Analysis of Performance Limitations in Fiber Bragg Grating Based Optical Add-Drop Multiplexer due to Crosstalk

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Abstract— Wavelength division multiplexing (WDM) optical networks are attracting more and more attention because of their ability to provide increased capacity and flexibility. Optical add-drop multiplexer (OADM) becomes a key component to add or drop wavelengths in high bit rate optical networks. Crosstalk in OADM often degrades the performance of WDM system drastically. In this article, we have developed analytical model for low crosstalk of fiber Bragg grating based OADM with isolator. We have also derived analytical expressions for relative intensity noise (RIN), bit error rate (BER) and power penalty to evaluate the performance limitations of this OADM. Results show that crosstalk, RIN and BER of the proposed OADM are significantly lower and provide better performance than the existing OADMs.

Index Terms— Bit error rate, optical add-drop multiplexer, optical network and relative intensity noise.

I. INTRODUCTION

A wavelength division multiplexing (WDM) system is a high-speed optical transmission system that simultaneously transports optical signals of different wavelengths over a single optical fiber. WDM is developed as a next generation optical signal transport technology after traditional time division multiplexed systems offering much greater potential capacities. In a WDM optical network system, it is necessary to add or drop different wavelengths and optical add drop multiplexer (OADM) is one of the key components to enable greater connectivity and flexibility of the network. Fiber grating based devices seems to be promising candidates for OADMs since they have the characteristics of small volume, inherently low loss, spectrally selective and easy to be coupled with optical fiber systems. An important technical issue for OADM design is the reduction of crosstalk, which can severely degrade system performance. Crosstalk arises in OADMs through component imperfections and limits the performance of the system. Optical crosstalk at the same wavelength as the information signal is generally referred to as homodyne crosstalk. Homodyne crosstalk is particularly serious because it cannot be removed by filtering [1-3]. Homodyne crosstalk can be incoherent and coherent. In Incoherent crosstalk causes rapid power fluctuations and coherent crosstalk changes the optical power of the signal [4]. It occurs when the signal and interferer are from different optical sources.

Over the years a number of research works is carried out to determine various types of crosstalk, their detrimental effects and develop different techniques to suppress those. The statistical impact of coherent and incoherent crosstalk contributions on an optical signal passing through optical fiber grating couplers in WDM optical networks is identified through simulation in [5]. Homodyne crosstalk characteristics of a number of different OADM structures, in the context of WDM ring and bus network links is compared experimentally [6]. In [7-8], 3-kinds of OADM structure with low crosstalk have been demonstrated experimentally based on multiport circulator and fiber Bragg grating (FBGs). Crosstalk reduction in arrayed waveguide grating wavelength multiplexer/demultiplexer is demonstrated in [9]. Smit et al. [10] designed a non-uniform crosstalk model, along with a procedure for interactive user calibration of the model parameters. A detailed analytical investigation of incoherent crosstalk on FBG based OADM without isolator is reported in [12]. In this paper, we have analyzed and evaluated the incoherent crosstalk performance of FBG based OADM with isolator and circulator in terms of BER, RIN and power penalty and found that it introduces minimum incoherent crosstalk in the system.

II. SYSTEM MODEL

A FBG is a periodic or aperiodic perturbation of the effective refractive index in the core of an optical fiber. Light propagating through the core will be reflected if Bragg condition is satisfied. Analysis of the incoherent crosstalk of the typical structure of an OADM based on FBG (without isolator) and circulators is illustrated in detail in [12] and shown in Fig. 1.
In this paper, we have proposed an OADM based on FBG (with isolator) and circulators which is shown in Fig. 2. The function of the isolator is to allow transmission of signal in one direction through it but block all transmission in the other direction. In a three-port circulator, an input signal on port 1 is sent out on port 2, an input signal on port 2 is sent out on port 3 and an input signal on port 3 is sent out on port 1. An information signal is added at the add port, reflected back through FBG and passed through the output (circulator 2). Another signal with the same wavelength as the informational signal is entered at the input port (circulator 1). This signal is reflected through the grating and dropped at the drop port. Some power of the dropped signal leaks through the grating because the reflection of the grating is not perfect. The leakage of the dropped signal interferes with the informational signal and causes incoherent crosstalk at the output. Isolator prevents any kind of leakage of the added signal and does not introduce crosstalk at the drop port.

