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Bit Error Rate and Crosstalk Performance in Optical Cross Connect without Wavelength Converter

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***Abstract*-An analytical approach is presented for modeling crosstalk and to evaluate the bit error rate (BER) performance in a wavelength division-multiplexing (WDM) network for link with optical cross connect (OXC) without wavelength converter. Factors that affect the magnitude of crosstalk in the OXC are investigated and parameters that play important role in determining magnitude of crosstalk and BER are identified. The effects of OXC induced crosstalk on the BER performance is evaluated at a bit rate of 10 Gb/s by optimizing different parameters.**

I. Introduction

WDM is a technique to increase the information capacity of a fiber by transmitting a number of optical signals of different wavelengths simultaneously over the same fiber. WDM networks are very promising due to their flexibility and possibility of upgrading the existing optical fiber networks to WDM networks [1]. The OXC is an essential network element enabling reconfigurable optical networks, where lightpaths can be set up and taken down as needed [2]-[4]. It offers routing flexibility and transport capacity to WDM networks. Propagation through the switching elements that are part of the OXC results in signal degradation both due to the device intrinsic losses and their imperfect operation. Imperfect switching gives a leakage signal, whose wavelength can be equal or different from the signal wavelength. The build-up of crosstalk noise on a certain optical channel due to interference with other signals while propagating through the different elements of the WDM network could result in serious problems. Crosstalk due to OXC is one of the basic criteria that characterize the performance of WDM network [5]-[8]. Crosstalk leads to transfer of power from one channel to another. Crosstalk can be classified as linear and non-linear. Linear crosstalk occurs due to channel-selection devices such as due to the imperfect nature of de-multiplexing components used; which in this case are the arrays of power splitter. Non-linear crosstalk occurs due to non-linear effects in optical fiber such as four-wave mixing (FWM), stimulated Raman scattering, stimulated Brillouin scattering and cross-phase modulation (XPM). Since optical crosstalk is a major limiting factor, therefore, the commercial use of all-optical OXC so far prevented in WDM networks. In this paper we present an analytical approach to identify and determine the optimum values of parameters that induce crosstalk in OXC without wavelength converter and its influence on the overall BER performance at a bit rate of 10 Gb/s.

II. Topology for Optical Cross-Connect Without Wavelength Converter

There are currently a few OXC topologies that show promising future. As suggested by [1], OXC is basically made up of splitter that splits different channels to be fed into different switches. Switches are used to cross-connect the channels to desired paths. Combiner is then used to combine all the channels into a number of output fibers. OXC without wavelength converter used in this paper is based on array of gates shown in Fig. 1. The OXC is based on the gain-clamped semiconductor optical amplifier (GC-SOA) and wavelength converter. It uses a combination of space and wavelength switching. The wavelength channel to be transmitted is multiplexed by a WDM MUX and fed to an incoming fiber. This OXC enables any wavelength channel from any input fiber to be cross-connected to any output fiber, on condition that no two channels in the output fiber have the same wavelength. Fiber *a* carries wavelength channels λ_{a1}, λ_{a2} ... λ_{aM} and fiber *b* carries wavelength channels λ_{b1}, λ_{b2} ... λ_{bM}.. Given that *N* is the number of input fiber and *M* is the number of wavelengths, then there are a total of *N x M* wavelength channels. If there are *N x M* channels at the input of the OXC, then all the wavelength channels pass through first array of power splitters. There are only *N* power splitters for all each of the *N* input fibers (called first array of splitters). All the different wavelength channels appear at the output of the power splitter at lesser power due to power splitting. Wavelengths λ_{a1}, λ_{a2} ... λ_{aM} are then fed to another array of *M* power splitters. There is a total of *N* x *M* power splitters at the second array. The output of the second array of power splitters are fed to gates made from GC-SOA, which allows only specific wavelength to pass through. The combiner at first output fiber, such as combiner λ_1, receives its inputs from λ_{a1}, λ_{b1}, ... $\lambda_{\zeta 1}$. Output of *N* x *M* combiners is fed to *N* x *M* filters. The second array of *N* combiners, combine all cross-connected wavelength channels and output them to *N* output fibers.

