Crosstalk Analysis of a DWDM System with FBG-based Optical Multi/De-multiplexer

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***Abstract*— Semi-Analytical approach is presented to find the crosstalk in a Dense Wave Division Multiplexing (DWDM) transmission system with Fiber Bragg Grating (FBG) based wavelength multiplexer (MUX)/ De-multiplexer (DE-MUX). The analytical expression of crosstalk due to FBG based MUX/DE-MUX is developed considering the FBG Transfer function. The amount of crosstalk is evaluated by simulation and Bit Error Rate (BER) of a Wave Division Multiplexing (WDM) system with cross talk is evaluated numerically. The penalty due to crosstalk at a BER of 10^{-9} is determined for different FBG and channel parameters. It is found that crosstalk is significant and can be reduced by increasing channel separation and also can be minimized by choosing optimum system parameters.**

Keywords— DWDM; FBG, crosstalk; BER, Optical Add-Drop Multiplexer (OADM); power penalty

I. INTRODUCTION

Optical fibers have revolutionized telecommunication. Much of the success of optical fiber lies in its near-ideal properties: low transmission loss, high optical damage threshold, and low optical nonlinearity. The combination of these properties has enabled long-distance communication to become a reality [1]. Although the optical fibers have been used for decades, the last 10 to 20 years have shown a lot of further development [2]. The introduction of FBGs, photonic crystal fibers and new fields, has dramatically widened the range of possible applications.

The FBGs are used extensively in telecommunication industry for DWDM, dispersion compensation [3,4], laser stabilization, and Erbium amplifier gain flattening, simultaneous compensation of fiber dispersion, dispersion slope and optical CDMA [5,6]. By exploiting the characteristics exhibited by this grating, numerous areas have been marked in which their usage has brought drastic advancements and continues to do the same. The optical fiber with germanium doped core remains the most important material for grating purpose. The first in fiber grating was demonstrated by Ken Hill in 1978 [7].

FBG can be used as a wavelength multiplexer/de-multiplexer or OADM for dropping/ adding of number of wavelengths. The tails of the transmittance and the reflectance functions of an FBG results in optical crosstalk and causes degradation in the DWDM link performance. Several research works are reported on the transfer functions of FBG without and with apodization which results in a better output signal [2,8]. However, the amount of crosstalk due to FBG is yet to be reported for several FBG and DWDM parameters.

In this paper, a semi-analytical approach is presented to evaluate the amount of crosstalk that results at the output of an OADM due to non-ideal transmittance/reflectance characteristics of a FBG. The results are evaluated as a function of several FBG parameters, DWDM channel and system parameters and system BER. Power penalty due to crosstalk at a given BER is also determined for several FBG parameters

II. SYSTEM MODEL

The block diagram of a DWDM system with OADM is shown in Fig 1. All the input wavelength channels are multiplexed by a DWDM multiplexer and fed to the single mode fiber (SMF) transmission link with optical signal amplifier (OA) in cascade. The received optical signal is first de-multiplexed using a FBG based wavelength de-multiplexer and a desired optical channel is dropped to the receiver.

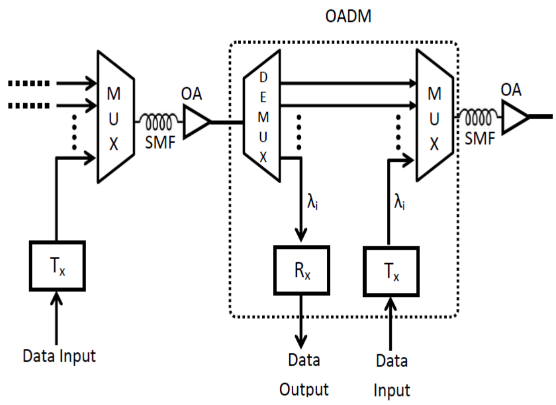

Fig 1: Block Diagram of a DWDM transmission system with Optical Add Drop Multiplexer (OADM)

The use of FBG as a wavelength multiplexer and de-multiplexer is shown in Figures 2(a) and 2(b) respectively.

