Performance Degradations due to Crosstalk in Multiwavelength Optical Networks Using Optical Add Drop Multiplexers Based on Fibre Bragg Gratings

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***Resumo* – Neste trabalho é estudado o impacto da diafonia homodina e heterodina num sinal óptico que atravessa um nó óptico de remoção e adição de canais (OADM), numa rede com multiplexagem densa no comprimento de onda (DWDM), são derivadas as expressões da penalidade de potência. O impacto estatístico nos sinais ópticos da diafonia é estudada, através de simulação, os resultados são comparados com dados laboratoriais.**

***Abstract* – The impact of homodyne and heterodyne crosstalk on an optical signal passing through an optical add drop multiplexer (OADM) node in dense wavelength division multiplexing (DWDM) network is studied, and the analytical expressions for the power penalty are obtain. The statistical impact of crosstalk on signal is studied by simulation and the results compared with experimental data.**

I. INTRODUCTION

The optical add drop multiplexer (OADM) is used for selectively dropping and inserting optical signals into a transparent dense wavelength division multiplexing (DWDM) network. Several wavelength OADM's have been proposed based on arrayed wave-guide gratings (AWG) [1], Fabry-Perot filters [2], combination of dielectric thin film MUX and DEMUX [3] and Bragg gratings written in Mach-Zhender interferometers [4]. In this work, we propose a more simple, cost effective, flexible, easily upgrade and transparent configuration, using a fibre Bragg grating (FBG) and an optical circulator [5].

A fundamental difficulty of wavelength routing is the crosstalk from neighbouring inputs, which cause severe degradation in system performance.

In this paper we present a model for the power penalty due to crosstalk. The analytical results are compared with experimental results obtain from a FBG based OADM, from these results we verify that the model represent the crosstalk statistic which are likely to occur in a optical network.

II. CROSSTALK

Due to wavelength reuse scheme, the crosstalk is a major problem. Linear crosstalk can be classified into two categories, depending on its origin.

Optical filters and demultiplexers often let leak a fraction of the signal power from neighbour channel that interferes with the detection process, resulting in noise addiction on the detector, such incoherent crosstalk is called heterodyne or out-of-band.

Another case of crosstalk is the homodyne or in-band crosstalk, due to is coherent nature is far more penalising that the heterodyne. This kind of crosstalk usually occurs on wavelength routing where a specified wavelength is added to a WDM network where already exists a leakage signal at the same wavelength due to incomplete filtering.

II A. Heterodyne Crosstalk

A example of heterodyne crosstalk can find on a filter used to selected a single channel among N channels incident on it. Considering that the m channel is selected, then the optical power reaching the detector is

$$P = P_m + \sum_{n \neq m}^{N} T_n \cdot P_n \tag{1}$$

where P_m is the power of the m channel, T_n and P_n is the filter transmittivity and the power for the n channel, respectively.

To evaluate the system performance is useful to determine the power penalty due to crosstalk. The power penalty of the system is defined as the additional power required at the receiver to counteract the effect of the crosstalk.

The photocurrent generate in response to incident optical power by the photodetector is

$$I = I_S + I_{XT} = R_m \cdot P_m + \sum_{n \neq m}^{N} R_n \cdot T_n \cdot P_n \tag{2}$$

where R_m and R_n are the responsivity of the photodetector for the different channels, I_{XT} denotes the crosstalk contribution to the receiver current I_S. The power penalty will depend on the bit sequence of the channels, the worst case situation occurs when all the interfering channel carry the bit 1 simultaneously.

The power penalty could be calculated based on the eye closure occurring as result of the crosstalk. The maximum eye closure happen in the worst case for which I_{XT} is maximum. If I_S need to be increase by a factor of P_{PX}, the peak current correspondent to the top of the eye diagram (bit 1) is

$$I_1 = P_{PX} \cdot I_S + I_{XT} \tag{3}$$

If the decision level is dynamically adjustable to his optimum value to minimise the bit error rate (BER), and considering a non-return to zero (NRZ) modulation with a infinite extinction ratio and a Gaussian noise statistic for the system, them the decision level, I_D, will be at the centre of the eye.

$$I_D = \frac{I_1}{2} \tag{4}$$

Then in the presence of crosstalk the eye opening from I_D to the top level of the eye diagram will be maintained at its original value (I_S/2) if:

$$\frac{I_S}{2} = (P_{PX} \cdot I_S + I_{XT}) - I_{XT} - \frac{1}{2} \cdot (P_{PX} \cdot I_S + I_{XT}) \tag{5}$$

