Waveguide structure optimization of arrayed waveguide gratings concatenation in cascaded optical add/drop multiplexers

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The dimensions of input waveguide and output waveguide of arrayed waveguide gratings (AWGs) determine the crosstalk, insertion loss and 1-dB bandwidth. In cascaded optical add/drop multiplexers (OADMs), the value of these parameters will largely affect the power penalty of system. The power penalty of cascaded OADMs is calculated with different waveguide dimensions of AWGs in this paper. Considering of wavelength misalignment, an optimization design of AWGs is obtained.

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Wavelength devision multiplexing (WDM) technologies are widely used in optical networks in recent years. AWGs are the most important multiplexers/demultiplexers in WDM systems for scaling a large number of channels[1]. The dimensions of waveguides affect AWGs' character greatly and therefore change the power penalty of the whole optical transmission systems, especially in cascaded OADMs. In this paper, we describe waveguide structure optimization of AWGs' concatenation in cascaded OADMs. In the following discussions, we will introduce the influence of waveguide dimensions on insertion loss and crosstalk of AWGs. Then, an investigation about power penalty of cascaded OADMs will be given in detail: the influence of waveguide dimensions and central wavelength misalignment. At the end of this paper, conclusions about waveguide structure optimization of AWGs in cascaded OADMs will be presented.

As shown in Fig. 1, the AWG is composed of input waveguides, two slab waveguides (also called free propagation region), waveguide arrays and output waveguides. According to the analysis in Ref. [2], parameters of waveguide arrays must keep consonant to satisfy the grating function in AWGs. Therefore, main contributors to the optimization of the performance in AWGs focus on the dimensions of the input and output waveguides. The insertion loss and crosstalk of AWGs are mainly determined by $W_{\rm I}$ (the mode field radius of input waveform), $W_{\rm O}$ (the mode field radius of output waveform) and D (I/O waveguide pitch). The following discussion will be based on this analysis and the data used in stimulation come from Ref. [3].

Figure 2 shows a system of cascaded OADMs based on AWGs. Here we will investigate the power penalty of this system. The appropriate length of fiber is selected to maintain that the signal power does not change at each stage. Considering of filter characteristics of AWGs concatenation, the power penalty is sensitive to waveguide dimensions of AWGs.

According to Ref. [4], one way to define the power penalty is as the increase in signal power required (in dB) to maintain the same bit error rate (BER) in the presence of impairments. Another way to define the power penalty is as the reduction in signal-to-noise ratio as quantified by the value of γ (defined by erfc(γ) =BER, erfc(x) is the complementary error function) due to a specific impairment. We will use the former definition since it is more popular and it can be treated as an absolute limitation

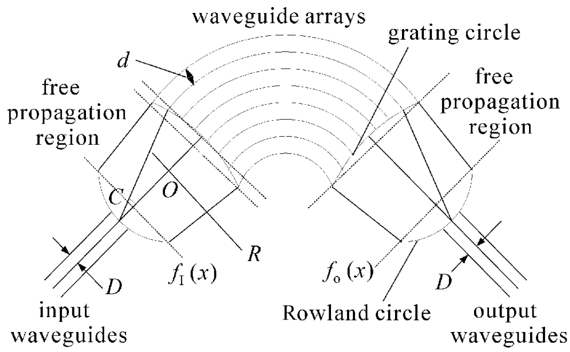

Fig. 1. The structure of arrayed waveguide gratings.

