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Performance Limitations of Optical Cross Connect without Wavelength Converter due to Crosstalk

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Summary

Crosstalk in optical cross connect (OXC) caused by nonideal wavelength demultiplexing and space switching has deleterious effect on the network performance. In this paper, we have developed an analytical approach for modeling crosstalk and to evaluate the bit error rate (BER) performance in a WDM transmission link with OXC without wavelength converter. The factors that have direct impact on the crosstalk are investigated and parameters that influence BER performance are identified. An optimal set of OXC parameters is evaluated to reduce the total crosstalk at a bit rate of 10 Gbit/s. The results show that for optimized values of filter transmission factor, number of wavelengths and input fibers, and gate extinction ratio, the minimum input power is about -20 dBm to -24 dBm to maintain a BER of 10^{-9}.

1 Introduction

Wavelength division multiplexing (WDM) optical networks are attracting more and more attention because of their ability to provide increased capacity and flexibility [1]. The OXC controls the lightpaths in a large network in an automated manner, without having to resort to performing manual patch panel connections [2-4]. While cross-connecting wavelengths from input to output fibers, OXC introduces homodyne and heterodyne crosstalk, which are combined with the signal, degrades the transmission performance seriously [5-7]. These crosstalk leads to transfer of power from one channel to another. Homodyne crosstalk has the same wavelength as the signal and generates noise power as well as fluctuate the signal power and penalty is highest when the state of polarization (SOP) of the crosstalk signal is the same as the SOP of the desired signal. Heterodyne crosstalk signal is at a wavelength sufficiently different from the desired signal's wavelength and larger than the receiver's bandwidth. This type of crosstalk occurs as a result of indirect interactions, such as imperfect isolation between switching ports, nonlinearity effects of the fiber etc. During optical detection, heterodyne crosstalk act as a random factor reducing the signal extinction ratio and thus affecting the accuracy of clock recovery. System penalty associated with the above crosstalk of OXC is used as the basic criteria for characterizing the performance of a mesh connected WDM network. The crosstalk performance of an OXC with wavelength converter is reported in [8]. Extending from earlier optical OXC crosstalk analysis and modeling, we have developed an theoretical approach to analyze the performance limitations of an OXC without wavelength converter due to crosstalk based on WDM transmission link and to find the optimal system and device parameters at a bit rate of 10 Gbit/s.

2 OXC topology 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. 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. 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 gain clamped-semiconductor optical amplifier (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,

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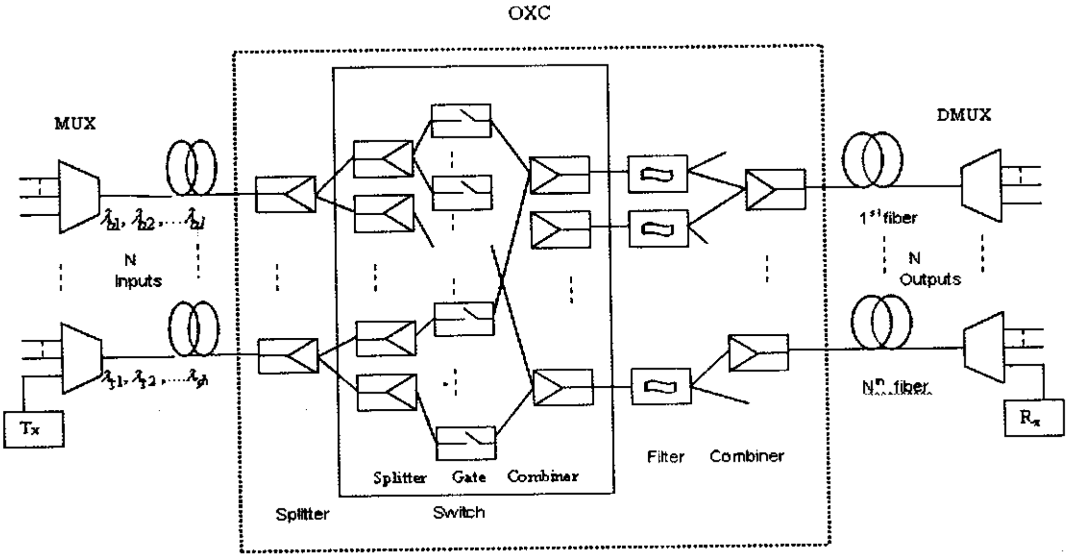

Fig. 1: Block diagram of a WDM transmission link with an OXC based on GC-SOA and without wavelength converter

combine all cross-connected wavelengths channels and output them to N output fibers.

