APSS Apollo Application Note on Array Waveguide Grating (AWG)

Design, simulation and layout

APN-APSS-AWG

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Abstract

This application note describes how to design, simulate, and layout wavelength multiplexer devices based on Array Waveguide Grating (AWG), using a pre-defined model in the Device Module of the Apollo Photonics Solution Suite (APSS).

This application note:

- describes the operation principle, basic design considerations, and performance parameters of AWG
- presents the basic design process for AWG-based devices, based on established analytical and numerical methods
- outlines steps that are specific to the design of AWG, such as import projects, solver settings, and mask layout and export
- provides an example in order to compare simulation results with published papers
- discusses key issues related to the design of AWG-based devices, such as polarization dependence, insertion loss, cross-talk, flat-top wavelength response, and thermal control/tuning

> ***Note***: This application note focuses on using the APSS Device Module to design AWG-based devices. For more general information about other modules in the APSS, refer to other available APSS application notes. For detailed information about using the Device Module of the APSS, refer to APSS User manual.

The APSS application consists of four different modules: Material, Waveguide, Device, and Circuit. Because each module specializes in different specific design tasks, APSS can handle almost any kind of device made from almost any kind of material.

Keywords

APSS, device module, array waveguide grating (AWG), wavelength multiplexer (MUX), wavelength demultiplexer (DeMUX), dense wavelength division multiplexing (DWDM), insertion loss, cross-talk, free spectral range

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1 Introduction

In recent years, arrayed waveguide gratings (AWG, also known as the optical phased-array—Phasor, phased-array waveguide grating—PAWG, and waveguide grating router—WGR) have become increasingly popular as wavelength multiplexers/demultiplexers (MUX/DeMUX) for dense wavelength division multiplexing (DWDM) applications [1][2]. This is due to the fact that AWG-based devices have been proven to be capable of precisely demultiplexing a high number of channels, with relatively low loss.

Main features of the M (input) x N (output) AWG MUX/DeMUXes are low fiber-to-fiber loss, narrow and accurate channel spacing, large channel number, polarization insensitivity, high stability and reliability, and being suitable for the mass production. Table 1 provides a summary and comparison of most characteristics of WDM MUX/DeMUX technologies used in the current WDM optical communications [3]. Because the fabrication of the AWG is based on standardized photolithographic techniques, the integration of the AWG offers many advantages such as compactness, reliability, large fabrication tolerances (no vertical deep etching), and significantly reduced fabrication and packaging costs. The inherent advantages of the AWG also include precisely controlled channel spacing (easily matched to the ITU grid), simple and accurate wavelength stabilization, and uniform insertion loss.

Table 1 Comparisons of WDM demultiplexing technologies

Specifications	Interference filter	BG filter	AWG	Etching grating
Channel spacing	>100GHz	>100GHz	>25GHz	>10GHz
Absolute λ	Angle tuning	Strain tuning	Thermal tuning	Thermal tuning
Loss	nonuniform	Low, nonuniform	Very low	Very low
Cross talk (adj)	-25~ -33 dB	-30~ -35dB	-25~ -35 dB	-25~ -35 dB
Cross-talk (bkg)	Very low	Very low	-25~ -35 dB	<-32 dB
PDL	0.25dB	Excellent	0.5dB	0.5dB
Packaging	discrete	discrete	integration	integration
size	large	large	small	small
reliability	Good(epoxy)	Poor (tuning)	Very good	Good
Cost/channel	$500	$3000	$50	$30
Comment	For small channel	For small channel	For 16+ channel	For 16+ channel

2 Theory

In this section, the operation principle of the AWG devices is described [5][6]. Basic design considerations and performance parameters for AWG-based devices are also provided.

2.1 Operation principle

Generally AWG devices serve as multiplexers, demultiplexers, filters, and add-drop devices in optical WDM and DWDM applications. Figure 1 shows a schematic representation of the MxN AWG. The device consists of two concave slab waveguide star couplers (or free propagation zones/ranges, FSZ), connected by a dispersive waveguide array with the equal length difference between adjacent array waveguides. The operation principle of the AWG multiplexers/demultiplexers is described briefly as follows.

Light propagating in the input waveguide is diffracted in the slab region and coupled into the arrayed waveguide by the first FSZ. The arrayed waveguides has been designed such that the optical path length difference ΔL between adjacent array waveguides equals an integer (m) multiple of the central wavelength λ_0 of the demultiplexer. As a consequence, the field distribution at the input aperture will be reproduced at the output aperture. Therefore, at this center wavelength, the light focuses in the center of the image plane (provided that the input waveguide is centered in the input plane). If the input wavelength is detuned from this central wavelength, phase changes occur in the array branches. Due to the constant path length difference between adjacent waveguides, this phase change increases linearly from the inner to outer array waveguides, which causes the wavefront to be tilted at the output aperture. Consequently, the focal point in the image plane is shifted away from the center. The positioning of the output waveguides in the image plane allows the spatial separation of the different wavelengths.

