Influence of filtered ASE noise and optical filter shape on the performance of a WADM cascade

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Abstract – This paper presents a theoretical study of the impact of filtered Amplified Spontaneous Emission noise and signal distortion on the performance of a cascade of Wavelength Add-Drop Multiplexers. Analysis and computer simulation are used to determine the maximum allowable laser and filter misalignments in order to maintain a bit error rate lower than 10^{-9}.

Introduction – Wavelength Division Multiplexing (WDM) is a promising technique in order to achieve high-capacity, transparent optical networks [1], [2]. Two major impairments in multiwavelength optical networks are: (i) the accumulation of the Amplified Spontaneous Emission (ASE) noise generated in Erbium Doped Fiber Amplifiers (EDFAs), and (ii) the signal distortion arising from the non-flat optical filter shape and the frequency drifts of laser sources and optical filters due to temperature, aging and manufacturing. These effects deteriorate the network performance [3]-[5] and limit the number of network elements that can be cascaded together.

This paper presents a theoretical study of the performance degradation of a chain of Wavelength Add-Drop Multiplexers (WADMs) due to the above effects. The study is divided into two independent parts: (a) The signal distortion is evaluated analytically instead of numerically as done previously [3]-[5]; (b) Wavelength-domain simulation is used in addition to compute the effect of ASE noise accumulation in the presence of laser and filter misalignments. The two approaches provide guidelines for the selection of filters and determine the maximum laser and filter misalignment tolerances in order to maintain a bit error rate (BER) lower than 10^{-9}.

System model – The block diagram of the multiwavelength optical network topology under study is shown in Figure 1(a) [6]. Eight equally spaced externally modulated wavelengths propagate through a cascade of equidistant WADMs. Two wavelengths are dropped and added at each WADM according to a periodic add/drop plan, and only one wavelength is allowed to propagate through the whole WADM cascade.

The structure of a WADM is shown in Fig. 1(b). It is composed of two identical EDFAs, a multiplexer/demultiplexer (MUX/DMUX) pair, 2x2 switches for adding and dropping signals, and variable attenuators that are used to equalize the power levels at the output of the second amplifier.

In the following, it is assumed that the wavelength spacing is 1.6 nm; wavelength 5 propagates through the whole chain; the bit rate is $R_b = 10$ Gb/s; the average amplifier gain is 18 dB/wavelength; the 3-dB bandwidth of individual MUX/DMUXs is assumed $B_o = 125$ GHz; a third order Butterworth electrical lowpass filter with bandwidth $B_e = 6.5$ GHz is used at the receiver. Laser phase noise, external modulator chirp, fiber chromatic dispersion and fiber non-linearities are neglected.

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Analytical evaluation of signal distortion – MUX/DMUXs composed of Fabry-Perot (FP) and multi-layer interference (MI) filters are considered for use in the WADMs. According to [4], the magnitude of the transfer function of FP and MI filters can be fitted by first and third order Butterworth functions respectively.

It is well-known [3], [4] that the overall transfer function of a large number of uniformly misaligned MUX/DMUXs in cascade has a smaller bandwidth than the individual MUX/DMUX bandwidth. An analytical relationship is derived that describes the effect of bandwidth narrowing as a function of the filter number and the maximum allowable filter central frequency offset.

Fig. 2(a),(b) show contour plots of the 3-dB bandwidth of the overall transfer function of a large number of uniformly misaligned MUX/DMUXs in cascade composed of FP and MI filters respectively. By comparison of these plots, we conclude that a larger number of MUX/DMUXs can be cascaded in the case of MI filters since these filters have flatter top. Obviously, MUX/DMUXs composed of FP filters are inappropriate for national scale networks since the bandwidth of the overall transfer function narrows dramatically even after a small number of filters. It is worth noting that this effect can not be compensated by reducing the maximum allowable filter central frequency offset. Therefore, in the following, only the case of MUX/DMUXs composed of MI filters is considered. For these devices, the maximum allowable filter offset is arbitrarily chosen as 12.5 GHz (i.e. 10% of the 3-dB bandwidth) based on current fabrication limitations. In this case, Fig. 2(b) shows that if 100 uniformly misaligned MI filters are cascaded, the bandwidth is reduced to about 40% of its initial value (i.e. 50 GHz instead of 125 GHz).

