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Simulative investigations of power penalty for DWDM link in the presence of FWM

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Abstract

In this paper, the eight channels dense wavelength division multiplexing (DWDM) optical communication system has been simulated, and power penalty introduced due to neighboring channels required to compensate the crosstalk has been calculated. It has been observed that the intermediate channels are more affected as compared to the boundary channels and more power is required to compensate the loss of information due to crosstalk.

Keywords: DWDM; Power penalty; FWM

1. Introduction

Four-wave mixing (FWM) is one of the major limiting factors in wavelength division multiplexing (WDM) optical fiber communication systems. FWM is a third-order nonlinearity in silica fibers, which is analogous to inter-modulation distortion in electrical systems. It is due to change in the refractive index with optical power called the optical Kerr effect. FWM occurs when light of three different wavelengths is launched into a fiber; it gives rise to a new wave. This newly generated wave as a result of FWM co-propagates with the originally transmitted signal and interferes with them. It causes severe degradation of the WDM channels and introduces the crosstalk and required power to reduce the crosstalk.

Agarwal [1] discussed the case of equal bit rates and equal received power in all channels and observed that the crosstalk from each channel should be below −12 dB. Further he proposed that the minimum channel spacing of about 4 or 5 times the bit rate is dependent upon the filter bandwidth whether it is 2 or 3 times respectively. To reduce the power penalty below 0.1 dB, crosstalk should be less than −18 dB and should have a minimum channel spacing of about 10 times the bit rate.

Hedekvist et al. [2] presented an all-optical time-division de-multiplexer with 22 dB conversion efficiency, using FWM at 1550 nm in a single-mode dispersion-shifted fiber. Error-free de-multiplexing of 20 Gb/s data to 10 Gb/s was obtained, with 1.4 dB power penalty at BER $= 10^{-9}$. Hwang and Tonguzc [3] described the comparisons of power penalty due to FWM between equal channel spacing and the unequal channel spacing for the 20-channel WDM system. They show that for an intensity modulation/direct detection (IM/DD)

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transmission system operating in an optical bandwidth of 16 nm with 0 dBm (1 mW) peak optical input power per channel achieve BER $= 10^{-9}$ with an FWM cross-talk power of less than 1 dB, which was not achieved by a conventional equal channel spacing WDM system with 0.84-nm channel spacing. Witte et al. [4] proposed that the power penalty encountered in linear electronic compensation of dispersion-induced LED pulse distortion could be reduced by using an electronic decision feedback equalization scheme.

This paper simulates the dense wavelength division multiplexing (DWDM) optical communication system having a channel spacing of 10 GHz to investigate the power penalty introduced due to neighboring channels required to compensate the crosstalk.

2. System description

A DWDM optical communication system for eight channels has been set up using OptSim^{TM}. The length of the fiber for simulation is taken as 200 km having two spans of 100 km each. The continuous wave semiconductor laser is used, externally modulated by 10 Gb/s NRZ-raised cosine for each channel. The dispersion has been varied from 0 to 12 ps/nm/km and is compensated by using ideal FBG. The output of the modulator from eight channels is fed to the optical combiner (Multiplexer) and amplified by the optical amplifier (OA) (Fig. 1).

The core effective area of the fiber is $67.43 \times 10^{-12}\,\mathrm{m}^2$ and the nonlinear refractive index is 3×10^{-20}. The central frequencies of the first laser are taken as 192.930 THz and the channel spacing is 0.02 THz. The optical amplifier with maximum small signal gain of 35 dB is used. At the receiver, a raised cosine band pass filter with supergaussian of bandwidth 20 GHz has been taken. The PIN diode with quantum efficiency of 0.7 and −3 dB of 40 GHz with dark current 0.1 nA has been considered. The Q-meter at the receiving end estimates the average eye opening.

3. Results and discussions

The light information transmitted by the optical transmitter is exhibited by power fluctuations. Such fluctuations are referred to as intensity noise. The optical receiver converts these fluctuations into current fluctuations, which add to those resulting from shot noise and thermal noise. This degrades the signal-to-noise ratio of the receiver. The power penalty due to normalized maximum inter-symbol interference (ISI) can be calculated from the eye diagram [5] as shown in Fig. 2:

$$\mathrm{ISI} = (B - A)/B$$

$$\text{Power penalty} = -10\log_{10}(1 - \mathrm{ISI})$$

Here the power penalty of the WDM optical communication system has been calculated. Figs. 3–10 depict the graph between power penalty and dispersion. In Fig. 3 the power penalty due to channel 2 on channel 1 has been observed. It has been observed that the power penalty at a value of dispersion near zero dispersion is higher but it reduces with the increase in dispersion. The power penalty seen at zero dispersion is at 3.66 dBm, but with increase in dispersion up to 6 ps/nm/km it decreases significantly and beyond 6 ps/nm/km the reduction becomes almost constant and is in the range of 0.4–0.25 dBm. This observation leads to the conclusion