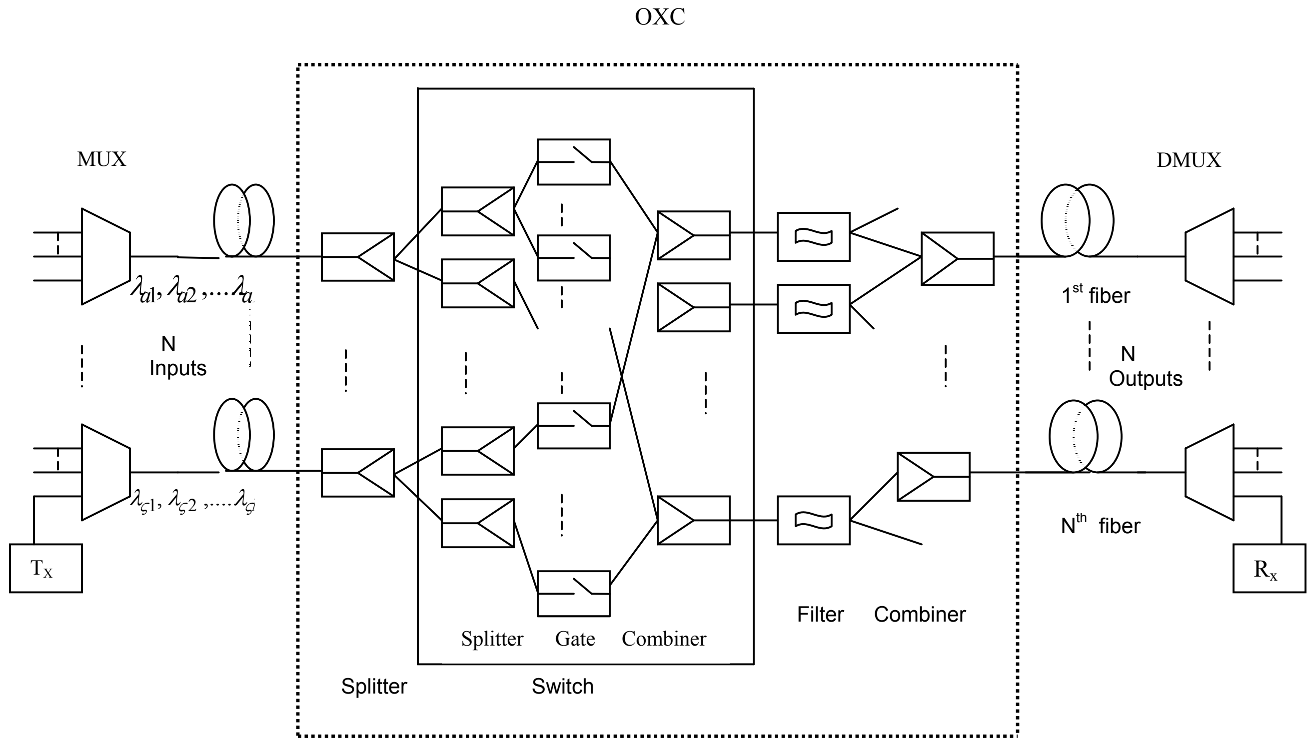

Fig.1: Block diagram of a WDM transmission link with an OXC based on GC-SOA and without wavelength converter

III. CROSSTALK AND BER MODEL

Analytical model of crosstalk due to OXC is presented in this section and used to evaluate the BER performance of the WDM link with OXC. Analytical expressions are given that describe the output power of the OXC as a function of input power and component parameters. The OXC in Fig.1 is used to derive the crosstalk model. Assuming P_{io}^{jo} is the input power of a channel, then the output power P_{io1}^{out} is as shown in (1) based on [1]. P_{io1}^{out} is defined as the output power of wavelength channel i_o with crosstalk contributions added (assume all wavelength channels carry bit 1). T_F is filter transmission factor, R_{gate} is gate extinction ratio and X_{gate} is gate crosstalk. N is the number of input fiber into OXC. M is the number of wavelengths per input fiber.

