Performance Limitations due to Crosstalk in a WDM System using Optical Cross-connect based on Tunable Fibre Bragg Gratings and Optical Circulators

Sanjoy Dey
Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Palashi, Dhaka-1000, Bangladesh. ankan_eee@yahoo.com

ABSTRACT
Performance analysis is carried out to evaluate the impact of crosstalk on an optical signal passing through an FBG-OC (Fibre Bragg Grating-Optical circulator) based optical cross connect in WDM network in terms of bit-error-rate (BER) performance. Results show that the system suffers a power penalty (at BER=10^{-9}) of 7.25 dB if the value of fibre Bragg grating crosstalk factor ($X_{FG}$) is increased from -80 dB to -50 dB for a fixed value of optical circulator crosstalk factor ($X_{OC}$) and a power penalty (at BER=10^{-9}) of 2.5 dB when the value of $X_{OC}$ is increased from -30 dB to -15 dB for a fixed value of $X_{FG}$.

Keywords: Fiber Bragg grating, optical circulator, WDM, bit-error-rate (BER), performance evaluation.

1. INTRODUCTION
Wavelength Division Multiplexing (WDM) technique has evolved to meet up the huge bandwidth demand of present communication networks. Researchers are designing new generation networks exploiting WDM technology which can not only provide quality of service (QoS) but also can solve the electronics bottleneck problem. Optical cross-connects based on fibre Bragg grating and optical circulator are network elements of a WDM system which have a better performance than other conventional cross-connects [1, 2]. A FBG-OC based optical cross-connect [3, 4, 5] can interconnect optical signals between multiple input and output ports enabling switching and routing capabilities. While cross connecting optical signals from input to output ports, FBG-OC cross connects introduces both inter-band and intra-band crosstalk. Inter-band crosstalk arises from the interferences outside the channel’s bandwidth and intra-band crosstalk arises from interferences inside the channel’s bandwidth.

In characterization of the performance of a WDM network, crosstalk is one of the fundamental criteria. High crosstalk in an optical cross-connect (OXC) has so far prevented commercial use of all optical OXC in WDM networks. As crosstalk is a major limiting factor to the implementation of optical cross-connect in WDM systems, in this paper the performance limitations of a FBG-OC based cross-connect due to intra-band crosstalk in terms of bit-error-rate performance has evaluated.

2. SYSTEM DESCRIPTION

The configuration of a 4×4 FBG-OC optical cross connect is shown in Fig. 1.

Fig. 1: Basic architecture of a FBG-OC based optical cross-connect.

At the input port of the cross connect each fibre carries wavelength channels $\lambda_1, \lambda_2, \ldots, \lambda_M$. There are $N$ number of input fibres in this structure and each fibre carries $M$ number of wavelengths. So there are $N \times M$ number of wavelength channels in this structure. This OXC has $(2n-1)$ number of stages where $N=2^n$. To evaluate the worst case performance here it is considered that the OXC is in the cross state so that an arbitrary channel signal $\lambda_i$ entering into the $k^{th}$ input fibre will pass out from the $j^{th}$ output fibre where $k \neq j$. In Fig. 2 a cross-state FBG-OC cross-connect with main channel signal and crosstalk is shown.

Fig. 2: A FBG-OC based cross-connect in cross-state.
3. ANALYSIS OF CROSSTALK

The analytical equations for the FBG-OC cross-connect are depicted in this section. Here in this analysis the signal power is defined by $P_{io}^j$, where $i$ denotes the wavelength channel and $j$ denotes the number of fibres. $i_0$ designates the fibre which contain the channel under study and $i_0$ designates the wavelength under study. The input power of the channel under study is defined by $P_{io}^{out}$ and the optical power at the output of the first stage is defined by $P_{io}^{out}$ (assuming all wavelength channels carry bit 1) and is given as [6]:

$$P_{io}^{out} = P_{io}^{in} + (P_{io}^{in} X_{FG} + P_{io}^{in} X_{OC}) - 2 \sqrt{P_{io}^{in} P_{io}^{in}} \sqrt{X_{FG} - 2}$$

$$ \sqrt{P_{io}^{in} P_{io}^{in}} \sqrt{X_{FG} - 2}$$

$$ \sqrt{P_{io}^{in} P_{io}^{in}} \sqrt{X_{FG} - 2}$$

$$ \sqrt{P_{io}^{in} P_{io}^{in}} \sqrt{X_{FG} Y_{OC}}$$

(1)

