Department of Electrical and Computer Systems Engineering

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Effects of optical filtering on 40Gb/s DWDM optical transmission using VSB modulation format

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Abstract

We present the transmission of optical multiplexed channels of 40 Gb/s using vestigial modulation format over a long reach optical fibre transmission system. The effects of fibre dispersion, filter pass and roll off bands and channel spacings on the Q-factor are described. The performance of the optical transmission using low and non-zero dispersion fibre or/and dispersion compensation. It has been demonstrated that BER of 10e-12 or better can be achieved across all channels and minimum degradation of the channels can be obtained under this modulation format.

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1 Introduction

Even though optical communications networks have been developed for ultra-high capacity, the demand for high-speed communication system over ultra-long reach and ultra-long haul offer greater capacity is expected to increase further technical development for networking, hence tremendous works for more superior alternative superior transmission systems.

Current worldwide commercial transmission technology is the 10 Gb/s DWDM transmission system. 40 Gb/s optical communication systems are considered as the core transmission technology for the next generation Tb/s networks.

The common modulation formats for 40 Gb/s optical system are the RZ and NRZ (NRZ). The VSB-RZ modulation format has been considered as the appropriate choice for terabits long haul optical transmission systems due to its high dispersion tolerance and nonlinearity tolerance. However, this paper examines the vestigial sideband (VSB)-NRZ modulation format as it could provide higher spectral efficiency than VSB-RZ format since NRZ occupies only half of the RZ bandwidth and requires a lower peak transmit power in order to maintain the same energy per bit that leads to the same bit-error-rate (BER) as RZ format. Simulation is presented for eight channels DWDM of 400 GHz channel spacing optical fibre transmission system. The channels are transmitted at 40 Gb/s over a dispersion-managed 100 km span.

This paper is structured as follows. Section 2 gives an overview of the simulation design and the transmission system. Sections 3 and 4 describe the optical transmitter and modulation format as well as the feature of the optical filter passband and the signal spectra describes the VSB modulation format. Section 5 presents the details of the design of the VSB filters and the DWDM, multiplexing and demultiplexing followed by. Section 6 discusses the roles of the Group Velocity Dispersion and dispersion compensation. Section 7 gives the evaluation of the transmission performance using the received eye diagram and the Q-factor and the effects of several factors on the bit-error rate (BER). Finally Section 8 the note a number of concluding remarks.

2 Transmission System

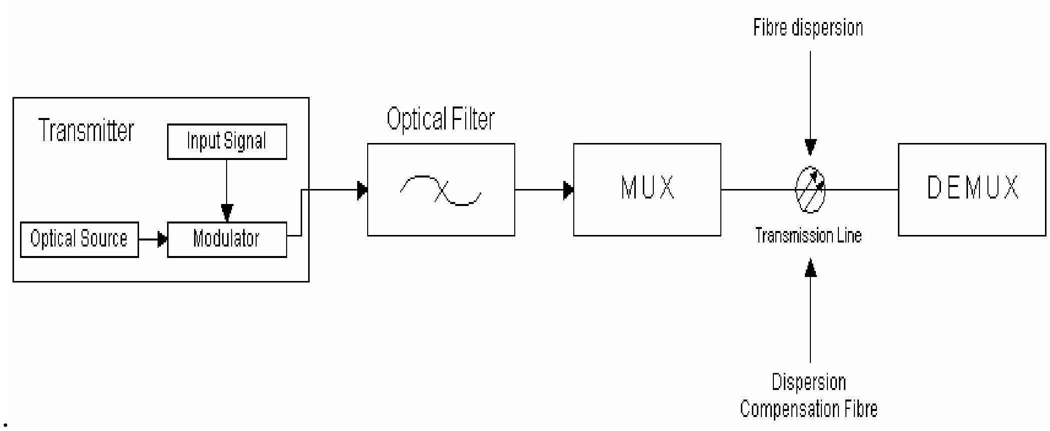


Figure 1 Schematic diagram of the modelled VSB transmission system.

The schematic diagram of the optical transmission employing VSB modulation format is shown in Figure 1. An optical light that carries eight information channels is launched from an optical source. The data format that is used in this design is NRZ format. In order to increase the information-carrying capacity of the communication media, a Vestigial Side Band modulation technique is used. To achieve the VSB format, an optical filter is implemented to filter out the unwanted sideband of the information channel. After filtering each channel is multiplexed and then transmitted through the dispersion-managed fibre span. The back-to-back eye diagram is observed when dispersion compensation fibre is used with appropriate dispersion slope for equalisation of appropriate channel spacing. Naturally at the end of the transmission line, the multiplexed channels are separated via a demultiplexer.

3 Optical NRZ-VSB Modulation Format

Optical transmitter converts an electrical input signal into optical signal and then launches it into the optical fibre, which is used as a media transmission. Lightwaves emitted and coupled to an external modulators usually LiNbO3 MZ intensity modulator. For 40 Gb/s the stabilisation and linearity of the external modulator is critical. Normally two modulators would be used, one for generating the required NRZ format and the other used for either carrier suppression and phase modulation if required depending on the transmission format. For VSB modulation format an optical filter is used to filter unwanted sideband. The effects of these filters on back to back and dispersion tolerance are the principal objects investigated in this paper.

