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BIT ERROR RATE AND CROSSTALK PERFORMANCE IN OPTICAL CROSS CONNECT WITH WAVELENGTH CONVERTER

Ngee Thiam Sim[1], *S P Majumder*[2], *M S Islam*[3]

[1]Telekom Malaysia Berhad, Sarwak, Malaysia, E-mail: *simngeethiam@hotmail.com*
[2]Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh, E-mail: *spmajumder@eee.buet.ac.bd*
[3]Institute of Information and Communication Technology, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh, E-mail: *mdsaifulislam@iict.buet.ac.bd*

ABSTRACT

An analytical approach is presented for modelling crosstalk and to evaluate the bit error rate (BER) performance in a wavelength division multiplexing (WDM) network for link with optical cross connect (OXC). Factors that affect the magnitude of crosstalk in the OXC are investigated and 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. The results show that for optimized values of gate extinction ratio, filter transmission factor, and number of wavelengths and input fibers, the minimum input power is around –10dBm to –8dBm to maintain a BER of 10^{-9} .

1. 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]. 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 [9] we present an analytical approach to identify and determine the optimum values of parameters that induce crosstalk in OXC with wavelength converter and its influence on the overall BER performance at a bit rate of 10 Gb/s.

2. OPTICAL CROSS-CONNECT TOPOLOGY

The block diagram of a WDM transmission link with an optical cross-connect (OXC) is 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. At the input of OXC the incoming signals are splitted by a first array of power splitters followed by a second array of power splitters. At the input of GC-SOA gates, all channels are present. The gate selects the wavelength that carries the desired channel. A wavelength converter is used to convert the channel wavelength from one wavelength to other wavelength. The 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. In Fig.1, 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 different wavelengths, there are a total of N x M wavelength channels. The N x M wavelength channels passed through first array of power splitters. There are N power splitters for all the N input fibers.

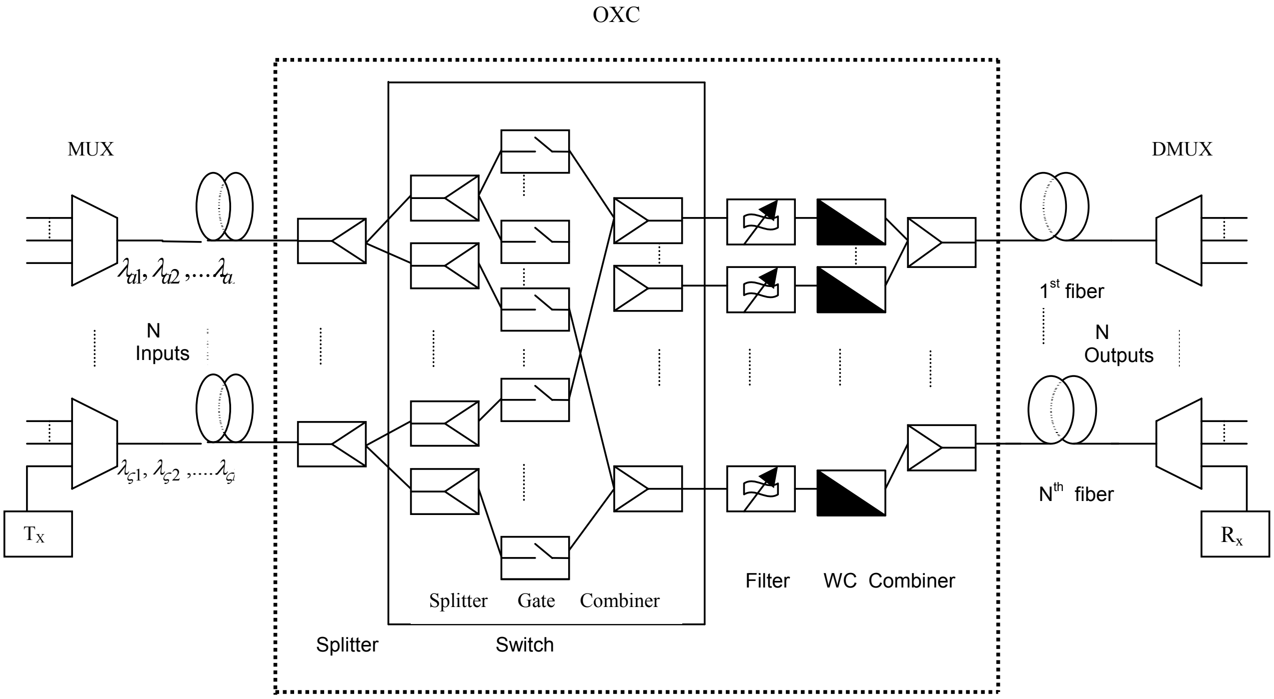

Fig.1: Block diagram of a WDM transmission link with an OXC based on GC-SOA and wavelength converter

