Bit error rate and cross talk performance in optical cross connect with wavelength converter

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An analytical approach is presented for modeling cross talk and evaluating the bit error rate (BER) performance in a WDM network for link with optical cross connect (OXC). Factors affecting the magnitude of cross talk in the OXC are investigated and identified. The effects of OXC induced cross talk on the BER performance is evaluated at a bit rate of 10 Gbits/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 approximately −10 to −8 dBm to maintain a BER of 10^{-9}. © 2007 Optical Society of America

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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 optical cross connect (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 scalability, bit rate and protocol independence, power saving, and increased transport capacity to WDM networks [5,6]. 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, the wavelength of which can be equal to or different from the signal wavelength. The cross-talk induced power penalties could also be caused by various nonlinear mechanisms including four-wave mixing (FWM). The effect of this cross talk would be smaller for spectrum-sliced light sources since these light sources are relatively insensitive to the nonlinear cross talk caused by FWM [7]. The build-up of cross talk 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. Cross talk due to the OXC is one of the basic criteria that characterize the performance of the WDM network [8–11]. Since optical cross talk is a major limiting factor, the commercial use of an all-optical OXC is 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 cross talk in the OXC with a wavelength converter and its influence on the overall bit error rate (BER) performance for spectral-sliced light sources at a bit rate of 10 Gbits/s.

2. Optical Cross-Connect Topology

The block diagram of a WDM transmission link with an OXC is shown in Fig. 1. The OXC is based on the gain-clamped semiconductor optical amplifier (GC-SOA) and wavelength converter (WC). It uses a combination of space and wavelength switching. The wavelength channel to be transmitted is multiplexed by a WDM multiplexer and fed to an incoming fiber. At the input of OXC the incoming signals are split 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

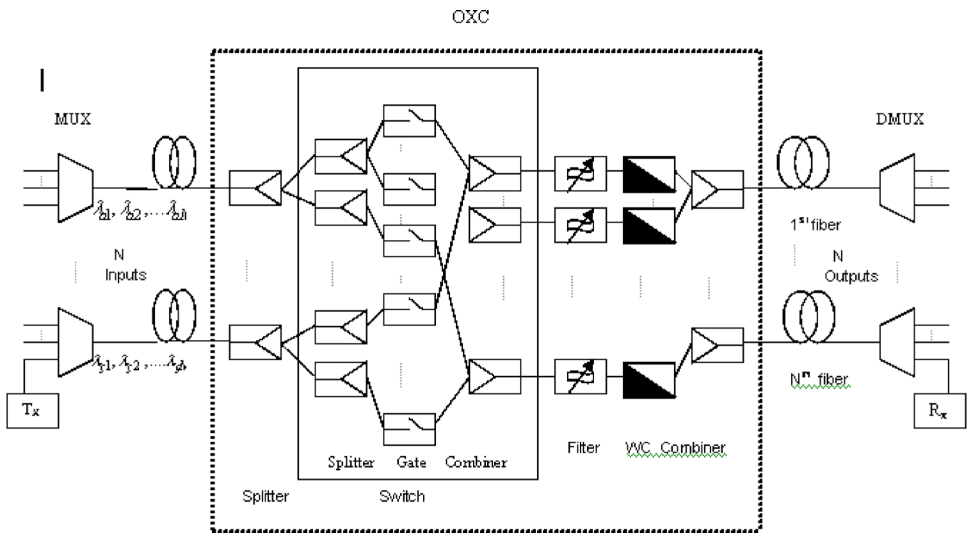

Fig. 1. Block diagram of a WDM transmission link with an OXC based on GC-SOA and wavelength.