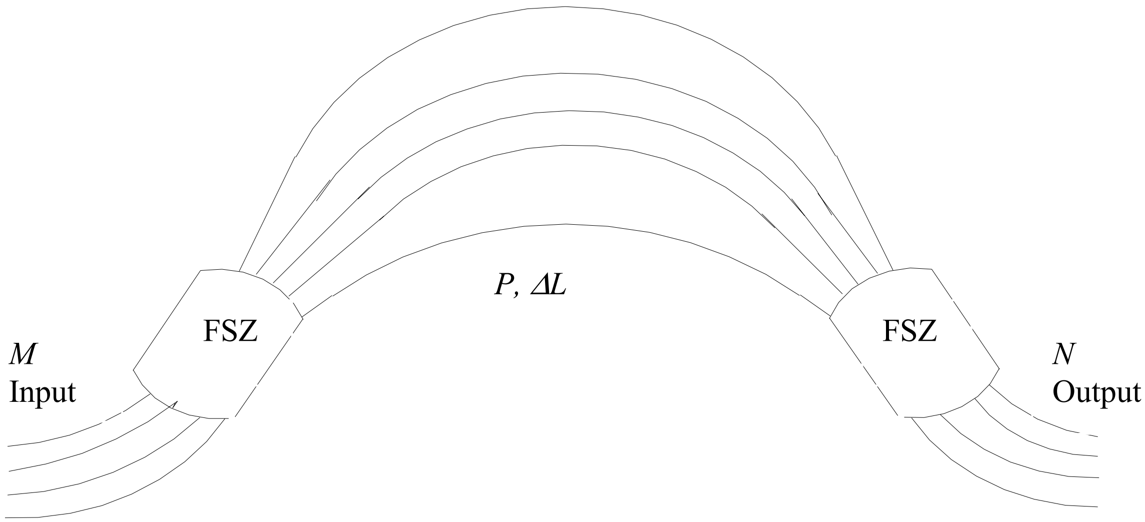


Figure 1 Schematic representation of the MxN AWG demultiplexer

Here the Gaussian beam approach (GBA), one of the analytical methods, is used to illustrate the 1x1 imaging effect in the AWG device. The coupling coefficients K_i from the input waveguide to the *i*-th arrayed waveguide are calculated by:

$$K_i = |f(yi,zi)| = \sqrt{\frac{\omega_0}{W_0(z_i)}}\exp\left(-\frac{L_f^2\sin^2\theta_i}{\omega^2(\theta_i)}\right) \qquad \text{Eq. 1}$$

where θ_i ($y=L_f\sin\theta$ and $z=L_f\cos\theta$) is the angle between the array waveguide and the optical axis, and ω_0 is the initial spot size. Due to the reciprocity, the coupling from the FSZ to the output waveguides can be described by the same coupling coefficients.

The transfer function for an output waveguide *q* for an input waveguide *p* near the optical axis can be obtained by summing the contributions of the different array waveguides (assume *NxN* AWG with *P* array waveguides):

$$H_0(\lambda)=\sum_{i=1}^{P} K^2_i \exp\left(jkn_c i\Delta L - j\frac{2\pi}{N}(p-q)i\right) \qquad \text{Eq. 2}$$

where coupling power $P_i=K^2_i$ is the optical power in the *q*-th arm normalized to the total power. The frequency response of the corresponding channels follows the result from the overlap of this field with the modals of the output waveguides.

2.2 *Basic design considerations and design parameters*

After understanding the operation principle of AWG devices, (depending on different materials, such as silica or InP); and design requirements, such as number of channels, wavelength spacing, and PDL, it is possible to apply some related analytical and numerical solvers to design AWG-based devices.

2.2.1 Wavelength dispersion angle and distance

The wavelength dependent shift (or wave-front tilting angle $d\theta$) of the focal point in the image plane can be calculated as follows:

$$\frac{d\theta}{d\lambda} = k\Delta L\, d\lambda\, n_g/(k\, n_s \lambda_0 d) = \frac{n_g\, m}{n_c n_s d} \qquad \text{Eq. 3}$$

where d and n_s are the propagation constant, the pitch length, and 2D effective index in the slab waveguide, n_c is the effective index in the array waveguides, ΔL is the path length difference between adjacent array waveguides, λ_0 is the center wavelength of the AWG, and m the diffraction order of the demultiplexer defined as:

$$m = \frac{n_c \Delta L}{\lambda_0} \qquad \text{Eq. 4}$$

and n_g is the group refractive index of array channel waveguides:

$$n_g = (n_c - \lambda_0 \frac{dn_c}{d\lambda_0}) = (n_c - \lambda_g \frac{dn_c}{d\lambda_g}) \qquad \text{Eq. 5}$$

Using the wavelength measured in the material $\lambda_g = \lambda_0 / n_c$, the wavefront titling can be simplified to:

$$\frac{d\theta}{d\lambda_g} = \frac{n_g\, m}{n_s d}, \text{ and } m = \frac{\Delta L}{\lambda_g} \qquad \text{Eq. 6}$$

Finally, with the tilted distance $dx = L_f\, d\theta$, the relative dispersion distance of the focused spot in the image plane is determined as:

$$\Delta x = (dx/d\lambda_g)\, \lambda_g = L_f\, (d\theta/d\lambda_g)\, \lambda_g = \lambda_g \frac{n_g\, m L_f}{n_s d} \qquad \text{Eq. 7}$$

where L_f is the focal length of the slab waveguide.

