Trends In Opto-Electro & Optical Communications
Volume 1, Issue 1-3 Compilation, 8-15

STM JOURNALS

Effect of Crosstalk of a Proposed Optical Cross-Connect Topology in OXC Switched WDM Networks

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ABSTRACT

This paper presents an optical wavelength division multiplexed cross-connect topology, which is modified form of the existing optical cross-connect (OXC) topologies. An analytical approach is developed for the proposed topology to explore the effect of crosstalk induced in multichannel WDM networks due to OXC. Factors that affect the magnitude of crosstalk in the OXC are investigated and different parameters are optimized to reduce the total OXC-induced crosstalk. The crosstalk performance of the proposed topology is compared with the existing topologies. The scalability of the proposed topology in terms of wavelengths and input fibers as well as the total crosstalk in function of the number of cascaded OXC's is presented. The bit error rate (BER) performance of a WDM optical system is evaluated at a bit rate of 10 Gb/s on account of OXC-induced crosstalk and different noises. The power penalty evaluated at BER = 10^{-9} shows that there is a significant impact of crosstalk on the number of wavelengths and input fibers. The results obtained from the present study demonstrate that the crosstalk performance of the proposed topology can be improved significantly than the existing topologies.

Keywords: optical cross-connect, OXC-induced crosstalk, optical filter and switches, Wavelength division multiplexing

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1. INTRODUCTION

A dynamic increase in the information carrying capacity of a fiber is achieved by the advent of wavelength division multiplexing (WDM) technique in which a number of optical signals of different wavelengths are transmitted simultaneously over the same fiber with properly spaced peak emission wavelengths [1-8]. WDM has the potential for exploiting the large bandwidth offered by optical fiber. WDM networks are very promising due to their large bandwidth, large flexibility and the possibility to upgrade the existing optical fiber networks to WDM networks [2-5].

WDM has already been introduced in commercial systems. Optical cross-connect (OXC) is an essential element in a WDM optical network [9-11]. OXC offers a dynamic wavelength routing scheme that can reconfigure the network while maintaining its nonblocking (transparent) nature to WDM networks [12-14]. In practical systems while propagating through the switching element that are the part of OXC, many signals and wavelength channels could influence each other and cause significant crosstalk results in signal degradation. The crosstalk sources are related to the different components of the OXCs [15-16]. Up to now several OXC topologies [4] were utilized to evaluate the bit error rate (BER) performance of WDM optical fiber transmission system including the effect of OXC-induced crosstalk [17-18]. Since crosstalk is a major limiting factor to the implementation of OXCs in WDM systems, it is desirable to develop a suitable OXC topology, so that, it contributes minimum crosstalk due to OXC. It is also desirable to investigate the BER performance of a WDM transmission system including the effect of crosstalk induced by the OXC components of the proposed topology.

In this paper, we have proposed an OXC topology that is modified form of the existing topologies. Some preliminary results of this topology have been reported in our recent study [19]. Here crosstalk performances of the proposed topology are explained in details by identifying and quantifying different crosstalk sources. The influence of component parameters on the crosstalk is also studied and compared with the existing topologies of the same type. The scalability of the new topology in terms of wavelengths and input/output fibers is investigated. Afterward, the total crosstalk