the desired channel. A wavelength converter is used to convert the channel wavelength from one wavelength to the other wavelength. The OXC enables any wavelength channel from any input fiber to be cross-connected to any output fiber, on the condition that no two channels in the output fiber have the same wavelength. In Fig. 1, fiber a carries wavelength channels $\lambda_{a1}, \lambda_{a2}, \ldots, \lambda_{aM}$ and fiber b carries wavelength channels $\lambda_{b1}, \lambda_{b2}, \ldots, \lambda_{bM}$. Given that N is the number of input fiber and M is the number of different wavelengths, there are a total of $N \times M$ wavelength channels. The $N \times M$ wavelength channels passed through first array of power splitters. There are N power splitters for all the N input fibers. All the different wavelength channels appear at the output of the power splitter at lesser power due to power splitting. Wavelengths $\lambda_{a1}, \lambda_{a2}, \ldots, \lambda_{aM}$ are then fed to another array of M power splitters. There is a total of $N \times M$ 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 wavelengths to pass through. The combiner at first output fiber, such as combiner λ_1, receives its inputs from $\lambda_{a1}, \lambda_{b1}, \ldots, \lambda_{\zeta 1}$. The output of $N \times M$ combiners is fed to $N \times M$ 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 demultiplexer and is received by a direct detection receiver.

3. Cross Talk and the Bit Error Rate Model

An analytical model of cross talk due to the OXC is presented in this section and used to evaluate the BER performance of the WDM link with the 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, ${P_{io1}}^{\text{out}}$ is defined as the output power of wavelength channel i_o with cross talk contributions added (with all wavelength channels carrying bit 1). T_F is the filter transmission factor, R_{gate} is the gate extinction ratio, X_{gate} is gate cross talk, N is the number of input fiber into the OXC, and 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. ${P_{io1}}^{\text{out}}$ 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, $X_{\text{gate}} = P_{\text{gate}(ref)}/P_{\text{gate}}$; where P_{gate} is the power output from the GC-SOA gate. $P_{\text{gate}(ref)}$ is the reference output power of the GC-SOA gate. T_F is derived from the filter suppression of wavelength channel, ${T_F}^{-1}$.

In the OXC with wavelength converter, there is one gate in the ON state for every group of N gates. Hence there are NM gates in the 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, $R_{\text{gate}}=P_{\text{off}}/P_{\text{on}}$. P_{in} is defined as the input power through each gate. The expression for output power with cross talk of wavelength channel i_0 is given by Eq. (1) based on [1] based on the assumption that all channels carry bit 1.

$$
\begin{aligned}
P_{io}^{\text{out}} = {} & P_{io}^{jo} + P_{io}^{jo}\{X_{\text{gate}}[(M-1)P_{i}^{jo} + P_{io}^{jo}]\} + P_{io}^{j}\{(N-1)R_{\text{gate}}[1+X_{\text{gate}}MP_{i}^{j}] \\
& + (M-1)T_F[1+X_{\text{gate}}MP_{i}^{j}] + (N-1)(M-1)^2T_FR_{\text{gate}}\} - 2\sqrt{P_{io}^{jo}}\sqrt{P_{io}^{j}}\{(N-1)\sqrt{R_{\text{gate}}} \\
& + (M-1)\sqrt{T_F} + (N-1)(M-1)\sqrt{R_{\text{gate}}}\sqrt{T_F}\} - 2P_{io}^{j}\{(N-1)(M-1)\sqrt{R_{\text{gate}}}\sqrt{T_F} + (N \\
& -1)^2(M-1)R_{\text{gate}}\sqrt{T_F} + (N-1)(M-1)^2\sqrt{R_{\text{gate}}}T_F\} - 2P_{io}^{j}\left\{R_{\text{gate}}\sum_{t=1}^{N-2}t + T_F\sum_{t=1}^{M-2}t\right. \\
& \left. + R_{\text{gate}}T_F\sum_{t=1}^{(M-1)(N-1)-1}t\right\}.
\end{aligned}
\tag{1}
$$

P_{io}^{jo} is defined as N times of P_{in} since there is one gate in the ON state for every group of gates. $P_{io}^{\text{out}(ref)}$ 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 cross talk. $P_{io}^{\text{out}(ref)}$ is given by, $P_{io}^{\text{out}(ref)}=P_{io}^{jo}+X_{\text{gate}}(P_{io}^{jo})^2$. Since wavelength channel i_o may carry bit 1 or bit 0 at any instant of time, Eq. (1) has to be modified. If wavelength channel i_o carries bit 0, then Eq. (1) reduces to Eq. (2).