2.2.2 Free spectral range

An important property of the AWG is the free spectral range (FSR), also known as the demultiplexer periodicity. This periodicity is due to the fact that constructive interference at the output FSZ can occur for a number of wavelengths. The free spectral range ($\Delta\lambda_{FSR,}$) denotes the wavelength and frequency spacing between the maxima of the interference pattern because of the periodic characteristic of the AWG transfer function, and can be obtained after ignoring material dispersion of n_c,

$$\Delta\lambda_{FSR} = N\Delta\lambda \approx \lambda_0 / m \qquad \text{Eq. 8}$$

where N is the number of wavelengths or frequency channels, and $\Delta\lambda$ is the wavelength channel spacing.

2.2.3 The channel spacing and focal length

The wavelength channel spacing is obtained by:

$$\Delta\lambda = \left(\frac{d\theta}{d\lambda}\right)^{-1}\Delta\theta = \frac{n_s\, d\, n_c}{m\, n_g}\,\frac{\Delta x}{L_f} \qquad \text{Eq. 9}$$

where Δx is the pitch between input and output waveguide and L_f is the focusing length of the focusing slab waveguide. The focal length of FPZ is obtained when assuming the $n_s = n_c$:

$$Lf = \frac{n_s\, d\, n_c}{m\, n_g}\,\frac{\Delta x}{\Delta\lambda} \approx \frac{n_s\, d}{m}\,\frac{\Delta x}{\Delta\lambda} \qquad \text{Eq. 10}$$

2.2.4 The maximum number of the wavelength channels

The maximum number of the wavelength channels N depends on the $\Delta\lambda_{FSR}$: $\Delta\lambda_{FSR} \geq N\Delta\lambda$ to prevent the overlapping of orders in the spectral region.

$$N < n_c\, \lambda_0 / (n_g\, m\, \Delta\lambda) \qquad \text{Eq. 11}$$

It is found that m must be small in order to increase the number of wavelength channels. This characteristic is the same for other multiplexers such as Mach-Zehnder interferometers (MZI) and Fabry-Perot (FP) interferometers.

2.3 Performance parameters

Except some commonly used performance parameters such as insertion loss $L_i(dB)$ and return loss $L_r(dB)$, this section will discuss performance parameters more specifically related to AWG-based devices. The excess loss $L_e(dB)$ of the device is defined as the difference between the sum of the powers exiting the outputs and the power entering the devices:

$$L_e(dB) = -10\log_{10}(\sum_j P_j / P_{in}) \quad \text{Eq. 12}$$

As a multiplexer, two performance parameters, cross-talk and loss uniformity, should be evaluated. The cross-talk $L_c(dB)$ is a ratio of the desired power output (P_d), to unwanted outputs (P_u) in a channel passband. There are two types: device optical cross-talk in an adjacent channel and optical cross-talk in a non-adjacent channel. Loss uniformity $L_u(dB)$ is a ratio between the maximum and minimum desired outputs:

$$L_c(dB) = 10\log_{10}(P_d / P_u) \quad \text{Eq. 13}$$

$$L_u(dB) = -10\log_{10}(P_{d1} / P_{d2}) \quad \text{Eq. 14}$$

where the cross-talk and the loss uniformity of the AWG are also evaluated by the isolation and the power imbalance, respectively.

As an integrated component, two performance parameters, polarization dependent loss (PDL) and ripple, should be evaluated. PDL $L_P(dB)$ is the difference in insertion loss for one polarization compared to another. Ripple $L_R(dB)$ is the peak to peak difference in insertion loss within one channel.

$$L_P(dB) = 10\log_{10}(P_s / P_p) \quad \text{Eq. 15}$$

$$L_R(dB) = 10\log_{10}(P_{d,\max} / P_{d,\min}) \quad \text{Eq. 16}$$

3 Design and simulation

3.1 Overall design

This section introduces a general design procedure for creating an AWG device. According to some related design experiences, the following process should be used:

(i) Decide the type of the AWG according to the materials and device functions.

(ii) Use a regular shaped AWG to check device performance using analytic solvers and to determine possible sizes for the device.

(iii) Use a tapered shape and tapered port in the final design. Compared with the regular shaped AWG device, the tapered AWG device can improve the transverse bandwidth while keep the uniform output and loss insertion loss, as a result of the length reduction and mode conversion in the tapered area.

(iv) Fine tune the AWG device by using the scan function and dense mesh setting in the device simulations.

In general, the user should finish the material and waveguide design (using the Material Module and the Waveguide Module) before starting to design an AWG device in the Device Module.

Because AWGs are very complicated devices, consisting of straight waveguides, star couplers, arc bend waveguides, and taper waveguides, the designer should be familiar with the optical properties of these individual subcomponents before starting to design an AWG device.

> ***Note***: For more general information straight waveguides, star couplers, arc bend waveguides, and taper waveguides, or for more information about the symbols used in this section, refer to other available APSS application notes or to APSS user manual.

3.2 *General design procedure*

Based on the properties calculated above, a simple design strategy can be devised and is described below in sequence of importance. A more elaborate discussion of AWG design aspects can be found in [6]. Of course, there are many parameters and equations that determine the characteristics of an AWG device. This section describes the detailed process at a high level to provide an overview.

3.2.1 Basic design parameters

Before we start to design the AWG wavelength multiplexer, we should know some basic design parameters, such as the center passband wavelength λ_0, the core and cladding effective refractive indices n_c and n_0 of the wafer, and the size of the core channel with the interface. These are used to calculate the effective index n_s and group refractive index n_g of array channel and slab waveguides. Some related parameters of the above values such as the spot size ω_0 can also be obtained.