There are two format types, the RZ and the NRZ formats. Unlike in the RZ format, where the amplitude of optical pulse returns to zero after half of the bit period, in the NRZ format, the amplitude of optical pulse remains the same during the bit period. The main advantage of NRZ format is that it occupies half of the RZ bandwidth. VSB modulation allows a small amount of the unwanted sideband exists in the output of modulator. Instead of eliminating the entire second sideband (as in SSB), VSB modulation eliminates most but not all of the second sideband. With this technique, the difficulty in creating sharp cut-off as in the SSB modulator has been overcome. VSB modulation technique can be carried out by implementing optical filter in the DSB signal to filter out most of the second sideband. VSB modulation also improves low-frequency response. The spectrum of the VSB signal can be obtained as:

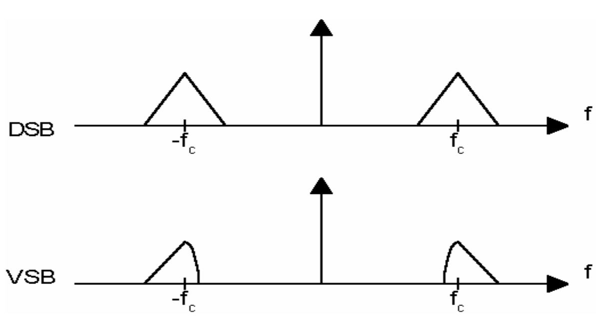
$$x_c(t) = \frac{1}{2} A\mathrm{E}\cos(\omega_c - \omega_1)t + \frac{1}{2} A(1-\mathrm{E})\cos(\omega_c + \omega_1)t + \frac{1}{2} B\cos(\omega_c + \omega_2)t \qquad (1)$$

The signal can be demodulated by multiplying by $4\cos(\omega_c t)$ and applying lowpass filtering leading to:

$$E(t) = A\,E\cos\omega_1 t + A(1-E)\cos\omega_1 t + B\cos\omega_2 t \qquad (2)$$

$$\text{or} \qquad e(t) = A\cos\omega_1 t + B\cos\omega_2 t \qquad (3)$$

The basic principal of VSB filtering is shown in the Figure 2:



(a)

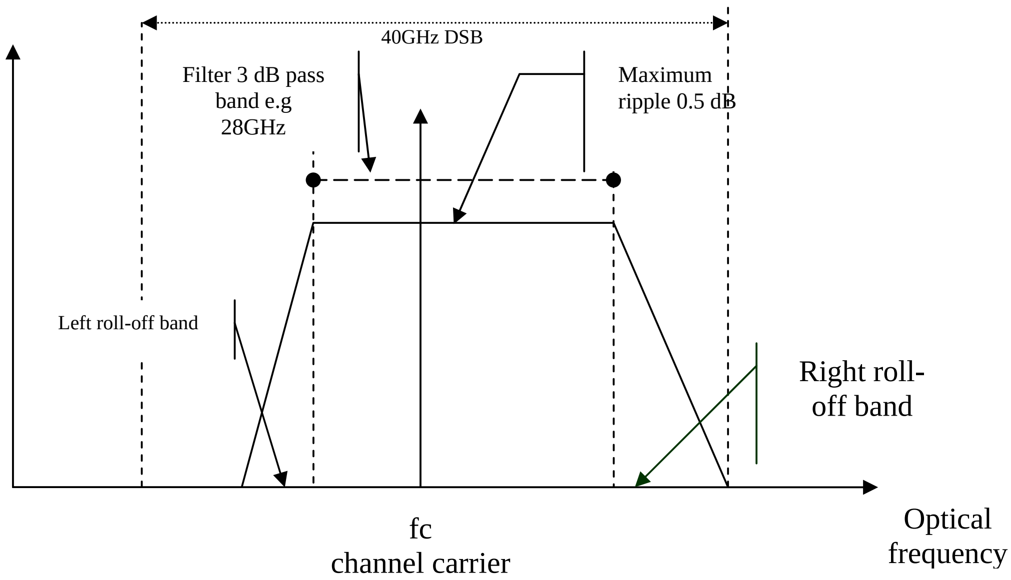


Figure 2 Spectral property of the VSB modulation format as compared to that of DSB (a) general frequency shifting and (b) details of optical VSB filter passband and roll-off band.

4 VSB Filtering and WDM channels

To achieve the VSB modulation technique, optical filtering is implemented in the DSB signal. In this paper, a number of low pass elliptic filters have been chosen since this filter type gives the steepest transition region between the passband and stopband without suffering the unstability. The elliptic filter is a combination of the Chebyshev Type I and Chebyshev Type II and some amplitude response ripples exist in the passband and stopband. The main advantage of elliptic filter is the width of the transition band is minimized for a finite ripple limit in the passband and a minimum attenuation in the stopband. The magnitude-squared spectral response of the low pass elliptic prototype of order N is given by:

$$|H_{LP}(j\omega)|^2 = \frac{1}{1+\varepsilon^2 E_N{}^2(\omega)} \tag{4}$$

where $E_N^2(\omega)$ is the Chebyshev rational function and can be determined from the specified ripple characteristics. Similarly the s-domain transfer function of the low pass elliptic filter of order N can be obtained as:

$$H_{LP}(s) = \frac{H_0}{D(s)} \prod_{i=1}^{r} \frac{s^2 + A_{0i}}{s^2 + B_{1i}s + B_{0i}} \tag{5}$$

where $r = \dfrac{N-1}{2}$ for odd N and $r = \dfrac{N}{2}$ for even N. Figure 3 illustrates the elliptic filter response.

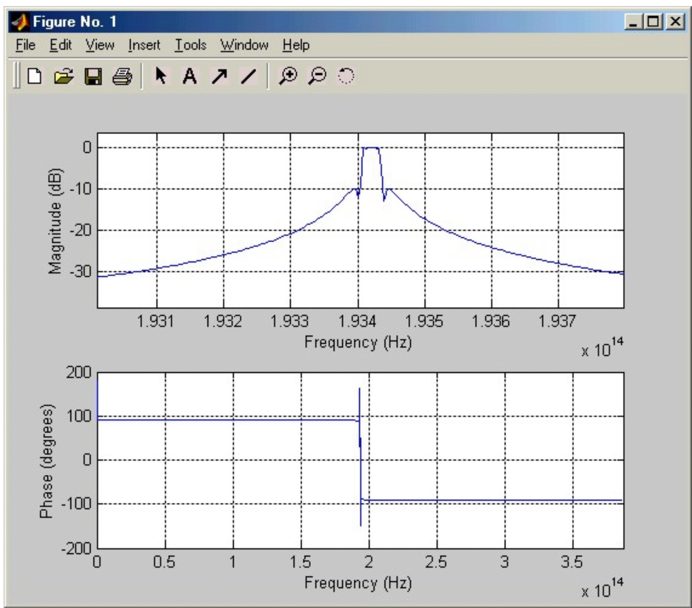


Figure 3 Frequency responses of the elliptic filter including the amplitude (upper curve) and phase (bottom curve).