Therefore,

$$P_{PX} = 1 + \frac{I_{XT}}{I_S} \tag{6}$$

Rearranging the expression 6 in logarithmic scale and using the definitions of the expression 2, them the heterodyne power penalty will be:

$$P_{PX} = 10 \cdot Log\left(1 + \frac{\sum_{n \neq m}^{N} R_n \cdot T_n \cdot P_n}{R_m \cdot P_m} \right) \tag{7}$$

if the peak power is assumed to be the same for all the channels and the responsivity of the detector is independent of the wavelength, them the heterodyne power penalty is given by expression 8 [6].

$$P_{Px} \approx 10 \cdot Log(1 + X) \tag{8}$$

where $X = \sum_{n \neq m}^{N} T_n$ represents the fraction of the power leaked into a specific channel from all other channels.

II B. Homodyne Crosstalk

The output signal from a optical node at a l_m wavelength, with N interfering signals at the same wavelength, can be described by is optical field.

$$E_m(t) = \left(E_m(t) + \sum_{n \neq m}^{N} E_n(t) \right) \cdot e^{\left(-j \cdot \frac{2 \cdot p \cdot c}{l_m} \cdot t \right)} \tag{9}$$

where E_m is the desired signal and E_n the crosstalk wave. The receiver current for a photodetector with a responsivity, R, is:

$$I(t) = R \cdot \left| E_m(t) \right|^2 \tag{10}$$

Due to the coherent nature of the crosstalk the current will contain beat terms.

$$\begin{aligned} I(t) \approx\ & R \cdot E_m^2(t) + \\ & 2 \cdot R \cdot \sum_{n \neq m}^{N} E_m(t) \cdot E_n(t) \cdot Cos[q_m(t) - q_n(t)] + \\ & 2 \cdot R \cdot \sum_{k,n \neq m (k > n)}^{N} E_k(t) \cdot E_n(t) \cdot Cos[q_k(t) - q_n(t)] + \\ & R \cdot \sum_{n \neq m}^{N} E_n^2(t) \end{aligned} \tag{11}$$

where $q_i(t)$ are the phase of the ith wave, we can also calculate the optical power for the ith waves using the following relationship:

$$P_i(t) = \left| E_i(t) \right|^2 \tag{12}$$

The first and last terms of expression 11 are the optical power of the signal and crosstalk, respectively. The third term is the crosstalk-crosstalk beat noise, this is negligible compared with the other terms and can be ignored. The second term is the is the signal-crosstalk beat noise, the worst case situation occurs when the beating waves have the same state of polarisation (SOP), therefore the beat noise is maximum.

Since the phase of the signals are likely to fluctuate randomly and $P_n << P_m$, them the expression 11 can be rewrite [6], considering that a phase to intensity noise conversion occurs.

$$I(t) = R \cdot (P_m + \Delta P) \tag{13}$$

If we consider that the receiver bandwidth is wider than the beat noise spectrum then all the beating noise will be converted by the receiver. In these case the normalised total noise power or relative intensity noise, considering only the signal-crosstalk beating and a mark probability of 0.5, will be

$$s_{RIN}^2 = \frac{1}{(E_m^2(t))^2} \cdot \sum_{n \neq m}^{N} 2 \cdot E_m^2(t) \cdot E_n^2(t) = X \tag{14}$$

Where X is the optical power ratio for all the crosstalk components.

The signal to noise ratio (SNR), Q parameter, considering a Gaussian distributed noise and a infinite extinction ratio is

$$Q = \frac{2 \cdot R \cdot \overline{P}_{rec}}{\left(s_T^2 + s_S^2 + s_{RIN}^2\right)^{\frac{1}{2}} + s_T} \qquad (15)$$

where $\overline{P}_{rec}$ is the mean optical power on the receiver, s_T and s_s are the root mean square (RMS) value of the thermal and shot noise, respectively.

Solving the expression 15 in order to obtain the receiver sensitivity, we can obtain.

$$\overline{P}_{rec}(X) = \frac{Q \cdot s_T + Q^2 \cdot q \cdot \Delta f}{R \cdot \left(1 - X \cdot Q^2\right)} \qquad (16)$$