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

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

$$
\text{cross talk} = \frac{(P_{io}^{\text{out}(ref)} - P_{io1}^{\text{out}})}{P_{io}^{\text{out}(ref)}}.
\tag{3}
$$

To evaluate the BER of a WDM system, the cross talk model for the OXC with a wavelength converter is used to derive the BER model for the OXC with a wavelength converter. The expression for the BER of a WDM network with a wavelength converter in an IM-DD system can be given by Eq. (4). This equation assumes the scenario when a bit 1 is interfered with by a cross talk bit 1, bit 0 is interfered with by cross talk bit 0, bit 1 is interfered with by cross talk bit 0, and bit 0 is interfered with by cross talk bit 1 as reported by [9].

$$
\begin{aligned}
BER_{\text{worse case}} = \frac{1}{8}\Bigg[& \text{erfc}\left(\frac{1}{\sqrt{2}}\frac{i_1 + i_{CT0} - i_D}{\sigma_{1\_0}{}^2}\right) + \text{erfc}\left(\frac{1}{\sqrt{2}}\frac{i_D - i_0 - i_{CT0}}{\sigma_{0\_0}{}^2}\right) \\
& + \text{erfc}\left(\frac{1}{\sqrt{2}}\frac{i_1 + i_{CT1} - i_D}{\sigma_{1\_1}{}^2}\right) + \text{erfc}\left(\frac{1}{\sqrt{2}}\frac{i_D - i_0 - i_{CT1}}{\sigma_{0\_1}{}^2}\right)\Bigg],
\end{aligned}
\tag{4}
$$

where

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

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

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

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

The variance of the interference is given in Eqs. (5)–(8) where $\sigma_{1\_0}{}^2$ is the variance when signal bit 1 is interfered with by cross talk due to bit 0 and $\sigma_{0\_0}{}^2$ is the variance when signal bit 0 is interfered with by cross talk due to bit 0. $\sigma_{1\_1}{}^2$ is the variance when signal bit 1 is interfered with by cross talk due to bit 1, and $\sigma_{0\_1}{}^2$ is the variance when signal bit 0 is interfered with by cross talk due to bit 1. $\sigma_{th}{}^2$ is the power of thermal noise, R_d is the receiver responsivity, B is the bandwidth of the receiver low-pass filter, and P_S is signal power. The photocurrent for a transmitted bit 1 is given by $i_1=2R_dP_S$. For transmitted bit 0, the photocurrent is $i_0=0$, with P_S assumed to be zero, and i_D is the threshold current. The expression for amplified spontaneous emission (ASE) power (P_{sp}) is given by $P_{sp}=hfF(G-1)B$. The amount of cross talk power due to bit 1 is $P_{CT1}=-P_{io1}{}^{\mathrm{out}(ref)}-P_{io1}{}^{\mathrm{out}}$, and cross talk power due to bit 0 can be expressed as $P_{CT0}=-P_{io0}{}^{\mathrm{out}}$.

The threshold current, i_D, is shown in Eq. (9). $\sigma_{S-sp}{}^2$ is the power of the beating of signal and ASE, shown in Eq. (10). $\sigma_{CT-sp}{}^2$ is the power of the beating of cross talk and ASE, shown in Eqs. (11) and (12) for cross talk due to bits 1 and 0, respectively. $\sigma_{S-CT}{}^2$ is the power of the beating of signal and cross talk, shown in Eqs. (13) and (14) for cross talk due to bits 1 and 0, respectively. $\sigma_{sp-sp}{}^2$ is the power of the beating of ASE and ASE, shown in Eq. (15). $S_{sp}(f)$ is the power spectral density of ASE noise, $S_{CT1}(f)$ is the power spectral density of cross talk due to bit 1, $S_{CT0}(f)$ is the power spectral density of cross talk due to bit 0, and $S_S(f)$ is the power spectral density of the signal.

