Analysis of a pulsed broadband source in multi-channel transmission

Nimish Dixit and R. Vijaya
Department of Physics, I. I. T. Bombay, Powai, Mumbai-400 076, India
E-mail: rvijaya@phy.iitb.ac.in

ABSTRACT
The performance of a multi-channel optical source derived from a broadband spectrum has been numerically studied for its utility in a wavelength division multiplexed (WDM) transmission system. The eye-opening penalty is calculated in order to measure the performance degradation of the system. A comparison is made between with and without dispersion slope compensation in a WDM transmission link. It is found that full dispersion slope compensation drastically improves the performance of the system provided correct input power is chosen.

Keywords: fiber optic communication, wavelength division multiplexing, WDM source, multi-channel propagation, beat signal compression

1. INTRODUCTION
The source in a wavelength division multiplexed (WDM) network is required to provide multiple outputs at pre-specified wavelengths. Hence, they contain a separate laser diode of narrow line-width along with a modulator for each wavelength channel. But, in dense WDM systems, the wavelength stability of each channel is of prime importance, which may be attained more easily by spectrally slicing the output of a single broadband source to get multiwavelength GHz output

One method for the generation of broadband spectrum is to compress an optical beat signal in time domain and enrich its spectral content through propagation in a low-dispersion fiber. In an earlier work, we have studied the generation of picosecond pulse train of 10 GHz frequency at 16 different wavelengths suitable for WDM transmission beginning with a beat signal. Then, we numerically studied the performance of such a WDM source in a practical WDM communication system. We considered the propagation of 8 channels at 10 GHz repetition rate with an inter-channel spacing of 100 GHz. For ease of interpretation of results, the number of channels was kept low. It is possible to analyze more number of channels and faster data rates of 40 Gb/s since the basic design can support these possibilities. Eye-opening penalty (EOP) may be used as a measure of the performance degradation of the system. The variation of EOP as a function of span length and input power per channel can provide the mechanism for improved performance. In the present work, a comparison is established between with and without full dispersion slope compensation in the transmission network. The importance of full dispersion slope compensation is brought out for the pulses with small duty ratio. It is shown here that full dispersion slope compensation along with a correct choice of input power improves the system performance enormously.

2. METHODOLOGY
The method used here for modeling the WDM system is based on the total field approach. This technique automatically includes the effects of SPM, XPM, FWM and Raman cross talk. The nonlinear Schrödinger equation is solved numerically using the well known split step Fourier transform algorithm. Input data for each channel is a random bit sequence consisting of 128-bits. The amplifier noise with a chosen noise figure of 6 dB is modeled as a white noise created by a gaussian random number generator and added to the optical field at the output of each amplifier. At the end of the fiber link, the channels are filtered using a suitable optical filter. The performance of the different wavelength channels for WDM transmission is evaluated in terms of the eye-opening penalty (EOP). EOP predicts the qualitative behavior of the signal at the output of the link. Generally, a good system performance is associated with an EOP less than 1 dB.
3. RESULTS AND DISCUSSION

3.1 Generation of 10 GHz multi-wavelength optical pulse train

The scheme proposed for the generation of multi-wavelength 10 GHz output consists of generating a beat signal at 10 GHz and passing it through an erbium-doped fiber amplifier (EDFA) to increase its average power. The beat signal is compressed with a nonlinear optical loop mirror (NOLM) consisting of appropriate length of SMF. When the shaped pulse train from NOLM is passed through 9 km of dispersion flattened fiber (DF), the 3-dB bandwidth of the spectrum is enhanced to 1600 GHz. This spectrum is then sliced using a 1×8 WDM DEMUX having a gaussian profile with a bandwidth of 40 GHz resulting in a pulse train with FWHM of 15.2 ps corresponding to a duty ratio of 15%. A power variation of 5.2 mW is observed across the channels. The wavelengths of the channels 1-8 sliced from the spectrum are 1546.92, 1547.72, 1548.52, 1549.32, 1550.12, 1550.92, 1551.72 and 1552.53 nm corresponding to the ITU-T DWDM grid. References [3] and [4] describe this part in detail.

3.2 Multi-channel propagation

The power of all the channels is equalized before propagation. Block schematic of the simulated WDM system is given in fig.1. The system set-up is composed of a 50 km SMF and 10 km DCF. The DCF length is chosen such that it compensates for the total dispersion of SMF at the central wavelength of 1549.72 nm. Then an EDFA is employed which makes up for the total loss suffered by the pulses during their propagation in one span (SMF + DCF). This is the same as proposed in our earlier work. Each channel is modulated with a 128-bit random sequence. Number of Fourier points in the spectral window are chosen to be 32768 in order to meet the bandwidth requirements of the calculations. The step size is 50 m, which gives a nonlinear phase shift of 1.1 mrad/step even for the maximum peak power used in these calculations.

3.2.1 Without dispersion slope compensation

A data stream of 10 Gb/s is modulated on the pulse train with 15% duty cycle. Input power of each channel is fixed at 0 dBm. In this case, DCF is assumed to compensate the effect of dispersion completely but dispersion slope (or third order dispersion) remains uncompensated. We have calculated the EOP in dB and plotted it as a function of the number of spans in fig. 2(a). EOP increases with the increase in the number of spans as expected. In addition, the EOP of the channels 1&8, 2&7, 3&6 and 4&5 are nearly the same for up to 25 spans. The residual dispersion experienced by the pair of channels 1&8, 2&7, 3&6 and 4&5 will be the same in magnitude. But the channels 1 to 4 experience normal
residual dispersion and the channels 5 to 8 experience anomalous residual dispersion. The presence of residual dispersion is due to the uncompensated dispersion slope (the variation of dispersion with the channel wavelength). The central two channels have the smallest value of EOP and it increases as we move towards the outer channels. This is due to the fact that residual dispersion for the central two channels will be the least among all the channels. One interesting point here is that even for the larger number of spans up to 25 spans, the EOP of the channels 1&8, 2&7, 3&6 and 4&5 is the same. Normal and anomalous dispersion should give qualitatively different results in the presence of the optical nonlinearity. Therefore, the trends in the present results lead to the conclusion that dispersion is playing a relatively more important role as compared to the nonlinearity.