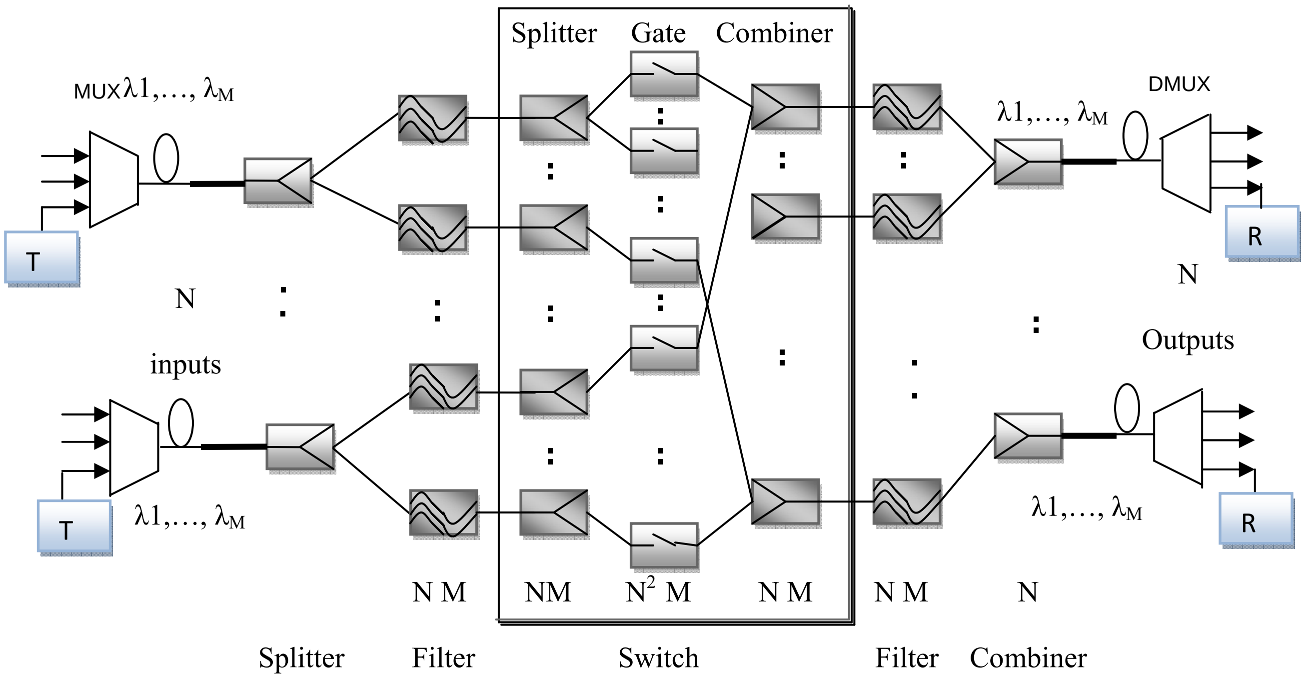

Figure 1. Block diagram of a WDM optical system with a new OXC topology.

in function of the number of cascaded OXCs is presented. The BER performance for a particular WDM system is evaluated at 10 Gb/s considering OXC-induced crosstalk and different noises. Finally, with a specific BER, the amount of power penalty as a function of the component parameters of the OXC is evaluated. In every step the performance of the proposed topology is compared with the existing topologies. The results obtained from the present study demonstrate that the OXC-induced crosstalk can be reduced by a considerable amount in the proposed topology than the existing topologies.

2. PROPOSED OXC TOPOLOGY

Several topologies exist for all optical WDM cross connects [11, 15]. The most suitable topology for an application depends in general on the required functionality and on the cost, capacity and flexibility constraints. In this paper, we have analyzed the performance of OXC by placing filter before and after the switching matrix and selecting of the wavelength channels. The schematic diagram of the proposed OXC topology is shown in fig. 1. This topology is the combination of the first and third topology as defined in Ref. [15]. In the proposed topology, the switching matrix of topology 1 is used but the wavelength channels are selected by the filters (with a fixed centre frequency), before and after being routed to the desired output fiber.

The block diagram of a WDM transmission link with proposed OXC is shown in fig.1 where the switching matrix is based on an array of gates which are implemented by gain-clamped semiconductor optical amplifier (GC-SOA) [20] to route the different wavelength channels. Splitters and combiners are placed in front of and behind the switch matrix and filters are used to select the wavelength channels. The wavelength channel to be transmitted is multiplexed by a WDM MUX and fed to an incoming fiber. At the input of cross-connect, the incoming signals are splitted by a first array of power splitters followed by a array of filters and a second array of power splitters. At the input of GC-SOA gates, all channels are present. The gate selects the wavelength of the desired channel. 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, each fiber carries wavelength channels λ_1, λ_2 … λ_M. Given that the *N* input fibers are routed to the desired *N* output fibers, each carrying *M* wavelength channels, so there are total number of $N\times M$ wavelength channels. These wavelength channels are passed through first array of the 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 which are fed to *N* different filters. Wavelengths λ_1, λ_2 ... λ_M , from the output filters are then fed to another array of *M* power splitters, one for each wavelength. So there are total number of $N\times M$ power splitters at the second array. The output of the second array of power splitters are fed to $N^2\times M$ gates, which allows only specific wavelength to pass through. The outputs of the gates are combined by $N\times M$ combiner at the first array of combiner. Outputs of $N\times M$ combiners are fed to $N\times M$ filters. Then, N times M outputs with a different central wavelength, are combined into the N output fibers by the second array of N combiners. Finally, the desired wavelength channel of an outgoing fiber is demultiplexed by a WDM DMUX and is received by a direct detection receiver.