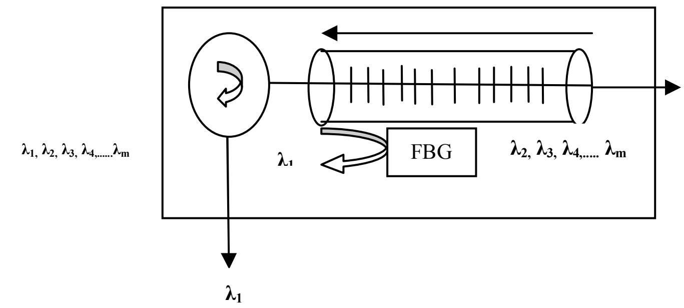

Fig. 2 (a): *FBG as a de-Multiplexer*

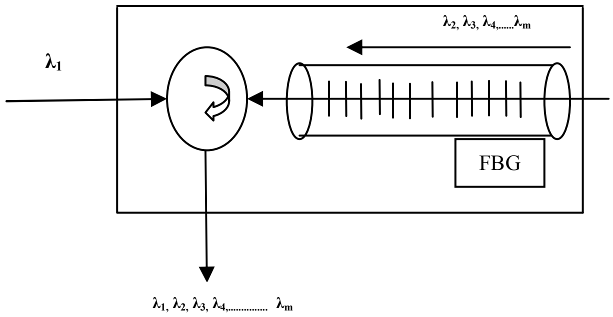

Fig. 2 (b): *FBG as a Multiplexer*

III. ANALYSIS OF CROSSTALK AND BER

The input optical signal at a wavelength λ_i can be expressed as:

$$S_i(t) = \sqrt{2P_{in}}\, e^{j\left(\frac{2\pi}{\lambda_i} + \phi_i\right)} \tag{1}$$

where P_{in} is the average optical input power at any wavelength, λ_i is the i-th channel wavelength of a channel DWDM system and φ_i is the initial phase of the i-th optical carrier.

The expression for reflectivity obtained according to the Coupled Mode Theory i,e grating with uniform index modulation and period of reflectivity is given by [1,2]:

$$R\ (L,\lambda) = \{K^2 Sinh^2(\gamma L)\}/\{\Delta\ \beta^2\ Sinh^2(\gamma L) + \gamma^2\ Cosh^2(\gamma L)\} \tag{2}$$

where *R (L, λ)* is the reflectivity as function of grating length *L* and wavelength *λ*. Detuning wave vector, $\Delta\beta = \beta - (\pi/\Lambda)$ where Λ is the grating period, Fiber core propagation constant, $\beta = \frac{2\pi n_i}{\lambda_i}$ and $\gamma = \sqrt{k^2 - \Delta\beta^2}$.

If there is no wave vector detuning for light at the Bragg grating, λ_B and as such $\Delta\beta$=0, then, the reflectivity function becomes:

$$R(L,\lambda) = \tanh^2(\gamma L) \tag{3}$$

The spectrum of the optical signal at the output of OADM and input to the photo detector is given by:

$$Y(\lambda - \lambda_0) = S(\lambda).\ R\ (L,\ \lambda - \lambda_0) \tag{4}$$

where λ_0 is the centre wavelength of FBG and S (λ) is the spectrum of the WDM signal s(t) which can be expressed respectively as:

$$S(\lambda) = FT\ \{s(t)\} = \frac{1}{2\pi}\int_{-\infty}^{\infty} s(t) e^{j\frac{2\pi t}{\lambda}} dt \tag{5}$$

The optical signal and crosstalk power at the i-th wavelength at the output of de-multiplexer which is the input to the photo-detector can be expressed as:

$$P_{sig} = \frac{1}{2\pi}\int_{-\frac{\lambda_i+\Delta\lambda}{2}}^{\frac{\lambda_i+\Delta\lambda}{2}} Y(\lambda - \lambda_i) d\lambda \tag{6}$$

$$P_c = \sum_{j=1, j\neq i}^{M} \int_{-\frac{\lambda_i+\Delta\lambda}{2}}^{\frac{\lambda_i+\Delta\lambda}{2}} Y(\lambda - \lambda_i) d\lambda \tag{7}$$

where $\Delta\lambda$ is the channel separation. The output signal photo current (I_s) and photo current due to optical crosstalk signal (I_c) are given by:

$$I_s = R_d.P_{sig} \tag{8}$$

$$I_c = R_d.P_c \tag{9}$$

where R_d is the responsivity of the photodiode. The electrical crosstalk power at the output of the receiver is given by $\sigma^2_c = \langle i^2_c \rangle = (R_d.P_c)^2$ and the signal power at the output of receiver is I_s^2 . The noise currents at the receiver output are due to photo-detector shot noise and pre-amplifier thermal noise. The total noise variance σ^2_n is given by:

$$\sigma^2_n = \sigma^2_{th} + \sigma^2_{shot} \tag{10}$$

where σ^2_{th} and σ^2_{shot} represents thermal and shot noise respectively and are given by:

$$\sigma^2_{th} = \frac{4kTB}{R_L} \text{ and } \sigma^2_{shot} = 2eB\,[R_d.P_{sig} + R_d.P_c] \tag{11}$$

Signal to crosstalk plus noise ratio (SCNR) at the output of receiver can then be expressed as:

$$SCNR = \frac{I_s^2}{(\sigma_c^2 + \sigma_{shot}^2)} \tag{12}$$

The Bit Error rate (BER) can now be expressed as:

$$BER = 0.5 erfc(\sqrt{SCNR}/2\sqrt{2}) \tag{13}$$

IV. RESULTS AND DISCUSSION

The analysis presented in section III is followed to carryout simulation to find the amount of crosstalk and optical signal power at the output of optical ADM and input to the receiver photodiode. Simulation is carried out for different number of wavelength channels each operating at a bit rate of 10 Gbps for several channel separation $\Delta\lambda$. The results evaluated by simulation are in terms of crosstalk power and optical signal power at the input of photo-detector at the dropped optical wavelength. The system parameters used for the FBG are shown in Table 1.

TABLE 1

FBG and System Parameters	
Grating Length, L	15mm
Core index,n_1	1.47
Cladding Index,n_2	1.457
Wavelength, λ	1550nm
Change in Refractive Index, Δn_{eff}	1e-4
Grating Period, Λ	5.3e-7
Δf	0.1e9
f_o	10e9,20e9,30e9
R_L	50
R_b	10 Gbps
B	10 GHz
R_d	0.85

The amount of crosstalk at the output FBG de-multiplexer is determined by simulation for FBG parameters at a bit rate of 10Gbps for 8 wavelength channels for different values of channel separation. The plots of crosstalk versus channel separation, $\Delta\lambda$ are depicted in Fig.3 for FBG length L= 15mm, 20mm, 25mm, 30mm, 35mm, 40mm.

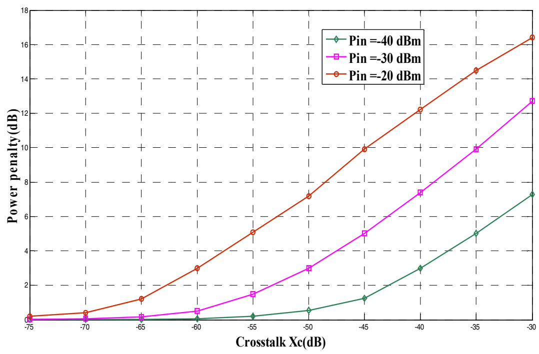

Fig 3. Plots of Crosstalk versus Channel Separation, $\Delta\lambda$ for FBG length L= 15mm, 20mm, 25mm, 30mm, 35mm, 40mm

It is noticed that the amount of crosstalk due to FBG is significant. The crosstalk can however, be reduced by increasing the channel separation at a given FBG grating length. It is further noticed that as the grating length is increased, there is no appreciable increase in crosstalk at a given value of channel separation. The bit error rate (BER) performance results of a DWDM system with crosstalk due to OADM are depicted in Fig 4 for input power P_{in}= -20 dbm and relative crosstalk X_c= *-30*dB. The BER performance without crosstalk is also depicted in the figure. It is noticed that there is significant deterioration in BER performance due to crosstalk.

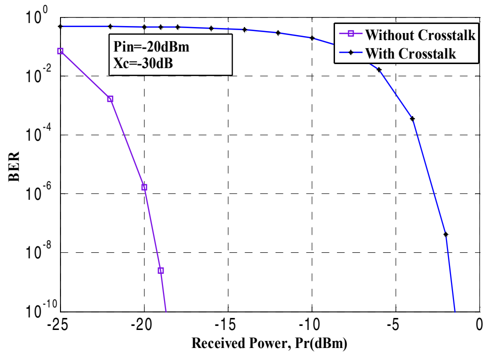

Fig 4: Plot of BER Vs Received Optical Power for P_{in} = -20 dBm and X_c = -30dB

The similar results for different input optical power and crosstalk power are depicted in fig 5 through Fig 12.

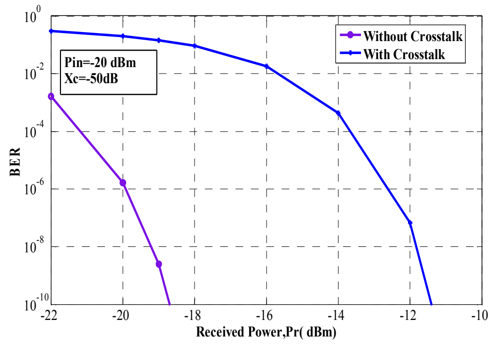

Fig 5: Plot of BER Vs Received Optical Power for P_{in} = -20 dBm and X_c = -50dB

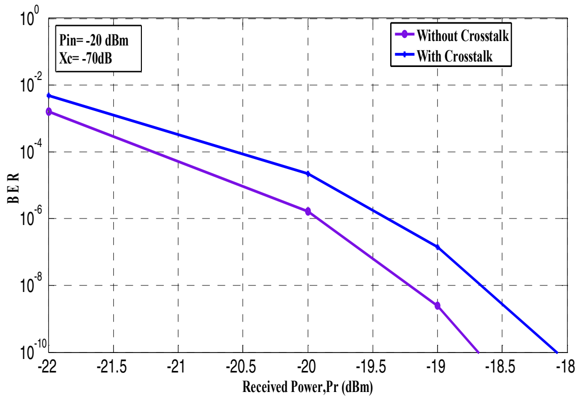

Fig 6: Plot of BER Vs Received Optical Power for P_{in} = -20 dBm and X_c = -70dB

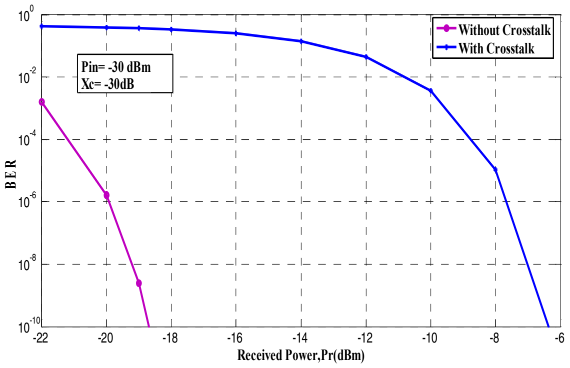

Fig 7: Plot of BER Vs Received Optical Power for P_{in} = -30 dBm and X_c = -30dB

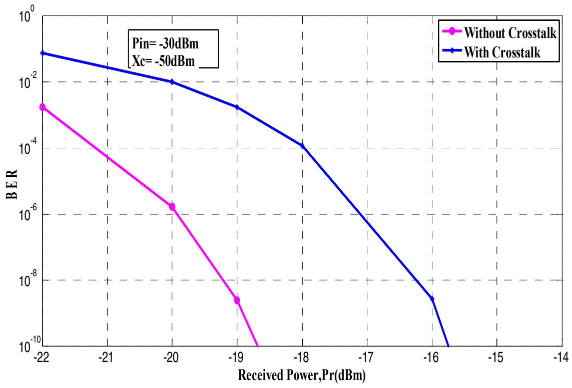

Fig 8: Plot of BER Vs Received Optical Power for P_{in} = -30 dBm and X_c = -50dB

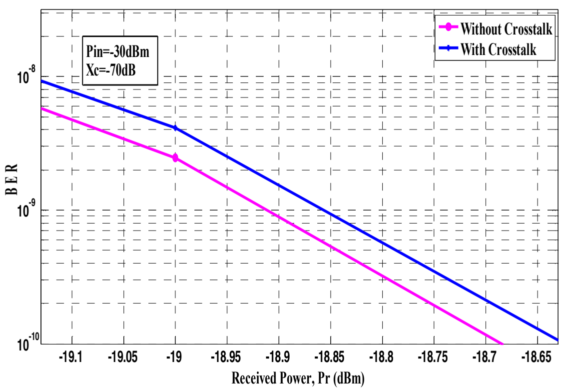

Fig 9: Plot of BER Vs Received Optical Power for P_{in} = -30 dBm and X_c = -70dB

It is noticed that effect of crosstalk depends on the input power as well as channel separation which determines the amount of crosstalk at a given set of FBG parameters. The system thus suffers power penalty due to crosstalk caused by FBG based OADM at a given BER.