$$i_D = \frac{\sigma_{0\_1}i_1 + \sigma_{1\_1}i_0}{\sigma_{0\_1} + \sigma_{1\_1}}, \quad (9)$$

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

$$\sigma_{CT1-sp}{}^2 = R_d{}^2\int_{-B/2}^{B/2} S_{sp}(f) * S_{CT1}(f)|H(f)|^2\mathrm{d}f, \quad (11)$$

$$\sigma_{CT0-sp}{}^2 = R_d{}^2\int_{-B/2}^{B/2} S_{sp}(f) * S_{CT0}(f)|H(f)|^2\mathrm{d}f, \quad (12)$$

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

$$\sigma_{S-CT0}{}^2 = R_d{}^2\int_{-B/2}^{B/2} S_S(f) * S_{CT0}(f)|H(f)|^2\mathrm{d}f, \quad (14)$$

$$\sigma_{sp-sp}{}^2 = R_d{}^2\int_{-B/2}^{B/2} S_{sp}(f) * S_{sp}(f)|H(f)|^2\mathrm{d}f. \quad (15)$$

4. Bit Error Rate and Cross Talk Results

Following the analytical approach presented in Section 3, the BER performance results are evaluated at a bit rate of 10 Gbits/s. We determine the relation between filter transmission (T_F) and the number of wavelength (M) under certain computation conditions such as varying R_{gate}, N, and P_{in}. The same models are used to determine the relation between R_{gate} and N using selected set of T_F, M, and P_{in} parameters.

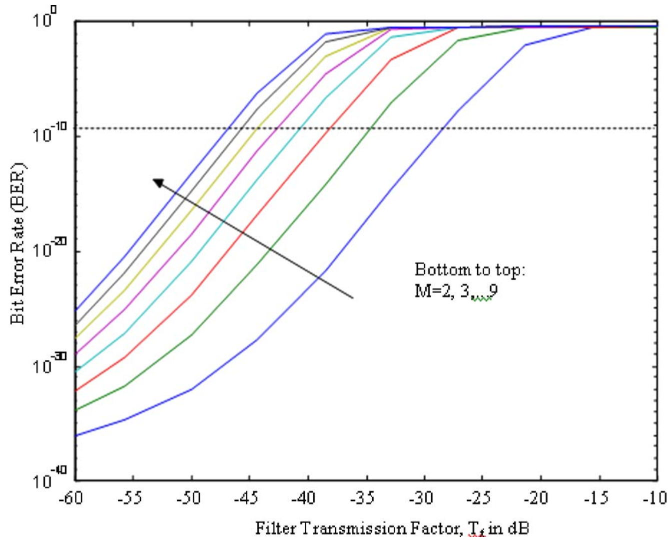

Fig. 2. Plot of BER versus filter transmission factor T_F with optimized parameters. ($N=13$, $M=16$, $R_{gate}=-46.6$ dB, $P_{in}=-6.88$ dBm).

The plot of BER versus filter transmission factor T_F is shown in Fig. 2. It is observed that for a certain number of wavelengths passing through the OXC, the quality of T_F needs to be better than a value determined by setting BER to be at least 10^{-9}. 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.

A plot of the BER versus number of wavelength (M) is shown in Fig. 3. Figure 2 also shows a relationship between T_F and M. This means that for a number of wavelengths BER is less than 10^{-9} if the filter transmission factor (T_F) is chosen to be smaller than the value of T_F at BER$=10^{-9}$. It is confirmed in Fig. 3 and seen that the BER is successfully maintained below 10^{-9}. The plot of the number of wavelength (M) versus filter transmission factor (T_F) (Fig. 5) shows that the BER increases as T_F quality is decreased (larger value).