Fig. 3 shows analytically calculated eye-diagrams at the output of the direct-detection receiver. The maximum eye-opening in the absence of optical filters is set equal to unity (Fig. 3(a)). Fig. 3(b) shows the degradation of the eye-diagram when a channel misaligned by 30 GHz propagates through a chain of 100 uniformly misaligned MI filters. Misalignments result in attenuation (excess loss) and waveform distortion. The distortion-induced penalty, evaluated from eye-closure, is less than 0.3 dB for laser misalignments up to 24 GHz in agreement with [4]. The corresponding signal excess loss is much higher because, due to the misalignment, the signal passes through the edge of filters. To determine the excess loss-induced penalty, it is necessary to know the associated ASE noise power. Due to the complexity of the system, this is done using wavelength-domain simulation, as discussed below.

Wavelength-domain simulation of filtered ASE noise – In the following example, it is assumed that wavelength 5 is misaligned from its nominal position and that the MUX/DMUXs are perfectly aligned.

Fig. 4 presents the power spectral density (PSD) at the output of the 24th and 50th WADM for a misalignment of channel 5 by 40 GHz. In Fig.4(b) wavelength 5 is completely covered by noise. The irregularities in the noise spectrum of the other wavelengths are due to the add/drop scheme.

Figure 5 (a) shows the signal and noise power at each WADM, for wavelength 5. With more than 20 WADMs the signal power decreases, since the EDFAs can not provide the necessary gain to compensate for the extra insertion losses due to the laser detuning from the center of the passband of the MUX/DMUXs. The ASE noise power grows as the signal weakens and eventually equals the signal power level at 40 WADMs. Fig. 5 (b) shows the electrical SNR as a function of the number of WADM stages. Calculations include signal-ASE, ASE-ASE, shot and thermal noise contributions assuming typical values for the receiver parameters [7] . The broken line corresponds to the electrical SNR level necessary to achieve a bit error rate (BER) of 10^{-9} at 10 Gb/s (approximately 16 dB) at an ideal direct detection ASK receiver. For laser misalignments of up to 30 GHz, the wavelength propagating through the whole chain can go through more than 50 WADMs. For a laser misalignment equal to 40 GHz, the signal can only go through 24 WADMs.

Conclusions – This theoretical study of the performance degradation due to filtered ASE noise and signal distortion in a WADM chain, where the two effects are studied independently, shows that the maximum allowable laser offset is approximately 30 GHz in each case. The combined effect dictates that maximum laser misalignment tolerances must be smaller than 30 GHz, and indicates that further study is needed to determine the requirements where both effects are considered simultaneously. This can be accomplished in future work by refining the above model to allow evaluation the error probability using semi-analytical methods.

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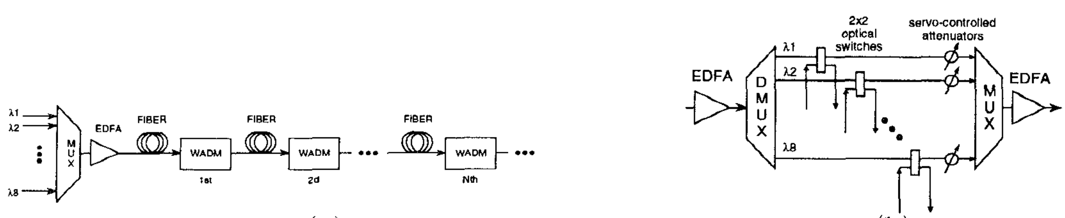
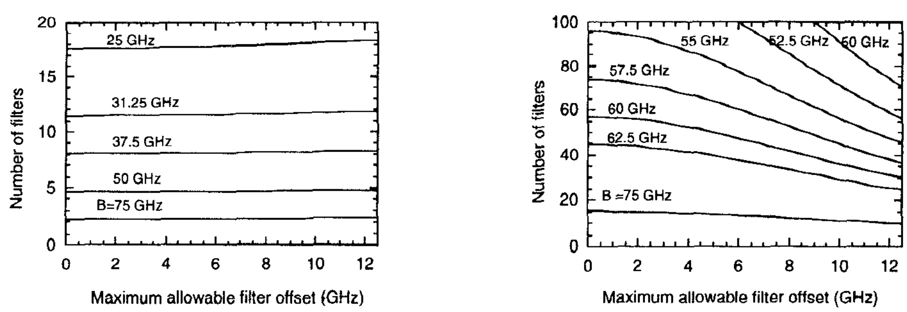