The wavelength 1550 nm is used as the center wavelength corresponding to the optical frequency of 193.41 THz. The characteristic of the elliptic filter is designed with the following characteristics: Passband ripple = 0.5dB or less; Minimum stopband attenuation = 10 dB; Passband region = 28 GHz; Stopband = 2 GHz and Roll-off band = 10 GHz. The filter characteristic is plotted in Figure 3 and Figure 4 and the definitions of all the bands can be referred to Figure 2.

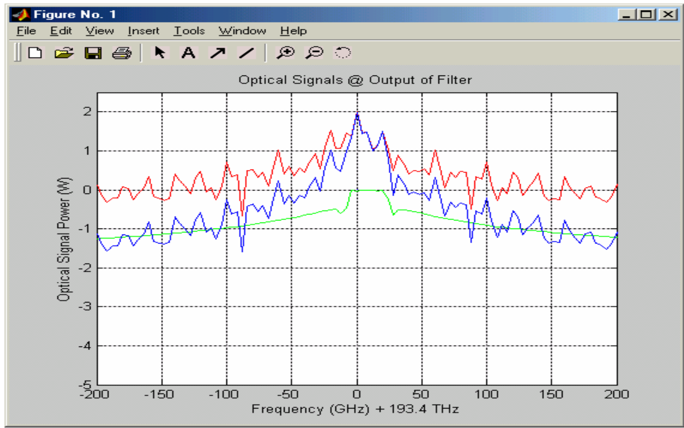


Figure 4 Filter characteristics and signal spectra before(most upper) and after filtering (middle curve). The filter frequency response is also included.

The reconstructed signals for the 8 channels at the output of VSB filter in time domain are plotted in Figure 5.

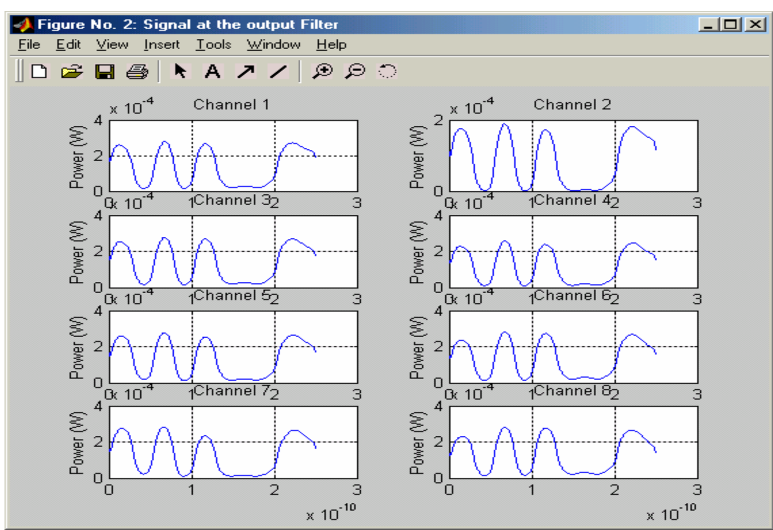


Figure 5 Signals of the DWDM muxed channels at the output of the VSB filters.

The optical transmission system is simulated for 8 channels where the 1550 nm wavelength is taken as the centre wavelength. After filtering out the unwanted sideband using the VSB filter, the multi channels are then multiplexed and then propagated through the single mode low non-zero dispersion fibre. The multiplexing is based on the wavelength division multiplexing (WDM) technique in which multiple optical carriers at different wavelength are modulated using independent electrical bit streams and then will be transmitted over the same fibre. WDM is a condition where optical pulses with different wavelengths propagate without interfering with each other, so several information channels that have different frequency carrier can be transmitted simultaneously over a single fibre. WDM increases the capacity of a fibre in carrying information. Our design employs variable channel spacing and typically from 50 GHz to 500 GHz as the multiplexing parameter. The signal spectrum in frequency domain and time domain at the output of multiplexer are depicted in Figure 6.

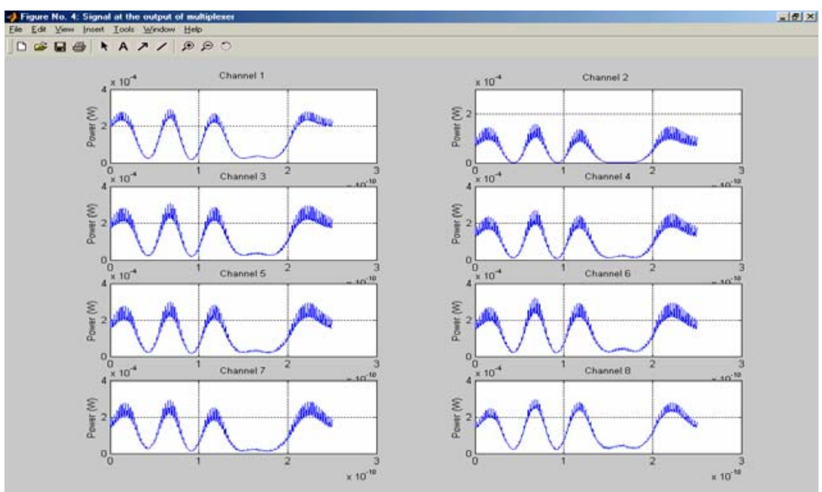


Figure 6 Time-domain signal at the output of the multiplexer.

From Figure 6, we observe that there is some ripple in the signal. This ripples phenomenon appear at the output of multiplexer due to the cross talks generated in multi channel transmission. At the output of the optical filter, there are no ripples as the channels are filtered independently to each other.