3.2.2 Channel spacing and the number of ports

Wavelength channel spacing $\Delta\lambda$ and the number of the wavelength channels M and N are the most important parameters to design the AWG wavelength multiplexer. Usually the wavelength channel spacing $\Delta\lambda$ is selected according to the ITU-grid standard such as 50 GHz, 100 GHz, or 200 GHz. The numbers of the wavelength channels M are determined according to the requirements of the WDM/DWDM network and its customers. Generally there are two kinds of AWG: 1xN (M=1) and NxN (M=N). The number of the wavelength channels N is selected with the exponent of 2 such as 16, 32, 64, and 128.

3.2.3 Free spectral range and the diffraction order

After obtaining the wavelength channel spacing $\Delta\lambda$ and the number of the wavelength channels N, the wavelength free spectral ranges $\Delta\lambda_{FSR}$ is easily calculated:

$$\Delta\lambda_{FSR} = N\Delta\lambda \qquad \text{Eq. 17}$$

and the diffraction order m is calculated as:

$$m < n_c\,\lambda_0/[\,n_g\,N\,\Delta\lambda] \quad or \quad m=floor(\frac{\lambda_c}{\Delta\lambda_{FSR}}) \qquad \text{Eq. 18}$$

The flooring of the nearest integer is necessary to fix the center wavelength to the specified value. Note that this will lead to a slight correction of the FSR.

3.2.4 Length difference

Length difference ΔL between the neighboring arrayed waveguides is calculated by:

$$\Delta L = m\frac{\lambda_0}{n_c} \quad \text{Eq. 19}$$

3.2.5 Pitches and shift positions

In general, the shift positions Δx and pitches d should be as small as possible to obtain a compact design for the AWG MUX/DeMUX. In order to achieve sufficient isolation between neighbor output waveguides, the gap between the output waveguides should be sufficiently large. As a general rule, this gap should be twice the width of the waveguide. With the output waveguide spacing fixed, the relative dispersion Δx can be calculated to be:

$$\Delta x = d\,\lambda_0 / \Delta\lambda \quad \text{Eq. 20}$$

where $\Delta\lambda$ is the channel spacing of the demultiplexer.

3.2.6 Focusing length

As long as the array order has been fixed, the focal length Lf can be calculated:

$$Lf = \frac{n_s\, d\, n_c}{m\, n_g}\frac{\Delta x}{\Delta\lambda} \approx \frac{n_s\, d}{m}\frac{\Delta x}{\Delta\lambda} = \frac{n_s\, d}{m}\frac{\Delta x}{\Delta\lambda} \quad \text{Eq. 21}$$

3.2.7 Number of the array waveguides

The number of the array waveguides P is not a dominant parameter in the AWG design because the $\Delta\lambda$ and N do not depend on it. Generally, P is selected so that the number of array waveguides is sufficient to make the numerical aperture (NA), in which they form a greater number than the input/output waveguides, such that almost all the light diffracted into the free space region is collected by the array aperture. As a general rule, this number should be bigger than four times the number of wavelength channels.

$$P = (4\text{-}6) * \max(M, N) \quad \text{Eq. 22}$$

3.2.8 Other design parameters

The current design still has several areas for design decisions, such as the taper length *Lt*, L_3, and L_4, which may be used to optimize the design. To determine the minimum radius of the device bend, the phase velocity of exponential tails of the mode profile should be less than that of the cladding layer:

$$\frac{c}{n_r}\frac{R + w_{eff}/2}{R} < \frac{c}{n_0},\ or\ R_{min} > \frac{w_{eff}}{2}\left[\frac{n_r}{n_0} - 1\right]^{-1} = \frac{w_{eff}}{2\Delta} \qquad \text{Eq. 23}$$

where n_r, n_0, and Δ are the core, cladding indices, and index difference, and w_{eff} is the effective waveguide width. We can find that the waveguide bend with a tight mode confinement and a larger index difference has a small-bend radius. The input/output port pitch d_1/d_2 can be determined by the optical fiber diameter, for example, 250 μm for the single mode optical fiber.

3.3 Simulation and optimization

This section provides an overview of the simulation and optimization process performed using the APSS Device Module.

Although an AWG device is typically complex, the Device Module provides a user-friendly wizard that can be used to build an AWG device based on a pre-defined model. After loading the waveguide information and selecting “Device type” as “AWG”, the wizard asks the user to enter some information related to the device ports, star couplers, and array waveguides, as shown in Figure 2.