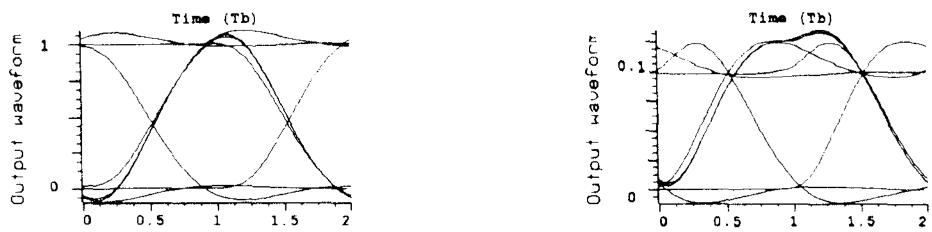
(a) (b)

Figure 1: (a) Block diagram of a cascade of WADMs; (b) Block diagram of a WADM.



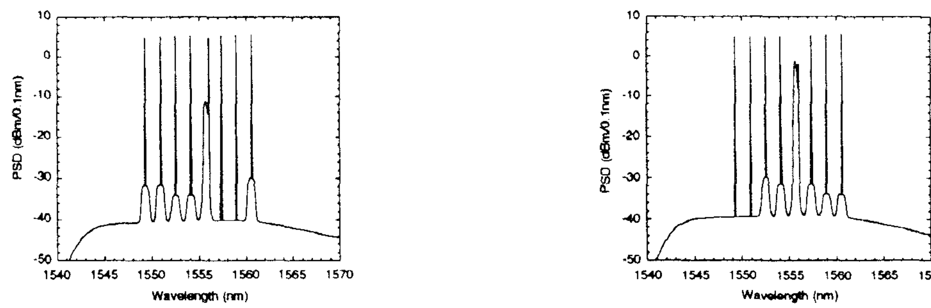
(a) (b)

Figure 2: Contour plots of the 3-dB bandwidth B of the overall transfer function of a large number of uniformly misaligned MUX/DMUXs in cascade (a) composed of Fabry-Perot filters; (b) composed of multilayer interference filters. Condition: each optical filter has 3-dB bandwidth B_o= 125 GHz.



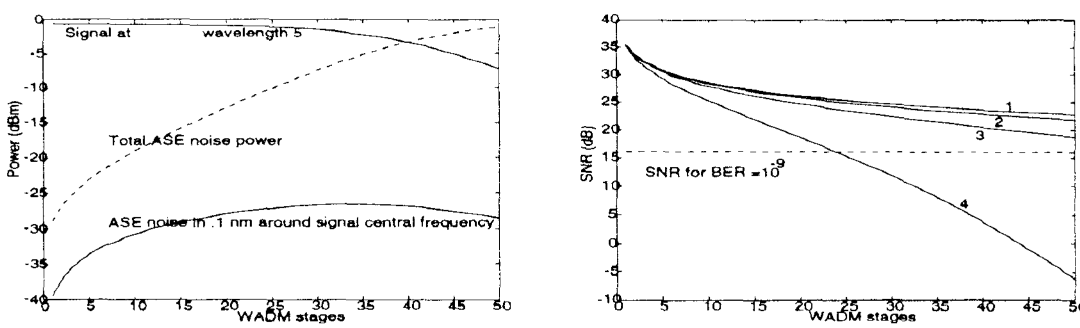
(a) (b)

Figure 3: Eye-diagrams at the output of the direct detection receiver (a) no laser misalignment, no MUX/DMUXs; (b) laser misalignment 30 GHz, 100 uniformly misaligned MUX/DMUXs composed of MI filters.



(a) (b)

Figure 4: Power spectral density (a) at the output of the 24th WADM; (b) at the output of the 50th WADM. Condition: wavelength 5 misaligned by 40 GHz.



(a) (b)

Figure 5: (a) Signal and ASE noise optical powers at wavelength 5 laser misalignment of 40 GHz; (b) Electrical SNR at drop site at wavelength 5 for different laser misalignments: (curve 1) 0 GHz; (curve 2) 20 GHz; (curve 3) 30 GHz; (curve 4) 40 GHz. Broken line: electrical SNR level necessary to achieve a bit error rate (BER) of 10^{-9} at 10 Gb/s at an ideal direct detection ASK receiver.