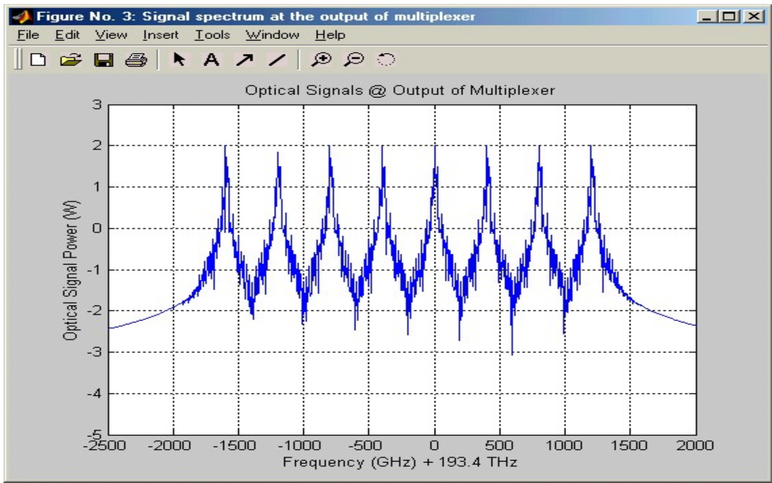


Figure 7 Eight 40Gb/s multiplexed signal spectrum at the output of multiplexer.

5 Fibre Dispersion and compensation

A single mode fibre optic is chosen as the transmission media in this simulation. The main benefit of single mode fibres is that intermodal dispersion is not present because the energy of the emitted pulse is carried by a single mode. However, pulse broadening still occurs. Due to chromatic dispersion, the group velocity is frequency dependent. Consequently, different spectral components of the pulse travel at a different velocity and causes fibre dispersion or group velocity dispersion (GVD) that limits the performance of single mode fibre. Fibre dispersion consists of two components: material dispersion and waveguide dispersion. The material dispersion factor can be calculated by using:

$$M(\lambda) = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2} \qquad \text{(ps/nm.km)} \tag{6}$$

While the waveguide dispersion parameter is:

$$D_W(\lambda) = -\frac{n_2(\lambda)\Delta}{c\lambda} V \frac{d^2(Vb)}{dV^2} \quad \text{(ps/nm.km)} \tag{7}$$

The waveguide dependent factor can be approximated by when the V-parameter is constricted with the single node range of 1.3 to 2.6 as:

$$V\frac{d^2(Vb)}{dV^2} = 0.080 + 0.549(2.834 - V)^2 \tag{8}$$

or by using cut-off wavelength parameter, the V parameter is:

$$V\frac{d^2(Vb)}{dV^2} = 0.08 + 3.175\left[1.178 - \frac{\lambda_c}{\lambda}\right]^2 \tag{9}$$

Therefore, the total dispersion fibre is given by

$$D_T = M(\lambda) + D_w(\lambda) \tag{10}$$

In order to obtain non-zero low total dispersion over a wide wavelength range, techniques for design of dispersion-flattened fibres are employed. An optimised large effective area fibre with pure silica material as the cladding material is designed for transmitting multi-channel since it gives the best dispersion slope for matching with those of the dispersion compensation module. The Sellmeier's constants for pure silica fibre are: G_1 = 0.696750 λ_1 = 0.069066e-6; G_2 = 0.408218 λ_2 = 0.115662e-6; G_3 = 0.890815 λ_3 = 9.9900559e-6. The refractive index of pure silica can be expressed as:

$$n(\lambda) = c_1 + c_2\lambda^2 + c_3\lambda^{-2} \tag{11}$$

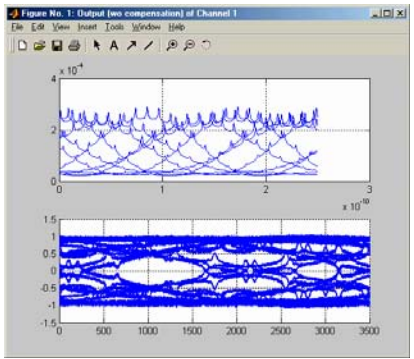
with c_1= 1.45084, c_2 = -0.00343 μm^{-2} and c_3 = 0.00292 μm^2, then the refractive index [n(λ)] for pure silica fibre is 1.45.

In designing the optical fibre for transmitting several channels with regard to fibre dispersion and the dispersion compensation module, the following parameters are used in this simulation: fibre radius (a) = 1.6 μm; relative refractive index difference (Δ) = 0.0339. The pulse broadening can be expressed as:

$$\Delta\tau = D(\lambda).\ \sigma_\lambda.\ L \tag{12}$$

where D(λ) is fibre spectral dispersion (ps/nm.km) and σ_λ is the signal bandwidth when the laser linewidth is much smaller than that of the VSB signals and L is the fibre transmission distance.