3 Crosstalk and BER model

Based on the OXC architecture described above, this section outline the 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. Assuming P_{io}^{jo} is the input power of a channel, then the output power P_{iol}^{out} is as shown in (1) based on [1]. P_{iol}^{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 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_{iol}^{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 without 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_o is given by (1) based on [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; wavelength channel i_o, such as when there is no crosstalk. $P_{io}^{out(ref)}$ is given by, $P_b^{out(ref)} = P_b^p + X_{gate}(P_b^p)^2$. Since wavelength channel i_o may carry bit 1 or bit 0 at any instant of time, (1) has to be modified. If wavelength channel i_o carries bit 0, then (1) reduces to (2).

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

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

$P_{io}^{out(ref)}$ 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 given by

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

$$\text{Crosstalk (dB)} = 10\log_{10}(\text{Crosstalk}) \; . \quad (4)$$

To evaluate the BER of a WDM system, the crosstalk model for OXC with wavelength converter is used to derive BER model for OXC without wavelength converter. The expression for BER of a WDM network with wavelength converter in an IM-DD system can be given by,

$$BER_{wc} = \frac{1}{8}\begin{bmatrix} erfc\left(\frac{1}{\sqrt{2}}\frac{i_1 + i_{CT0} - i_D}{\sigma_{0\_1}^2}\right) + erfc\left(\frac{1}{\sqrt{2}}\frac{i_D - i_0 - i_{CTo}}{\sigma_{0\_1}^2}\right) \\ + erfc\left(\frac{1}{\sqrt{2}}\frac{i_1 + i_{CT1} - i_D}{\sigma_{0\_1}^2}\right) + erfc\left(\frac{1}{\sqrt{2}}\frac{i_D - i_0 - i_{JC1}}{\sigma_{0\_1}^2}\right) \end{bmatrix} \quad (5)$$

where,

$$\sigma_{1\_0}^2 = \sigma_{th}^2 + 2eR_d(P_S + P_{sp} + P_{CT\,0})B + \sigma_{S-sp}^2 + \sigma_{CT\,0-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{S-CT\,0}^2 \quad (6)$$

$$\sigma_{0\_0}^2 = \sigma_{th}^2 + 2eR_d(P_{sp} + P_{CT0})B + \sigma_{CT0-sp}^2 + \sigma_{sp-sp}^2 \quad (7)$$

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

$$\sigma_{1\_1}^2 = \sigma_{th} + 2eR_d(P_{sp} + P_{CT1})B + \sigma_{S-sp}^2 + \sigma_{CT1-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{S-CT1}^2 \; . \quad (9)$$

(5) 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 equation (6) to (9). 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, $i_1 = 2R_dP_s$. 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, $P_{CT\,1} = -P_{iol}^{out(ref)} - P_{iol}^{out}$ and crosstalk power due to bit 0 can be expressed as, $P_{CT\,0} = -P_{io0}^{out}$. The power of beating signal, crosstalk and ASE-ASE expressions are given in [8] and the threshold current, i_D is given by

$$i_D = \frac{\sigma_{0\_1} i_1 + \sigma_{1\_1} i_0}{\sigma_{0\_1} + \sigma_{1\_1}} \; . \quad (10)$$

4 Results and discussion

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

The plot of number of wavelengths per fiber (M) vs. filter transmission factor (T_F) is shown in Fig. 2 for increasing values of gate extinction ratio. From the figure, 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.

Plot of crosstalk vs. filter transmission factor (T_F) is shown in Fig. 3. 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).