3. MATHEMATICAL MODEL

3.1. Crosstalk Model

The analytical equation illustrated in this paragraph which describes the output power of the proposed topology in function of the input powers and OXC component parameters. The crosstalk is calculated for a certain wavelength channel defined as the channel under study. The absolute power levels are only relevant in front of the GC-SOA. Therefore, the power levels at the input of the gate are taken as reference, gains and losses are not relevant since they are assumed uniform for all possible routing ways.

To drive the equations for the proposed topology, the signal power is defined by P_i^j, where i designates the wavelength channels and j the number of the fibers. The fiber which contains the channel under study is indicated by j_0, and the wavelength under study is i_0. P_{i0}^{j0} is the input power of a channel, P_{i0}^{out} is defined as the output power of wavelength channel i_0 with crosstalk contributions added with all wavelength channels carrying bit 1. P_i^{j0} is the signal power at fiber j_0 with another wavelength i. P_{i0}^{j} is the signal power at another fiber j that carries the wavelength under consideration, i_0. We assume that all wavelength channels including P_{i0}^{j0} carry bit 1. P_{i0}^{out} is the power at any fiber output may be just $1/N$ of the output power, due to division of power before entering the GC-SOA. However, it is also assumed that the GC-SOA is set with gain of N times to compensate for the division of output optical power. N is the number of input fibers into OXC, M is the number of wavelengths per input fiber. Due to the gate's imperfection in gain clamping, it adds crosstalk. The crosstalk power at wavelength i is then given by [15]

$$P_{cros,i} = X_{gate} P_{in,i} \sum_{k=1}^{M} P_{in,k} \tag{1}$$

with X_{gate} is the crosstalk parameter of the GC-SOA, $P_{in,k}$ is the power at wavelength k and M the number of wavelength channels at the input of the gate. The sum is made over all M wavelength channels. T_F is derived from the filter suppression of wavelength channel, T_F^{-1}. This means that T_F is the transmission of the filter seen by that channel (< 1). The ON–OFF ratio of the gate is given by R_{gate}^{-1}, so that R_{gate} is the transmission of a gate or gate extinction ratio in the off-state (<1). Extinction ratio is defined as, $R_{gate} = P_{off}/P_{on}$ where P_{on} is the input power and P_{off} is the off state power through each gate. The expression for output power with crosstalk of wavelength channel i_0 can be given by

$$\begin{aligned}
P_{i0}^{out} &= P_{i0}^{j0} + P_{i0}^{j0}\left\{X_{gate}\left((M-1)T_F P_i^{j0} + P_{i0}^{j0}\right)\right\} \\
&+ P_{i0}^{j}\begin{Bmatrix}(N-1)R_{gate}[1+X_{gate}T_F M P_i^j] \\ +(M-1)^2 T_F^{\,2}[1+X_{gate}T_F M P_i^j] \\ +(M-1)^2(N-1)T_F^{\,2} R_{gate}\end{Bmatrix} \\
&- 2\sqrt{P_{i0}^{j0}}\sqrt{P_{i0}^{j}}\left\{(N-1)\sqrt{R_{gate}} + (M-1)^2 T_F + (M-1)^2(N-1)T_F\sqrt{R_{gate}}\right\} \\
&- 2P_{i0}^{j}\begin{Bmatrix}(N-1)(M-1)^2 T_F\sqrt{R_{gate}} \\ +(N-1)^2(M-1)^2 T_F R_{gate} \\ +(N-1)(M-1)^4 T_F^{\,2}\sqrt{R_{gate}}\end{Bmatrix} \\
&- 2P_{i0}^{j}\left\{R_{gate}\sum_{t=1}^{N-2} t + TF^2 \sum_{t=1}^{(M-1)^2-1} t + T_F^{\,2} R_{gate}\sum_{t=1}^{(M-1)^2(N-1)-1} t\right\}
\end{aligned} \tag{2}$$

for the proposed topology under the assumption that all channels carry bit 1. The above equation has six contributions. The first three terms are the non interfering contributions and the last three terms are the contributions due to the interference of different channels (beat terms). The analytical equations for the proposed topology differ from the topology 1 and 3 due to the filters placed both sides of the switching matrix. It is expected that the crosstalk performance of the proposed topology may improve because the desired wavelength channels are selected by the filters (with a fixed centre frequency) before and after the channels are routed to the output fiber. $P_{i0}^{out(ref)}$ is the output power of wavelength channel i_0 when the OXC carries only this wavelength channel, such as when there is no crosstalk. $P_{i0}^{out(ref)}$ is given by

$$P_{i0}^{out(ref)} = P_{i0}^{j0} + X_{gate}(P_{i0}^{j0})^2 \tag{3}$$

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3.2. BER Model

To evaluate the BER of a WDM system, the crosstalk model presented for the proposed OXC topology is used to derive BER model. The mathematical formulation for BER of the proposed topology in case of IM-DD system can be given by [21] .