Figure 8 show the signals at the output of the demultiplexer for each channel (channel 1 to channel 8) without dispersion compensation.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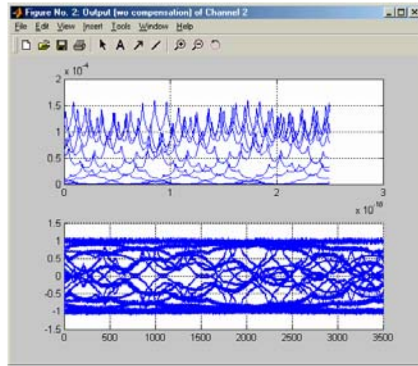
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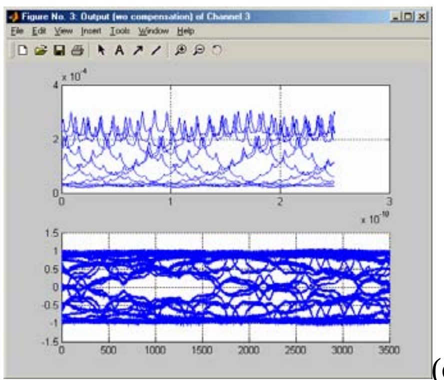
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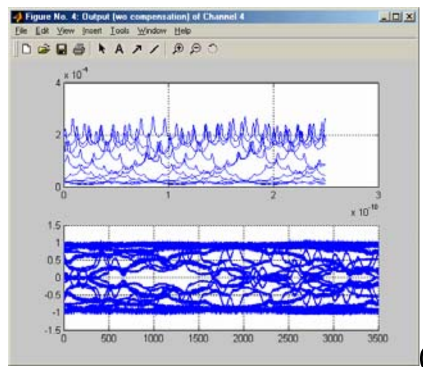
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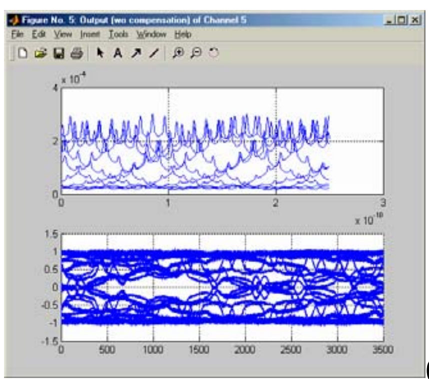
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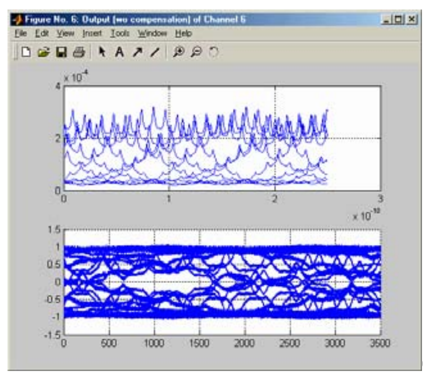
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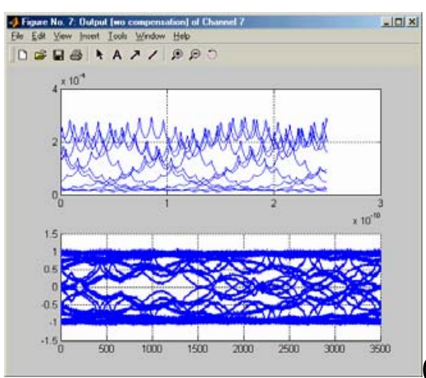

(g)

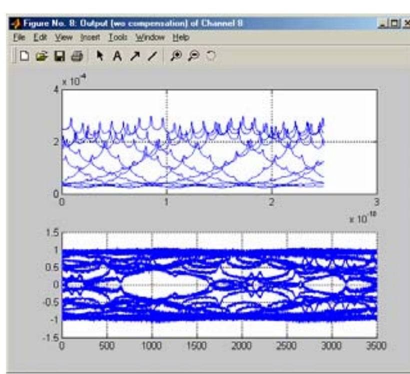

(h)

Figure 8 Signal outputs at the end of transmission fibre without dispersion compensation (a) Channel 1 at 1563 nm with a total dispersion D_T = 2.7334e-6 ps/(nm.km) (b) Channel 2 at 1560 nm D_T = 2.7393e-6 ps/(nm.km) (c) Channel 3 D_T = 2.7433e-6 ps/(nm.km) (d) Channe 4) at 1553 nm : D_T = 2.7454e-6 ps/(nm.km) (e) Channel 5 at 1550 nm: D_T = 2.7455e-6 ps/(nm.km) (f) Channel 6 at 1547 nm : D_T = 2.7436e-6 ps/(nm.km)(g) Channel 7 at 1543 nm: D_T = 2.7398e-6 ps/(nm.km) (h) Channel 8 at 1543 nm: D_T = 2.7339e-6 ps/(nm.km).

From the graphs of *Figure 8*, the simulation results show that in just 100 km span transmission line, the quality of the transmitted data decreases sharply, as expected, due to fibre dispersion. This fact shows that fibre dispersion limits the transmission performance.

6 Dispersion Compensation Fibre (DCF)

Since the group velocity dispersion limits optical fibre performance in transmitting pulses, it is necessary to implement a dispersion compensating fibre (DCF). The condition of dispersion compensation can be expressed as:

$$D_1L_1 + D_2L_2 = 0 \tag{13}$$

where D_1 = total dispersion of the fibre transmission fibre section (ps/nm.km); L_1 = fibre transmission distance (km); D_2 = fibre dispersion compensation distance (ps/nm.km); L_2 = dispersion compensation distance (km). Equation (13) shows that the DCF must have GVD less than zero at 1550 nm, since the fibre dispersion is valued higher than zero. The parameters of the DCF in this design are: Fibre radius (a) = 1.7 μm; Relative refractive index difference (Δ) = 0.0243. Figure 9 shows the transmitted data at the end of transmission line with dispersion compensation for channels 1 to 8:

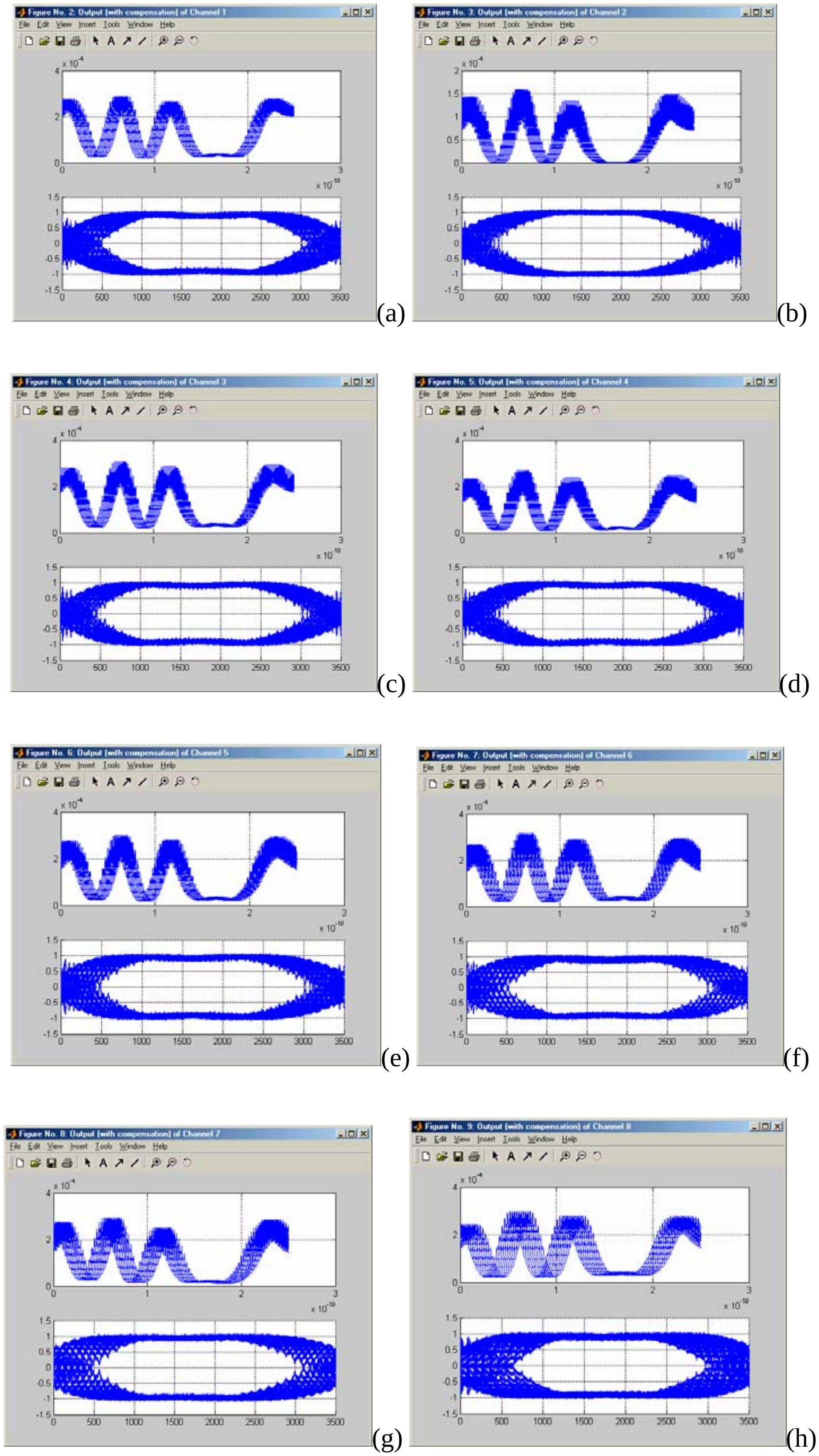


Figure 9 Signal outputs at the end of transmission line with dispersion compensation (a) Channel 1 at 1563 nm (channel 1) with a dispersion compensation D_{DCF}= -2.7811e-6

ps/(nm.km) (b) Channel 2 with D_{DCF} = -2.7829e-6 ps/(nm.km) (c) Channel 3 at 1556 nm with D_{DCF} = -2.7853e-6 ps/(nm.km) (d) Channel 4 at 1553 nm with DCF= -2.7883e-6 ps/(nm.km) (e) Channel 5 at 1550 nm (channel 5) with DCF = -2.7918e-6 ps/(nm.km) (f) Channel 6 at 1547 nm with DDCF= -2.7960e-6 ps/(nm.km) (g) Channel 7 at 1543 nm with D_{DCF}= -2.8008e-6 ps/(nm.km) (h) Channel 8 at 1540 nm with DDCF= -2.8062e-6 ps/(nm.km)

From the figure above, the simulation result shows that dispersion compensation fibre plays an important role in optical transmission system since it recovers the quality of the data close to the original quality.

In order to transmit more than one channel over an optical fibre, a multiplexing technique is used to combine all channels into the fibre. An optic multiplexer combines light from individual sources to the transmitting fibre. At the receiver, the channels are then separated into separate channels by an optical demultiplexer.

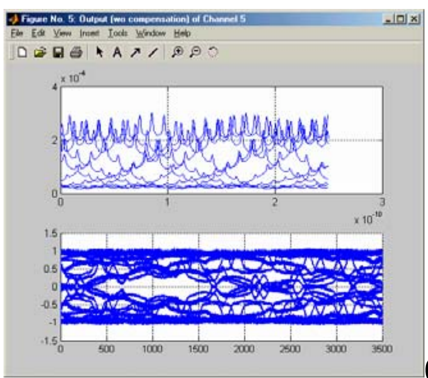
Figure 8 plot the simulation result of transmitted signals at the output of multiplexer without applying dispersion compensation fibre. While Figure 9 shows the transmitted signals at the output of multiplexers with DCF in cascade with the transmission fibre.

7 Eye Diagram and Q-factor

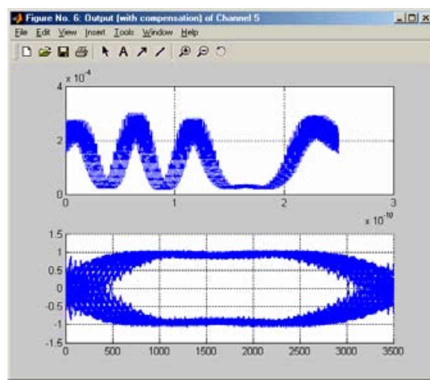
Eye diagram is used to measure the system performance. Digital optical pulses suffer distortion by noise, pulse broadening and timing errors (jitter) introduced in the optically amplified fibre transmission system. The eye diagram can be used to estimate the Q-factor which can be obtained by

$$Q = \frac{\mu_{1-}\mu_0}{\sigma_1 - \sigma_0} \tag{14}$$

where μ_1 and μ_0 are the means of the current at the decision circuitry of the receiver at the sampling instant respectively for symbol "1" and '0'. While σ_1 and σ_0 are the standard deviations of the current at the decision circuit input at the sampling instant respectively for symbol "1" and '0'. Figure 10 (a) and (b) show the eye diagram of simulation result for transmitted pulse at 1550 nm (channel 5) with 400 GHz channel spacing which depict the eye diagram at the end of the transmission line without and with dispersion compensation fibre respectively. The eye diagram of data with dispersion compensation is wide open compared to that without dispersion compensation. The wide-open eye diagram shows that the system performance is good since the error has been compensated.