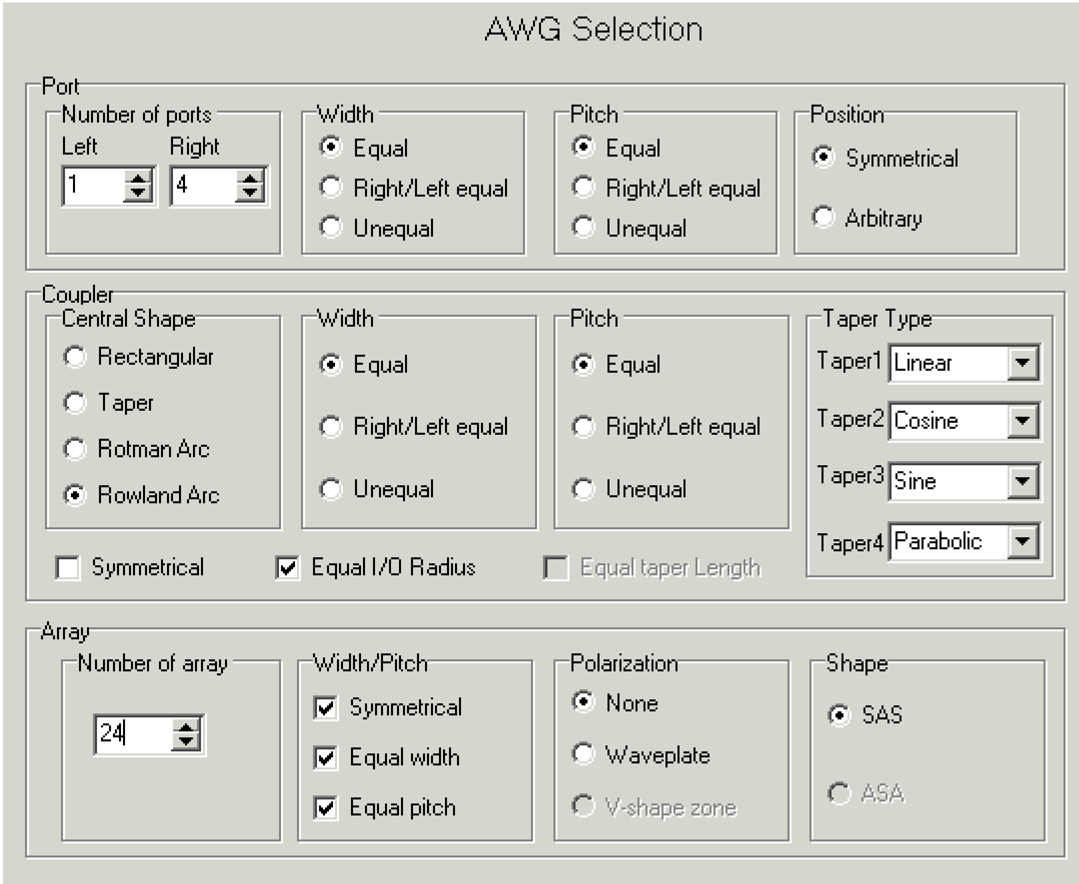


Figure 2 The pre-defined model wizard of the AWG device

The device wizard provides many possible combinations for the following parameters:

- ports (for example, port width, port position, port pitch, and port type; but does not allow specifying the number of ports)
- couplers (for example, shape type, width, and taper type)
- array waveguides (for example, shape type, width, and pitch)

There are two major types of coupler taper shapes for AWG devices: regular (rectangular shape) and taper (function shape). Only the former can be analyzed by analytical approaches. The star coupler shape can have the following tapers: “rectangular”, “linear”, “sine”, “cosine”, “parabolic” or “user-defined”.

After the device is defined in detail, the user can then perform a simulation, and scan for related variables. There are many choices for the device solver settings that can be used for the simulation and analysis. For example, the user can select an analytical or numerical solver, without or with tapers. In general, for a strongly guided AWG device, an analytical solver is sufficient for most applications.

Finally, the user can display the simulation results to view the different performance parameters such as insertion loss, phase difference, and cross-talk. The user can also export them in different formats such as ASCII text (*.txt), Microsoft Excel (*.xls), or as a bitmap (*.bmp) file. The layout mask files can be exported in two different file formats: EXF and GDSII.

4 EXAMPLE

This section provides an example outline of the process for the creation and simulation of a typical silica AWG, using the equivalent index of a 3D waveguide. This section also demonstrates how the flexible simulation and scan function enables the optical designer to efficiently and effectively perform sensitivity analysis of an AWG device, related to length, polarization, wavelength dependence, port width effect, FSZ width, FSZ taper, and coupler pitch.

4.1 Creation of predefined device

In order to illustrate the design and simulation concepts outlined in the previous chapters, the example used is for an 1x16 AWG with the design parameters specified in the following references: [7], [8].

The user selects "user-input" and selects a predefined "AWG" (as shown in Figure 2) where M=1 (number of input ports), $N=16$ (number of output ports), P = 60 (number of array waveguides), and all other values remaining set at the default settings ("Symmetrical", "Equal", and "None" for the port, coupler, and array, respectively). The user then clicks "Next", and on the following window, changes the necessary design parameters. The user clicks "Finish" to create the device project (which, in this example, is named "D_AWG1x16x60"). Note that the corresponding equivalent indices (1.4551 of core and 1.4441 of cladding) can be input here as shown in Figure 3. The layout and detailed design parameters can be obtained as shown in Figure 4(a) and Figure 4 (b), respectively. The die size is 14.5x16 mm^2. After changing these parameters, the user should click the “Refresh” button to update the drawing.