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

where, i_D is the threshold current. In equation (4), it is assumed that 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 so far [13]. The variance of the interference is given in equations (5) to (8)

$$\sigma^2_{1\_0} = \sigma^2_{th} + 2qR_d(P_s + P_{sp} + P_{CT0})B + \sigma^2_{s-sp} + \sigma^2_{sp-sp} + \sigma^2_{CT0-sp} + \sigma^2_{s-CT0} \quad (5)$$

$$\sigma^2_{1\_1} = \sigma^2_{th} + 2qR_d(P_s + P_{sp} + P_{CT1})B + \sigma^2_{s-sp} + \sigma^2_{sp-sp} + \sigma^2_{CT1-sp} + \sigma^2_{s-CT1} \quad (6)$$

$$\sigma^2_{0\_1} = \sigma^2_{th} + 2qR_d(P_{sp} + P_{CT1})B + \sigma^2_{CT1-sp} + \sigma^2_{sp-sp} \quad (7)$$

$$\sigma^2_{0\_0} = \sigma^2_{th} + 2qR_d(P_{sp} + P_{CT0})B + \sigma^2_{CT0-sp} + \sigma^2_{sp-sp} \quad (8)$$

where $\sigma^2_{1\_0}$ is the noise variance when signal bit 1 is interfered by crosstalk due to bit 0 and $\sigma^2_{0\_0}$ is the noise variance when signal bit 0 is interfered by crosstalk due to bit 0. $\sigma^2_{1\_1}$ is the noise variance when signal bit 1 is interfered by crosstalk due to bit 1 and $\sigma^2_{0\_1}$ is the noise variance when signal bit 0 is interfered by crosstalk due to bit 1. σ_{th}^2 is variance of thermal noise, q is the electronic charge, R_d is the receiver responsivity, B is the bandwidth of the receiver low-pass filter, P_S is signal power. i_1 is the photocurrent for a transmitted bit 1 and is given by $i_1 = 2R_d P_s$, The photocurrent $i_0 = 0$ for a transmitted bit 0, with P_S assumed to be zero. The expression for amplified spontaneous emission (ASE) power, P_{sp} is given by $P_{sp} = hf\eta_{sp}(G-1)\Delta\upsilon_{sp}$, where h is the plank's constant, f is the optical frequency, η_{sp} is spontaneous emission factor, G is the optical amplifier gain, and $\Delta\upsilon_{sp}$ is the effective bandwidth of spontaneous emission. The crosstalk currents due to bit 1 is $i_{CT1} = R_d P_{CT1}$ and due to bit 0 is $i_{CT0} = R_d P_{CT0}$.The corresponding crosstalk powers are $P_{CT1} = P^{out(ref)}_{i0\ 1} - P^{out}_{i0\ 1}$ and $P_{CT0} = -P^{out}_{i0\ 0}$. Where $P^{out}_{i0\ 1}$ is the output power when wavelength channel i_0 carry bit 1 and $P^{out}_{i0\ 0}$ is the output power when wavelength channel i_0 carry bit 0 at any instant of

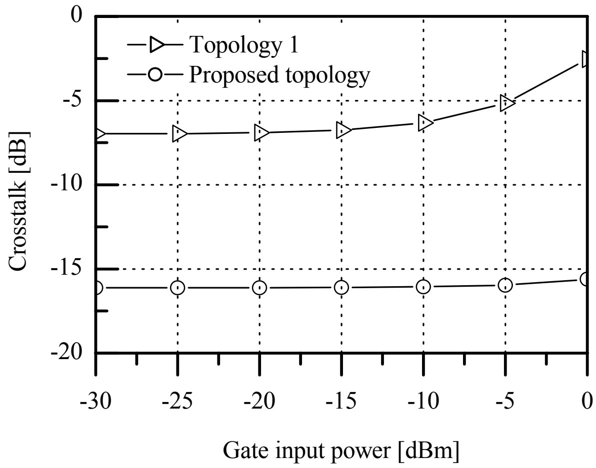

Figure 2. Crosstalk versus gate input power plotted for M = 4 and N = 2. The results calculated for the proposed topology and topology 1 are indicated by open circles and triangles, respectively

time. $P^{out}_{i0\ 1}$ can be obtained for equation (2) but when i_0 carry bit 0 equation (2) has to be modified and reduces to equation (9).