$$
\begin{aligned}
P_{io1}^{out} = {} & P_{io}^{jo} + P_{io}^{jo}\left\{X_{gate}\left[(M-1)P_i^{jo} + P_{io}^{jo}\right]\right\} + P_{io}^{j}\left\{\begin{array}{l}(N-1)R_{gate}\left[1+X_{gate}MP_i^{j}\right]\\ +(M-1)T_F\left[1+X_{gate}MP_i^{j}\right]\\ +(N-1)(M-1)^2T_FR_{gate}\end{array}\right\} \\
& -2\sqrt{P_{io}^{jo}}\sqrt{P_{io}^{j}}\left\{\begin{array}{l}(N-1)\sqrt{R_{gate}}\\ +(M-1)\sqrt{T_F}\\ +(N-1)(M-1)\sqrt{R_{gate}}\sqrt{T_F}\end{array}\right\} - 2P_{io}^{j}\left\{\begin{array}{l}(N-1)(M-1)\sqrt{R_{gate}}\sqrt{T_F}\\ +(N-1)^2(M-1)R_{gate}\sqrt{T_F}\\ +(N-1)(M-1)^2\sqrt{R_{gate}}T_F\end{array}\right\} \\
& -2P_{io}^{j}\left\{R_{gate}\sum_{t=1}^{N-2}t + T_F\sum_{t=1}^{M-2}t + R_{gate}T_F\sum_{t=1}^{(M-1)(N-1)-1}t\right\}
\end{aligned} \qquad (1)
$$

$$
\begin{aligned}
P_{io0}^{out} = {} & P_{io}^{j}\left\{\begin{array}{l}(N-1)R_{gate}\left[1+X_{gate}MP_i^{j}\right]\\ +(M-1)T_F\left[1+X_{gate}MP_i^{j}\right]\\ +(N-1)(M-1)^2T_FR_{gate}\end{array}\right\} - 2P_{io}^{j}\left\{\begin{array}{l}(N-1)(M-1)\sqrt{R_{gate}}\sqrt{T_F}\\ +(N-1)^2(M-1)R_{gate}\sqrt{T_F}\\ +(N-1)(M-1)^2\sqrt{R_{gate}}T_F\end{array}\right\} \\
& -2P_{io}^{j}\left\{R_{gate}\sum_{t=1}^{N-2}t + T_F\sum_{t=1}^{M-2}t + R_{gate}T_F\sum_{t=1}^{(M-1)(N-1)-1}t\right\}
\end{aligned} \qquad (2)
$$

P_i^{jo} is the wavelength channel power in fiber j_o which has wavelength i. P_{io}^{j} is the wavelength channel power at another fiber j that carries a wavelength i_o. P_i^j is the wavelength channel power at another fiber j with other wavelengths i. P_{io1}^{out} at any output fiber is just $1/N$ of the output power, due to division of power before entering GC-SOA. However, in this paper, we set the gain of the GC-SOA to N to compensate for the division of output optical power. X_{gate} is a parameter that measures the gate's imperfection in gain clamping and is given by, $X_{gate} = P_{gate(ref)} / P_{gate}$; where P_{gate} is the power output from the GC-SOA gate. $P_{gate(ref)}$ is the reference output power of the GC-SOA gate. T_F is derived from the filter suppression of wavelength channel, T_F^{-1}. The OXC with wavelength converter, there is one gate in *on* state for every group of N gates. Hence there are NM gates in *on* state at any time for a total of NM^2 gates. The calculation is done for worst-case situation, where the OXC is handling full traffic and also the amplitudes of the beat term are assumed to be maximum. Extinction ratio is defined as, $R_{gate} = P_{off} / P_{on}$. P_{in} is defined as the input power through each gate. The expression for output power with crosstalk of wavelength channel i_0 is given by equation (1) based on Ref. [1] shown in the previous page under the assumption that all channels carries bit 1. P_{io}^{jo} is defined as N times of P_{in} since there is one gate in *on* state for every group of. gates. $P_{io}^{out(ref)}$ is the output power of wavelength channel i_o when the OXC is carrying only. wavelength channel i_o, such as when there is no crosstalk. $P_{io}^{out(ref)}$ is given by, $P_{io}^{out(ref)} = P_{io}^{jo} + X_{gate}(P_{io}^{jo})^2$. Since wavelength channel i_o may carry bit 1 or bit 0 at any instant of time, equation (1) has to be modified. If wavelength channel i_o carries bit 0, then equation (1) reduces to (2).