![Add-Drop multiplexer based on isolator, Bragg gratings and circulators](image)

Fig. 2: Add-Drop multiplexer based on isolator, Bragg gratings and circulators

III. THEORETICAL ANALYSIS

Figure 2 shows that the input signal that is added at the add port of the multiplexer reflected back through FBG and passed through the output can be written as [1]

\[ S_S(t) = \sqrt{R} \sqrt{2P} \cos[2\pi f_c t + \phi_S(t)] \]  

where \( P \) is the signal power, \( f_c \) is the carrier wave frequency and \( R \) is the reflectivity of the uniform grating, which is

\[ R(l, \lambda) = \tanh^2 \left( \frac{\Omega l}{2} \right) \quad \text{and} \quad \Omega = \frac{\pi \Delta n \eta(v)}{\lambda} \]

where \( l \) is the grating length, \( \Delta n \) is the amplitude of the induced refractive index perturbation (typically 10^{-5}-10^{-2}), \( \eta(v)=1-1/v^2 \), \( v \gg 2.4 \), \( \eta \) is a function of the fiber parameter \( v \) that represents the fraction of the integrated fundamental mode intensity contained in the core and \( \lambda \) is the wavelength.

The \( n \)-channel WDM signals with the same wavelength as the added signal are launch into the input port. The leakage of \( n \)-channel WDM signals that come from the input port and interfere to the information signal at the output port can be written as [1]

\[ S_i(t) = \sqrt{1-R} \sqrt{2P} \sum_{i=1}^{n} \sqrt{\epsilon_i} \cos[2\pi f_c t + \phi_i(t)] \]  

where \( P \epsilon_i \) is the power for each interfering channel. The electric field at the output can be written as [1]

\[ E(t) = \sqrt{R} \sqrt{2P} d_i(t) \cos[2\pi f_c t + \phi_i(t)] \]

\[ + \sqrt{1-R} \sqrt{2P} \sum_{i=1}^{n} d_i(t) \epsilon_i \cos[2\pi f_c t + \phi_i(t)] \]  

where, \( d_i(t) \{0,1\} \), depending on whether a 0 or 1 is being sent in the desired channel, \( d_i(t) \{0,1\} \), depending on whether a 0 or 1 is being sent in the crosstalk channel, \( \phi_i(t) \) is the random phase of the information signal, \( \phi_i(t) \) is the random phase of the crosstalk signal, \( f_c \) is optical carrier frequency.

The photo detector produces a current that is proportional to the received power within its received bandwidth. The power at the output is written by squaring the equation (3) and after solution as [1]

\[ P_f = R \epsilon_i d_i(t)^2 + (1-R)^2 P \sum_{i=1}^{n} \epsilon_i [d_i(t)^2 - R R_P] \]

\[ + 2 \sqrt{R} \sqrt{(1-R)^2} P d_i(t) \sum_{i=1}^{n} \epsilon_i \sum_{j=1, j \neq i} d_j(t) \epsilon_j \cos[\phi_i(t) - \phi_j(t)] \]  

The first and second terms in (4) are the optical power of the signal and the crosstalk power respectively. The last term is called signal crosstalk beat noise, which is of interest to us.

A. Signal Crosstalk Beat Noise

The cosine function in the last term on the right hand side of equation (4) denotes the beat of the output current due to crosstalk light interference. The beat noise spectrum is of the order of the laser line width and is centred at the frequency difference of the lasers. In a practical system the frequency difference may be larger than the receiver bandwidth and the beat would give no in-band noise. In the worst case, whole noise power is inside the receiver bandwidth. In such case the electrical noise power for each beat component is written as

\[ 2P \sqrt{(1-R)^2} \epsilon_i \]  

The normalized total noise power is obtained by adding the individual beat noise power and dividing the sum by the signal power. Thus normalized total noise power can be given as

\[ \sigma_{RIN}^2 = \frac{1}{(PR)^2} \sum_{i=1}^{n} [2P^2 R (1-R) \epsilon_i] \]

\[ \sigma_{RIN}^2 = \frac{(1-R)^2}{R} \sum_{i=1}^{n} 2 \epsilon_i \]  

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where we define $\epsilon_i$ as the optical power ratio of each crosstalk component to the signal. $\sigma^2_{\text{RIN}}$ is referred to as relative intensity noise (RIN). The signal crosstalk beat occurs when the crosstalk channel is in the “1” state. If the “1” state density is 0.5, the noise power is reduced by half. So the RIN of the signal-crosstalk beat noise is given by

$$\sigma^2_{\text{RIN}} = \frac{(1-R)^2}{R} \sum_{i=1}^{n} \epsilon_i$$  \hspace{1cm} (7)