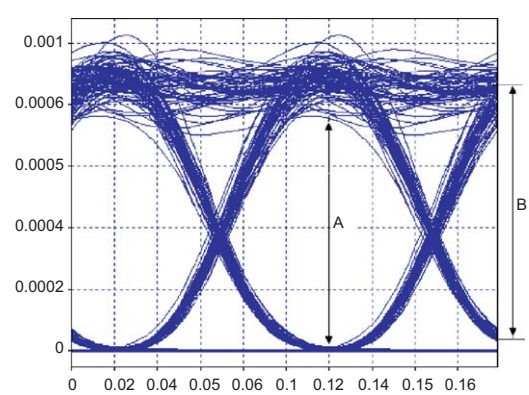

Fig. 2. Power penalty calculations from the eye diagram.

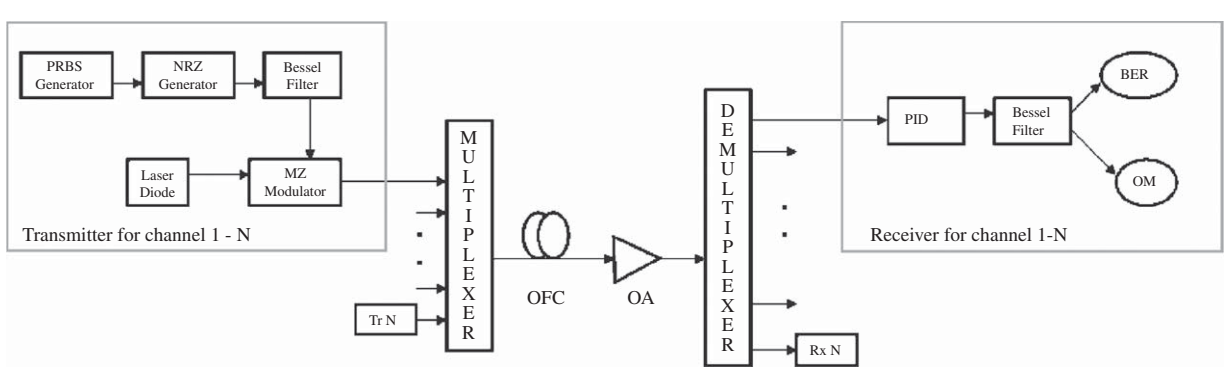

Fig. 1. Simulation setup.

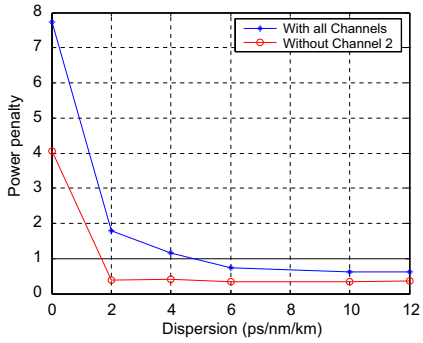

Fig. 3. Power penalty for channel 1.

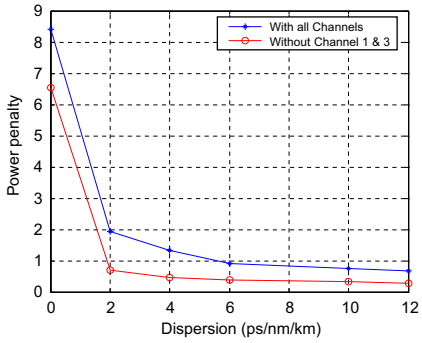

Fig. 4. Power penalty for channel 2.

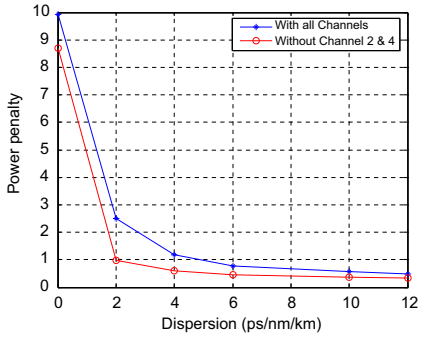

Fig. 5. Power penalty for channel 3.