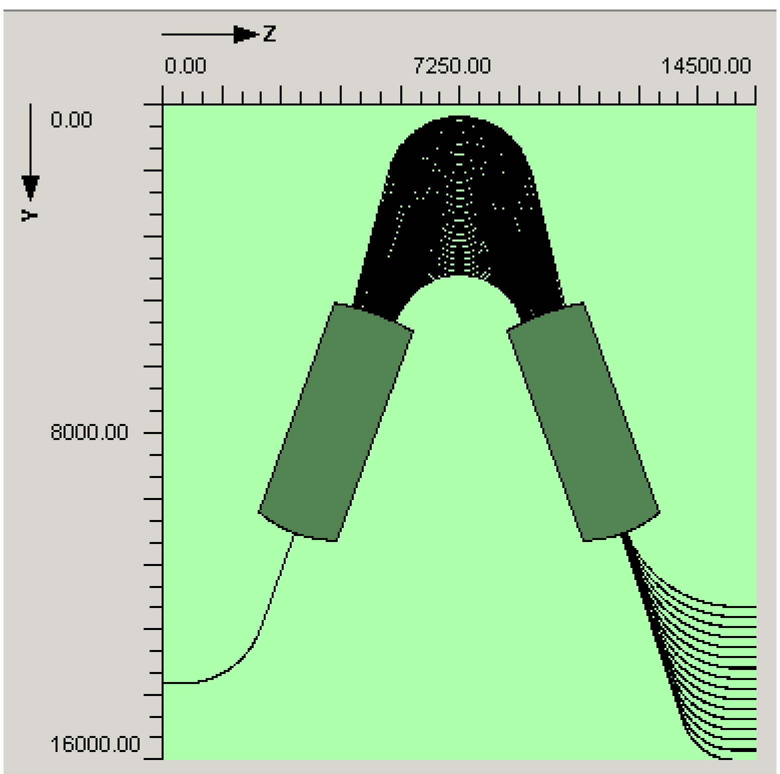
Domain	Material / Index		X Index (R)	X Index (I)	Y Index (R)	Y Index (I)
Background Refractive Index	Background Refractive Index	...	Table	Table	Table	Table
Core Refractive Index	Material	...	Table	Table	Table	Table

(a) Original material parameters

Domain	Material / Index		X Index (R)	X Index (I)	Y Index (R)	Y Index (I)
Background Refractive Index	Background Refractive Index	...	1.4442	0.0	1.4442	0.0
Core Refractive Index	Material	...	1.4551	0.0	1.4551	0.0

(b) Updating material parameters

Figure 3 Material parameters of a 16-channel AWG



(a) Layout

Name	Variable	Expression
Left port length	L1	500.0000
Right port length	L2	531.1300
Straight length of left coupler	L3	2500.0000
Straight length of right coupler	L4	L3
Minimum radius of AWG	Rmin	1000.0000
Center radius of AWG	R	2000.0000
Distance between couplers	L	8000.0000
Coupler angle(degree)	alpha	70.0000
Focal length of couplers	Lf	5680.0000
Width of coupler	W	2000.0000
Width of port	PortW	7.0000
Pitch of the coupler	dx	20.0000
Array pitch	dd	18.5000
Straight length of shortest array	Sp	300.0000
Array path difference	dL	124.8540
Width of Array	ArrayW	7.0000
Port pitch	D	250.0000
Left region of left star	F1	300.0000
Right region of left star	F2	F1
Left region of right star	F3	F1
Right region of right star	F4	F1
Device upper offset	OS1	300.0000
Device down offset	OS2	16.7500

(b) Design parameters

Figure 4 Layout (a) and design parameters (b) of a 16-channel AWG

4.2 Solver settings of predefined device

After the creation of the 1x16 AWG, the user must select the appropriate solver setting for the simulation by clicking the button. Figure 5 shows the "Device Solver Setting" window, which has three tabs: "General Information", "Solver Selection", and "Variable Selection".

On the "General Information" tab, the user can select appropriate "Polarization", check "Port Information Based on Effective Index Values" and "Single Mode Width", and view all related port mode profiles by clicking "View Mode Profile".

The "Solver Selection" tab allows the user to specify for the "Output Selection": "S parameter" and "Field" as shown in Figure 5. If the user selects "S parameter", the user must then select the appropriate solvers, either analytical or numerical. The following considerations should be made:

- only the field pattern in the second FSZ can be viewed
- only numerical solvers are available for tapered AWG (the mesh setting option under "Advanced Setting" is used for the two star coupler zones with region lengths *F1*, *F2*, *F3*, and *F4*)
- current AWG solvers can only do 2D analysis