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}, ... $\lambda_{\varsigma 1}$. Output of N x M combiners is fed to N x M filters and wavelength converter. The second array of N combiners, combine all cross-connected wavelength channels and output them to N output fibers. The desired wavelength channel of an outgoing fiber is demultiplexed by a WDM DMUX and is received by a direct detection receiver.

3. 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 powers and component parameters. Here, P_{io}^{jo} is the input power of a channel, P_{io1}^{out} is defined as the output power of wavelength channel i_o with crosstalk contributions added (with all wavelength channels carrying bit 1). T_F is filter transmission factor, R_{gate} is gate extinction ratio, X_{gate} is gate crosstalk, N is the number of input fiber into OXC, M is the number of wavelengths per input fiber.

P_i^{jo} is the signal power at fiber j_o with another wavelength i. P_{io}^{j} is the signal power at another fiber j that carries the wavelength under consideration, i_o. P_i^j is the signal power at another fiber j with other wavelengths, i. We assume that all wavelength channels including P_{io}^{jo} carry bit 1. P_{io1}^{out} at any output fiber may be just $1/N$ of the output power, due to division of power before entering the GC-SOA. However, in this paper, it is also assumed that the GC-SOA is set with gain of N times 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 next 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

$$P_{io1}^{out} = P_{io}^{jo} + P_{io}^{jo}\left\{X_{gate}\left[(M-1)P_i^{jo} + P_{io}^{jo}\right]\right\} + P_{io}^{j}\begin{Bmatrix}(N-1)R_{gate}\left[1+X_{gate}MP_i^j\right] \\ +(M-1)T_F\left[1+X_{gate}MP_i^j\right] \\ +(N-1)(M-1)^2T_FR_{gate}\end{Bmatrix} \quad (1)$$

$$-2\sqrt{P_{io}^{jo}}\sqrt{P_{io}^j}\begin{Bmatrix}(N-1)\sqrt{R_{gate}} \\ +(M-1)\sqrt{T_F} \\ +(N-1)(M-1)\sqrt{R_{gate}}\sqrt{T_F}\end{Bmatrix} - 2P_{io}^j\begin{Bmatrix}(N-1)(M-1)\sqrt{R_{gate}}\sqrt{T_F}\\ +(N-1)^2(M-1)R_{gate}\sqrt{T_F} \\ +(N-1)(M-1)^2\sqrt{R_{gate}}T_F\end{Bmatrix} - 2P_{io}^j\left\{R_{gate}\sum_{t=1}^{N-2}t + T_F\sum_{t=1}^{M-2}t + R_{gate}T_F\sum_{t=1}^{(M-1)(N-1)-1}t\right\}$$

$$P_{io0}^{out} = P_{io}^{j}\begin{Bmatrix}(N-1)R_{gate}\left[1+X_{gate}MP_i^j\right] \\ +(M-1)T_F\left[1+X_{gate}MP_i^j\right] \\ +(N-1)(M-1)^2T_FR_{gate}\end{Bmatrix} - 2P_{io}^j\begin{Bmatrix}(N-1)(M-1)\sqrt{R_{gate}}\sqrt{T_F}\\ +(N-1)^2(M-1)R_{gate}\sqrt{T_F} \\ +(N-1)(M-1)^2\sqrt{R_{gate}}T_F\end{Bmatrix} \quad (2)$$

$$-2P_{io}^j\left\{R_{gate}\sum_{t=1}^{N-2}t + T_F\sum_{t=1}^{M-2}t + R_{gate}T_F\sum_{t=1}^{(M-1)(N-1)-1}t\right\}$$

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,

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

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,

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

where

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

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

$$\sigma_{1\_0}^2 = \sigma_{th}^2 + 2eR_d(P_S+P_{sp}+P_{CT0})B + \sigma_{S-sp}^2 + \sigma_{CT0-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{S-CT0}^2 \quad (7)$$

$$\sigma_{1\_1}^2 = \sigma_{th}^2 + 2eR_d(P_S+P_{sp}+P_{CT1})B + \sigma_{S-sp}^2 + \sigma_{CT1-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{S-CT1}^2 \quad (8)$$

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, $\sigma_{1\_0}^2$ is the variance when signal bit 1 is interfered by crosstalk due to bit 0 and $\sigma_{0\_0}^2$ is the variance when signal bit 0 is interfered by crosstalk due to bit 0. $\sigma_{1\_1}^2$ is the variance when signal bit 1 is interfered by crosstalk due to bit 1 and $\sigma_{0\_1}^2$ 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, $i_1 = 2R_dP_S$. 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, $P_{CT0} = -P_{io0}^{out}$.