B. Bit Error Rate

The bit error rate (BER) is the number of erroneous bits to the total transmitted bits at the receiver that have been altered due to noise, interference and distortion. Here we describe the BER degradation resulting from the signal-crosstalk beat noise. The general formula for the BER of the practical receiver is given by

$$\text{BER} = \frac{1}{2} \left[ Q \left( \frac{I_1 - I_0}{2\sigma_1} \right) + Q \left( \frac{I_1 - I_0}{2\sigma_0} \right) \right]$$

where $I_i$ is the mean photocurrent when 1 is transmitted, $I_0$ is the mean photocurrent when 0 is transmitted, $\sigma^2_1$ is the sum of the variance of the thermal and shot noise when 1 is transmitted and $\sigma^2_0$ is the sum of the variance of the thermal and shot noise when 0 is transmitted. It is assumed that the receiver noise is mainly thermal noise and shot noise and there is no difference between the “1” and “0” states. Here $I_0 = 0$. Hence the BER can be written as

$$\text{BER} = \frac{1}{4} \text{erfc} \left( \frac{1}{\sqrt{2}\sigma_1} \right) + \frac{1}{4} \text{erfc} \left( \frac{1}{\sqrt{2}\sigma_0} \right)$$  \hspace{1cm} (9)

We assumed that the beat noise has Gaussian probability density distribution, therefore, the total noise power in the presence of the crosstalk is given by the sum of the beat noise and receiver noise; $\sigma^2_1 + \sigma^2_{\text{RIN}} I_1^2$ and $\sigma^2_0 + \sigma^2_{\text{RIN}} I_1^2$, where $\sigma^2_{\text{RIN}} I_1^2$ is the absolute value of the beat noise respectively. The BER is obtained by replacing $\sigma_i$ with $\sqrt{\sigma^2_1 + \sigma^2_{\text{RIN}} I_1^2}$ in (9). There is no need to replace $\sigma_0$ in (8) because the beat noise occurs only when the signal is in “1” state. Hence the BER is given by the following expression

$$\text{BER} = \frac{1}{4} \text{erfc} \left( \frac{1}{\sqrt{2}\sqrt{\sigma^2_1 + \sigma^2_{\text{RIN}} I_1^2}} \right) + \frac{1}{4} \text{erfc} \left( \frac{1}{\sqrt{2}\sqrt{\sigma^2_0 + \sigma^2_{\text{RIN}} I_1^2}} \right)$$  \hspace{1cm} (10)

C. Power Penalty

Power penalty is the extra power required to account for degradations due to different impairments that are present in the system. The power penalty is given by

$$PP = -10 \log \left( \frac{P_r'(1)}{P_r(1)} \right)$$  \hspace{1cm} (11)

where $P_r(1)$ denotes the received optical power during 1 bit in the absence of crosstalk and $P_r'(1)$ denote the received optical power during 1 bit in presence of crosstalk. From (4), we can write $P_r'(1)=RP$ and the expression for $P_r'(1)$ is written as

$$P_r'(1) = RP + (1-R)^2P \sum_{i=1}^{n} \epsilon_i$$

$$+ 2 \sqrt{R} \sqrt{(1-R)^2P \sum_{i=1}^{n} \epsilon_i} \left( \sqrt{\epsilon_i} \cos(\phi_i) - \phi_i(t) \right)$$  \hspace{1cm} (12)

Assuming $\epsilon_i << 1$, we can neglect the term $\epsilon_i$ compared to $\sqrt{\epsilon_i}$. Also the worst case is when the $\cos(.) = -1$. Using this, in (12) can be written as

$$P_r'(1) = RP - 2 \sqrt{R} \sqrt{(1-R)^2P \sum_{i=1}^{n} \sqrt{\epsilon_i}}$$  \hspace{1cm} (13)

Therefore power penalty is

$$PP = -10 \log \left( 1 - 2 \sqrt{(1-R)^2P \sum_{i=1}^{n} \sqrt{\epsilon_i}} \right) \sqrt{\frac{R}{\epsilon}}$$  \hspace{1cm} (14)

IV. RESULTS AND DISCUSSION

A. Analysis the Performance of Proposed OADM

Following the analytical approach discussed in section III, we have plotted a set of graphs to show the effect of RIN, power-penalty, BER etc. for different number of interfering channels in an OADM.