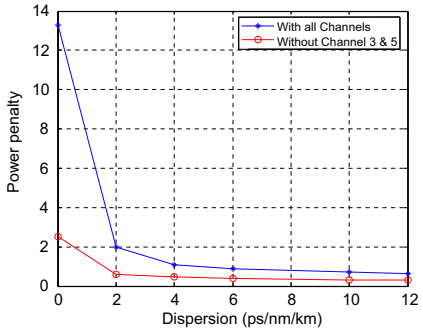

Fig. 6. Power penalty for channel 4.

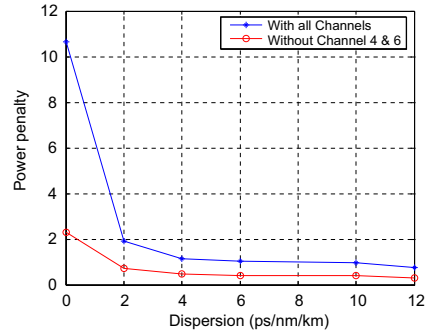

Fig. 7. Power penalty for channel 5.

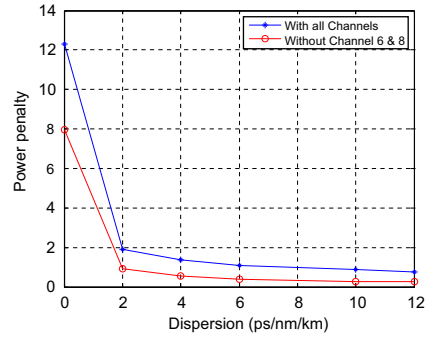

Fig. 8. Power penalty for channel 6.

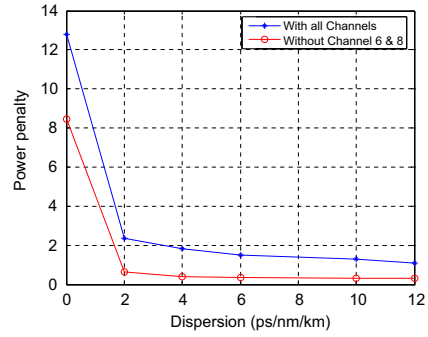

Fig. 9. Power penalty for channel 7.

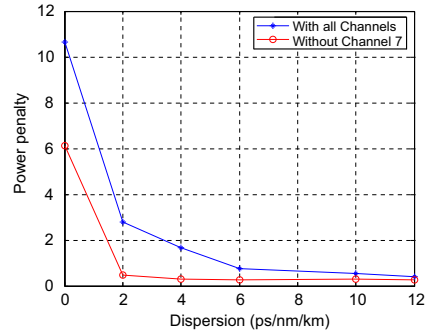

Fig. 10. Power penalty for channel 8.

Table 1. Power penalty for various channels at different dispersion values

PP required for the channel	$D = 0$ ps/nm/km	$D = 2$ ps/nm/km	$D = 4$ ps/nm/km	$D = 6$ ps/nm/km	$D = 10$ ps/nm/km	$D = 12$ ps/nm/km
Channel 1	3.66	1.41	0.76	0.39	0.28	0.25
Channel 2	1.86	1.23	0.86	0.53	0.44	0.39
Channel 3	1.24	1.49	0.58	0.31	0.18	0.16
Channel 4	10.7	1.38	0.65	0.49	0.38	0.33
Channel 5	8.38	1.22	0.67	0.63	0.56	0.45
Channel 6	4.31	0.99	0.81	0.68	0.62	0.47
Channel 7	4.34	1.72	1.42	1.15	1.01	0.76
Channel 8	4.51	2.35	1.36	0.46	0.22	0.16

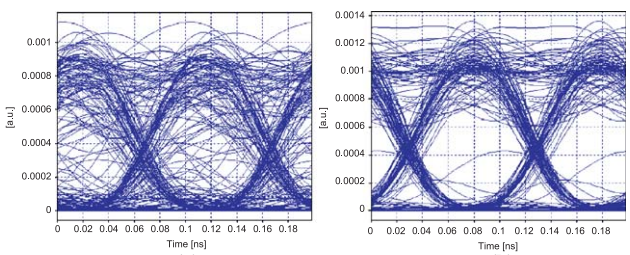

Fig. 11. Eye diagram for channel 1 at $D = 0$ ps/nm/km (a) with all channels, (b) without channel 2.