$$P^{out}_{i0\ 0} = P^j_{i0}\left\{\begin{array}{l}(N-1)R_{gate}[1 + X_{gate}T_F MP_i^j] \\ +(M-1)^2 T_F{}^2[1 + X_{gate}T_F MP_i^j] \\ +(M-1)^2(N-1)T_F{}^2 R_{gate}\end{array}\right\}$$

$$-2P^j_{i0}\left\{\begin{array}{l}(N-1)(M-1)^2 T_F\sqrt{R_{gate}} \\ +(N-1)^2(M-1)^2 T_F R_{gate} \\ +(N-1)(M-1)^4 T_F{}^2\sqrt{R_{gate}}\end{array}\right\}$$

$$-2P^j_{i0}\left\{R_{gate}\sum_{t=1}^{N-2} t + TF^2\sum_{t=1}^{(M-1)^2-1} t + T_F{}^2 R_{gate}\sum_{t=1}^{(M-1)^2(N-1)-1} t\right\} \quad (9)$$

$P^{out(ref)}_{i0}$ is the power when wavelength channel i_0 carries bit 0 and can be written as, $P^{out(ref)}_{i0} = 0$

4. RESULTS AND DISCUSSION

4.1. Crosstalk Performance

Following the analytical equations for the proposed OXC topology presented in section III, the crosstalk contributions from different crosstalk sources are quantified and total crosstalk is calculated in this section. The expression for relative crosstalk for a channel under study can be given by [15]

$$Crosstalk = \frac{P^{out(ref)}_{i0} - P^{out}_{i0\ 1}}{P^{out(ref)}_{i0}} \quad (10)$$

The plots of crosstalk as a function of input power for the proposed topology and topology 1 are depicted in Fig. 2, for the number of channels per fiber M = 4, total number of fiber N = 2, filter transmission factor $T_F = -30dB$, transmission of the gate in the off state $R_{gate} = -50dB$, gate crosstalk parameter $X_{gate} = -0.1\,\text{mW}^{-1}$. It is seen in Fig. 2 that the crosstalk added by the gate is almost constant for the proposed topology and topology 1 up to the input power of the gate -20 dB. After that, the crosstalk power increases gradually in the topology 1 with increasing input power of the gate. However, crosstalk power is found to be almost constant in the proposed topology for the entire range of the input power as shown in Fig. 2. Similar results are also obtained for the topology 3. But, the crosstalk level is approximately 9 dB lower in the proposed topology than the topology 1 and 3.

The amount of the crosstalk produced by the gate is shown in Fig.3. The crosstalk is calculated for different values of the crosstalk parameter of the GC-SOA. The results of three OXC topologies are compared in Fig. 3. For the OXC topology 1, the crosstalk increases with the increase of the gate crosstalk. However, the results obtained for the OXC topology 3 and proposed topology are found to be almost constant against crosstalk of the gate, because the channels are filtered before being passed through the gates. As seen in Fig. 3 the total crosstalk obtained for the proposed topology is much lower than that of Topology 1 and 3 for a certain value of X_{gate}. This is because; the channels are filtered by placing filters on both sides of the switching matrix. So, the crosstalk for this topology is almost independent of the crosstalk parameter of the gate.

The plots of crosstalk in function of the filter parameter, T_F for different values of ON–OFF ratio of the gate, R_{gate} for the OXC topology 1, 3, and proposed are shown in Fig. 4. The ON–OFF ratio varied between 10 dB and 90 dB in steps of 20 dB. The results for topology 1 and 3 are the same and are shown in Fig. 4(a). The results obtained for the proposed topology are shown in Fig. 4(b). It is found that the total crosstalk performance almost same at the higher ON–OFF ratios of the gate for all topologies. In contrast, at the lower ON–OFF ratios (<-90 dB), the total crosstalk is dominated by the filter. As a result, better crosstalk performance is found for the proposed topology than the existing topologies, which is clearly observed in Fig. 4.