The plot of cross talk versus number of wavelength, M, in Fig. 4 shows an almost linear relationship between cross talk and number of wavelength, M. It is evident that there is an inverse relationship between the filter transmission factor, T_F, and M as shown in Fig. 5. It is discovered that increasing the suppression ratio (T_F^{-1}) reduces the requirement for better gate extinction ratio (R_{gate}) and vice versa. However, there is a minimum practical value of T_F beyond which a requirement for better R_{gate} will be impractical.

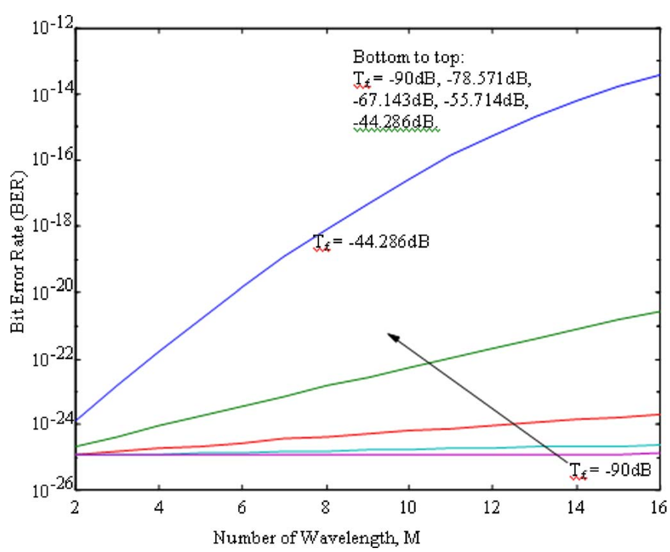

Fig. 3. Plot of BER versus number of wavelength, M, with optimized parameters. ($N=13$, $M=16$, $R_{gate}=-46.6$ dB, $P_{in}=-6.88$ dBm).

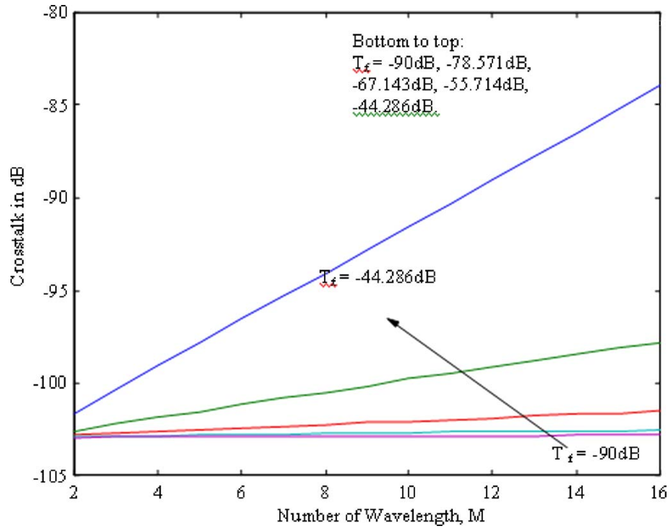

Fig. 4. Cross talk versus number of wavelength, M, with optimized parameters. ($N=13$, $M=16$, $R_{\text{gate}}=-46.6$ dB, $P_{\text{in}}=-6.88$ dBm).

The penalty for increasing M in terms of the need to increase the wavelength suppression capability of the OXC is decreasing as M is increased. From the plot in Fig. 5, it is evident that the slope of the plot increases as M increases. This means that the penalty for increasing M can be minimized by decreasing N and can also be optimized to minimize the BER.

There is a minimum BER for the plot of input fiber, N, versus BER for different R_{gate}. For a particular R_{gate} (for which the corresponding T_F had been determined from Fig. 5), N should be chosen from the minimum point of Fig. 6. The corresponding N versus cross talk plot shows a maximum at around $N=4$. The plot of cross talk versus input fibers, N, is shown in Fig. 7. It is found that for N larger than 4, cross talk in the OXC decreases; this does not reflect improvement in the BER because the BER is not only influenced by cross talk in the OXC but also on the signal power compared to the cross talk power, noise power, and variance of signal–cross-talk noise.

