Chromatic Dispersion Compensation Using an Optical All Pass Filter for a 10 Gb/s Optical Communication System at 160 km

W. Loedhammacakra, W.P. Ng, and R.A Cryan

Northumbria University

wisit.loedhammacakra@unn.ac.uk

ABSTRACT: This paper proposes a promising technique to compensate chromatic dispersion (CD) by using an optical all pass filter (OAPF) as an optical equaliser. The phase response of OAPF will be designed to cancel the phase delay of single mode fibre (SMF) which is the main cause of CD. The simulation of the mathematical model of the optical communication system at 10 Gb/s employing the proposed OAPF will be presented. A minimum mean square error (MMSE) technique was used to optimise the equaliser and the simulation results show that a pulse, after travelling 160 km of SMF, is fully compensated to its original pulse spread at full width half maximum (FWHM). The eye diagram also show an eye opening improvement of 68% compared to a fully opened eye and the dispersion penalty is reduced 32 dB.

1. Introduction.

Dispersion in a single mode optical fibre (SMF) is the bottleneck of long haul optical communication systems. Dispersion, attenuation and nonlinear effects are the key problems associated with the optical fibre communication system [1]. Attenuation is no longer a main problem due to the invention of the Erbium doped fibre amplifier (EDFA) [2]. Nonlinear effects such as four wave mixing (FWM) can also be reduced by introducing some dispersion [3]. Dispersion then becomes the main limitation on the bit rate and the length of optical links. Most SMF that have been installed have zero dispersion at the operating wavelength of 1.31 µm. When wavelength division multiplexing (WDM) system was introduced to increase the fibre bandwidth, the operating wavelength moved to 1.55 µm due to the lowest attenuation region of SMF [3] and the operating wavelength of EDFA [2]. At operating wavelength of 1.55 µm the dispersion in a SMF is known as chromatic dispersion (CD) and it will result in pulse spreading and causes intersymbol interference (ISI) [4]. CD is made up of material dispersion (MD) and waveguide dispersion (WD) [5], as shown in Fig. 1. The phenomenon of different wavelengths travelling at different speed due to the variation of refractive index of the SMF is known as MD. Furthermore, a proportion of the light will also travels in the cladding of the SMF, which has a different refractive index compared to the core and introduces an effect known as WD. Fig. 1 shows dispersion compensation is desirable for high speed optical communication system using SMF operating at the wavelength other than 1.31 µm. At 1.31 µm, the CD of a SMF is zero because the negative WD cancelling out the positive MD. However at operating wavelength of 1.55 µm the CD is 17 ps/nm-km [4] which is the amount of broadening in picoseconds that would occur in a pulse with a spectral width of optical source one nanometre while propagating through one kilometre of fibre. For example in the case of a single frequency laser and assuming that the spectral width due to modulation is much larger than the inherent source spectral width, the bit rate length product can be obtained as [4]

$$B^2 L = \frac{c}{4 D \lambda_0^2} \tag{1}$$

where B is the bit rate, L is the SMF length, c is the velocity of light, D is the dispersion coefficient and λ_0 is the operating wavelength. The length of SMF with different system is shown in Table 1. In summary, doubling the bit rate (B) would reduce the length (L) of optical link by a factor of 4 and at the operating wavelength of 1.55 µm the dispersion is the limit to the repeater-less span length of an optical communication system.

Table 1 The lengths of SMF are limited by the bit rate length product.

	SMF operating at the wavelength 1.3 µm D ~ 1 ps/nm-km	SMF operating at the wavelength 1.55 µm D ~ 17 ps/nm-km
2.5 Gb/s	L = 6,993 km	L = 294 km
10 Gb/s	L = 437 km	L = 18 km

In order to investigate the effect of dispersion in a SMF, the SMF is modelled as a band pass filter with a flat amplitude response and linear group delay in the data bandwidth. The attenuation of the fibre is beyond the scope of this paper.

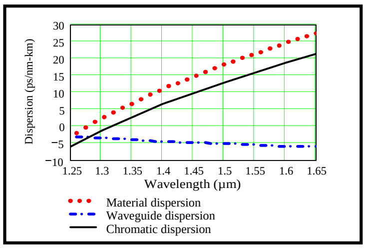


Fig. 1. Variation of MD, WD and CD due to wavelength.

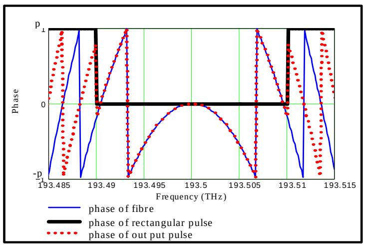


Fig. 2. The phases of SMF, rectangular and output pulse.