The crosstalk (coherent) is calculated as a function of the number of input fibers N and the number of wavelengths in a fiber M to study the scalability. The results are presented in Figs. 5(a), and 5(b) for the topology 1/topology 3, and the proposed topology, respectively. It is found in Fig. 5 that the crosstalk strongly increases with increasing

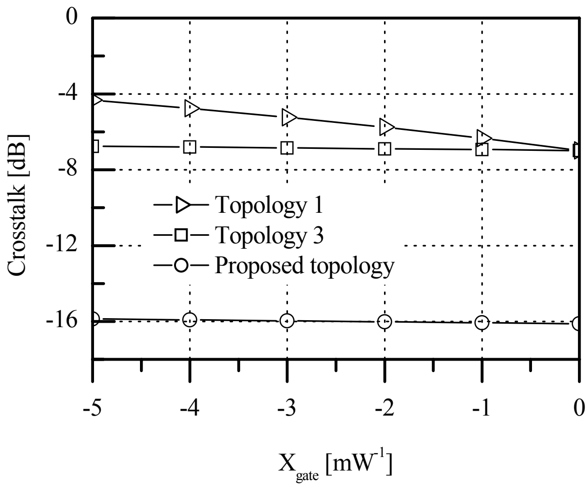

Figure 3. Crosstalk (coherent) versus the crosstalk parameter of the GC-SOA. The results indicated by triangles, squares, and open circles are corresponding to the topology 1, 3 and proposed, respectively.

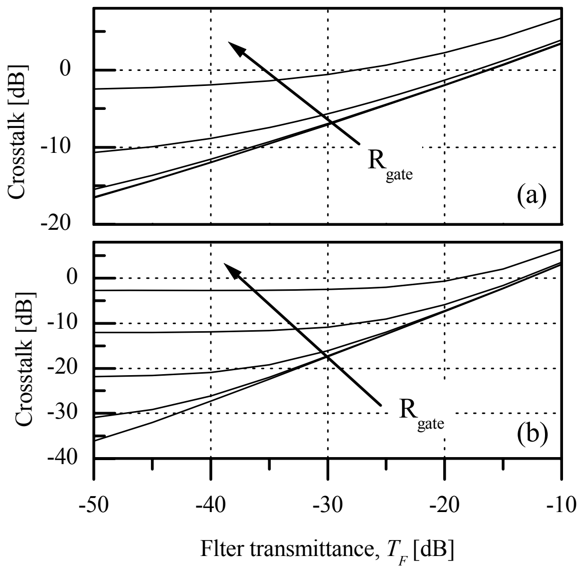

Figure 4. Crosstalk (coherent) in function of the filter parameter for different on/off ratios (Rgate= -10; -30; -50; -70 and -90 dB) (a) for the Topology 1 and 3 [15] and (b) for the Proposed Topology.

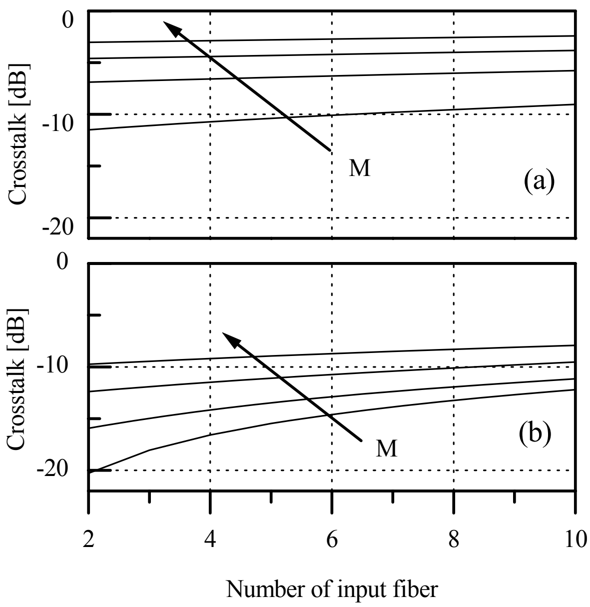

Figure 5. Crosstalk (coherent) in function of the number of input fibers for different number of wavelength channels in a fiber (M = 2; 4; 6 and 8) (a) Topology 1 and 3 and (b) proposed topology.

the number of wavelengths as well as the number of fibers. For a certain throughput (*N* multiplied with *M*) lowest crosstalk is obtained with large *N* and small *M*. For a constant crosstalk, the number of fibers (*N*) can be increased without penalty if the performance of the switch i.e. the ON–OFF ratio (R_{gate}) is increased. Again, the number of wavelengths (M) can be increased if suppression of the channels i.e. the filter suppression (T_F) is increased. With the same value of T_F and R_{gate}, the more number of fibers and wavelengths can be used in the proposed topology than the topology 1 and 3.