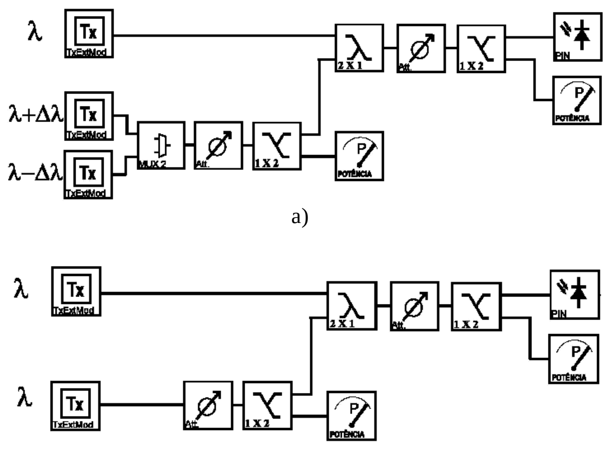
where q is the electron charge and Df the receiver bandwidth. The power penalty due to homodyne crosstalk is defined as the increase in the mean optical power on the receiver when X ≠ 0, necessary to maintain the same Q value [7].

$$P_{PX} = 10 \cdot \log\left(\frac{\overline{P}_{rec}(X)}{\overline{P}_{rec}(0)}\right) = -10 \cdot \log(1 - X \cdot Q^2) \qquad (17)$$

A BER of 10^{-9} correspond to a Q of 6.

II C. Crosstalk Analysis

To investigate if the proposed model is precise, we have implemented a experimental set-up to measure the power penalty due to the homodyne and heterodyne crosstalk for an amplitude shift keying direct detection system. The signals were externally modulated at 2.48832 Gbit/s (STM-16) with uncorrelated sequences. Figure 1 a) and b) shows respectively the set-up used to investigate the heterodyne and homodyne crosstalk.



a)

b)

Figure 1 – Set-up used to investigate the crosstalk: a) heterodyne, b) homodyne.

The experimental results were compared with simulated results obtained from a photonic transmission simulator (PTDS from Virtual Photonics ©) and with the analytical expression from equation 8 and 17.

Figure 2 displays the results for the heterodyne crosstalk. In these case two channels with a wavelength separation of 200 GHz from the detected channel were used as crosstalk waves.

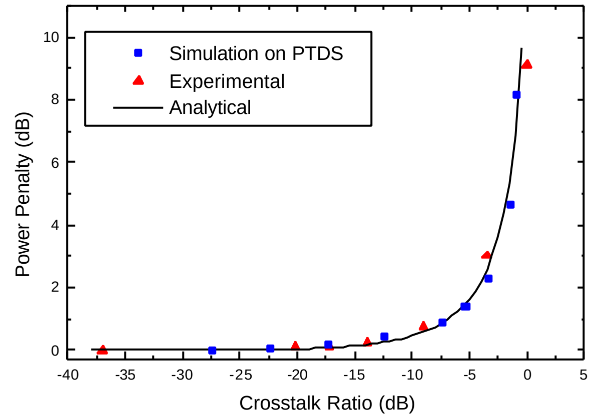


Figure 2 – Power penalty due to heterodyne crosstalk.

Figure 3 displays the results for the homodyne crosstalk, where a channel with the same wavelength that the detected channel was used as crosstalk wave.

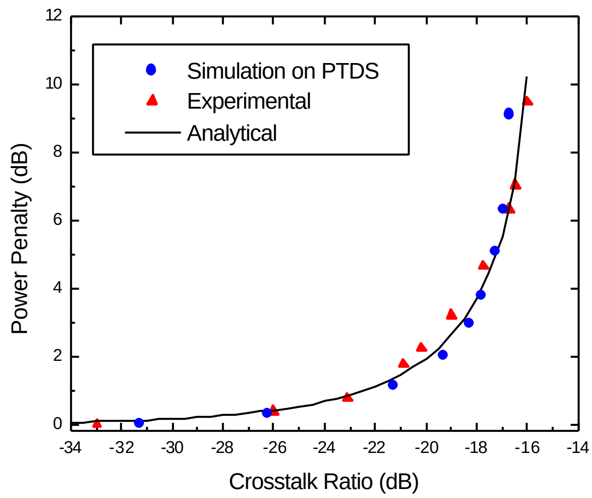
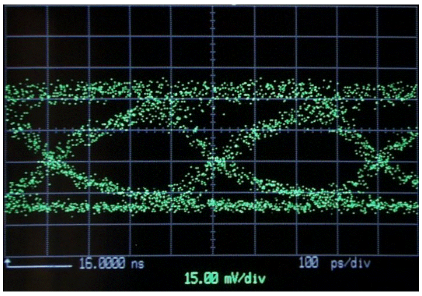


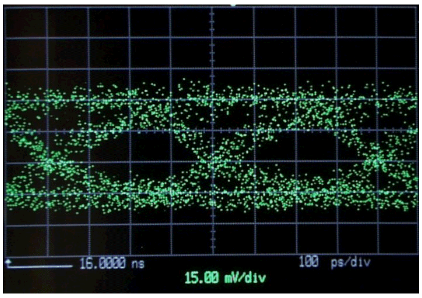
Figure 3 – Power penalty due to homodyne crosstalk.