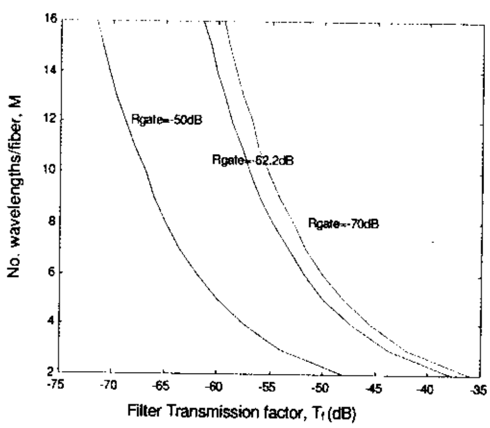

Fig. 2: Plot of M vs. T_f for different gate extinction ratio, R_{gate}

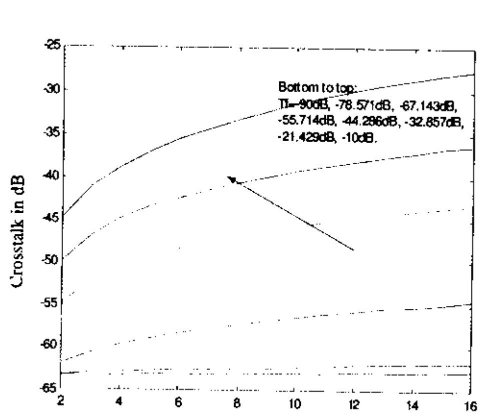

Fig. 3: Plot of crosstalk vs. no. of wavelength, M;
(N=6, M=16, R_{gate}= - 62.20dB, P_{in}= - 20dBm, X_{gate}= - 0.10/mW)

For example, if number of input fiber (N) is fixed to a small value (around 5 to 6), as shown in Fig. 4 (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.

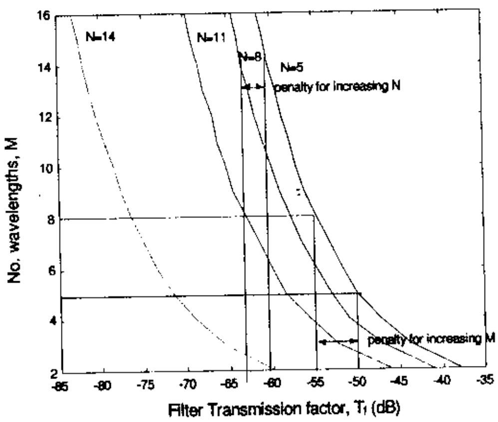

Fig. 4: Plot of M vs. T_F for different N to maintain BER<10^{-9}

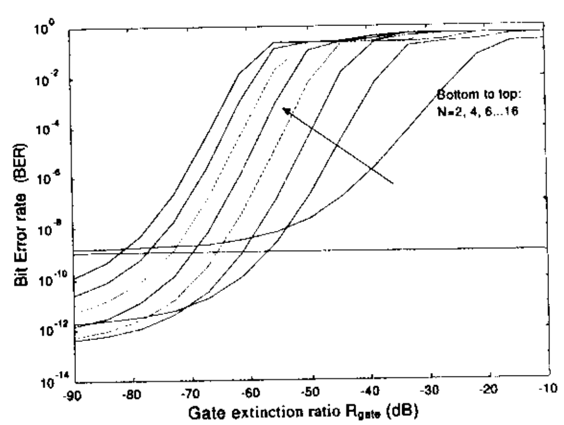

Fig. 5: Plot of BER vs. gate extinction ratio, R_{gate}. (M=16, T_F= - 61.7dB, P_{in}= - 20dBm, X_{gate}= - 0.10/mW)