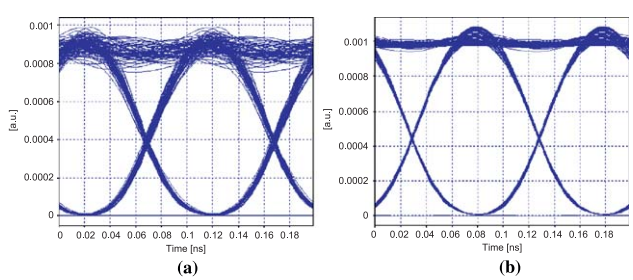

Fig. 12. Eye diagram for channel 1 at $D = 12$ ps/nm/km (a) with all channels, (b) without channel 2.

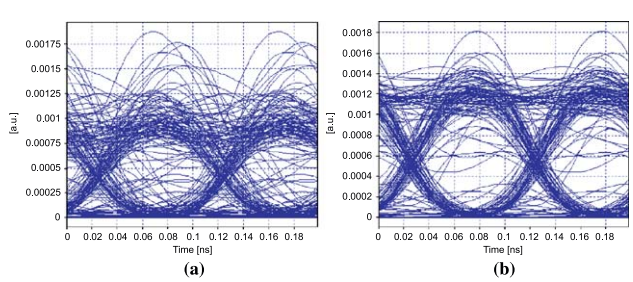

Fig. 13. Eye diagram for channel 2 at $D = 0$ ps/nm/km (a) with all channels, (b) without channels 1 and 3.

that the power penalty at higher dispersion is lesser as compared to the power penalty at zero dispersion.

Further channel 2 reports the power penalty in the range of 1.86–0.39 dBm at a dispersion of 0 and

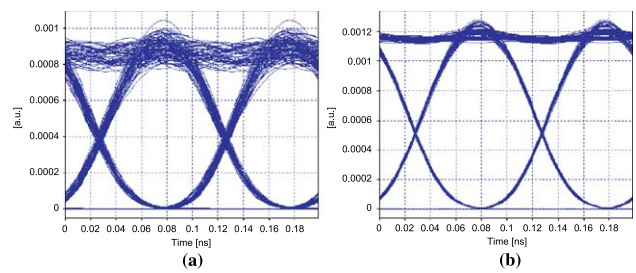

Fig. 14. Eye diagram for channel 2 at $D = 12$ ps/nm/km (a) with all channels, (b) without channels 1 and 3.

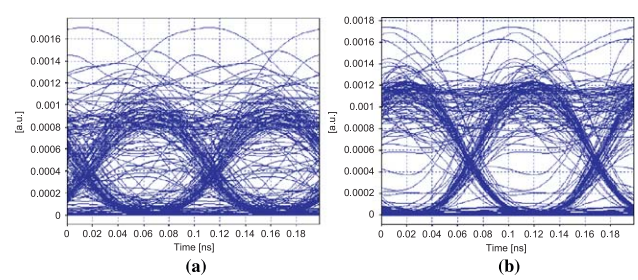

Fig. 15. Eye diagram for channel 3 at $D = 0$ ps/nm/km (a) with all channels, (b) without channels 2 and 4.

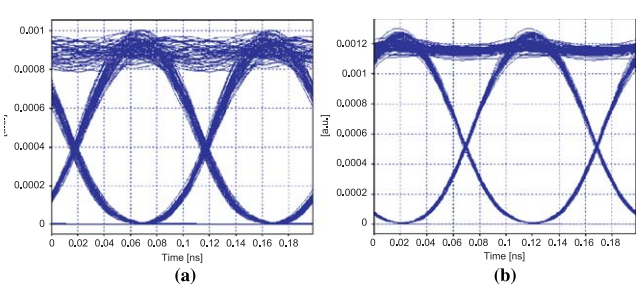

Fig. 16. Eye diagram for channel 3 at $D = 12$ ps/nm/km (a) with all channels, (b) without channels 2 and 4.