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

Increasing the input power P_{in} reduces the requirement for better suppression ratio (T_F^{-1}) and vice versa. The plot of cross talk versus input power P_{in} is depicted in

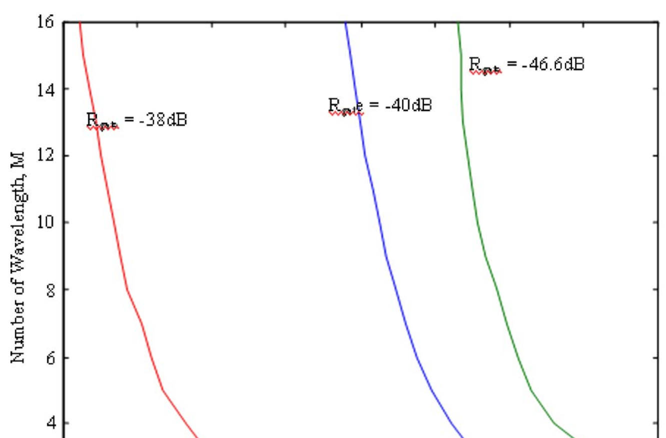

Fig. 5. Plot of number of wavelength, M, versus filter transmission factor, T_F.

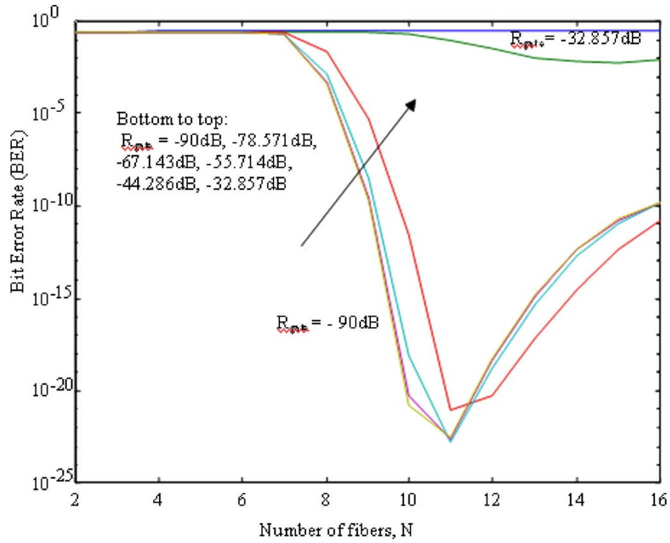

Fig. 6. Plot of the BER versus gate extinction ratio, R_{gate}, with optimized parameters. ($N=13$, $M=16$, $T_f=-37$ dB, $P_{\text{in}}=-6.88$ dBm).

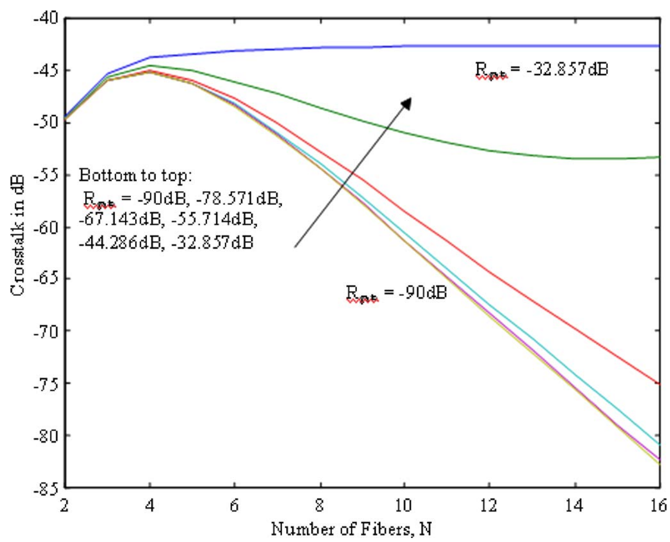

Fig. 7. Plot of cross talk versus input fibers, N, with optimized parameters. ($N=13$, $M=16$, $T_f=-37$ dB, $P_{\text{in}}=-6.88$ dBm).