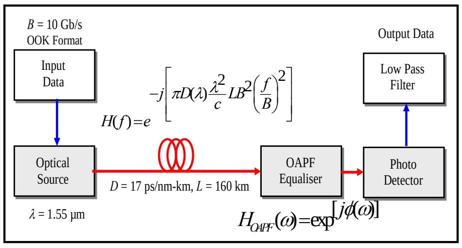


Fig. 3. Optical Communication System using SMF.

The transfer function of the SMF, *H*(*f*), can be modelled using the low pass equivalent model as shown below [6]

$$H(f) = e^{-j\left[\pi D \frac{\lambda_0{}^2}{c} L B^2 \left(\frac{f}{B}\right)^2\right]} \tag{2}$$

Fig. 2 shows the phase of the *H*(*f*) for a 160 km long SMF at an operating wavelength of 1.55 µm (193.5 THz). The phase of the *H*(*f*) is parabolic and at frequency periods of 2π the phase gets shorter as *f* moves away from the centre frequency (193.5 THz) because of f^2 term. The phase of a 10 Gb/s rectangular pulse is zero at a frequency 193.5 THz ± 10 GHz and switches between π and zero every 10 GHz. In the region of interest (193.5 THz ± 10 GHz) the phase of the rectangular pulse after traveling 160 km in a SMF is in-phase with the phase of the SMF. Therefore, in order to realise the high bit rate over long distance with SMF, the dispersion compensation technique should concentrate in region of interest. Other compensation techniques such as dispersion shifted fibre (DSF), dispersion compensating fibre (DCF), chirp fibre Bragg grating (FBG), Mach-Zehnder interferometer (MZI), and optical phase conjugation (OPC) have been introduced to compensate CD. DSF has the zero dispersion point shifted to a wavelength of 1.55 µm. However, FWM occurs in DSF and causes the optical equivalent of near end crosstalk or interference between the optical channels [3]. DCF is a specially designed fibre with negative dispersion is employed to compensate for positive dispersion over large lengths of SMF. DCF typically has a much narrower core than a SMF, causing the optical signal to be more tightly confined and accentuating the problem caused by nonlinear high power effects which results in higher attenuation compared to the SMF [3]. Chirp FBG can compensate CD of a SMF by using the varying distance of grating to delay the faster wavelengths in relation to the slower wavelengths of an optical pulse. By recombining all the wavelengths of an optical pulse, the original optical pulse can be restored. The chirp FBG is limited by its narrow bandwidth and ripple in the opposite group velocity delay (GVD) [3]. MZI has been proposed to compensate for CD by providing wavelength dependent paths of different lengths for different spectral components of the signal. In the MZI, the light is split into two paths of different length and then recombined by a 2×2 combiner. The distribution of light in the two output ports will depend on the relative phase delay provided by the two arms. The main limitations of the MZI are its relatively narrow bandwidth and sensitivity to input polarisation [2]. OPC is employed to compensate CD by installing a device in the middle of the link to invert the spectrum. If the spectrum of optical pulse is inverted in the middle of the SMF link, the second half of the link acts in the opposite direction. The OPC cannot compensate for the third order dispersion and it is difficult to be implemented in all situations [2]. Therefore this paper proposes the use of optical all pass filter (OAPF) compensate CD.

2. Optical All Pass Filter.

The system of interest, as shown in Fig. 3, is based on a 10 Gb/s, non return to zero (NRZ) on off keying (OOK) pulse, optical source (λ_0) 1.55 µm, length of SMF (*L*) is 160 km with dispersion (*D*) is 17 ps/nm-km, square law detector and second order of Butterworth low pass filter.

All pass filter (APF) can be used to equalise a phase of a signal without introducing any amplitude distortion [7]. The design of an optical all pass filter (OAPF) is based on APF. From the transfer function of OAPF, the phase response of the OAPF can be made arbitrarily close to any desired phase response. By changing the coefficients of the transfer function of the OAPF it is possible to create a group delay with the desired characteristics [8]. These characteristics should be designed as such that when the OAPF is placed in cascade with the SMF, the overall CD would be zero throughout the band of frequencies of interest. In order to achieve zero dispersion overall the OAPF should introduce an opposite phase delay effect to that of the SMF. If designed correctly, are potentially very important devices in optical transmission systems since they can be compensate any dispersion in very small structures with very low loss. Since the OAPF response is periodic, the free spectral range (FSR) of OAPF can be chosen so that the OAPF response coincides with each channel passband providing dispersion compensation for multiple channels in a WDM system. OAPFs have the potential for providing the highly stable third order dispersion compensation in optical fibre transmission systems. However, there is a tradeoff between the maximum group delay and the bandwidth as well as the FSR. Performance may be improved by increasing the number of stages or designing the poles and zeros of OAPF closer to the unit circle, however this poses practical problem such as increased in fibre complexity, unacceptable losses and unacceptable ripple of GVD which OAPF produces [1]. OAPF is a lossless device, but in cases where several stages are used the finite insertion loss in practical devices needs to be considered. In practice there will be loss associated to the OAPF in the form of coupling losses, however if the loss is small over the bandwidth of interest, then the degradation in the performance will be minimal. This paper considered the ideal lossless case. OAPFs are linear systems which have a unity magnitude response over all frequencies. The phase response of OAPFs varies with frequency. Because of magnitude response of OAPF is constant value of 1, then the transfer function of OAPF can be written as [8]