12 ps/nm/km, respectively. However the reduction in power penalty for channel 2 due to channel 1 and 3 remains almost the same for dispersion varied from 0 to 2 ps/nm/km and beyond this range the power penalty decreases and this trend continues up to 6 ps/nm/km dispersion. Further, beyond dispersion 6 ps/nm/km the

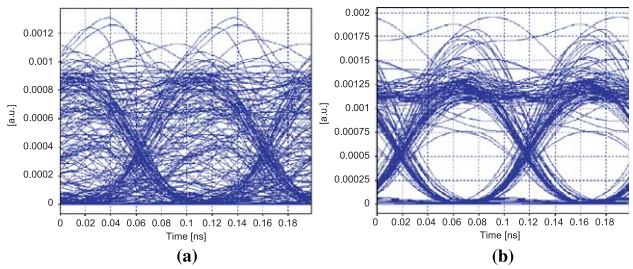

Fig. 17. Eye diagram for channel 4at $D = 0$ ps/nm/km (a) with all channels, (b) without channels 3 and 5.

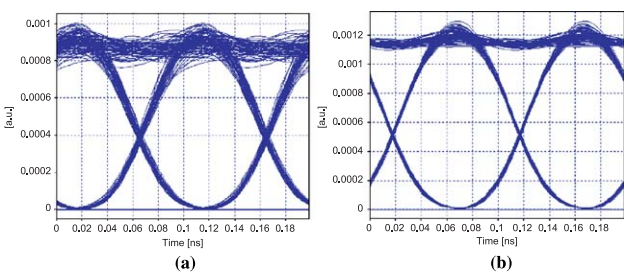

Fig. 18. Eye diagram for channel 4 at $D = 12$ ps/nm/km (a) with all channels, (b) without channels 3 and 5.

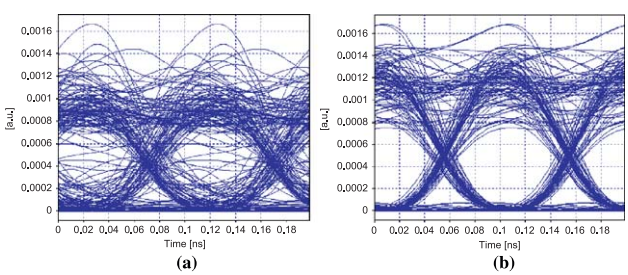

Fig. 19. Eye diagram for channel 5 at $D = 0$ ps/nm/km (a) with all channels, (b) without channels 4 and 6.

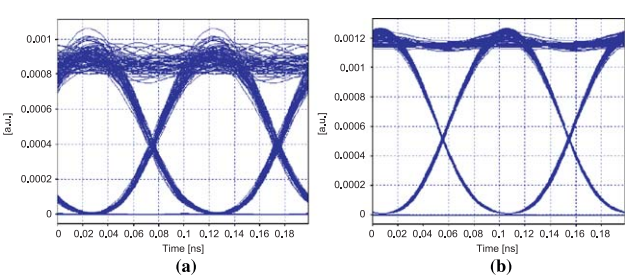

Fig. 20. Eye diagram for channel 5 at $D = 12$ ps/nm/km (a) with all channels, (b) without channels 4 and 6.

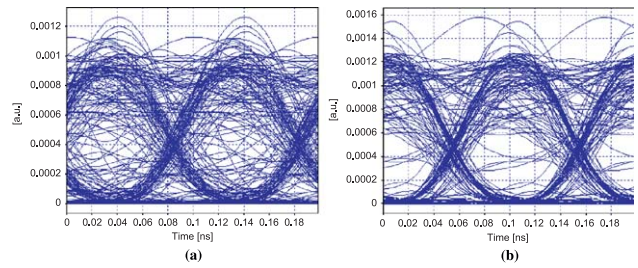

Fig. 21. Eye diagram for channel 6 at $D = 0$ ps/nm/km (a) with all channels, (b) without channels 5 and 7.

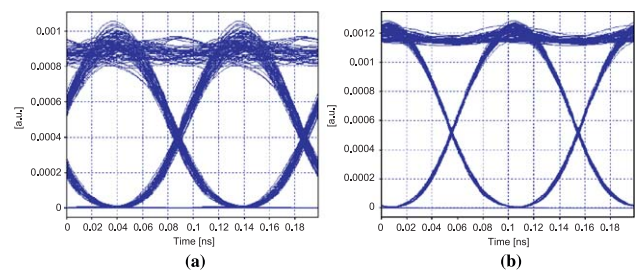

Fig. 22. Eye diagram for channel 6 at $D = 12$ ps/nm/km (a) with all channels, (b) without channels 5 and 7.