(a)



(b)

Figure 10 Signal (a) without dispersion compensation and (b) with dispersion compensation

This section investigates the effect of the GVD, channel spacing and the VSB filtering on the Q-parameter as received at the transmission end.. The analysis is evaluated for 8 channels transmission and the data rate is 40 Gb/s. Therefore, the total transmission capacity is 320 Gb/s.

7.1 The effect of channel spacing on Q-factor

The capacity of the WDM system depends on how close channels can be packed into the wavelength domain. The minimum channel spacing is limited by interchannel crosstalk. The typical value of channel spacing should exceed four times that of the bit rate. The Q-factor is obtained for each channel at the output of the multiplexer and at the output of the demultiplexer, at the end of the transmission haul without dispersion compensation in Figure 11 .

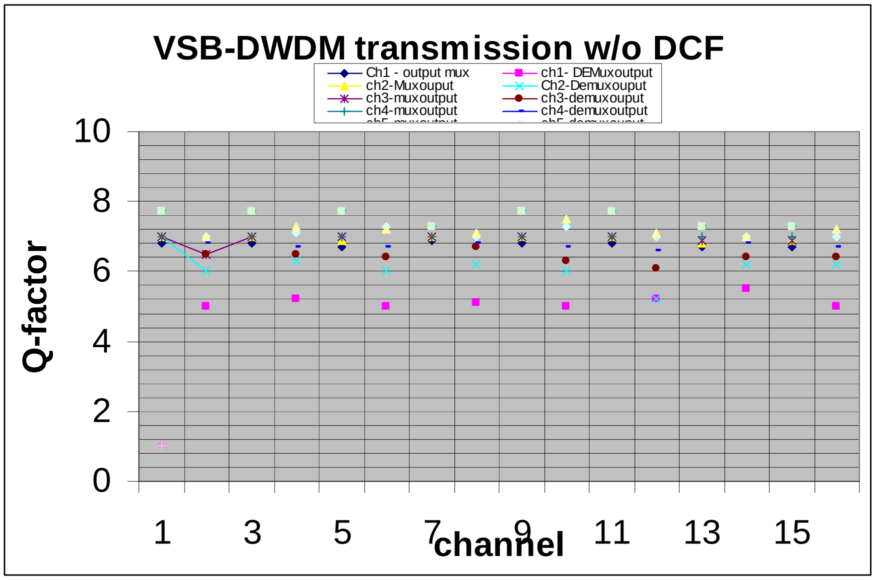


Figure 11 Channel spacing as a function of Q-factor for the multiplexed channels 1 to 8 at the output of the optical mux (before transmission) and at the output of the demux (after transmission)

The Q-factor at the output of demultiplexer decreases significantly for channel spacing 100, 200 and 300 GHz. While, the Q-factor for 400 GHz channel spacing or above only slightly decreases

7.2 The effect of GVD on Q-factor

In this section the effects of GVD on transmitted channels with and without dispersion compensation fibre are evaluated with the Q-factor as the reference performance parameter. Table 1 shows GVD effects on Q-factor. This process occurs at the end of the transmission media without applying dispersion compensation fibre. Based on the previous channel spacing analysis, the 400 GHz is the narrowest channel spacing that produces Q-factor at approximately 7.

Channel No.	GVD (ps/nm.km)	Q-factor
1	2.7334	0.67
2	2.7393	0.63
3	2.7433	0.61
4	2.7454	0.6
5	2.7455	0.6
6	2.7436	0.61
7	2.7398	0.63
8	2.7339	0.67

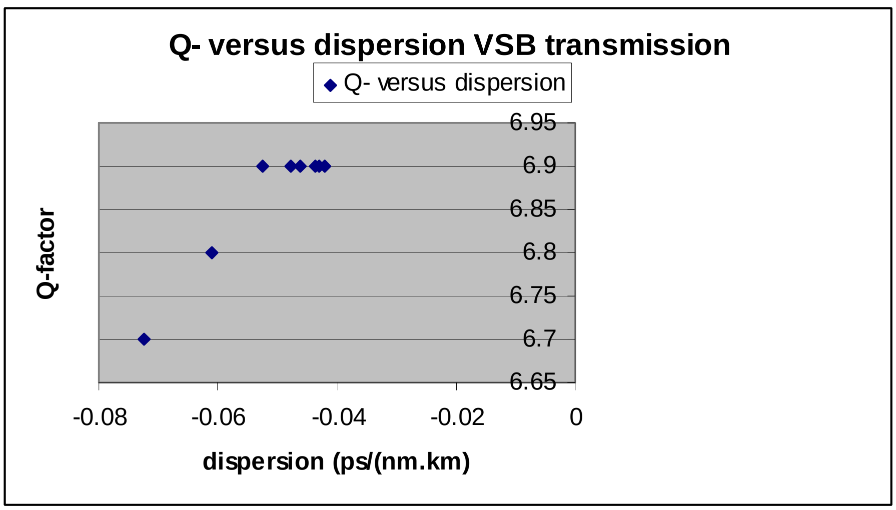
Table 1 Q-factor at output DEMUX without dispersion compensation

Dispersion compensation fibre plays important role in optical transmission since the GVD limits the transmission performance. By adding dispersion compensation fibre which has the opposite sign of the GVD, the effect of GVD can be considerably reduced. As expected in Table 2 the dispersion compensation fibre has improved the Q-factor at the receiver to an equivalent BER of about 10 e-12 which a typical value acceptable for practical implementation.

