass band width of 50 GHz and group delay ripple of <3-ps peak are demonstrated. With the careful design of APF's together with the feedback equalization used at the receiver, the 10Gbps WDM system with FSR = 50GHz, OSNR = 22.7 at BER of 10^{-9} may be realized. Raised cosine filters give the same results as that obtained with all pass filters but with less complexity, cost and RCF are easy to implement and realize. Hence RCFs are better than all pass filters for dispersion compensation.

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