Among the five contributions of this equation the first term is the input signal, the second and third terms express the crosstalk contributions and the last three are beating terms. Here it is assumed that for the worst case the sign of the beat terms are negative and the amplitude of the beat terms are maximum. Here $X_{OC}$ is the optical circulator crosstalk and $X_{FG}$ is the fibre Bragg grating (FBG) crosstalk which is given by,

$$X_{FG} = 10 \log_{10} (1 - R_{FG})$$

(2)

where $R_{FG}$ is the FBG reflectivity. $P_{io}^{in}$ is the wavelength channel power at another fibre $j$ that carries a wavelength channel 0 when the FBG-OC cross connect carries only wavelength channel $i_0$ when (there is no crosstalk). Then the crosstalk can be expressed as:

$$\text{crosstalk} = \frac{P_{io}^{out(ref)}}{P_{io}^{out}}$$

(3)

Equation (1) is valid only in that case when all wavelength channels including wavelength channel $i_0$ carries bit 1. As wavelength channel $i_0$ may carry bit 1 or bit 0 at any instant of time, equation (1) has to be modified. If wavelength channel $i_0$ carries bit 0, then (1) reduces to:

$$P_{io}^{out(0)} = P_{io}^{in} X_{FG} - 2 \sqrt{P_{io}^{in} X_{FG}}$$

$$- 2 \sqrt{P_{io}^{in} X_{FG} X_{OC}}$$

(4)

$$P_{io}^{out(0)} = 0$$

(5)

The crosstalk model for FBG-OC cross connect is used to derive bit error rate (BER) for the transmission link considering the detector shot noise and receiver noise. The BER can be expressed as:

$$BER_{worstcase} = \frac{1}{8} \left[ \text{erfc} \left( \frac{1}{\sqrt{2}} \frac{i_1 + i_{CT0} - i_D}{\sigma_{1.0}} \right) + \text{erfc} \left( \frac{1}{\sqrt{2}} \frac{i_D - i_{CT0} - i_0}{\sigma_{0.0}} \right) + \text{erfc} \left( \frac{1}{\sqrt{2}} \frac{i_1 + i_{CT1} - i_D}{\sigma_{1.1}} \right) + \text{erfc} \left( \frac{1}{\sqrt{2}} \frac{i_D - i_{CT1} - i_0}{\sigma_{0.1}} \right) \right]$$

(6)

Here $i_D$ is the threshold current and it is expressed as:

$$i_D = \frac{\sigma_{0.1} i_1 + \sigma_{1.1} i_0}{\sigma_{0.1} + \sigma_{1.1}}$$

(7)

Here $\sigma_{1.0}^2$ is the noise variance when signal bit 1 is interfered by crosstalk due to bit 0, $\sigma_{0.0}^2$ is the noise variance when signal bit 0 is interfered by crosstalk due to bit 0, $\sigma_{1.1}^2$ is the noise variance when signal bit 1 is interfered by crosstalk due to bit 1 and $\sigma_{0.1}^2$ is the noise variance when signal bit 0 is interfered by crosstalk due to bit 1. The variances of interferences are expressed as:

$$\sigma_{1.0}^2 = \sigma_{sh}^2 + 2 e R_d (P_s + P_{CT0}) B$$

(8)

$$\sigma_{0.0}^2 = \sigma_{sh}^2 + 2 e R_d P_{CT0} B$$

(9)

