Analysis of Non-adjacent channel crosstalk level of AWG based DWDM components induced by random phase errors

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Abstract: Adjacent and non-adjacent of Crosstalk level of AWG based DWDM components between its output waveguides maybe the most important disadvantage for its application in optical communication systems comparing with the thin film filter based DWDM component. In this paper, random phase errors of array waveguides induced by fabricate processing and their affects on crosstalk level of AWG based DWDM components between non-adjacent channel are analyzed. A very useful formula which can estimate crosstalk level of AWG devices is given. Using this formula, AWG based DWDM components can be optimized in order to reduce their crosstalk level.A very good design example using this formula which the non-adjacent crosstalk can reduce to -40dB has been presented.

Keywords: Crosstalk, array waveguide grating, Demultiplexer, non-adjacent, random phase errors

1. INTRODUCTION

Dense Wavelength De-multiplexer/Multiplexer(DWDM) technology has been proved to be an optimal solution for large capacity and long haul optical transport network. Telecommunication carriers trend to use the DWDM technology to increase the capacity of fiber optical transport network on the existing fiber optical cables. DWDM De-multiplexer is a key component in the DWDM system. Its performance will directly affect the capacity and performance of the whole system., A multiplexers/demultiplexers component based on the Arrayed waveguide grating (AWG) technology will develop rapidly with its great merits of compact size, easy integrated with other components, performance stability, easy to mass product and potential to reduce cost.

Comparing with DWDM components made from dielectric thin film narrow filter technology, those DWDM components based on the AWG technology with optimized design and improved process, have obvious advantages on insertion loss, bandwidth, channel space and channel number. The only disadvantage of AWG-DWDM components is the cross-talk performance. The critical and also most challenge technology are to reduce the cross-talk between channels, which put very stringent requirement on manufacturing process. So we need emphasize on cross-talk level during component design and considering of process phase in manufacturing. There are two types of cross-talk in AWG-DWDM components, adjacent channel cross-talk and non-adjacent channel cross-talk. At present, the adjacent channel cross-talk of the commercial 40 channels AWG –DWDM component is –25dB, and its non-adjacent channel cross-talk is –30dB. The adjacent channel cross-talk is mainly from mode-coupling between adjacent waveguide, which can be improved by trade-off in optimized design of waveguide structure and improvement of fabricating process. Arrayed waveguide phase error induced by fabricating process is a main source of cross-talk among all factors that affect the cross-talk performance of AWG-DWDM components.

This paper analysis the arrayed waveguide phase error induced by manufacturing process and its bad effect on cross-talk performance between non-adjacent channel. A useful formula for analysis of crosstalk level of AWG devices is given. Using this formula, non-adjacent channel cross-talk level can be analyze simply for designed AWG-DWDM components. Finally, the effectivity of this formula is verified ulteriorly by a design example.

2 The Theoretical Analyse

First, we will analysis the effect of random phase error induced by manufacturing process on the non-adjacent channel cross-talk level of AWG-DWDM component. Figure 1 illustrates the plane waveguide structure in AWG-DWDM components, where, d is the arrayed waveguide space in plane waveguide, L_f is focal length of plane waveguide, $\Delta \mathbf{x}$ is space of input/output waveguide in plane waveguide. Assuming that length difference of arrayed waveguide is $\boldsymbol{DL}$, the electrical field of AWG output waveguide from AWG grating formula is shown as following:

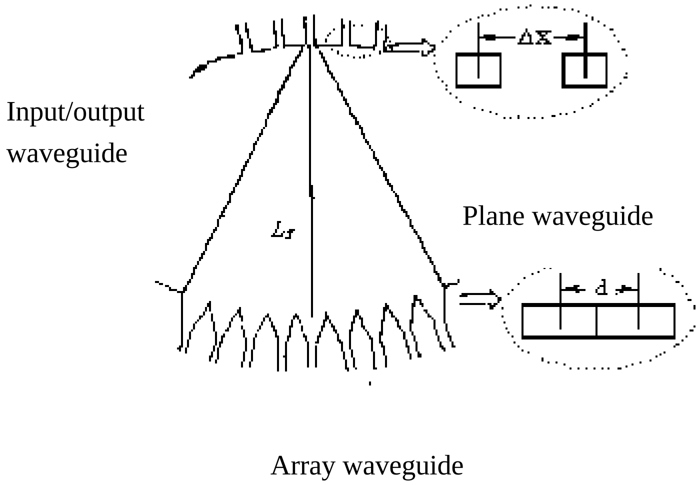

Fig.1 Schematic diagram of the slab waveguide in AWG -DWDM Demultiplexer

$$E = \sum_{j=0}^{n-1} h_j^2 \exp(ja \cdot \Delta L)\exp\left[\mathrm{i}F_j + \mathrm{i}2pj\left(n_g \Delta L + n_s dq\right)/\, l\,\right], \tag{1}$$

where h_j is coupling coefficient of the jth arrayed waveguide between fundamental model field and input waveguide. ΔL is length different of adjacent arrayed waveguide. q is angle between the point in output plane waveguide focal plane and central waveguide, a is attenuation coefficient of material, l is wavelength, and Φ_j is the phase error of the jth arrayed waveguide. Expanding equation (1) in Talor series:

$$E = \sum_{j=0}^{n-1} h_j^2 \exp(ja \cdot \Delta L)\exp\left[\mathrm{i}2pj\left(n_g \Delta L + n_s dq\right)/ l\right] + \mathrm{i}\sum_{j=0}^{n-1} h_j^2 \exp(ja \cdot \Delta L)\exp\left[\mathrm{i}2pj\left(n_g \Delta L + n_s dq\right)/ l\right]\Phi_j . \tag{2}$$

Assuming the output waveguide position of wavelength l is in q place, cross-talk of wavelength l in other non-adjacent channel can be shown in simple as:

$$\left|E_{xtalk}\right|^2 < \left|\sum_{j=0}^{n-1} x_j\right|^2 + \left|\sum_{j=0}^{n-1} x_j \Phi_j\right|^2 + 2\left|\sum_{j=0}^{n-1} x_j\right|\left|\sum_{j=0}^{n-1} x_j \Phi_j\right| , \tag{3}$$

where

$$x_j = h_j^2 \exp(ja \cdot \Delta L)\exp\left[\mathrm{i}2pj\left(n_g \Delta L + n_s dq\right)/ l\right] , \tag{4}$$

where, $\left|\sum_{j=0}^{n-1} x_j\right|^2$ is cross-talk level induced by coupling of non-adjacent waveguide, it's very small, so can be neglected. $\left|\sum_{j=0}^{n-1} x_j \Phi_j\right|$ is cross-talk level induced by arrayed waveguide random phase error. It has main contribution to non-adjacent channel cross-talk. The equation (3) can be approximately shown in following,

$$\left|E_{xtalk}\right|^2 \approx \left|\sum_{j=0}^{n-1} x_j \Phi_j\right|^2 , \tag{5}$$

Assuming that square-mean-root of random phase error of the jth arrayed waveguide is $s\left(\Phi_j\right)$, then,

$$\left|E_{xtalk}\right|^2 \approx \left|\sqrt{\sum_{j=0}^{n-1} x_j^2 s^2\left(\Phi_j\right)}\right|^2 , \tag{6}$$

As an approximation, let $s^2\left(\Phi_j\right) = j\,\dfrac{s^2\left(\Phi_{n-1}\right) - s^2\left(\Phi_0\right)}{n-1} + s^2\left(\Phi_0\right)$ (7)

then we have

$$\left|E_{xtalk}\right|^2 \approx \sum_{j=0}^{n-1} h_j^4 \cdot \frac{s^2(\Phi_{n-1})+s^2(\Phi_0)}{2} = \sum_{j=0}^{n-1} h_j^4 \bar{s}^2 \ , \tag{8}$$

where, $\bar{s}^2$ is mean value of square average difference of arrayed waveguide random phase error. Cross-talk induced by arrayed waveguide phase error can be shown as dB in following:

$$X_{talk} = 10\times\log\left|E_{xtalk}\right|^2 = 10\times\log\left(\sum_{j=0}^{n-1} h_j^4 \bar{s}^2\right) \ \text{(dB)} \tag{9}$$

At current, SiO_2 waveguide based on Si technology is used for manufacturing AWG type DWDM components. Manufacturing of SiO_2 waveguide based on Si mainly include the following steps: manufacturing buffering layer on Si substrate, deposit core layer on buffering layer, mask manufacturing, mask lithography, RIE etch to make waveguide, and deposit cover layer. The process technology of these steps will directly affect the refractive distribution of waveguide fabricating and error level of waveguide structure shape. The main factor to induce the random phase error comes from random various of arrayed waveguide structure and non-uniformity of refractive distribution. There are two parameters that can show these random variants: amplitude σ of random variants and related length *Lc*. Here, we only analysise two kind of related length: One is *Lc*<1 μm, which mainly show the reflect boundary un-flat induced by etch process and non-uniformity of refractive index distribution induced by thin film process. Another is *Lc* bigger than length of arrayed waveguide, which reflect manufacturing defect of lithography mask.

In the case of *Lc*<1 μm, when σ_w is root-mean-square of amplitude of random variants for arrayed waveguide structure, σ_g is root-mean-square of refractive index distribution of core layer, σ_c is root-mean-square of cladding layer, the average values of mean-square-difference of random phase error induced by each paremeter are shown in the following[5],

$$\bar{s}_w^{\ 2} = \left(\frac{2p}{l}\sqrt{L}\left|\frac{\partial n_g}{\partial W}\right| s_W\right)^2 \tag{10}$$

$$\bar{s}_g^{\ 2} = \left(\frac{2p}{l}\sqrt{L}\left|\frac{\partial n_g}{\partial n_1}\right| s_g\right)^2 \tag{11}$$

$$\bar{s}_c^{\ 2} = \left(\frac{2p}{l}\sqrt{L}\left|\frac{\partial n_g}{\partial n_2}\right| s_c\right)^2 \tag{12}$$

where, L is average length of arrayed waveguide, and n_g、 n_1、 n_2、 W are shown as effective refractive index, refractive index of cover layer, refractive index of cladding layer and width.

At another case of *Lc* >length of arrayed waveguide, it will introduce a random error σ_A between width of individual arrayed waveguide and average width of arrayed guide during fabricating lithographic mask. So it will induce random phase error at mean-square-different as following,

$$\overline{s}^2 = \left(\frac{2p}{l} L \left| \frac{\partial n_g}{\partial W} \right| s_A \right)^2 . \tag{13}$$

Based on the equations (11)~(13), we will get easily the arrayed wavdguide phase error level induced by the related process during fabricating the AWG type DWDM components.

3 A Design Example

As an example, we will design a 40 channels AWG type DWDM component with channel space of 100GHz at the specification of cross-talk of –40dB for non adjacent channels. Arrayed waveguide is a rectangular waveguide with section of 6×6 μm^2; The refractive index of the buffer layer and cladding layer are designed to 1.455 at wavelength of 1.55 μm, the related refractive index different between core layer and cladding layer is 0.73%; the diffracted number of AWG type DWDM components is 25. It has C type arrayed waveguide structure.

Based on the above parameter, we can calculate as $\sum_{j=0}^{n-1} h_j^4 \approx 0.003$. Assuming cross-talk is less than –40dB, we will require $\overline{s}^2 < 0.033$ rad from the above related formulas. For designed 40 channels AWG type DWDM component, when diffractive number is 25, the average length of arrayed waveguide $L = 24348$ μm; We will also have $\left|\partial n_g / \partial W\right| = 5.34 * 10^{-4}$/μm、$\left|\partial n_g / \partial n_1\right| = 0.82$ 、 $\left|\partial n_g / \partial n_2\right| = 0.18$ [5] , So we require that $s_W < 0.53$ μm 、 $s_g < 3.5 \times 10^{-4}$、$s_c < 1.6 \times 10^{-3}$ under the condition of $\overline{s}^2 < 0.033$ rad. These parameters can be achieved by current standard process technology during fabricating AWG type DWDM component.

From equation (13), random error of lithographic mask is required at $s_A < 3.4$ nm at the condition of $\overline{s}^2 < 0.033$ rad. This impose very high requirement on mask process. The s_A will have 10nm level under conventional mask-fabricate technology. So it will induce a cross-talk of –30dB. This is best performance that commercial components can reach. So random error must be precisely controlled for achieving better performance of AWG type DWDM component.

4 Conclusion

In this paper, random phase errors of array waveguides induced by fabricate processing and their affects on crosstalk level of AWG type DWDM components between non-adjacent channel are analyzed. A useful formula which can estimate crosstalk level of AWG devices is given. Using this formula, AWG type DWDM components can be optimized in order to reduce their crosstalk level. As a design example, the requirement of waveguide fabricate processing has been analyzed for cross-talk of –40dB, which further verify the effectivity of these formulas.

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