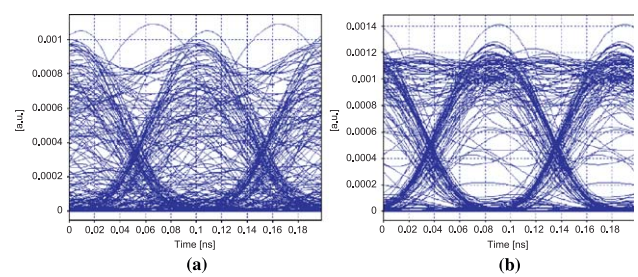

Fig. 23. Eye diagram for channel 7 at $D = 0$ ps/nm/km (a) with all channels, (b) without channels 6 and 8.

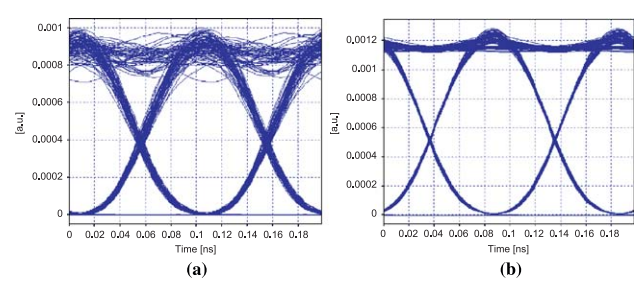

Fig. 24. Eye diagram for channel 7 at $D = 12$ ps/nm/km (a) with all channels, (b) without channels 6 and 8.

reduction in power penalty becomes constant and lies in the range of 0.4–0.3 dBm as reported in Fig. 4.

Similar trends in power penalty reduction have been witnessed for channel 3 as shown in Fig. 5 in the absence of channels 2 and 4. The same trends for power penalty for other channels from 4 to 8 due to the presence or absence of adjacent channels have been illustrated in Figs. 6–10, respectively. It has also been investigated that more power penalty is required at channels 4 and 5 at zero dispersion value as compared to other channels. Furthermore it has been observed that the power penalty required for low-frequency channels are lesser as compared to high-frequency channels.

The maximum power penalty has been observed at channel 4 and is 10.7 dBm at zero value of dispersion and this power penalty further reduces to 0.33 at

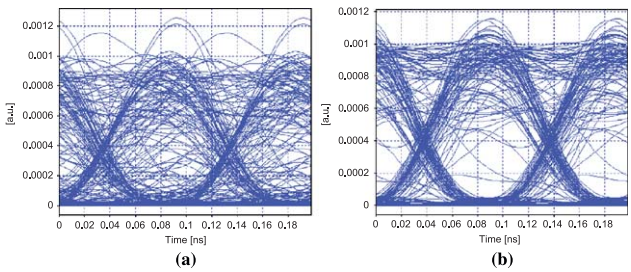

Fig. 25. Eye diagram for channel 8 at $D = 0\,\text{ps/nm/km}$ (a) with all channels, (b) without channel 7.

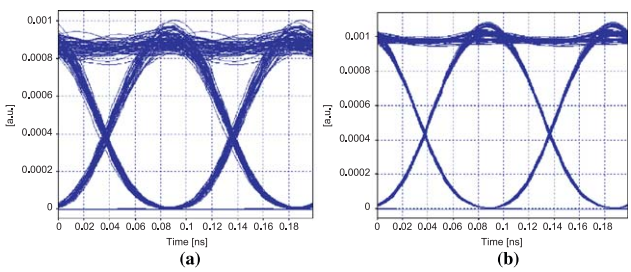

Fig. 26. Eye diagram for channel 8 at $D = 12\,\text{ps/nm/km}$ (a) with all channels, (b) without channel 7.

a dispersion value of 12 ps/nm/km. Channel 5 also shows the power penalty near channel 4 i.e. 8.38 dBm at zero dispersion and it further reduces to 0.45 at dispersion 12 ps/nm/km. However, for channel 6 to channel 8 the power penalty lies in the range of 4.31–4.51 dBm at dispersion 0 ps/nm/km.

Based on the graphs from 3 to 10 the values of power penalty for various channels have been tabulated in Table 1. It has been observed that the intermediate channels are more affected as compared to the boundary channels and more power is required to compensate the loss of information due to crosstalk at channels.

The eye closer and opening mentioned in Figs. 11–26 also indicate similar results for adjacent and intermediate channels.

4. Conclusions

The power penalty introduced by neighboring adjacent channels to an individual channel has been calculated. It has been observed that the intermediate channels are more affected as compared to the boundary channels and more power is required to compensate the loss of information due to crosstalk at channels.

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