4. THE BER AND CROSSTALK RESULTS

Following the analytical approach presented in section 3, the BER performance results are evaluated at a bit rate of 10 Gb/s.

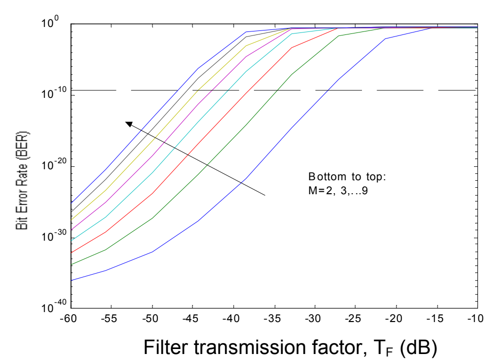

Fig. 2 : Plot of BER as a function of T_F with optimized parameters.
(N=13, M=16, R_{gate}= -46.6dB, P_{in}= -6.88dBm)

The plot of BER vs. filter transmission factor, T_F is shown in Fig.2. From this plot, it is observed that for a certain number of wavelengths passing through the OXC, quality of T_F needs to be better than a 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 of the filter has to be improved to maintain a specific BER.

Fig. 3 shows the plot of BER vs. P_{in} for different values of filter transmission factor, T_F . From the plot, we found that the input power, P_{in} corresponding to minimum BER is around -10dBm to –8dBm for filter transmission factor (T_F) around –80dB to –30dB

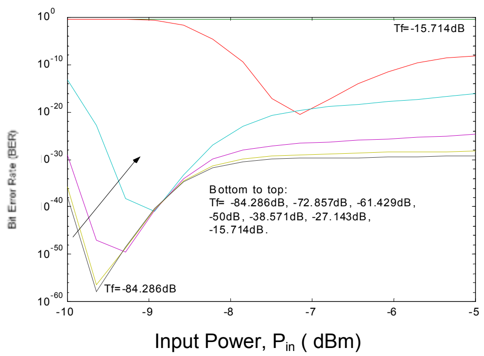

Fig. 3: Plot of BER vs. P_{in} with optimized parameters (N=13, M=16, T_F = -37dB, R_{gate}= -46.6dB)

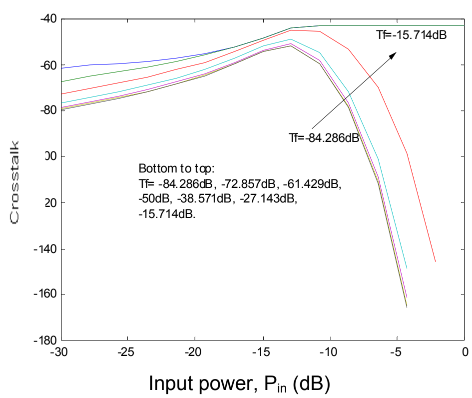

Fig. 4: Plot of crosstalk vs. P_{in} with optimized parameters (N=13, M=16, T_F = -37dB, R_{gate} = -46.6dB)

Increasing the input power, P_{in} reduces the requirement for better suppression ratio (T_F^{-1}) and vice versa. The plot of crosstalk vs. input power, P_{in} plot is depicted in Fig.4. It is found that crosstalk decreases tremendously at high P_{in} after achieving maximum point at around –10dBm.

From the above discussion, we observed that to operate the OXC at minimum input power, the values of filter transmission factor, T_F and gate extinction ratio, R_{gate} should be slightly better than the optimized value. This is to take into account of possible variation of input power, P_{in}.

5. CONCLUSION

In this paper, crosstalk and BER performance of a WDM network with OXC with wavelength converter are analytically determined and different factors that affect magnitude of crosstalk and BER in the OXC are investigated in detail. The OXC parameters that play important role in determining magnitude of crosstalk and BER are identified and parameters that result in minimum BER in the OXC are evaluated.

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