Fig.3 shows the effect of RIN for various crosstalk power and different number of interfering channels. It is observed that the power penalty is large while the numbers of interfering channels are increasing for a fixed RIN level. For example, the amount power penalty is about 1.7dB, 2.2dB and 2.7dB when the numbers of channels are 10, 15 and 20 respectively for RIN of -20dB.
Fig. 4: Plots of power penalty vs. crosstalk

The plots of power penalty vs. crosstalk for different values of $n$ are shown in Fig. 4. It is observed that for a fixed crosstalk power, the power penalty is increased with increasing the number of channels. For instance, the required power penalty is 0.6dB when $n=20$, 0.8dB when $n=40$ and 1.2dB when $n=60$ for the crosstalk of -70dB.

Fig. 5 shows the variation of BER and received power for different values of $n$. It is observed that for the same BER, the received power is varied with $n$. From Fig. 5, we found that as the number of channels increases the BER is also increased. For example, the received power is -15.5 dBm, -14 dBm and -11.5 dBm at a BER of $10^{-4}$ for channel number of 2, 3 and 4 respectively.

Fig. 6 describes the crosstalk as a function of wavelengths. The wavelengths in the reflected band may be used to add or drop. From Fig. 6, it is observed that the crosstalk results minimum (-230dB) for the interfering channels which input in the range of Bragg wavelength. The band of reflected wavelengths can be extended and made smooth by the use of proper apodization. For instance, the crosstalk is minimum at the wavelength of 1550 nm. The range of wavelength is measured at half power point. From Figure 6, it is seen that the reflected wavelength range is 1549.95 nm to 1550.05 nm.

In Fig. 3, we already observed that RIN is increased with increasing the number of channels. Fig. 7 shows the effect of the RIN for different number of channel. For instance, the RIN is about 0.001 mW when $n=10$.

B. Performance Comparison

There are many analytical, simulation and/or experimental works on OADM using different devices like- Mach-Zehnder modulator, array waveguide grating, FBG etc. But analytical model of crosstalk using FBG is yet to be reported in the literature. We developed analytical model of incoherent crosstalk of FBG based OADM without isolator and evaluated its performance in terms of BER, RIN and power penalty in [12]. In this section, we have established a comparison between these two types of OADMs. Fig. 8 shows the comparison of the incoherent crosstalk as a function of wavelength for OADMs with and without isolator. It is observed that the crosstalk of OADM with isolator is reduced drastically. For instance, at 1550 nm, the crosstalk of OADM is about -230 dB and -130 dB for with and without isolator respectively.

The variation of crosstalk and number of channels for different OADM structures is shown in Fig. 9. It is found that crosstalk reduces in OADM with isolator significantly. For example, at $n=10$, the crosstalk of OADM is -78.5 dB and -74 dB for with and without isolator respectively.
In addition to FBG based OADM, there are different types of OADMs, such as optical cross connect, array waveguide grating and coupler based OADM. OADMs based on FBG allow the extraction of a wavelength from a transmission loop and the addition of the wavelength to the network and provide interconnection between network structures with low loss. Other OADMs are more complicated. Implementation is more difficult and also causes high crosstalk. Table 1 depicts the performance of various types of OADM with different performance metrics. From Table 1, it is observed that OADM based on FBG is more efficient than any other technology. Thus, OADM with isolator increases the over all performance of the optical network when it is used to add/drop the signal.

Table 1 Parameter values use for theoretical calculations

<table>
<thead>
<tr>
<th>Performance metric</th>
<th>No. of channel</th>
<th>OADM based on AWG</th>
<th>OADM based on OXC</th>
<th>OADM based on FBG, circulator and isolator</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIN</td>
<td>16</td>
<td>0.028 mW [13]</td>
<td>Not available</td>
<td>0.002 mW</td>
</tr>
</tbody>
</table>

V. Conclusion

WDM systems make it possible to increase the transmission capacity tremendously in fiber-optic transmission systems. Various complex WDM networks such as layered fiber loops and fiber meshes have recently been proposed and investigated in optical domain to exploit its full potential. Optical fiber routing system using WDM transmission has also been given particular attention as the paths of the optical signals can be decided by their wavelengths. OADM is an important of optical node in WDM network system to add/drop wavelength and thus it is necessary to design an efficient OADM to ensure error free data transmission. In this research work, we have derived analytical model of crosstalk for FBG based OADM and evaluated its incoherent crosstalk performance. It is found that the proposed OADM increases the overall performance of the system and decreases the crosstalk significantly. Findings of this work will help to design an efficient WDM system with low crosstalk OADM considering reflectivity, impact of crosstalk and signal wavelength.

REFERENCES


**Biographies**

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