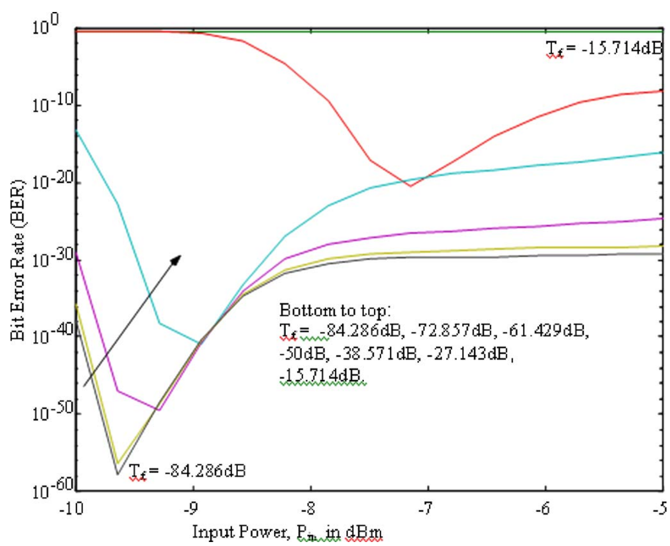

Fig. 8. Plot of the BER versus input power, P_{in}, with optimized parameters. ($N=13$, $M=16$, $T_f=-37$ dB, $R_{\text{gate}}=-46.6$ dB).

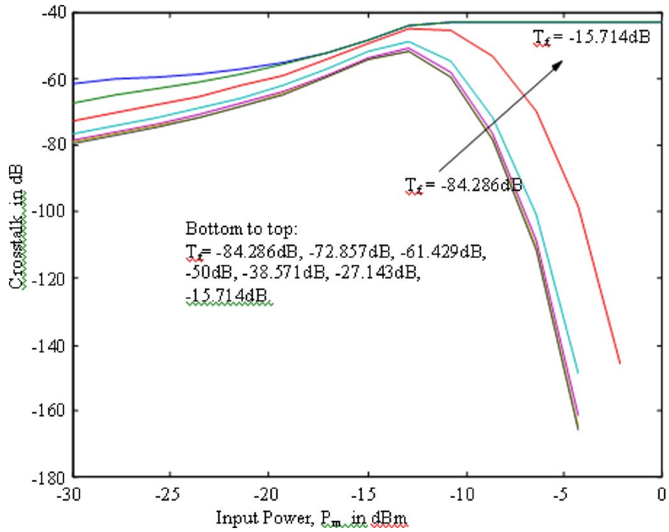

Fig. 9. Plot of cross talk versus input power P_{in}. (N=13, M=16, T_f=−37 dB, R_{gate}=−46.6 dB).

Table 1. Optimized Parameters

Parameters	Values	Unit
Number of wavelength (M)	16	Unitless
Filter transmission (T_f)	−37	dB
Number of input fiber (N)	13	Unitless
Gate extinction ratio (R_{gate})	−46.6	dB
Input power per gate (Pin)	−6.88	dBm
Gate cross talk (X_{gate})	−0.1	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)	1.9355×10^{14}	Hz

Fig. 9. It is found that cross talk decreases tremendously at high P_{in} after achieving maximum point at approximately −10 dBm.

From the above discussion, we observed that to operate the OXC at minimum input power, the values of the 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}.

The optimized parameters for M=16 and N=13 are as shown in Table 1. The assumptions used in computing the optimized parameters are as shown in Table 2.

5. Conclusion

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

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