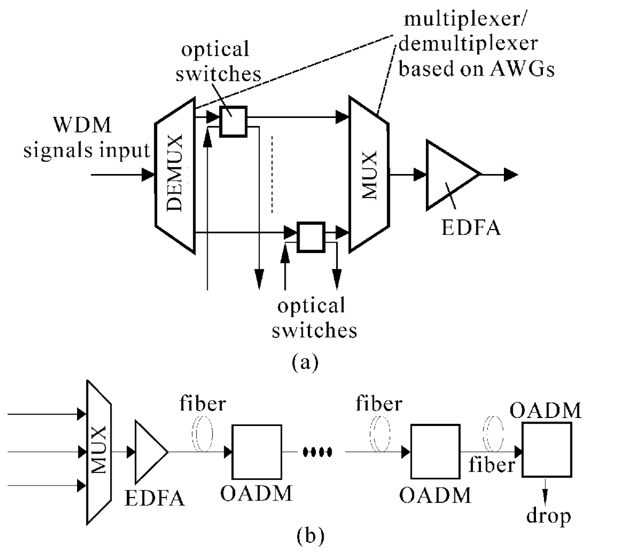

Fig. 2. (a) OADMs based on AWGs. (b) Optical transmission systems composed with cascaded OADMs.

of systems.

Here we just take account of optical path penalty caused by optical loss in transmission path, intersymbol interference and amplified spontaneous emission (ASE) noise[5]. Power penalties associated with the path, such as dispersion, jitter, and reflections are not discussed in this paper. The power penalty due to intrachannel crosstalk under an optimal decision threshold has been provided by[6]

$$\text{Penalty(dB)} = -10\log(1 - \sum \varepsilon_i Q^2), \quad (1)$$

where ε_i represents the ith intrachannel crosstalk $P_{i\text{th}}/P_{\text{sig}}$, and Q is the value to satisfy that $1/2\text{erfc}(Q/\sqrt{2}) = 10^{-9}$ or 10^{-12}. In the following analysis, we choose 10^{-12} as floor level of BER in systems under optimal decision threshold.

With similar analysis, we can draw the power penalty due to interchannel crosstalk

$$\text{Penalty(dB)} = -10\log(1 - \sum \varepsilon_i^2 Q^2/2). \quad (2)$$

Since the power of crosstalk from signals has been divided with a factor '2' because signals have 'mark' state and 'space' state, we need not to take account of this factor for ASE noise. Therefore we can get

$$\text{Penalty(dB)} = -10\log(1 - 2Q^2 \int_{\text{intraband}} \rho_{\text{ASE}} \text{d}v / P_{\text{sig}}) \quad (3)$$

for intraband ASE noise and

$$\text{Penalty(dB)} = -10\log(1 - Q^2 \int\int_{\text{interband}} \rho_{\text{ASE}} \text{d}^2 v / P_{\text{sig}}) \quad (4)$$

for interband ASE noise, where ρ_{ASE} is the ASE spectral density (W/Hz)[7]. Here we use electrical bandwidth as criterion to divide intraband ASE and interband ASE.

There are three key sources influencing power penalty of the cascaded OADMs: the leakage signals from switches in OADMs, the crosstalk of other channels and ASE. The leakage signals from switches belong to intrachannnel crosstalk and accumulate within the whole links. Therefore they should be considered at each stage, while the crosstalk of other channels can be taken account of just at the last stage, because it belongs to interchannel crosstalk and is filtered out by Demux and Mux.

Figure 3(a) shows calculated power penalty to maintain $\text{BER} = 10^{-12}$ in the concatenation of cascaded OADMs with different waveguide dimensions of AWGs for NRZ 10-G applications and with a channel spacing of 100 GHz (here we assumed that the isolation of optical switches is 40 dB and $\rho_{\text{ASE}} = 3 \times 10^{-17}$ W/Hz). To compare different stimulations, we assume $n \times L_{\text{fiber}} \approx$ constant, where n is the number of stages and L_{fiber} is the length of fiber between two adjacent nodes. We choose $n = 7$ and $L_{\text{fiber}} = 79.6$ km as a reference mark when $W_{\text{I}}/D = 0.25$ and $W_{\text{O}}/D = 0.5$, where D, the input/output waveguide pitch, is divided for normalization. Since 1-dB bandwidth and insertion loss are very sensitive with W_{I}, to maintain both of these two parameters to satisfy the practical demand, W_{I}/D is limited in a small range.