$P_{io}^{out(ref)}$ when wavelength channel i_o carries bit 0 can be written as, $P_{io}^{out(ref)} = 0$. The crosstalk is calculated for a certain wavelength channel; which is called the channel under study. The expression for relative crosstalk is given by,

$$crosstalk = \frac{(P_{io}^{out\ (ref)} - P_{io1}^{out})}{P_{io}^{out\ (ref)}} \tag{3}$$

$$Crosstalk\ (dB) = 10\log_{10}(Crosstalk) \tag{3a}$$

To evaluate the BER of a WDM system, the crosstalk model for OXC with wavelength converter is used to derive BER model for OXC with wavelength converter. The expression for BER of a WDM network with wavelength converter in an IM-DD system can be given by,

$$BER_{worstcase} = \frac{1}{8}\left[\begin{array}{l} erfc\left(\frac{1}{\sqrt{2}}\frac{i_1 + i_{CT0} - i_D}{\sigma_{1\_0}^2}\right) + erfc\left(\frac{1}{\sqrt{2}}\frac{i_D - i_0 - i_{CT0}}{\sigma_{0\_0}^2}\right) + \\ erfc\left(\frac{1}{\sqrt{2}}\frac{i_1 + i_{CT1} - i_D}{\sigma_{1\_1}^2}\right) + erfc\left(\frac{1}{\sqrt{2}}\frac{i_D - i_0 - i_{CT1}}{\sigma_{0\_1}^2}\right) \end{array}\right] \tag{4}$$

$$\sigma_{1\_0}^2 = \sigma_{th}^2 + 2eR_d(P_S + P_{sp} + P_{CT0})B + \sigma_{S-sp}^2 + \sigma_{CT0-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{S-CT0}^2 \tag{5}$$

$$\sigma_{0\_0}^2 = \sigma_{th}^2 + 2eR_d(P_{sp} + P_{CT0})B + \sigma_{CT0-sp}^2 + \sigma_{sp-sp}^2 \tag{6}$$

$$\sigma_{1\_1}^2 = \sigma_{th}^2 + 2eR_d(P_S + P_{sp} + P_{CT1})B + \sigma_{S-sp}^2 + \sigma_{CT1-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{S-CT1}^2 \tag{7}$$

$$\sigma_{0\_1}^2 = \sigma_{th}^2 + 2eR_d(P_{sp} + P_{CT1})B + \sigma_{CT0-sp}^2 + \sigma_{sp-sp}^2 \tag{8}$$

Equation (4) assumes the scenario when a bit 1 is interfered by a crosstalk bit 1, bit 0 is interfered by crosstalk bit 0, bit 1 is interfered by crosstalk bit 0 and bit 0 is interfered by crosstalk bit 1 as reported by [6]. The variance of the interference is given in (5) to (8). Where, σ_{1-0}^2 is the variance when signal bit 1 is interfered by crosstalk due to bit 0 and σ_{0-0}^2 is the variance when signal bit 0 is interfered by crosstalk due to bit 0. σ_{1-1}^2 is the variance when signal bit 1 is interfered by crosstalk due to bit 1 and σ_{0-1}^2 is the variance when signal bit 0 is interfered by crosstalk due to bit 1. σ_{th}^2 is the power of thermal noise, R_d is the receiver responsivity, B is the bandwidth of the receiver low-pass filter, P_S is signal power. Photocurrent for a transmitted bit 1 is given by, $i_1 = 2R_d P_S$. For transmitted bit 0, photocurrent, i_0=0, with P_S assumed to be zero and i_D is the threshold current. The expression for amplified spontaneous emission (ASE) power (P_{sp}) given by, $P_{sp} = hfF(G-1)B$. The amount of crosstalk power due to bit 1 is, $P_{CT1} = -P_{io1}^{out(ref)} - P_{io1}^{out}$ and crosstalk power due to bit 0 can be expressed as, $P_{CT0} = -P_{io0}^{out}$.

