MMI Couplers Effect on Insertion Losses in Arrayed Waveguide Gratings

M. R. Farhadi
Tarbiat Modarres University
P. O. Box 14115-143, Tehran
farhadim@modares.ac.ir

A. Zarifkar
Iran Telecommunication Research Center
North Kargar, Tehran, 14399
azarifkar@itrc.ac.ir

M. K. Moravvej-Farshi
Tarbiat Modarres University
P. O. Box 14115-143, Tehran
Farshi_k@modares.ac.ir

Abstract: In this paper we present design and modeling of insertion losses in arrayed waveguide gratings (AWG) demultiplexer without and with Multi mode interference (MMI) couplers. Using spatial Fourier transform approximation, we show that the total insertion loss with MMI couplers is almost four times greater than that without MMI couplers. Also we show that most of the loss comes from the spatial diffraction.

Keywords: wavelength-division multiplexing (WDM), phased arrayed, multimode interference, Fourier transform, modeling, insertion loss, and waveguides.

1. Introduction

Dense Wavelength Division Multiplexing (DWDM) is a cost effective way to increase the total capacity of the fiber optic links. Key enabling technologies for DWDM are devices that demultiplex and multiplex wavelengths. One of the most important structures for optical multiplexer (or demultiplexer) is the arrayed waveguide grating (AWG) [1] or phased array [2].

AWG is an extremely versatile device that features and combines simultaneously unique periodic spatial and frequency properties and the possibility of integration on a chip [3]. It has been proposed for the implementation of multiple applications that embrace the fields of devices, systems, and networks. Examples of these include the production of spectrum sliced sources, dispersion compensation, WDM devices, tunable filters, wavelength routing, and optical processing [4].

These devices suffer from high fiber-to-fiber insertion losses. Typically, the commercially available devices guarantee loss below 4.5 dB between the center input and center output ports. Between other ports, this loss may increase to 7 dB. It has been proposed that loss increases for flattened passbands [5]. A flattened response with single-mode outputs can be obtained by applying a short multimode interference (MMI) power splitter at the end of the input waveguide [6].

This paper provides the analysis and simulation of insertion losses for Arrayed Waveguide with MMI couplers. In Sec. 2, the simple AWG model and MMI couplers is reviewed. In Sec. 3, using an example, we compare insertion losses for two different AWG structures (with and without MMI couplers).

2. Theoretical model

2.1. Field in AWG

An AWG layout is shown in Fig. 1. It consists of a set of input waveguides, followed by a free space coupler or free propagation region (FPR). This coupler is followed by an array of waveguides that act as a grating between the two FPRs. The length of each waveguide in the array is increased by a fixed amount $\Delta l$ with respect to that preceding it. So the length of $r^{th}$ waveguide is given by

$$l_r = l_0 + \Delta l + \frac{N}{2}$$

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Where $l_0$ represents the length of the shortest waveguide, corresponding to $r = -N/2$, and $N$ is number of waveguides. The value of $\Delta l$ is set to an integer multiple, of the central wavelength, $\lambda_0$, in the waveguides

$$\Delta l = \frac{m\lambda_0}{n_c} = \frac{mc}{n_sV_0}$$  \hspace{1cm} (2)$$

where $m = 1, 2, 3, \ldots$ is an integer, and $n_c$ is the waveguide refractive index.

The inset on the upper left corner of Fig. 1 shows the waveguide layout with its corresponding parameters, the waveguide width $W_i$, the gap between waveguides $G_i$, and the waveguide spacing $d_i$. The inset on the upper right side of the figure shows the FPR's layout. It consists of two sets of waveguides positioned over two identical circumferences of radius $L_f$, which is called the focal length. The centers of these circumferences are separated by a distance equal to the focal length. It also consists of a set of output waveguides.

Consider the field at the output of the central input waveguide described by both its slowly varying amplitude and its spatial distribution profile. The fundamental mode profile in the central input waveguide can be approximated as a power normalized Gaussian function

$$h_i(x_0) = \sqrt{\frac{2}{\pi \omega_i^2}} e^{-(x_0/\omega_i)^2}$$  \hspace{1cm} (3)$$

where index $i$ denotes the input field, and $\omega_i$ is the mode field radius related to the waveguide width $W_i$ by [8]:

$$\omega_i = W_i(0.321 + 2.1V^{-3/2} + 4V^{-6})$$  \hspace{1cm} (4)$$

where $V$ is the waveguide normalized frequency.

This field is radiated from the central input waveguide to the first FPR. The light spatial distribution in the focal plane can be obtained by the spatial Fourier transform of the input distribution, using the paraxial approximation [7]

$$B_f(x_1) = \sqrt{2\pi} \frac{\alpha_v^2}{\alpha_v^2} e^{-\pi \omega_0^2 (x_1/\alpha_v)^2}$$  \hspace{1cm} (5)$$

$\alpha_v$ is Fourier optics coefficient and is called wavelength focal length, and is given by:

$$\alpha_v = \frac{cL_f}{n_sV} = \frac{\lambda L_f}{n_s}$$  \hspace{1cm} (6)$$

where $n_s$ is refractive index in FPRs.