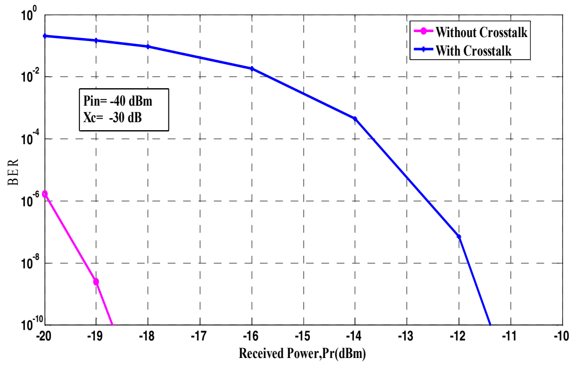

Fig 10: Plot of BER Vs Received Optical Power for P_{in} = -40 dBm and X_c = -30dB

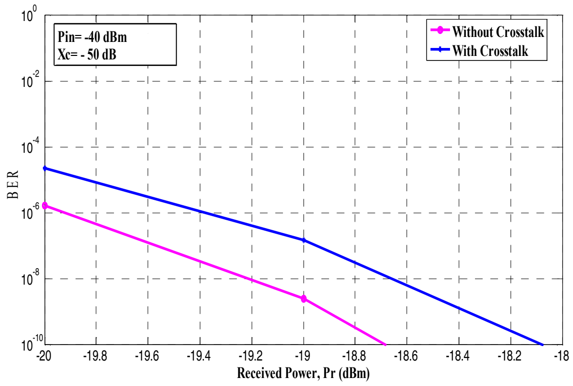

Fig 11: Plot of BER Vs Received Optical Power for P_{in} = -40 dBm and X_c = -50dB

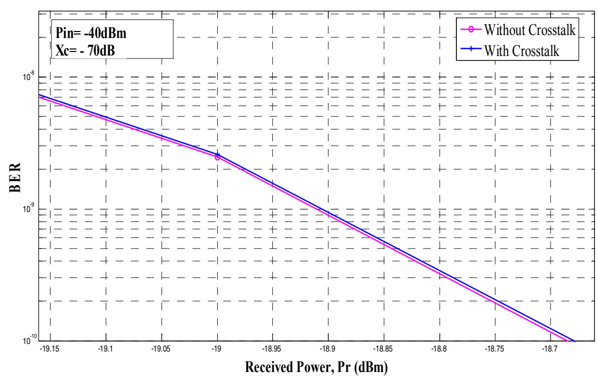

Fig 12: Plot of BER Vs Received Optical Power for P_{in} = -40 dBm and X_c = -70dB

The plots of power penalty at a BER of 10^{-9} are given in Fig 13 for different values of crosstalk and different input power level (-20dBm,-30dBm,-40dBm). It is noticed that power penalty is significant and is higher at higher input power level and higher values of crosstalk power.

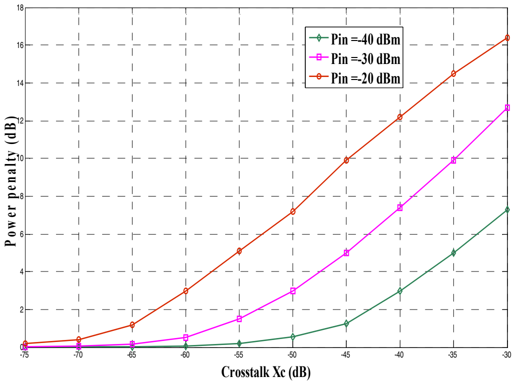

Fig 13: Plots of Power Penalty (dB) Vs Crosstalk (dB)

V. CONCLUSION

A semi-analytical approach is presented to evaluate the amount of crosstalk due to FBG based OADM in a WDM system. The results are presented in terms of BER for several input power, channel separation and relative crosstalk level. The crosstalk causes power penalty at a given BER and can be reduced by increasing the channel separation and selecting the optimum FBG parameters.

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