The plots of total crosstalk in function of the number of OXC cascaded are presented in Fig. 6 for the existing topologies 1 and 3 and the proposed topology. As can be expected the highest crosstalk is obtained for the first and third topologies. Both topologies perform equally. The topology presented in this paper performs much better. The better performance of the proposed topology compared to the topologies 1 and 3 can be expected due to the lower crosstalk values of the space switch, which are resulted by placing filters before and after the space switch. From the calculations in function of the OXC component parameters, we see that the performance of the existing topologies is limited by the filter. We can conclude that the topology with filter before and after the space switch performs better than with filter either before or after the switching matrix. Optimal crosstalk performance will be obtained if filtering before and after the switch matrix is accomplished and wavelength converter is used. Although the wavelength converter can improve the performance of an OXC topology, the drawback is that the converters are very expensive and they add jitter.

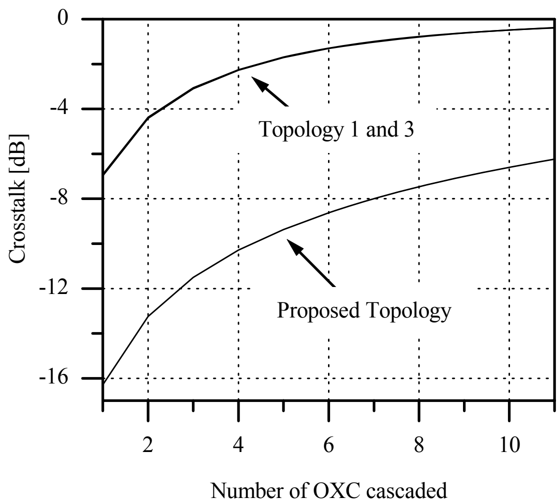

Figure 6. Crosstalk (incoherent) in function of the number of OXCs cascaded for different topologies (Existing and proposed).

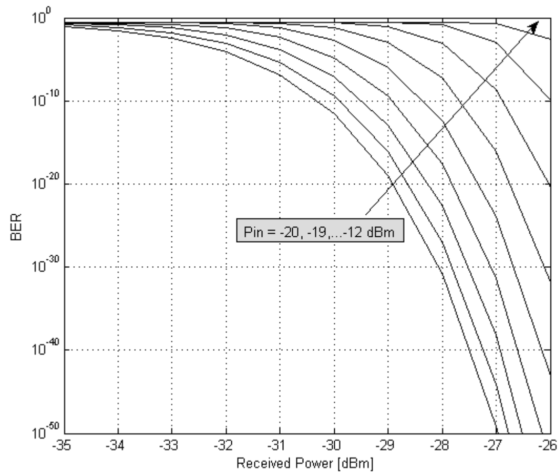

Figure 7. Plot of BER as a function of received power for 10 Gb/s optical WDM system with proposed OXC topology.

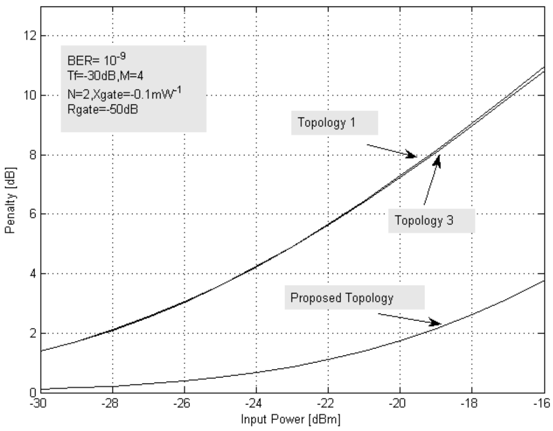

Figure 8. Comparison of power penalty for the proposed topology and the existing topologies 1 and 3. The penalty is calculated at 10Gb/s for M = 4, N = 2, T_f = -30dB, X_{gate} = 0.1mW^{-1} and R_{gate} = -50dB.