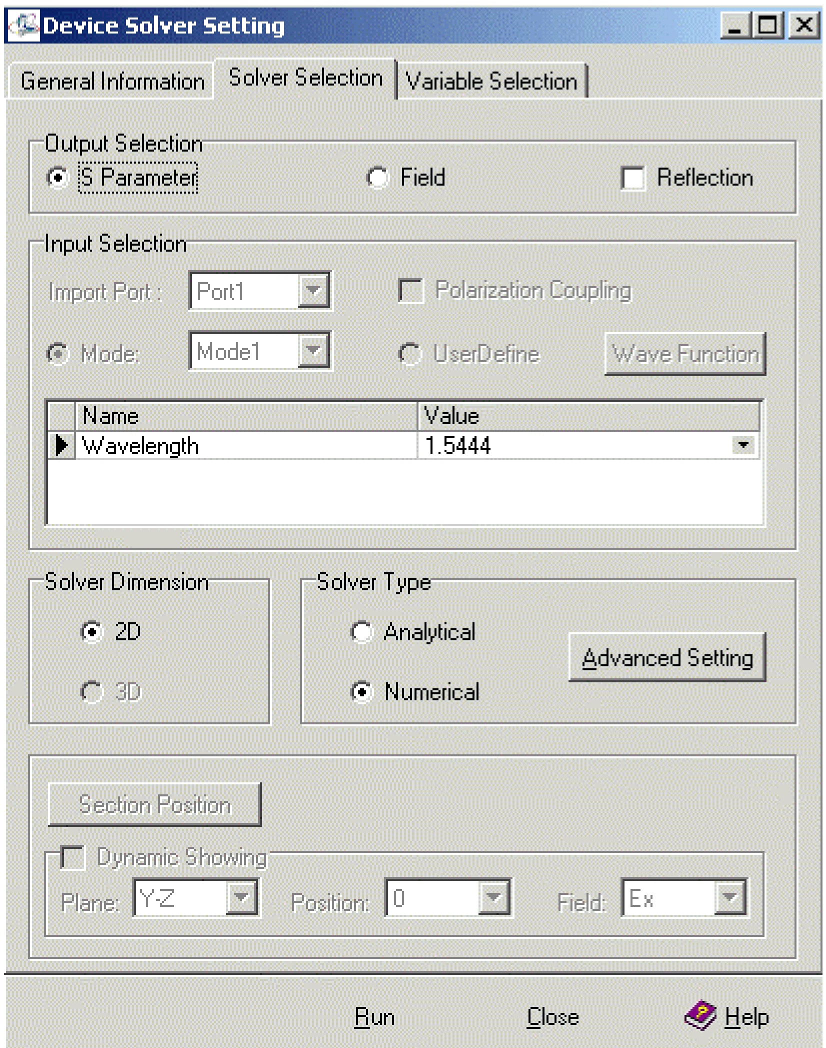


Figure 5 The device solver setting for the AWG MUX.

On the "Device Solver Setting" tab, the user must select appropriate variables for the variable scan. The user can also do a "Structure Check" for selecting scan parameters. In the current version of the APSS application, the maximum number of variables for the variable scan is two.

4.3 Run and Display

After selecting the solver settings, the user can click the “Run” button to simulate the S parameters and fields of the device. When the simulation is complete, the user can view the “S” parameters and EM fields at the positions defined in the “Section Position” by clicking the  or  button. Figure 6 shows the X-Z field pattern at the second star coupler.

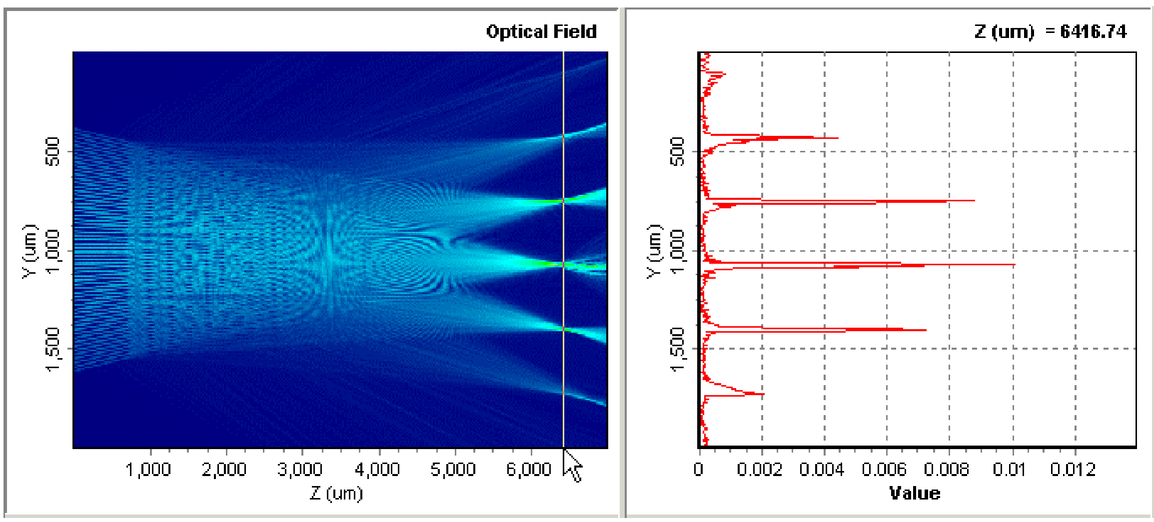


Figure 6 The field display at the second star coupler

As a final stage, the spectral response is calculated by performing a vary-run versus the wavelength. The wavelength step in this example was chosen to be 0.2 nm. Figure 7 shows the calculated spectral response for the AWG.