For an input power of 0 dBm, the EOP up to 10 spans of SMF (i.e. 500 km) is less than 1 dB, which is an indication of good system performance. Therefore, we fixed the number of spans to be 10 and varied the input power/channel. Fig. 2(b) shows the plot of EOP against the input power/channel. After a nearly constant value up to a certain power, the EOP increases with the increase in the power. This increase in the EOP for higher power/channel may be attributed to both dispersion and nonlinearity. Although nonlinear effects will play a significant role in the eye-degradation due to the increase in the power, dispersion is dominant since the duty ratio of the pulses is only 15 %. In this case also, the EOP of the channels 1&8, 2&7, 3&6 and 4&5 are the same, even though the sign of the residual dispersion on either side of the central wavelength is opposite.

Next, the average power of the ASE noise after each span is taken to be $-17$ dBm and included in the calculations. There is no difference between the EOP with and without the inclusion of noise. The effect of noise will be more important when the signal-to-noise ratio degrades for a larger number of spans. Moreover, the effect of noise is not significant even for signal powers as low as $-16$ dBm. From the calculated eye-diagrams, the eye-degradation is more due to the decrease in the peak power during propagation, which is attributed to the presence of residual dispersion. In addition, we do not see any appreciable timing-jitter in the output eye-diagram. These pulses have been derived from a beat signal, where the adjacent pulses have a phase difference of $\pi$, thus reducing the interaction among the pulses and hence the timing-jitter. Moreover, less jitter may also be attributed to the smaller effect of nonlinearity as compared to dispersion. Therefore, we can conclude that in our work, the effect of ASE noise at lower powers is not
significant for the number of spans considered here, and at larger powers, the performance is limited more by dispersion and less by nonlinearity.

Since the presence of residual dispersion is due to uncompensated dispersion slope, the performance of the system is expected to improve after full dispersion slope compensation.

### 3.2.2 With dispersion slope compensation

In this set of calculation, the value of third order dispersion (TOD) parameter ($\beta_3 = -0.82 \text{ ps}^3/\text{km}$) is chosen such that it compensates for the TOD (or dispersion slope) of SMF along with its dispersion. The condition for full slope compensation is that the relative dispersion slope, defined as the ratio of dispersion slope to the dispersion, of SMF must be equal to that of DCF$^{10}$. The variation of EOP as a function of number of spans for a fixed input power/channel of 0 dBm is plotted in fig. 3(a). It is observed from this figure that EOP of all the channels is less than 0.4 dB even after 35 spans of propagation. This shows a significant improvement over the previous case of without dispersion slope compensation, where EOP becomes nearly 1 dB after only 10 spans of propagation. One more noteworthy feature is that there is only a slight difference in EOP among all the channels which may be attributed to the dominance of optical nonlinearity in the absence of residual dispersion.

To show the dominant effect of optical nonlinearity after full dispersion slope compensation, variation in EOP as a function of input power/channel is plotted in fig. 3(b), for 25 spans of propagation. From this figure, we observe that, as the input power/channel is increased beyond 6 dBm, EOP becomes more than 1 dB, indicating nonlinearity limited performance. Thus, it may be concluded that dispersion slope compensation improves the performance of the system significantly. A correct choice of the input power/channel becomes extremely critical when the performance is dominated by optical nonlinearity.

To further confirm the increased effect of optical nonlinearity, two-bit wide eye-diagrams of output sliced channels after 25 spans of propagation with an input power/channel of 8 dBm, after dispersion slope compensation, are shown in fig. 4. It can be observed from this figure that eye-degradation is both due to decrease in the peak power and the fluctuation in peak powers of the received bits. It can be seen that the two central (4 and 5) and the two end (1 and 8) channels, all have nearly the same EOP. In contrast, the two central channels have lesser EOP as compared to the two end channels in the previous case due to the dominance of dispersion. In fig. 4, variation in the peak power among the bits and presence of timing-jitter confirms the dominance of nonlinearity in this case. Distortion is more in central channels 4&5 as compared to end channels 1&8 since the effect of nonlinearity would be more detrimental for the central channels as compared to the end channels.
4. CONCLUSION

In conclusion, we have studied the performance of a multi-channel optical source generated by compressing an optical beat signal in the time domain, for its utility in a realistic WDM communication system. By considering the propagation of 8 channels of 10 Gb/s at a duty ratio of 15%, the main cause for eye-degradation is the chromatic dispersion because of the smaller pulse width. Minimum timing jitter and larger tolerance to the input power fluctuations are the main advantages of this design. But residual dispersion limits the number of spans or the transmission distance. In order to improve upon this, the effect of dispersion slope compensation along with dispersion compensation is studied. It is conclusively shown here that the correct choice of input power along with full dispersion slope compensation would drastically improve the system performance with an increased transmission length. The correct choice of input power/channel is necessary to suppress the nonlinear effects on the system performance.

REFERENCES