$$H_{OAPF}(\omega) = \exp^{[j\phi(\omega)]} \tag{3}$$

From (3) the transfer function of OAPF, H_{OAPF} can be make arbitrarily close to any desired phase response by changing the coefficients of the transfer function of an OAPF in z domain. The CD compensation effectively means that the OAPF should delay lower frequencies of a pulse by a larger amount compared to the higher frequencies. The phase response of an OAPF can be designed to cancel the phase delay of the SMF (in equation (2)). The second order APF transfer function can be written in z domain as [8]

$$H(z) = \frac{(z - \frac{1}{r}e^{j\omega_0})(z - \frac{1}{r}e^{-j\omega_0})}{(z - re^{j\omega_0})(z - re^{-j\omega_0})} \tag{4}$$

where r and ω_0 are parameters which is used to control phase shift of APF.
Because of the design of OAPF is based on APF and from (4), the transfer function of OAPF can be written in frequency domain as:

$$H_{OAPF}(\omega) = \frac{[1 - \frac{1}{r}2\cos\omega T\cos\omega_0 + \frac{1}{r^2}\cos 2\omega_0] + j[\frac{1}{r}2\cos\omega_0\sin\omega T - \frac{1}{r^2}\sin 2\omega T]}{[1 - 2r\cos\omega T\cos\omega_0 + r^2\cos 2\omega_0] + j[2r\cos\omega_0\sin\omega T - r^2\sin 2\omega T]} \tag{5}$$

where T is time delay of delay unit. The phase response of the second order OAPF is given by

$$\theta_{OAPF}(\omega) = \tan^{-1}[\frac{\frac{1}{r}2\cos\omega_0\sin\omega T - \frac{1}{r^2}\sin 2\omega T}{1 - \frac{1}{r}2\cos\omega T\cos\omega_0 + \frac{1}{r^2}\cos 2\omega_0}] - \tan^{-1}[\frac{2r\cos\omega_0\sin\omega T - r^2\sin 2\omega T}{1 - 2r\cos\omega T\cos\omega_0 + r^2\cos 2\omega_0}] \tag{6}$$

From (6) the phase characteristics of the second order can be plotted, shown in Fig. 5, by using minimum mean square error (MMSE) technique given in (7).

$$err(T, a, \omega_0) = \sum_{n=0}^{n-1}\left(\arg(\frac{1}{H(f)}) - \theta_{OAPF}(T, a, \omega_0)\right)^2 \tag{7}$$

The MMSE technique produced an optimum result for the three variables, T = 30 ps, r = 0.66 and ω_0= 0.39π for CD compensation of a 160 km long SMF.

3. Results.

In this paper, the simulation assumes the worst case scenario for the optical system, where a 10 Gb/s rectangular pulse was employed and traveled through 160 km of SMF. The uncompensated and compensated phase characteristics of the pulse after 160 km are shown in Fig. 4. The result shows that the phase response is compensated to close to zero only at lower frequency, between 193.49 THz to 193.50 THz (10 GHz). However, in the frequency range higher than 193.5 THz the phase response is not properly compensated and results in a larger pulse width in low amplitude region as shown in Fig. 5. The effect of the asymmetric pulse will result in ISI and is subject to further investigation by the author in the next stage of the research. Nevertheless the use of the equaliser resulted in the received 10 Gb/s optical pulse being fully compensated with a pulse width at full wave half magnitude (FWHM) equivalent to the original pulse as shown in Fig. 5. Having the right parameters T, r and ω_0 are the key to compensation of fibre dispersion using OAPF. Fig. 6 (a) and 6 (b) shows the eye diagram at the receiver, at 160 km of SMF. The eye diagram of the system without the OAPF has an eye opening of 2% compared to a fully opened eye. The small eye opening will result in higher bit error rate (BER).

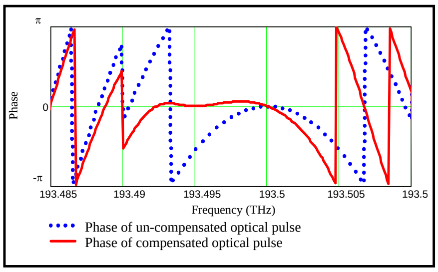


Fig. 4. The phases of optical pulse.