Threshold current, i_D is shown in (9). σ_{S-sp}^2 is the power of the beating of signal and amplified spontaneous emission (ASE), shown in (10). σ_{CT-sp}^2 is the power of the beating of crosstalk and amplified spontaneous emission (ASE), shown in (11) and (12) for crosstalk due to bit 1 and 0 respectively. σ_{S-CT}^2 is the power of the beating of signal and crosstalk, shown in (13) and (14) for crosstalk due to bit 1 and 0 respectively. σ_{sp-sp}^2 is the power of the beating of amplified spontaneous emission (ASE) and ASE, shown in (15). $S_{sp}(f)$ is the power spectral density of amplified spontaneous emission (ASE) noise, $S_{CT1}(f)$ is the power spectral density of crosstalk due to bit 1, $S_{CT0}(f)$ is the power spectral density of crosstalk due to bit 0 and $S_S(f)$ is the power spectral density of the signal.

$$i_D = \frac{\sigma_{0\_1} i_1 + \sigma_{1\_1} i_0}{\sigma_{0\_1} + \sigma_{1\_1}} \tag{9}$$

$$\sigma_{S-sp}^2 = R_d^2 \int_{-B/2}^{B/2} S_S(f) * S_{sp}(f) \cdot |H(f)|^2\, df \tag{10}$$

$$\sigma_{CT0-sp}^2 = R_d^2 \int_{-B/2}^{B/2} S_{sp}(f) * S_{CT0}(f) \cdot |H(f)|^2 \, df \quad (11)$$

$$\sigma_{S-CT0}^2 = R_d^2 \int_{-B/2}^{B/2} S_S(f) * S_{CT0}(f) \cdot |H(f)|^2 \, df \quad (12)$$

$$\sigma_{S-CT1}^2 = R_d^2 \int_{-B/2}^{B/2} S_S(f) * S_{CT1}(f) \cdot |H(f)|^2 \, df \quad (13)$$

$$\sigma_{CT1-sp}^2 = R_d^2 \int_{-B/2}^{B/2} S_{sp}(f) * S_{CT1}(f) \cdot |H(f)|^2 \, df \quad (14)$$

$$\sigma_{sp-sp}^2 = R_d^2 \int_{-B/2}^{B/2} S_{sp}(f) * S_{sp}(f) \cdot |H(f)|^2 \, df \quad (15)$$

IV. THE BER AND CROSSTALK RESULTS

Following the analytical approach presented in section III, the BER performance results are evaluated at a bit rate of 10 Gb/s and the relation between filter transmission factor (T_F) and number of wavelength (M) under varying gate extinction ratio (R_{gate},), number of input fiber (N) and input power (P_{in}) are investigated.

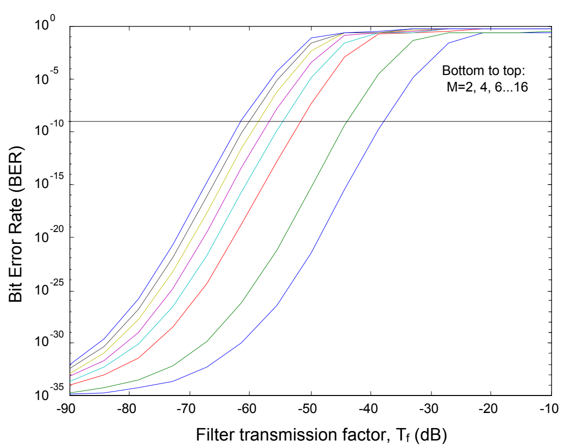

Fig. 2: Plot of BER vs. filter transmission factor, T_F
(N=6, R_{gate}= - 62.20dB, P_{in}= - 20dBm, X_{gate}= - 0.10/mW)

Plot of BER vs. filter transmission factor (T_F) is shown in Fig. 2 for increasing value M. For a fixed value of number of wavelength (M), BER decreases with decrease of filter transmission, which represents improvement in suppression of other wavelength channels by filters in the OXC. BER drops almost linearly with decrease of filter transmission from –40dB to –80dB. Beyond –80dB value, BER decreases at decreasing rate. Such a low value of filter transmission may not be achievable at the present moment but this serve as a target for the design of future OXC. From the plot of BER vs. filter transmission factor (T_F), (fig. 3) it is evident that for a certain number of wavelength (M) passing through an OXC, the quality of filter transmission has to be better than a cut off value determined by setting BER to be at least 10^{-9}. It is seen that as the number of wavelengths passing through an OXC increases, the wavelength suppression capability (T_F^{-1}) of the OXC has to be improved. Wavelength suppression capability refers to the ability of an OXC to reject wavelengths other than the intended wavelength or to prevent other wavelengths from entering the cross-connect intended for another wavelength.