$$\sigma_{1.1}^2 = \sigma_{sh}^2 + 2 e R_d (P_s + P_{CT1}) B$$

(10)

$$\sigma_{0.1}^2 = \sigma_{sh}^2 + 2 e R_d P_{CT1} B$$

(11)

where $e$ is the electronic charge, $R_d$ is the receiver responsivity and $\sigma_{sh}^2$ is the thermal noise in the detector with a temperature of 300 K and is expressed as:

$$\sigma_{sh}^2 = \frac{4 K T B}{R_L}$$

(12)
where \( K \) is Boltzmann constant, \( T \) is the temperature, \( B \) is the electrical bandwidth of the receiver and \( R_L \) is the receiver front end load (50Ω in this paper).

In relation (6), \( i_1 \) is the photocurrent for transmitted bit 1 and \( i_0 \) is the photocurrent for transmitted bit 0 assuming received signal power, \( P_S \) to be zero. \( i_1 \) can be expressed as:

\[
i_1 = 2R_LP_S
\]

(13)

If \( P_{CT1} \) represents the crosstalk power due to bit 1 and \( P_{CT0} \) is the crosstalk power due to bit 0, then they are expressed as:

\[
P_{CT0} = P_{i0}^{ref} - P_{i0}^{out}
\]

(14)

\[
P_{CT1} = P_{i1}^{out(ref)} - P_{i1}^{out}
\]

(15)

The corresponding crosstalk currents are given by,

\[
i_{CT1} = R_LP_{CT1}
\]

(16)

\[
i_{CT0} = R_LP_{CT0}
\]

(17)

4. RESULTS AND DISCUSSION

In this section, the crosstalk model presented in section 3 is applied to evaluate the bit error rate of a WDM transmission system taking into account the effects of component crosstalk \( X_{FG} \) and \( X_{OC} \) of a FBG-OC based optical cross connect. Calculations are performed for \( N=4 \), \( M=4 \) and for a bit rate of 10 Gb/s with several values of input powers. The plots of bit error rate (BER) versus received power for different values of \( X_{FG} \) are shown in Fig. 3. In this case it is assumed that \( X_{OC} = -55 \) dB. It is noticed from the plots that the system suffers power penalty due to the increment in the value of \( X_{FG} \) for a given value of \( X_{OC} \). The penalties due to crosstalk at a given BER of 10\(^{-9}\) are determined from the BER plots. For example, the system faces a power penalty of 2.5 dB when the value of \( X_{FG} \) increases from -30 dB to -15 dB. It is also noticed that if the value of \( X_{OC} \) is increased beyond the value of -15 dB keeping the value of \( X_{FG} \) then the power penalty becomes abruptly high. Crosstalk thus limits the amount of component crosstalk factor \( X_{FG} \) and \( X_{OC} \).

The plots of BER versus received power for different values of \( X_{OC} \) are shown in Fig. 4 assuming \( X_{FG} \) to be -95 dB. It is also noticed from the plots that the bit error rate increases and received power decreases as the optical circulator crosstalk factor \( (X_{OC}) \) increases for a given value of \( X_{FG} \). The system also suffers a power penalty due to the increment of \( X_{OC} \).

5. CONCLUSION

The bit error rate of WDM system comprising of a FBG-OC based cross-connect is evaluated. For an electrical bandwidth of 10 Gb/s, the power penalty due to crosstalk is evaluated at a BER of 10\(^{-9}\). It is noticed that higher values of \( X_{FG} \) and \( X_{OC} \) causes higher power penalty. The overall system performance can be improved by decreasing the values of \( X_{FG} \) and \( X_{OC} \) as the number of channels or the number of fibres do not have any contribution on the crosstalk or BER performance of this type of cross-connect. This research will be helpful in
designing a FBG-OC based optical cross-connect to keep a lower crosstalk and bit-error-rate.

6. REFERENCES