Calculated power penalty during wavelength misalignment is shown in Figs. 3(b) and (c), since central wavelength could have a shift up to 10 GHz for 10-G applications with a channel spacing of 100 GHz[8].

From these figures we can see that power penalty is more sensitive to the change of W_{O} than W_{I} and we can get the minimum power penalty when $W_{\text{O}}/D = 0.5$ and $0.25 < W_{\text{I}}/D < 0.4$.

Figure 4 shows power penalty with four values of W_{O}/D when $W_{\text{I}}/D = 0.25$. Obviously, for $W_{\text{O}}/D = 0.25$, power penalty can satisfy the demand of system with no shift of central wavelength while it exacerbates greatly with central wavelength misalignment. On the other hand, for $W_{\text{O}}/D = 0.75$, although power penalty does not exacerbate greatly with central wavelength misalignment, a power penalty of 3 dB is also unacceptable. As can be seen that $W_{\text{O}}/D = 0.5$ can maintain the power penalty < 2 dB even though when the central wavelength has a drift of 10 GHz.

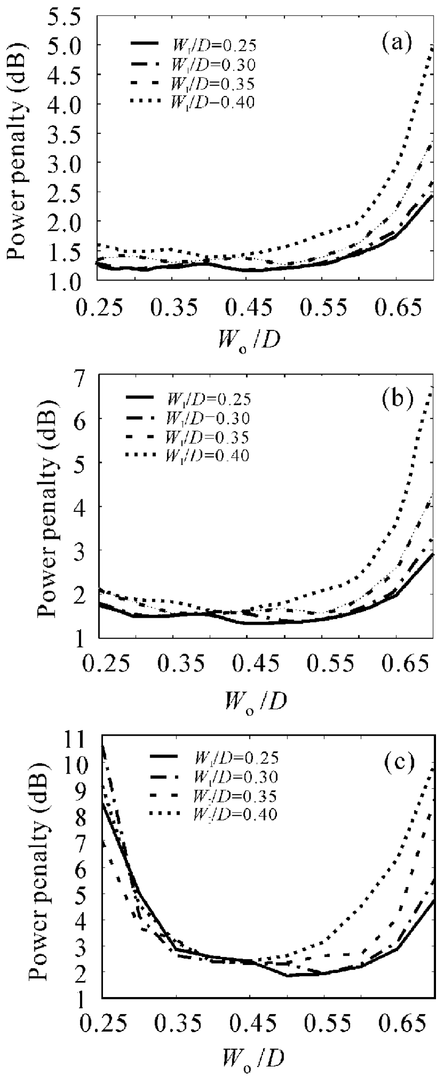

Fig. 3. Power penalty vs W_{O}/D. (a) No central wavelength drift, (b) central wavelength drift: 0.04 nm, and (c) central wavelength drift: 0.07 nm.

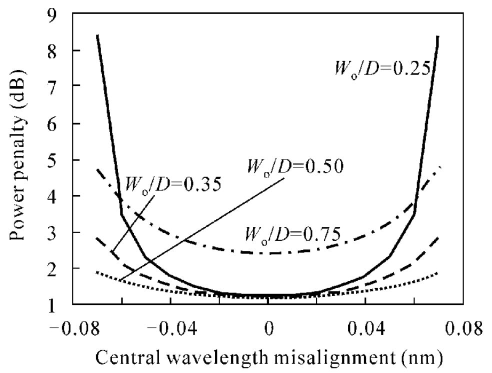

Fig. 4. Power penalty of cascaded OADMs with different central wavelength misalignment.