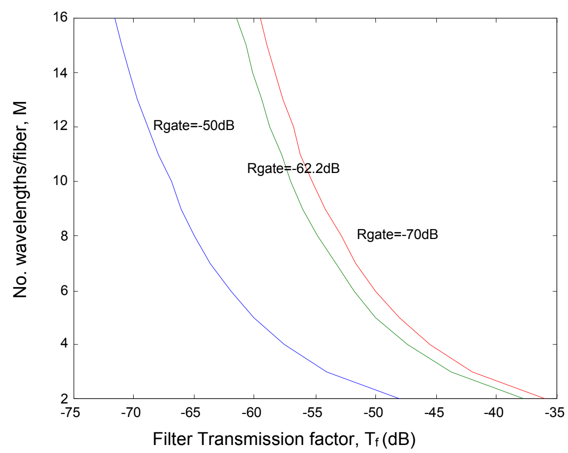

Fig. 3: Plot of M vs. T_f for different gate extinction ratio, R_{gate}

Plot of crosstalk vs. filter transmission factor (T_F) is shown in Fig. 4. from the plot, it is observed that crosstalk decreases with decrease in number of wavelength (M) and also with decrease in filter suppression (smaller value). That means, when more channels need to be accommodated, it is better to increase the number of wavelength (M) than to increase the number of input fiber (N). For example, if number of input fiber (N) is fixed to a small value (around 5 to 6), as shown in Fig. 5 (M vs. T_F,) the penalty in terms of necessity to increase quality of filter transmission becomes less critical as number of wavelength (M) is increased to large value. If the number of channels that need to be accommodated is large (>8), it is better to increase the number of wavelengths while maintaining the number of input fibers to a small value. If the number of channels to be accommodated is small, it is better to increase the number of input fibers with number of wavelengths fixed to a small value. A

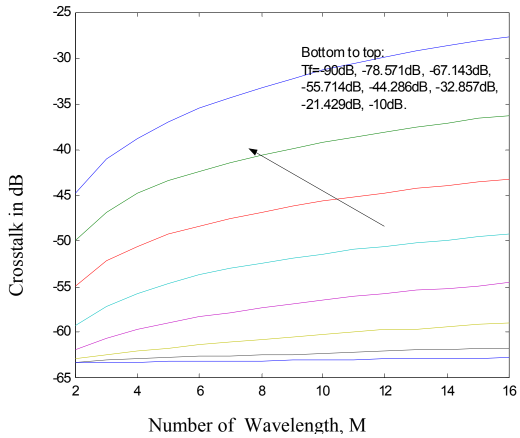

Fig.4 : Plot of crosstalk vs. no. of wavelength, M
(N=6, M=16, R_{gate}= - 62.20dB, P_{in}= - 20dBm, X_{gate}= - 0.10/mW)

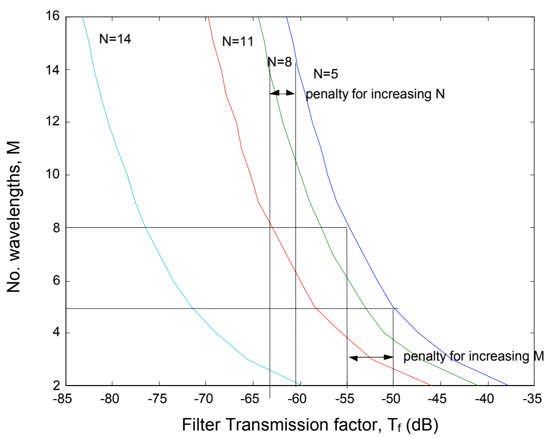

Fig. 5: Plot of M vs. T_F for different N to maintain BER<10^{-9}

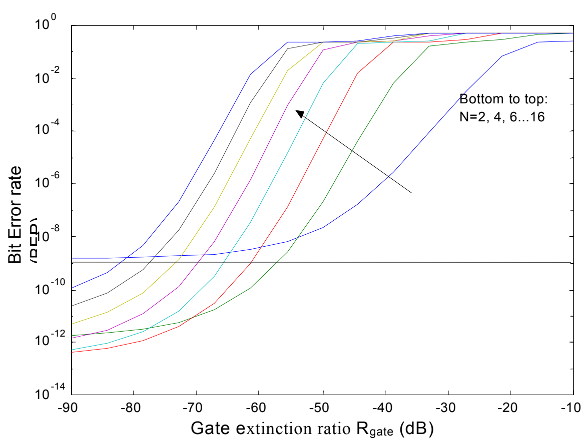

Fig. 6: Plot of BER vs. gate extinction ratio, R_{gate}
(M=16, T_F= - 61.7dB, P_{in}= - 20dBm, X_{gate}= - 0.10/mW)

Plot of BER vs. R_{gate} (gate extinction ratio) is shown in Fig. 6. The optimum number of input fiber for a certain value of gate extinction ratio corresponds to the point of the plot that shows minimum BER. The corresponding crosstalk value is shown in Fig. 7, shows the values of gate extinction ratio needed to maintain BER below 10^{-9}. The plot shows that the requirement for smaller gate extinction ratio increases linearly with increase of number of input fibers.

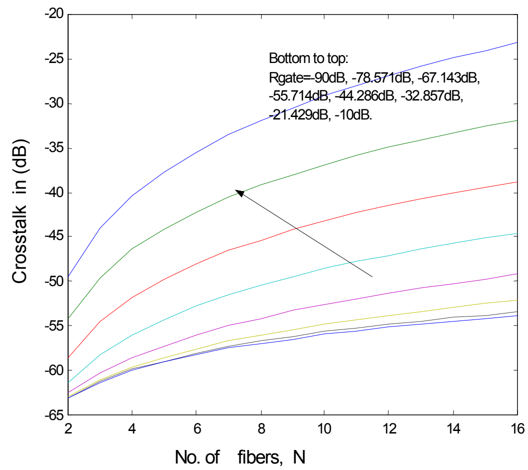

Fig. 7: Plot of crosstalk vs. no. of fiber, N
(, M=16, T_F= - 61.7dB, P_{in}= - 20dBm, X_{gate}= - 0.10/mW)

The plot of filter transmission factor (T_F) vs. number of wavelength (M) for different gate input power (P_{in}) is shown in Fig.8 and it is used to derive the value of gate input power that maintains BER less than or at least 10^{-9}. Here, it shows that as gate input power is decreased from –10dBm to –20dBm, filter transmission quality requirement becomes less stringent (larger value).

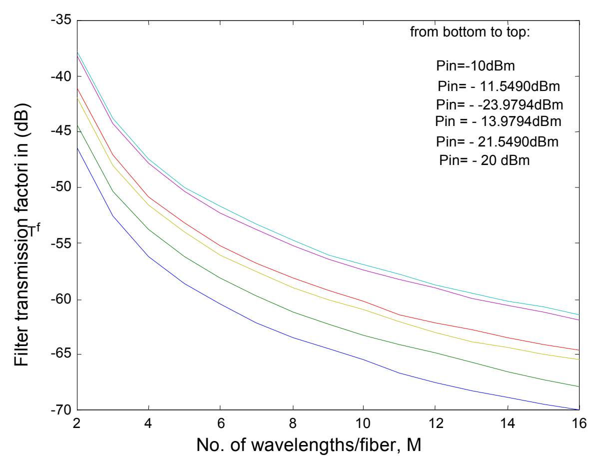

Fig 8: Plot of T_F vs. M to maintain BER<10^{-9}

However, as gate input power is further decreased from –20dBm to –24dBm and filter transmission quality requirement becomes more stringent (smaller value). Thus, P_{in} = - 20dBm represents an optimum power level. To confirm the discovery, BER vs. gate input power (P_{in}) for different filter transmission is plotted in Fig. 9. It shows a minimum BER at certain input power, P_{in}. For example, if N=6 and M=16 is chosen and P_{in} = -20dBm, then from Fig. 8, filter transmission factor (T_F) must be –61.7dB. From the plot, it is found that for T_F = –61.7dB, the plot touches BER=10^{-9} line at exactly P_{in} = -20dBm. The graph also shows that BER performance can be improved by improving filter transmission factor. Any OXC design should make use of the region at minimum BER.