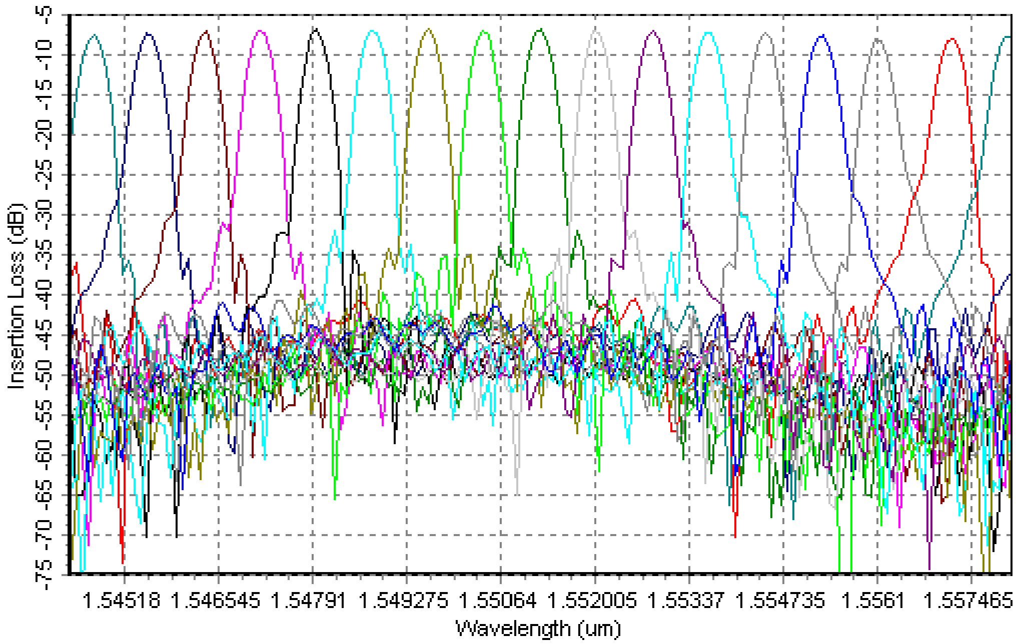


Figure 7 Calculated spectral response of the 1x16 AWG

5 Discussions

This section discusses some specific considerations that are important when designing an AWG device using the APSS Device Module. Example files have been included with the APSS software to aid the user in understanding how these designs were created.

5.1 Polarization

For practical AWGs, the equivalent refractive index is different for the TE and TM modes because of the stress-induced birefringence, which leads to a different focusing position for different polarizations and PDL. A reasonable PDL for a communication application is less than 0.5 dB. There are several ways to make the AWG polarization-independent [7]. The TE/TM mode conversion method, in which a thin half-wavelength wave-plate is inserted at the center of arrayed waveguides, is the simplest and most practical method.

5.2 *Insertion loss*

In WDM communications, it is very important for the AWG device to have low fiber-to-fiber loss. The main sources for the AWG insertion loss are:

- the propagation loss of bent waveguides
- the coupling loss between the fiber and the waveguide
- the transition loss between the star coupler and arrayed waveguides
- the material and scattering losses of silica

In practice, large radii and tapered transition (for example, horizontal and vertical tapers) are used, rendering bend loss negligible. Research groups have reported loss among 2.3–2.7 dB. Commercially available AWGs have a 4.5 dB loss for Gaussian passbands and 7.0 dB for flat top passbands.

5.3 *Cross-talk*

According to the review paper [4], there are many mechanisms that can cause cross-talk. Six sources are: receiver cross-talk, truncation, mode conversion, coupling in the array, phase transfer incoherence, and background radiation. The first four can be kept low through effective design.

The most obvious source of the cross-talk is caused by the coupling between the receiver sides of the star coupler. Using the overlap between the exponential tails of the propagation field and the waveguide mode profile, the cross-talk can be easily calculated.

Another source of cross-talk is caused from truncation of the propagation field by the finite width of the output array aperture. This truncation of the field produces the loss of energy and increases the output focal field side-lobe level. To obtain sufficiently low cross-talk, the array aperture angle of AWG should be larger than twice the Gaussian width of the field. The truncation cross-talk should be less than –35dB when this requirement is met.

Cross-talk by mode conversion is caused by a "ghost" image of multimode junctions. It can be kept low by optimizing the junction offset by avoiding first mode excitation.

The cross-talk caused by coupling in the array can be avoided by increasing the distance between the arrayed waveguide. However, due to imperfections of the fabrication process, the incoherence of the phased array, caused by the change of optical path length (in the order of thousands of wavelengths), may lead to considerable phased error, and, consequently, to increase the cross-talk. For this reason, on a practical level, the reduction of cross-talk for an AWG device is limited by imperfection in the fabrication process.

5.4 Flat-top wavelength response

In many applications, the flat-top passband is very important to relax the wavelength control requirements. There are several approaches that can be used to achieve this goal. The most simple method is to use multimode waveguides at the receiver side of the AWG. If the focal spot moves along these broad waveguides, almost 100% of the light is coupled into the receiver to have a flat region in the frequency response, in which the 1 dB bandwidth can be easily increased from 31% of the channel spacing to 65%. Another method is to apply a short MMI power splitter or a Y-junction (two output branches close together) at the end of the transmitter waveguide of the star coupler. The operation principle of such a device is to convert the single waveguide mode into the double (camel-like) image, and, consequently, to flatten the frequency response because the AWG is a 1:1 image system.

5.5 Thermal control/tuning

In order to use AWG devices in practical optical communication applications, precise wavelength control and long-term wavelength stability are needed. Of course, a channel wavelength will change according to the thermal coefficient of the material used, if the temperature of AWG fluctuates. By making use of the thermo-optic (TO) effect, a temperature controller can be built into the AWG to control and tune the device to the ITU grid or other desired wavelength.

6 Conclusion

As demonstrated with a practical example, APSS offers designers a feasible and efficient way to design and simulate an AWG device. This can be accomplished by taking advantage of the knowledge-based, pre-defined model in the APSS Device Module to create an effective, functional design. The theory and operational principle of the AWG device have been described. Finally, the design process has been outlined, and the simulation results agree well with experimental results.

7 References

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