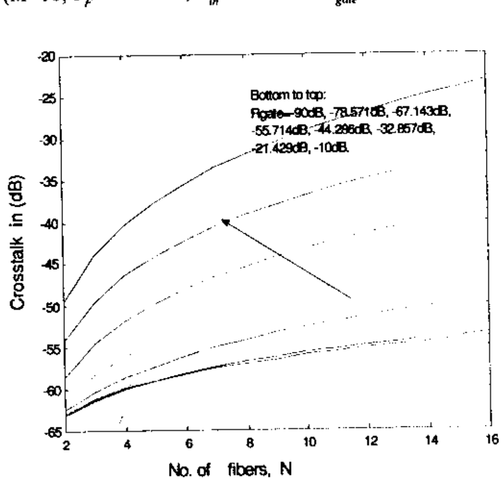

Fig. 6: Plot of crosstalk vs. no. of fiber, N (M=16, T_F= - 61.7dB, P_{in}= - 20dBm, X_{gate}= - 0.10/mW)

Plot of BER vs. R_{gate} (gate extinction ratio) is shown in Fig. 5. 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. 6, which 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.

The plot of filter transmission factor (T_F) vs. number of wavelength (M) for different gate input power (P_{in}) is shown in Fig. 7 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 –10 dBm to –20 dBm, filter transmission quality requirement becomes less stringent (larger value). However, as gate input power is further decreased from –20 dBm to –24 dBm 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. 8. It shows a minimum BER at certain input power, P_{in}. For example, if N=6 and M=16 is chosen and P_{in} = –20 dBm, then from Fig. 7, filter transmission factor (T_F) must be –61.7 dB. From the plot, it is found that for T_F = –61.7 dB, the plot touches BER=10^{-9} line at exactly P_{in} = –20 dBm. The

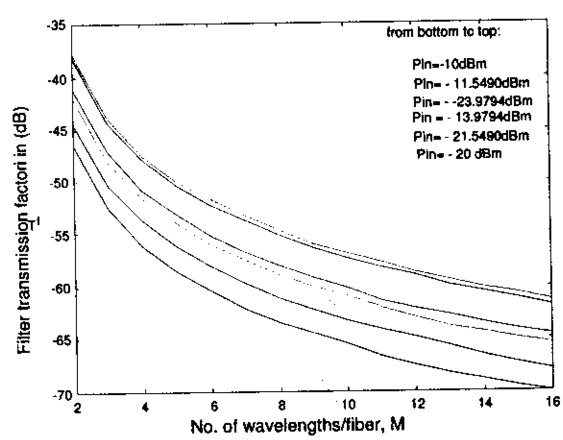

Fig. 7: Plot of T_F vs. M to maintain BER<10^{-9}

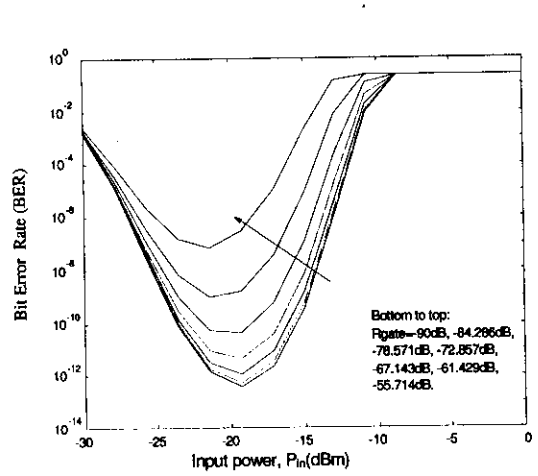

Fig. 8: Plot of BER vs. input power, P_{in}(N=6, M=16, T_F= –61.7dB, P_{in}=–20dBm, X_{gate}= –0.10/mW)

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.

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)	$1.93 \cdot 10^{14}$	Hz

5 Conclusions

In this paper crosstalk performance of a WDM transmission link with OXC without wavelength converter is analytically determined. Different factors and optimal value of the parameters that affect the magnitude of crosstalk and BER of the OXC have been evaluated. OXC parameters play an important role in determining magnitude of crosstalk and BER of a WDM network. Thus, the analytical results help to provide a qualitative performance evaluation of the system implications of the various crosstalk elements and could be a very useful consideration when carrying out overall WDM network design.

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