It can be seen that the analytical model used to predict the power penalty due to crosstalk, the measured values and simulated results are in agreement, within the experimental uncertainties. Usually, with the same crosstalk intensity, the effect of homodyne crosstalk is usually more than one order larger them that caused by the heterodyne crosstalk.

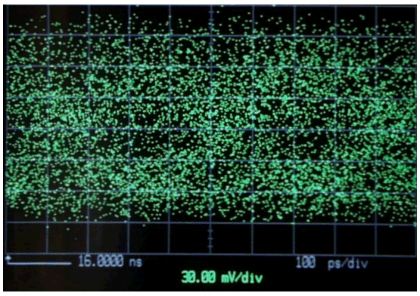
These results can be seen in figure 4, where the eye diagram from the detected signal with –5 dB of homodyne and heterodyne crosstalk are compared, is also plotted the eye diagram for the signal with no crosstalk.



a)



b)



c)

Figure 4 – Detected eye diagram: a) No crosstalk, b) – 5 dB heterodyne crosstalk, c) – 5 dB homodyne crosstalk.

Since the homodyne crosstalk power penalty will be far larger than the heterodyne crosstalk power penalty and may limit the ability to cascade many network elements simultaneously, is indispensable to have low homodyne crosstalk for increase the number of nodes in a network.

III. OADM PERFORMANCE

The basic architecture of the OADM node and the WDM system used to test it are displayed in figure 5. It consists of a fibre Bragg grating, an optical circulator, a power combiner and an optical switch. At first, N multiplexed wavelengths are led to the Bragg grating through the circulator, then the filtered signal is reflected and go back to the circulator where is removed. The remaining channels are coupled with the added channel in a power combiner, after passed by a variable attenuator.

The performance of the OADM is related with the spectral characteristics of the fibre Bragg grating (FBG), which have a central reflective wavelength of 1550.92 nm, with 0.73 and 1.388 nm for the – 3 and – 20 dB bandwidth, respectively. The rejection of the FBG for the adjacent channels is - 28.3 dB and the insertion loss to the central wavelength is - 30.7 dB which correspond to a 99.99 % reflectivity.

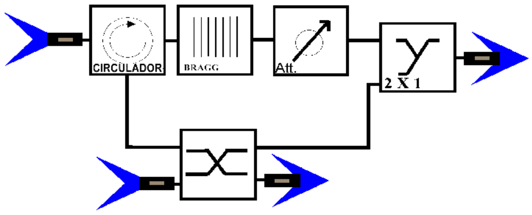
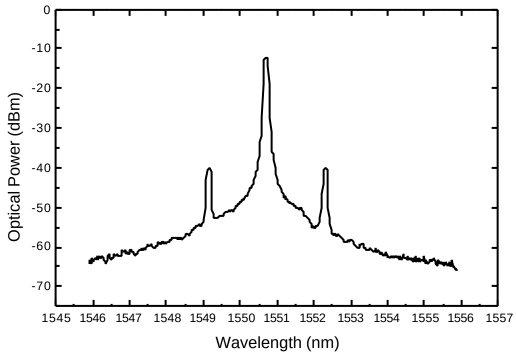
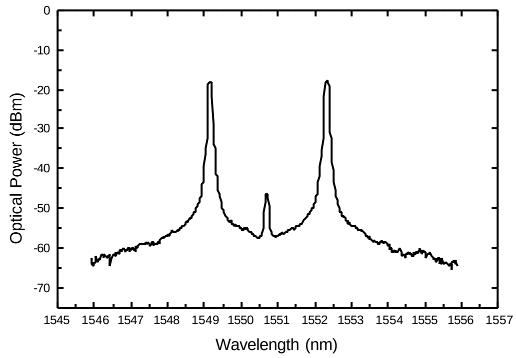


Figure 5 – OADM configuration

The figure 6 a) and b) presents the power spectra of the dropped signal at the OADM and the passed trough signal.



a)



b)

Figure 6 – Power spectra at the OADM: a) Dropped signal, b) pass-trough signal.

The two small components present with the dropped signal (Fig 6a) are due to residual reflections on the circulator and on the FBG and will result on heterodyne crosstalk. The small spectral component at 1550.92 nm (dropped channel) on the pass-through signal (Fig. 6b) results from the imperfect reflection of the central wavelength by the FBG and will result on homodyne crosstalk.