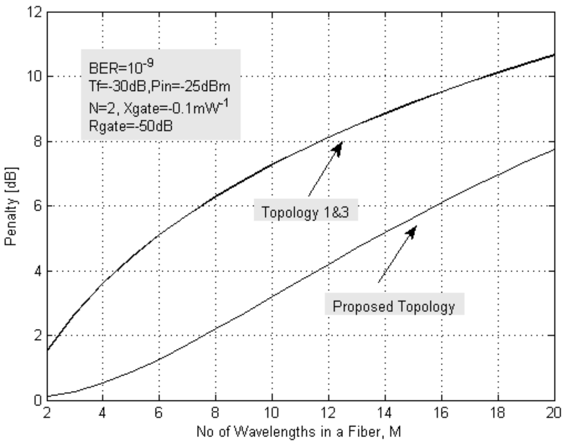

Figure 9. Power penalty vs number of wavelengths in a fiber for different topologies. Data for topolology 1 and 3 are taken from Ref. [15].

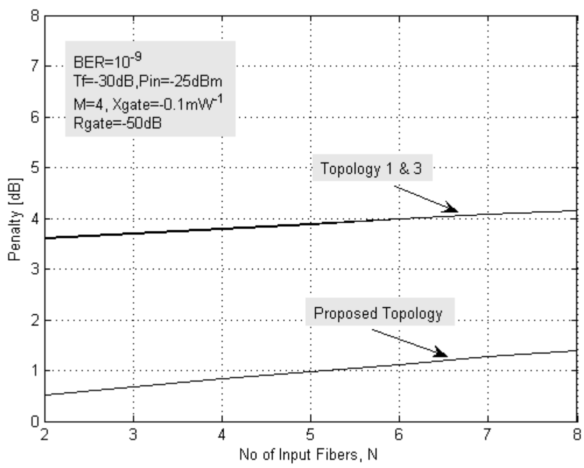

Figure 10. Power penalty vs number of input fibers for different topologies. Data for topologies 1 and 3 are taken from Ref. [15].

4.2 BER Performance

Using the analytical approach presented in section 3.2, the BER performance is evaluated for the proposed system at 10 Gb/s taking into account of OXC-induced crosstalk, ASEnoises, and receiver noises. The plots of BER vs received power is shown in fig 7 with different values of input powers. It is observed from fig. 7 that the BER decreases with increasing the received power. However, for a particular received power, the BER is found to increase with increasing the input power. The power penalties due to crosstalk are determined for the topology 1 and 3 [4] and the proposed topology at BER of 10^{-9}. The results obtained for M = 4, N = 2, T_f = -30 dBm, and R_{gate} = -50 dBm are shown in fig. 8. Form the plots, it is observed that the system suffers a power penalty due to OXC-induced crosstalk and the penalty increases with increasing input power for a given number of wavelengths and fibers. As seen in fig. 8 the power penalty for the topology 1 and 3 is almost the same. But, for the proposed topology the penalty is found to be lower than the topology 1 and 3. For a 2 dB penalty, the allowable input power for the topology 1 and 3 is less than -29 dBm. On the other hand, for the proposed topology it is less than -19 dBm. The increase in penalty at higher input power can be compensated if the performance of the switching matrix as well as that of filter is improved and wavelength converter is used. The plots of penalty versus the number of wavelengths and the number of fibers for different topologies are shown in figs. 9 and 10 that there is an increase in penalty with increasing number of wavelengths as well as the number of fibers, at a given input power. The proposed topology shows lower crosstalk level and lower power penalty than the topology 1 and 3.

From the above discussion it is cleared that OXC-induced crosstalk limits the number of wavelengths, the number of input fibers as well as allowable input power per fiber in a WDM system. Considering the system impairments, the performance of the proposed topology is found to improve significantly than the existing topology 1 and 3.

5. CONCLUSION

In this paper, we have proposed an OXC topology with the modification of the existing topologies. The crosstalk sources for this topology have been identified. The analytical equations for the proposed topology are derived and the total crosstalk is calculated based on these equations. Crosstalk and BER performances of a WDM network are evaluated analytically for a proposed OXC topology and then compared with the existing topologies 1 and 3. Different factors that affect magnitude of crosstalk and BER in the OXC are also investigated in details. The system performance is evaluated in terms of power penalty at BER of 10^{-9} with different OXC parameters and noises. It is found that the allowable input power for the proposed topology is higher than the exiting topologies, which means that the influence of OXC-induced crosstalk is lower in the proposed topology than the existing topologies. The results obtained from the present study indicate that for an allowable power penalty more number of wavelengths or fibers can be used in the proposed OXC topology than the existing topologies 1 and 3. Therefore, system throughput (*N* multiplied with *M*) can be increased by the proposed topology with the suffering of minimum power penalty.

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