Channel No.	GVD (ps/nm.km)	Q-factor
1	-0.0477	6.9
2	-0.0436	6.9

3	-0.042	6.9
4	-0.0429	6.9
5 (1550 nm)	-0.0463	6.9
6	-0.0524	6.9
7	-0.061	6.8
8	-0.0723	6.7

Table 2 Q-factor at output DEMUX with dispersion compensation



Dispersion tolerance of VSB format (corresponding to channel number- see Table 2)

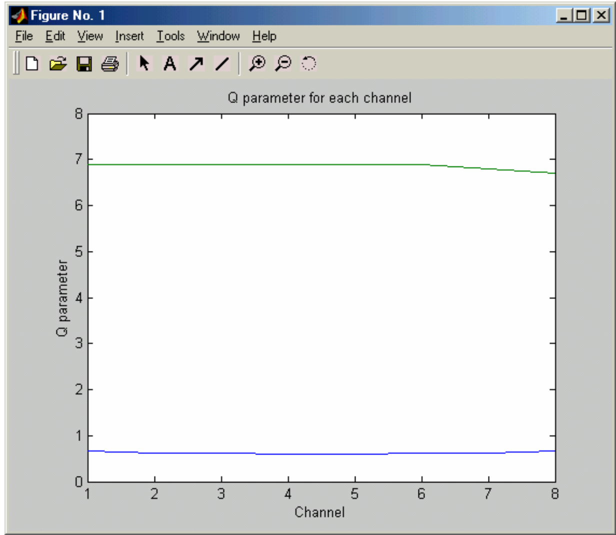


Figure 12 Q-factor after transmission with (lower curve) and without (upper curve) dispersion compensation.

Figure 12 shows the dispersion effect as a function of Q-factor for each channel number. It can be seen that the fibre dispersion can reduce the system performance, as expected in any optical transmission system, by 10 times. By using dispersion compensation fibre at the end of each fibre transmission span, the system performance can be restored by approximately 10 times.

7.3 The effect of VSB filter passband on Q factor

This section will examine the effect of VSB filtering on Q-factor by varying the passband characteristic of the VSB filter to obtain the Q-factor for each channel. The reading is taken at the output of demultiplexer with applying dispersion compensation fibre.

Passband (GHz)	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**
20	5	5.3	5.1	5.3	5.2	5.5	5.3	5.1
24	6.1	6.5	6.3	6.5	6.5	6.4	6.3	6.2

28	7.1	7.1	7.2	7	7.5	7	7	7
32	7	7	7	7	7.1	7.2	7	7
36	7	7.2	7	7	7.1	7	7	7
40	7	7	7.1	7.2	7.3	7	7	7.1

Table 3 VSB filter passband tolerance.

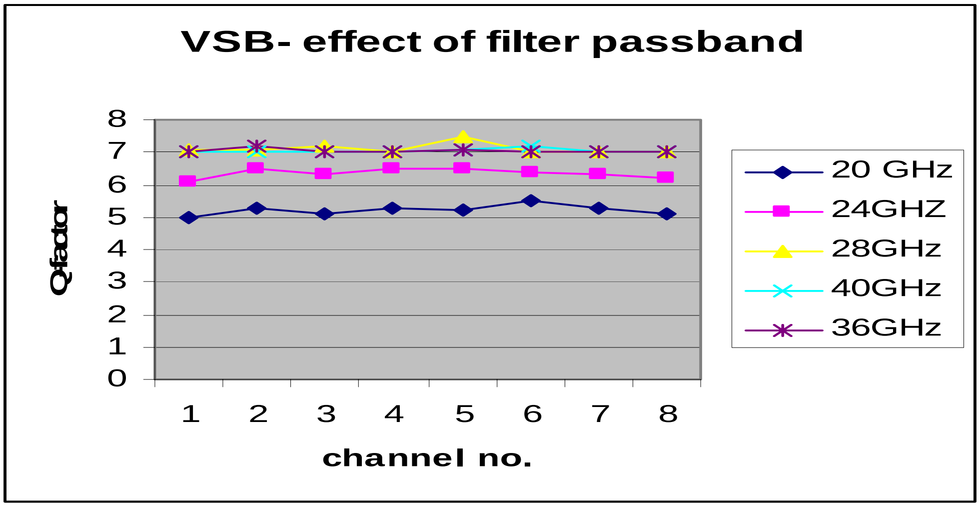


Figure 13 Q-factor as a function of the VSB filter passband.

From Figure 13 it is clear that for 40 Gb/s NRZ data format, the performance of optical transmission is low for 20 and 24 GHz passband. The low transmission performance could be caused by the unstable system since about half of the bandwidth is eliminated. While, for 28 GHz passband, the system performance (Q-factor) is considerably increasing to approximately 7. This fact shows that the performance of VSB modulation format is as good as double side band (DSB) modulation since the VSB format eliminates most but not all of the redundant sideband.

Any different values between this simulation result and theory could be caused by the eye-diagram closure.

8 Concluding remarks

This paper presents simulation results of 40 Gb/s DWDM optical transmission systems with Non-Return-to-Zero (NRZ) VSB modulation format. The effects of filtering on the Q-factor with respect to fibre dispersion and compensation, channel spectral spacing and the effects of symmetry and asymmetry of the filter pass and cut-off bands are examined. We could draw the following conclusions:

- The Q-factor at the output of demultiplexer decreases significantly for channel spacing 100, 200 and 300 GHz due to noise and crosstalk interference. While, the Q-factor for 400 GHz channel spacing or above only slightly decreases. A BER of 10E-12 can be achieved over all channels with these channel spacing. For dense and superdense WDM optical transmission the demands on the roll-off, cut-off and the passband of VSB optical filters are high.

- Fibre dispersion can reduce the system performance dramatically. Using dispersion compensation fibre along the transmission line will improve the system performance significantly. Specific designed fbres are used with deterministic dispersion are used.

- The 20 and 24 GHz passband optical filters give low performance. The low performance could be caused by the unstable system since about half of the bandwidth is eliminated. While, for 28 GHz passband, the Q-factor is considerably improved to 7. This fact shows that the performance of VSB modulation format is comparable and marginally better than the double side band (DSB) modulation format since the VSB format eliminates most but not all of the redundant sideband.

- Several types of optical filters are examined and sharp roll off band is expected to contribute to the improvement of the VSB transmission. However the roll- off band must not be fallen in the region of the center of the signal and carrier frequency spectrum to avoid the contribution of the dispersion at the roll-off.

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