From the crosstalk ratio values obtain on figure 6, which are in agreement with the specified values from the FBG, is possible to calculate, using the equations 8 and 17, the power penalty due to heterodyne and homodyne crosstalk, resulting in 0.01 dB and 0.15 dB, respectively.

To investigate the operation and system performance of this OADM, three distributed feedback lasers (DFB) based at the ITU grid of 200 GHz (≈ 1.6 nm) spacing with wavelengths of 1549.32 nm, 1550.92 nm (dropped channel) and 1552.52 nm, were externally modulated, through a Ti:LiNbO$_3$ Mach-Zehender intensity modulator, at 2.48832 Gbit/s (STM-16), with a non-return to zero (NRZ) 2^7–1 pseudo random bit sequence (PRBS). In the experimental transmission link, 70 km of single mode fibre is used. Two Erbium doped fibre amplifiers (EDFA) having saturated output powers of 13 dBm and 17 dBm and noise figures smaller than 4 dB are employed to provide the required power to compensate the link and OADM losses.

Figure 7 shows the BER performance against the receiver power, for the back to back operation (0 km), for the dropped channel on the OADM after propagation on 50 km of fibre and for the dropped channel after propagation on 50 km of fibre, the BER floor and the 10^{-9} BER are also indicated. The power penalty measured at a 10^{-9} BER is 0.08 dB.

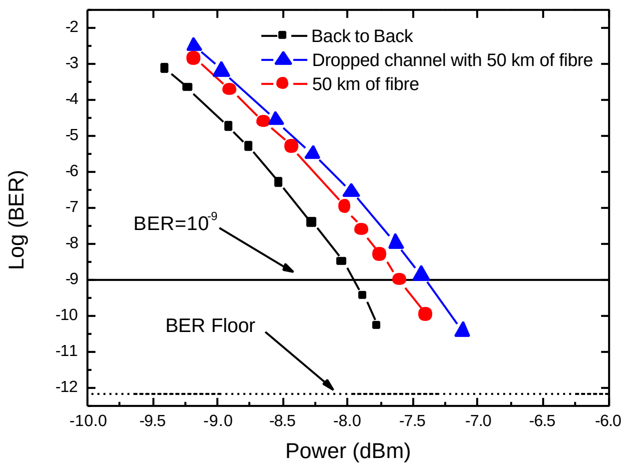


Figure 7 – BER performance against the receiver power for the dropped channel

Figure 8 presents the BER performance against the receiver power, for the back to back operation (0 km), for the added channel on the OADM before propagation on 20 km of fibre and for the dropped channel after propagation on 20 km of fibre, the BER floor and the 10^{-9} BER are also indicated. The power penalty measured at a 10^{-9} BER is 0.18 dB.

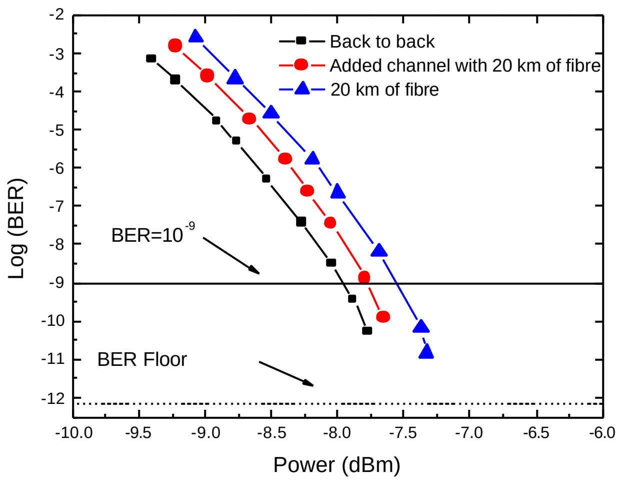


Figure 8 – BER performance against the receiver power for the added channel.

The power penalty measured on the figure 7 and 8 are in agreement, with the results calculated by the expressions 8 and 17, within the experimental uncertainties.

CONCLUSIONS

We have studied the effects of in-band and out-of-band crosstalk, the power penalty have been calculated as function of the magnitude of the crosstalk. The theoretical predictions have been compared with experimental results.

The system performance degradations due to homodyne and heterodyne crosstalk induced by a FBG based OADM have been measured. It has shown that the analytical model can predict with precision the system performance degradation.

The investigated OADM configuration is promising, due to its good spectral characteristics which results in low homodyne crosstalk, and consequentially potential high cascability.

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