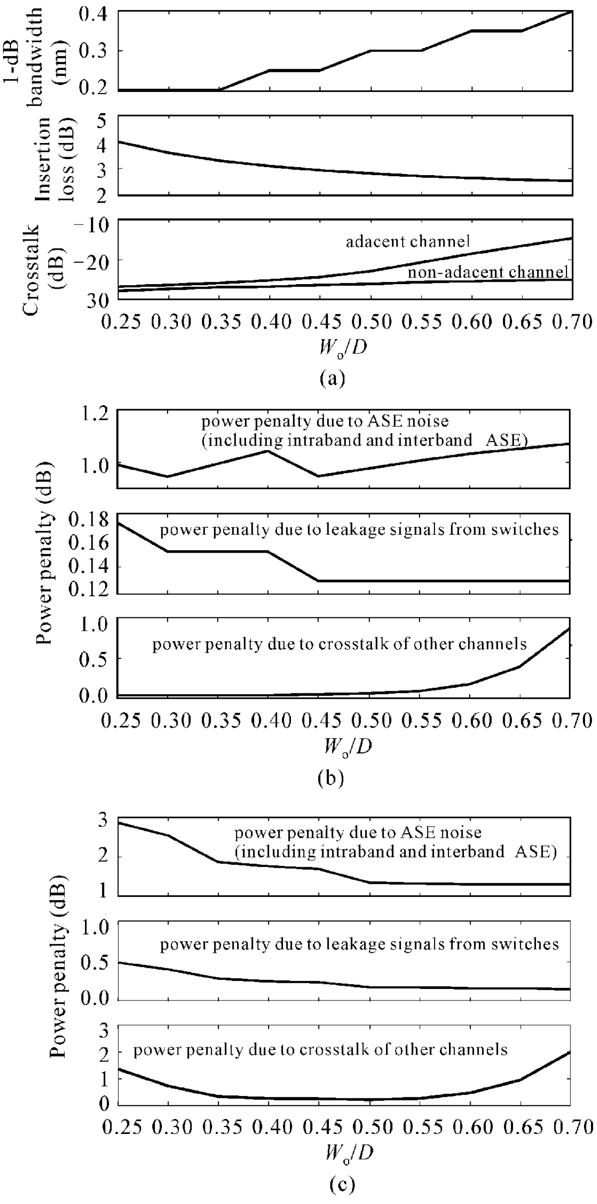

Fig. 5. (a) Optical 1-dB bandwidth, insertion loss and crosstalk of AWGs with different W_O/D, (b) power penalty for no central wavelength drift, $W_I/D = 0.25$, and (c) power penalty with a central wavelength drift of 0.07 nm, $W_I/D = 0.25$.

This result can be explained in Fig. 5. The power penalties, brought by three key sourses, the leakage signals from switches in OADM, the crosstalk of other channels and ASE noise, are described individually in Fig. 5(b) when there is no drift of central wavelength. Power penalty due to the leakage signal from optical switches is determined mainly by the number of stages and its change is insignificant in comparison with the other two sources when isolation of switches > 40 dB. Basing on the analysis above, the increase of W_O will result in the increase of crosstalk and decrease of insertion loss (shown in Fig. 5(a)). Penalty due to crosstalk of other channels increase with the increase of crosstalk of AWGs. Considering of a drift of central wavelength of signals (such as 0.07 nm in Fig. 5(c)), when W_O is very small, the corresponding 1-dB bandwith of AWGs is small too. Power of signals drops sharply and SNR_{ASE} decreases greatly. Therefore the exacerbation of penalty due to ASE is severe when $W_O/D < 0.35$. To satisfy the demand of systems, there must exist a value of W_O to get the lowest power penalty of the whole optical links when central wavelength detuning within electrical bandwidth of signals.

Further analysis shows that this optimal result is also appropriate while $0.1 < \sigma < 0.8$. When the number of stages increases, the value of optimal waveguide dimensions does not change, although the power penalty of system increases.

Power penalty is an important parameter to be considered in optical transmission system. Based on the discussion above, we can draw a conclusion that considering of wavelength misalignment, the optimal waveguide dimensions are $W_O/D = 0.5$ and $0.25 < W_I/D < 0.4$ for minimum power penalty in cascaded OADMs. It should be noticed that this result is drawn under the condition that the isolation of optical switches equals 40 dB. If the isolation is smaller than this value, such as thermo-optics switches, the result will change greatly and the optimal value of W_O/D should be larger.

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