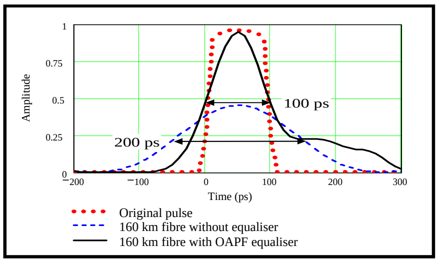
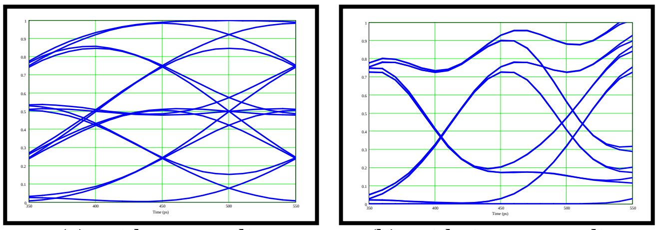


Fig. 5. The comparison of output pulses.



(a) Without equaliser. (b) With OAPF equaliser.

Fig. 6. Eye diagrams at 160 km.

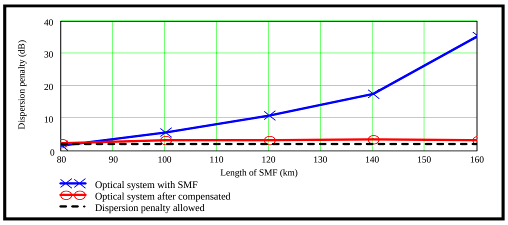


Fig. 7. Dispersion penalty of optical communication system.

The compensated eye diagram by using OAPF as an equaliser showed an eye opening of 70% compared to a fully opened eye which results an improvement of 32 dB, in terms of dispersion penalty, as shown in Fig. 7. Dispersion penalty is the additional signal to noise ratio (SNR) required to counteract the effects of the eye closure. The dispersion penalty increases according to the length of SMF, but the allowable dispersion penalty is less than 2 dB [9]. The compensated dispersion penalty is improved by 7, 14 and 32 dB at 120, 140 and 160 km of SMF, respectively. However the compensated dispersion penalty is approximately 1 dB above the allowable limit of 2 dB which requires further investigation.

4. Conclusions.

The phenomenon of phase shift in SMF resulting in dispersion will limit the bit rate and the length of optical communication link. The mathematical results presented in this paper are quite promising to achieve dispersion compensation employing OAPF. The result showed that a 100 ps optical pulse that travelled through a 160 km of SMF was able to be compensated back to 100 ps at FWHM. However at lower amplitude of the pulse, the application of OAPF results in a larger spread. The increased pulse width at the lower amplitude will affect the bit error rate and introduce ISI. The full effect will be investigated in the next stage of the research and it is currently beyond the scope of this paper. OAPF can be designed to compensate optical fibre dispersion for large bandwidth with low loss and ripple. In addition, OAPF is linear device and has an ability to tune the GVD to compensate dispersion at various length of SMF. These characteristics are good to support long haul WDM optical communication systems.

References.

[1] C. K. Madsen and G. Lenz, "Optical All Pass Filter for Phase Response Design with Application for Dispersion Compensation," *IEEE Photonics Technology Letters*, vol. 10, pp. 994-996, 1998.

[2] G. P. Agrawal, *Fiber Optic Communication Systems*. New York: John Wiley & son Inc, 1997.

[3] H. J. R. Dutton, *Understanding Optical Communications*. New York: Prentice Hall Inc, 1998.

[4] A. Ghatak and K. Thyagarajan, *Introduction to Fiber Optics*. Cambridge: University Press, 1998.

[5] J. Powers, *An Introduction to Fiber Optic Systems*, 2nd ed. New York: McGraw Hill Companies, 1997.

[6] A. F. Elrefaie, R. E. Wagner, and D. G. Daut, "Chromatic Dispersion Limitation in Coherent Lightwave Transmission Systems," *J. of Lightwave Technology*, vol. 6, pp. 704-709, 1988.

[7] G. Lenz and C. K. Madsen, "General Optical All Pass Filter Structures for Dispersion Control in WDM Systems," *J. of Lightwave Technology*, vol. 17, pp. 1248-1254, 1999.

[8] J. Proakis and D. Manolakis, *Digital Signal Processing*, 3rd ed. New York: Prentice Hall Inc, 1996.

[9] J. L. Miller and F. E., *Optical Communications Rules of Thumb*. London: McGraw-Hill, 2003.