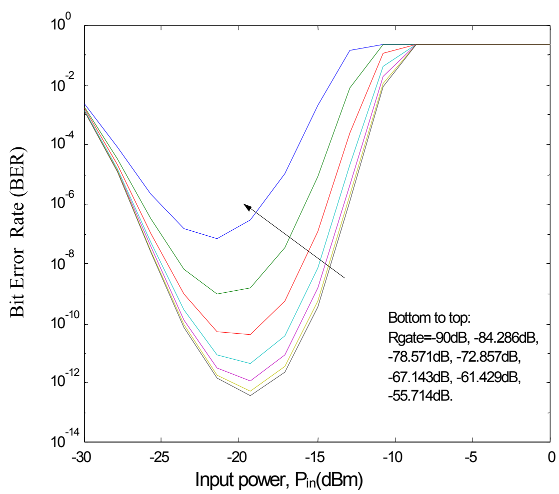

Fig. 9: Plot of BER vs. input power, P_{in}
(N=6, M=16, T_F= - 61.7dB, P_{in}=-20dBm, X_{gate}= -.1/mW).

The optimized parameters for M=16 and N=5 are as shown in Table 1. The assumptions used in computing the optimized parameters are as shown in Table 2.

Table 1
Optimized Parameters:

Parameters	**Values**	**Unit**
Number of wavelength (M)	16	unitless
Filter transmission (T_f)	-61.70	dB
Number of input fiber (N)	6	unitless
Gate extinction ratio (R_{gate})	-62.20	dB
Input power per gate (P_{in})	-20	dBm
Gate crosstalk (X_{gate})	-0.10	/mW

Table 2:
Assumptions:

Parameters	**Values**	**Unit**
Temperature (T)	300	K
Bandwidth (B)	10	GHz
Receiver load (R_L)	50	Ohm
Receiver responsivity (R_d)	1	A/W
Inversion factor (F)	3.9716	unitless
Amplifier gain (G)	250	unitless
Operating frequency (f)	1.93×10^{14}	Hz

V. CONCLUSION

In this paper, crosstalk and BER performance of a WDM network with OXC without wavelength converter are analytically determined and different factors that affect magnitude of crosstalk and BER in the OXC are investigated in detail. Factors that affect magnitude of crosstalk and BER in the OXC have been investigated. OXC parameters that play important role in determining magnitude of crosstalk and BER have also been identified and parameters that result in minimum BER in the OXC have been proposed.

REFERENCES

[1] Tim Gyselings, G. Morthier and R. Baets, “Crosstalk analysis of multiwavelength optical cross connect”, *Journal of Lightwave Technology*, vol. 17, no. 8, August 1999 , pp. 1273-1283.

[2] S. P. Majumder and S. Dey, “BER performance degradation due to component crosstalk of an arrayed Waveguide grating and FBG-OC based WDM cross-connect”, *INDICON 2005 Annual IEEE*, 2005, pp. 97-100.

[3] T. Song, H. Zhang, Y. Guo and X. Zheng, “Statistical study of crosstalk accumulation in WDM optical network with different topology”, *TENCON’02, proceedings*, 2002, pp. 1170-1173.

[4] E. Iannone and R. Sabella, “Optical path technologies: A comparison among different cross-connect architectures”, *Journal of Lightwave Technology,* vol. 14, no. 10, October 1996., pp. 2184-2195

[5] Y. Shen, K. Lu and W. Gu,, “Coherent and incoherent crosstalk in WDM optical networks”, *Journal of Lightwave Technology*, vol. 17, no. 5, May 1999, pp. 759-764.

[6] T. Y. Chai, H. Chen, S. K. Bose and C. Lu, “Crosstalk analysis for limited wavelength interchanging cross connects”, *IEEE Photonics Technology Letters*, vol.14, no.5, May 2002 , pp. 696-698.

[7] J. Zhou , E. Casaccia Cavazzoni and M. J. O’Mahony, “Crosstalk in multiwavelength OXC networks”, *Journal of Lightwave Technology*, June 1996, pp. 1423-1435.

[8] Y. S. Jang, C. –H. Lee and Y. C. Chung, “Effects of crosstalk in WDM systems using spectrum-sliced light sources”, *Photonics Technology Letters*, June 1999, pp. 715-717.