In order to calculate the amount of light that couples into one of the array waveguides, the overlap integral between the illuminating field and the waveguide modes must be solved [8]. The fundamental mode in the waveguides can be approximated by the following Gaussian function:

$$h_g(x_1) = \sqrt{\frac{2}{\pi \omega_g^2}} e^{-(x_1/\omega_g)^2}$$  \hspace{1cm} (7)$$

where $\omega_g$ is modal field radius in array waveguides.

The modes in the waveguides approximate by Gaussian functions in order to obtain a final analytical expression. Although, this is suitable for understanding the device operation, it is not precise. Therefore, we use real modes in the waveguides in order to obtain simulation response as close as possible to the physical response of the device. The latter is the main difference that makes the Gaussian AWG model fails in predicting the response outside the band, because the Gaussian function decays faster than the exponential function in the real mode.

The Gaussian approximation of the real modes is made through (4). This yields a Gaussian function that properly approximates the real field in the waveguide core. However, the decaying exponential nature of the real mode is underestimated by this approximation. In order to take advantage of the previously described procedure to normalize the AWG response, the real mode is approximated by the sum of three Gaussian functions with parameters, corresponding to input waveguide, array waveguide, and output waveguide, in the device:
where $\omega_{x,k}$ is the mode field radius of the $k^{th}$ waveguide, and $P_{bi}^3$ is a normalization constant. The Fourier transform of (8) is

$$B_x^3(x) = \frac{1}{P_{bi}^3} \sum_{k=1}^{3} e^{-\left(\omega_{x,k}/\omega_{x}\right)^2}$$

(9)

The real mode can be approximated by heuristically choosing $\omega_{x,1} = \omega_x$, $\omega_{x,2} = 0.6 \omega_x$, and $\omega_{x,3} = 1.95 \omega_x$.

### 2.2. MMI Couplers

To obtain a flat bandpass response from a MMI, we consider a two-fold imaging configuration, as stated in [9] the output field from the MMI device is composed by the superposition of two spatially shifted versions of the input field to the MMI. Since this field is given by a Gaussian, the output field distribution can be expressed as the summation of two Gaussian functions, as illustrated in Fig. 2.

![Figure 2: A MMI coupler layout](image)

The MMI coupler is used as the first FPR in the AWG structure. With this configuration, a center Gaussian field like the one in Eq. (3), is converted into a double Gaussian one, whose normalized power expression is:

$$b_{x}^1(x_0) = \left( \frac{2\omega_x}{\pi} \right)^{1/2} \left( 1 + e^{\frac{-2\Delta n^2}{\omega_x^2}} \right)^{-1/2} \times \left( e^{-\left(\frac{x-x_0}{\omega_x}\right)^2} + e^{-\left(\frac{x-x_0+\Delta x}{\omega_x}\right)^2} \right)$$

(10)

where $\Delta x_m$ is the peak separation between the two Gaussians. This separation is closely related to the width and index contrast in the MMI. For high contrast MMI’s, $W_m = 2\Delta x_m$ [9]. Since this input field will be imaged to the output waveguide’s over $x_3$, the overlap integral, i.e. the convolution, with the output waveguide fundamental mode profile, will yield the desired rectangular shape for the passing band. The Fourier transform of Eq. (10) is:

$$B_{x}^1(x_1) = \frac{2\alpha^2}{\pi\omega_f} \left[ 1 + e^{\frac{-\Delta n^2}{\omega_f^2}} \right]^{-1/2} \times \left( e^{-\frac{\pi\Delta n^2}{\alpha^2}} + e^{-\frac{\pi\Delta n^2}{\alpha^2}} \right)$$

(11)

this yields the field distribution in front of the array waveguide’s.

### 3. Simulation Results

Loss mechanisms in the AWG are due to:

1. propagation in waveguides;
2. coupling from fiber to input waveguide and from output waveguide to fibers;
3. coupling from the first FPR to array waveguides;
4. spatial diffraction to other orders on the output focal plane.

It is possible to incorporate waveguide losses in the array waveguides with

$$\epsilon_{a,\omega}(x_2) = e^{-\alpha_{a,\omega}d} = e^{-\alpha_{a,\omega}\left[N/2+x_2 \mid d_{a}\right]}$$

(12)

where $\alpha_{a,\omega}$ is the waveguide loss coefficient and $d_{a}$ is waveguide spacing in array waveguides [4].

Takada et al have experimentally measured the material (both intrinsic and scattering) losses of silica. They report losses of 1.7 dB/m for $\Delta n = 0.45\%$ glass grown by flame hydrolysis [10]. The light travels through roughly a 10 cm long silica, then an AWG would have a material loss of 0.17 dB.

Using overlap integral between fiber and waveguide modes, we obtain a fiber-input waveguide coupling loss of 0.0075 dB which becomes 0.015 dB, for two couplings [10].

An estimation of the diffraction loss is the ratio between the diffraction order focused to $x_3 = 0$ and the sum of energy passing through all array waveguides [11]. Loss due to coupling from the
and approximation are plotted in Fig. 3. Gaussian approximation and three Gaussian sum calculated with and without MMI couplers in where

\[ \Delta x_{3,FRS} = \frac{\alpha_l}{d_{\omega}} \]  

and \( B_g(x) \) is the Fourier transform of \( b_g(x) \). Results calculated with and without MMI couplers in Gaussian approximation and three Gaussian sum approximation are plotted in Fig. 3.

If we only take the energy loss due to transfer of energy from one order to its two neighboring orders into account, then an approximate formula can be used to estimate the ratio \( d_{\omega}/\omega_g \) [4]:

\[ d_{\omega} = \frac{\pi \sqrt{2}}{\ln \left[ \frac{2}{10^{-L_d/20}} \right]} \]  

where \( L_d = 10 \log_{10}(I_d) \), from which one can conclude that the approximation of (15) holds for \( d_{\omega}/\omega_g \leq 4 \). From Fig. 3, it is obvious beyond this point, the approximated results deviates from the exact one. This means that, for these values, a significant part of the power is carried by the orders \( m-1, m, \) and \( m+1 \). This is shown in Fig. 3.

However, it is clear from (15) that the diffraction loss also depends on the field profile in the waveguides, through its Fourier transform. Therefore, the prediction of the diffraction loss will be different if the three-Gaussian sum approximation for the modes in the waveguides is used. The diffraction loss with this approximation is also depicted in Fig. 3.

As expected from the shape of \( B_g(x) \) [Fig. 2 of Ref. 7], the energy loss due to adjacent diffraction orders for three-Gaussian sum approximation is larger than that obtained by the Gaussian approximation. The former is more accurate.

As are plotted, diffraction loss increases for flattened passbands with MMI couplers that it emanate from more diffraction in MMIs. Also the diffraction loss increase for both Gaussian approximation and three-Gaussian approximation is the same.

Now, we consider the loss non-uniformity \( L_u \) in the waveguides. The loss non-uniformity is due to the weighting of \( B_g(x) \) that is in output response. Therefore, the maximum value of the frequency response will be different depending on the output waveguide. The worst case corresponds to the outermost output waveguide, located a distance \( \Delta x_{Lu} \) away from the central output waveguide. So the loss non-uniformity can be defined as

\[ L_u(dB) = 20 \log_{10} \left( \frac{B_g(0)}{B_g(\Delta x_{Lu})} \right) \]  

and

\[ L_u(dB) = 20 \log_{10} \left( \frac{3}{e^{-0.6(b_{\omega r}/\sigma_g)^2} + e^{-b_{\omega r}/\sigma_g^2} + e^{-(1.95(b_{\omega r}/\sigma_g))^2}} \right) \]  

where

\[ \sigma_g = \frac{d_{\omega}}{\omega_g} \]  

The loss non-uniformity obtained with this approximation is plotted in Fig. 4.

The parameter \( \sigma_g \) controls the shape of the weighting function \( B_g(x) \). If the modal field radius \( \omega_g \) in the waveguides decreases, the weighting becomes more uniform, so losses along all output ports become more uniform, as does the loss difference between the central output waveguide and outermost output waveguide.

The ratio \( b_{\omega r} \) depends on the output port number \( N_o \) and the FPR. The frequency shift of the outermost output waveguide is \( \Delta L_u = \Delta \nu N_o / 2 \); where \( \Delta \nu \) is the frequency channel spacing. Thus, the maximum attainable value for the ratio \( b_{\omega r} \) is 0.5, corresponding to the case of frequency cyclic AWG design. For a given value of \( \sigma_g \), the more output ports are used, the bigger the loss non-uniformity on the outermost output waveguide will be, because the weighting function decreases out from the location of the central output waveguide. However, using MMI couplers, as shown in Fig. 5, loss non-uniformity increases with increase of the modal field radius \( \omega_g \). For higher modal field radius, loss non-uniformity with MMI and without it are the same.

Using parameters given by [4], we yield diffraction loss of \(-3.9592 \text{ dB}\) for three Gaussian approximation without MMI and \(-16.0004 \text{ dB}\) with MMI couplers. Also loss non-uniformity is 0.84 dB.
Figure 3: Diffraction loss (dB) vs. $\sigma_g = \omega_g / (\omega_g \pi)$

Figure 4: Loss non-uniformity (dB) vs. $\sigma_g$ for different values of $b\omega_r$ without MMI
4. Conclusion:

We have provided a mode for AWG with MMI couplers and investigated for insertion losses in this AWG. We have shown that most of the losses in AWG is due to diffraction loss which increases in presence of MMI couplers. This loss is almost four times the loss in an AWG without any MMI couplers.

Reference:


