# APSS Apollo Application Note

# Add-Drop Filter Based on Mach-Zehnder Interferometer with Bragg Gratings

***Computer-Aided Design and Simulation***

**APN-APSS-MZICircuit**

**Apollo Inc.**
**1057 Main Street West**
**Hamilton, Ontario L8S 1B7**
**Canada**
**Tel: (905)-524-3030**
**Fax: (905)-524-3050**

**www.apollophotonics.com**

## Disclaimer

In no event should Apollo Inc., its employees, its contractors, or the authors of this documentation be liable to you for general, special, direct, indirect, incidental or consequential damages, losses, costs, charges, claims, demands, or claim for lost profits, fees, or expenses of any nature or kind.

Document Revision: June 15, 2003

## Abstract

This application note provides an overview of how to use the Apollo Photonics Solution Suite (APSS) to design, simulate, and layout an optical add/drop wavelength filter using a Mach-Zehnder interferometer with Bragg Gratings.

This application note:

- describes the operation principle
- discusses key issues affecting add/drop filter design, such as bandwidth, side-lobe, and cross-talk
- describes how the APSS Circuit Module (CM) can be used to break a complicated component into its logical sub-components, which can then be more efficiently analyzed, and result in more accurate simulations
- describes the procedures for mask layout and exporting

## Keywords

Apollo Photonics Solutions Suite (APSS), Mach-Zehnder interferometer (MZI), Bragg Grating, Circuit Module (CM), wavelength division multiplexing (WDM), ring resonator, free spectral range, finesse

# Table of Contents

# 1 Introduction

The optical add/drop wavelength filter is a key component in wavelength division multiplexing (WDM) optical systems. One of the methods used to realize a fully integrated add/drop filter is to use an guided-wave Mach-Zehnder interferometer (MZI) with Bragg Gratings placed on both of its arms. This method was first demonstrated on fiber grating [1], and later on planar waveguides [2].

From a modeling point of view, it can appear challenging to simulate the structure of this kind of filter with existing numerical methods such as the beam propagation method (BPM), or the finite-difference time-domain method (FDTD). BPM cannot simulate the reflection because of the grating, and FDTD cannot be used for the whole structure of the filter because it requires a large amount of memory and has a long computation time.

The APSS Circuit Module (APSS-CM), however, allows the optical designer to divide a complex structure, such as an MZI with Bragg Gratings, into a number of logical sub-components. Each of these sub-components can then be simulated individually by suitable methods in the Device Module (APSS-DM), and finally reassembled using the APSS-CM to form an integrated circuit. Another advantage of using the APSS-CM is that simulation of identical devices does not have to be repeated, no matter how many times they are used in the circuit.

The device used as an example in this document is a 3 dB coupler and a very short length of Bragg Gratings (several periods long), linked together to form a large complex circuit.

# 2 Theory

## *2.1 Operation principle*

The central wavelength is determined by the period of the Bragg Gratings, and is also referred to as the Bragg wavelength. As shown in Figure 1, multiple wavelengths input into Terminal 1 will be equally split into the two arms with identical gratings. One of the wavelengths is the Bragg wavelength of the grating and is reflected back, while the rest of the wavelengths pass through. The reflected signals from both arms combine and emerge from Terminal 2 as a dropped wavelength. The pass-through signals combine and emerge from Terminal 3.

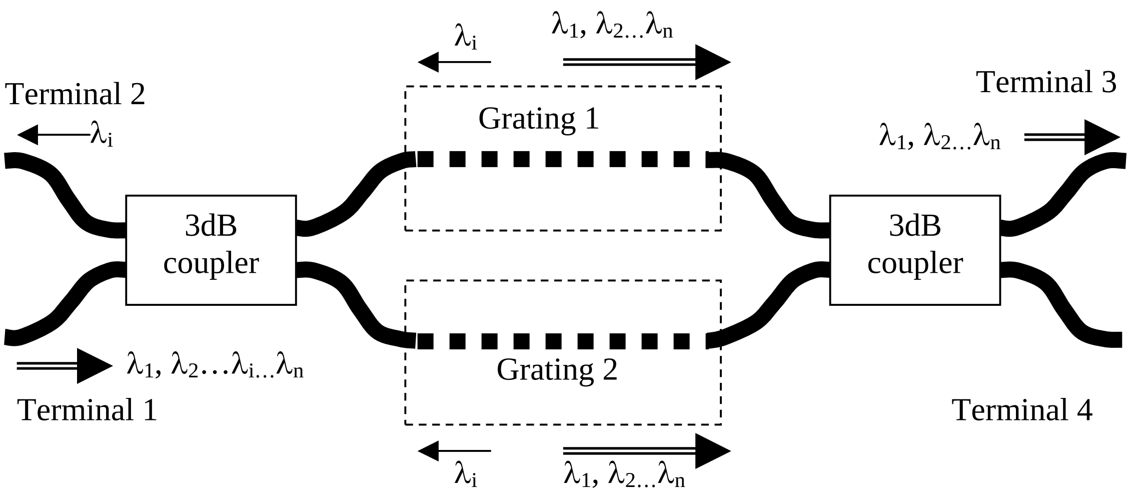



**Figure 1 Dropping mechanism of add/adding filter based on MZI with BG**

Similarly, as shown in Figure 2, an input signal from Terminal 4 with a Bragg wavelength that is the same as the gratings, is reflected by the two gratings, then combines with the other wavelengths, and emerges from Terminal 3 as an added wavelength.

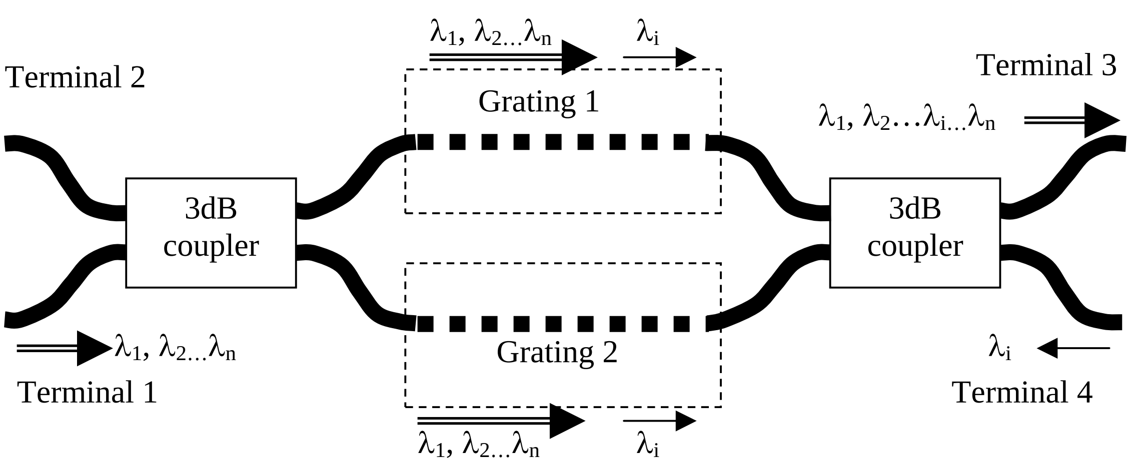



**Figure 2 Adding mechanism of add/drop filter based on MZI with Bragg Gratings**

### 2.2 Central wavelength

As mentioned in the previous section, the central wavelength, or Bragg wavelength, is determined by the period of the Bragg Gratings.

$$\lambda_i = \frac{\Lambda}{2n_{eff}} \tag{1}$$

where $n_{eff}$ is the effective index of the waveguide mode, usually the fundamental mode. Therefore, for a given waveguide, the grating period for a desired Bragg wavelength $\lambda_i$ should be:

$$\Lambda = \frac{\lambda_i}{2n_{eff}} \tag{2}$$

### 2.3 Bandwidth

The bandwidth of the reflected spectrum is determined by both grating length and grating strength [3].

$$\frac{\Delta\lambda}{\lambda_i} = \sqrt{\left(\frac{\delta n_{eff}}{n_{eff}}\right)^2 + \left(\frac{2\Lambda}{L}\right)^2} \tag{3}$$

where $\delta n_{eff}$ is the change in effective index induced by the grating and L is the grating length.

For a weak grating, $\delta n_{eff}$ is very small and the 1st is negligible compared with the 2nd term. Then the bandwidth can be simplified as:

$$\frac{\Delta\lambda}{\lambda_i} = \frac{2\Lambda}{L} = \frac{2}{N} \tag{4}$$

Here N is the number of gratings. Therefore, the spectrum is directly inverse, proportional to the grating length.

For a strong grating, the 1st is much bigger than the 2nd term, and the bandwidth can be simplified as:

$$\frac{\Delta\lambda}{\lambda_i} = \frac{\delta n_{eff}}{n_{eff}} \qquad (5)$$

In this case, the grating length will not affect the spectrum significantly, because the signal is reflected completely by the first several gratings, so the rest of the gratings will have no effect. For this reason, it is very important to balance the coupling strength and the grating length. A good design results in the reflection being uniformly distributed along the gratings, while all the power (or a certain percentage of the power) is reflected.

## *2.4 Side-lobe*

From the spectral point of view, a uniformly distributed grating may not be the ideal solution because the side-lobes of the spectrum will be very high. High side-lobes typically cause cross-talk between wavelengths. To overcome this shortcoming, apodization of the grating, that is, changing the strength of the grating along the waveguide can be done to make the coupling weaker at the two ends and stronger in the center. In practice, the level of the side-lobes and the main lobe bandwidth are strongly dependent on the profile of the apodization, and therefore proper selection and optimization of the apodization function is necessary to achieve the desired level of side-lobes for a given bandwidth [4].

## *2.5 Cross-talk*

There are different types of cross-talks for the MZI add/drop filter. These include:

- Wavelength or spectra cross-talk – Refers to partial reflection of the passthrough signals, which can be reduced by reducing the side-lobes through apodization as mentioned above.
- Spatial cross-talk – Refers to the cross-talk that occurs when partially reflected and transmitted signals emerge from the wrong terminals, which is mainly caused by the uneven splitting ratio of the 3 dB coupler and imbalance between the two

arms. Spatial cross-talk issues are in practice due to fabrication errors and can be reduced by controlling fabrication tolerance. A robust design that relaxes fabrication tolerance can also be useful in reducing spatial cross-talk.

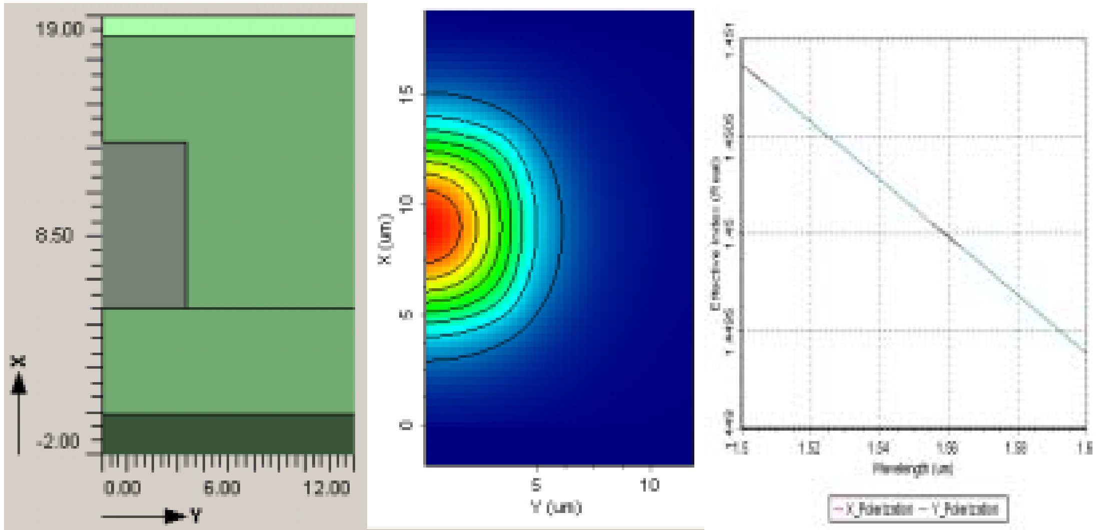
# 3 Design and Simulation

## *3.1 Overall design*

Our design goal is to achieve a low insertion-loss and polarization independent add/drop filter similar to that reported in [2]. The overall size of the device is about 0.5 x 10 $mm^2$. By taking advantage of the APSS-CM, the MZI add/drop filter can be theoretically disassembled into two 3 dB couplers based on 2x2 MMI, and a number of short Bragg Gratings. The FDTD method can be used for the grating simulation because it can accommodate the associated reflection. BPM or the mode-matching method (MMM) can be used for the MMI simulation. Because each device only needs to be designed once for APSS, even if it is being used in several places in the circuit, we only need to design two devices – a 2 x 2 MMI and a short Bragg Grating.

## *3.2 Waveguide Design*

Shown in Figure 3 (a) is a 8µmX8µm silica-on-silicon channel waveguide project with two materials (silica and Ge-doped silica) defined by a material project and one user-defined material (silicon). Only one half structure needs to be designed at first, because the system can take advantage of geometric symmetry to produce the other half.




**(a) Structure** **(b) Modal profile** **(c)Effective index curve**

**Figure 3 Waveguide project for the MZI-A/D filter**

Shown in Figure 3 (b) is the calculated modal profile and in Figure 3(c) are the calculated effective indices for both X- and Y-polarizations. They are exactly the same and polarization independence is preserved.

The mesh setting must be used correctly to achieve accurate results. For this case, 63 X 36 meshes are used to ensure the mesh boundaries are coincident with the dielectric boundaries, as well as being the same size in both directions, as explained in the section of Waveguide Module in the document "APSS-Getting Started"(File "Getting_Started.pdf" in the APSS folder).

## *3.3 2x2 3 dB Coupler Design*

MMI is an ideal coupler for equal power splitting due to its wide bandwidth, low polarization dependence, and low insertion loss. Figure 4 shows an APSS device project using the APSS waveguide project created in the last section. The geometric parameters are shown on the Geometry tab:

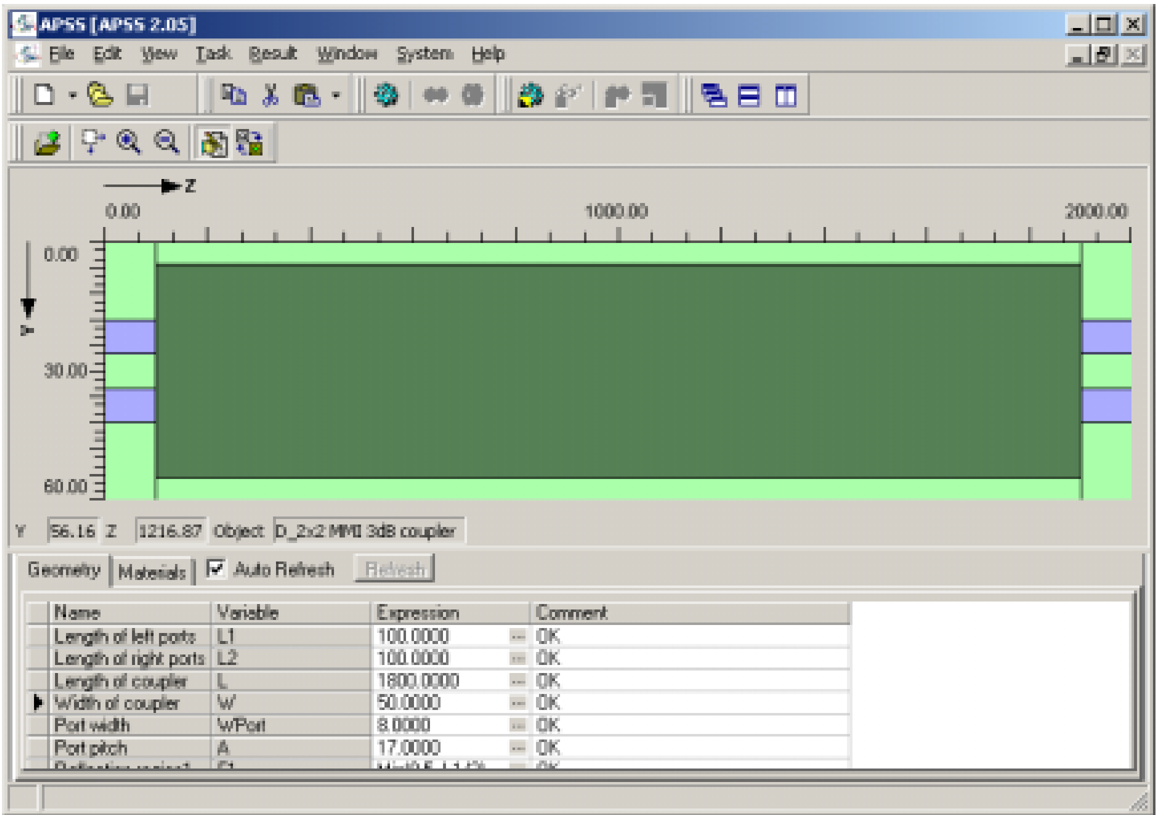



**Figure 4 APSS device project for a 2x2 MMI**

One of the advantages of the APSS is that it gives designers the flexibility to choose different methods to simulate the device. The available methods for this type of device are:

- 2D analytical MMM,
- 2D BPM,
- 2D BPM+ 2D FDTD,
- 3-D semi-vector BPM,
- 3-D semi-vector BPM + 3-D semi-vector FDTD,
- 3-D full-vector BPM,
- 3-D full-vector BPM + 3-D full-vector FDTD.

Because the waveguide is nearly symmetrical both vertically and horizontally, the effective index method should be reasonably accurate, and therefore the 2D simulation should be sufficient. Furthermore, the reflection at a single junction will probably be very small due to the low index contrast. Therefore, FDTD calculation is not necessary and 2D analytical or 2D BPM simulation should be sufficient for this device.

Figure 5 shows a spectra of the 2x2 MMI by 2D BPM. The splitting is relatively even and the polarization dependence is very small.

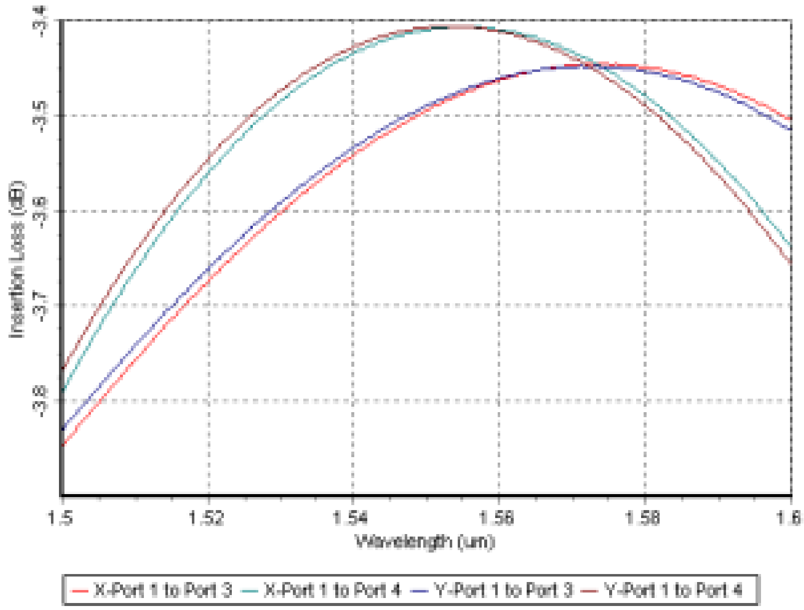



**Figure 5 Insertion loss spectra of the directional coupler**

## *3.4 Bragg Grating Design*

Although there is no pre-defined template for Bragg Gratings in the current version of APSS-DM, a designer could create such a structure by creating a user-defined device, and then specifying the appropriate variables, such as grating period, number of gratings, waveguide width, and grating height.

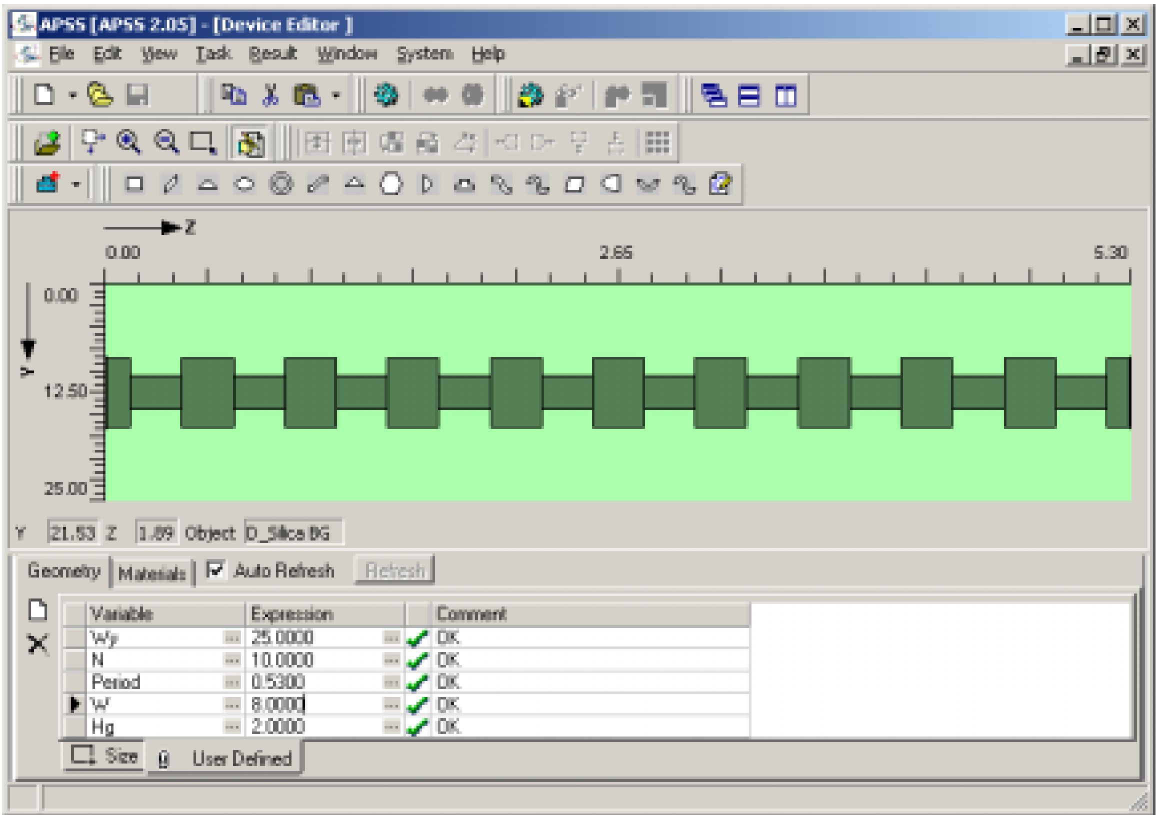
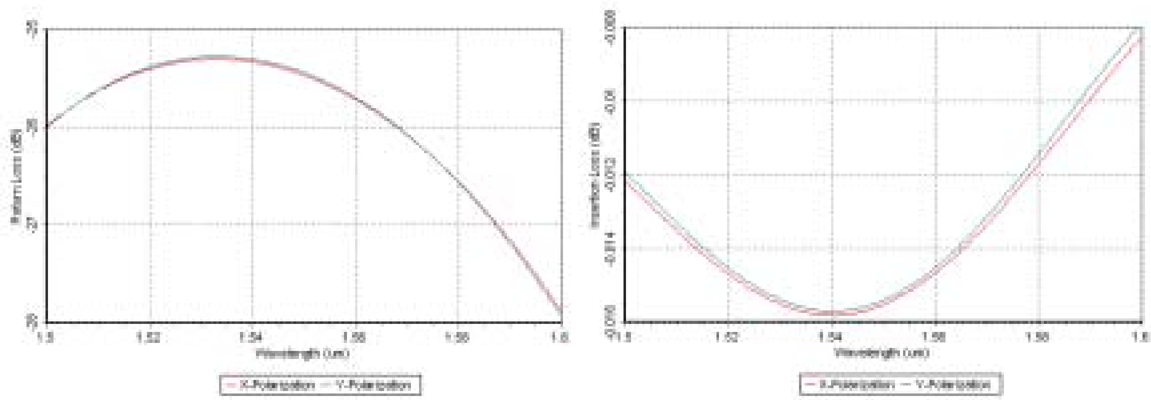



**Figure 6 Device project of a short Bragg Gratings**

Instead of using volume grating by UV exposure as used in [2], side gratings can be used so that the grating can be formed by the same mask as the MZI. This means another phase mask for the UV writing is not required. The coupling strength can be adjusted by varying the grating height $H_g$, and maximum coupling strength is reached by letting $H_g$=W/2.

As mentioned earlier, only a short Bragg grating needs to be designed and simulated. Once designed, several short gratings can then be cascaded to form a long grating. Assume the duty cycle is 0.5, the grating length (the length of each shape) should be half of the period. To ensure that there is no phase shift at the joints where two short gratings are connected, the gratings at the two ends of a short grating as shown in Figure 6 must be quarter period long so that the combined grating length at the joint is still half period when two short gratings are connected together.

Figure 7 shows the reflection and transmission spectra of the short Bragg Gratings when the grating height is 4µm, which is the maximum height. As shown in these graphs, insertion loss and polarization dependence are negligible.

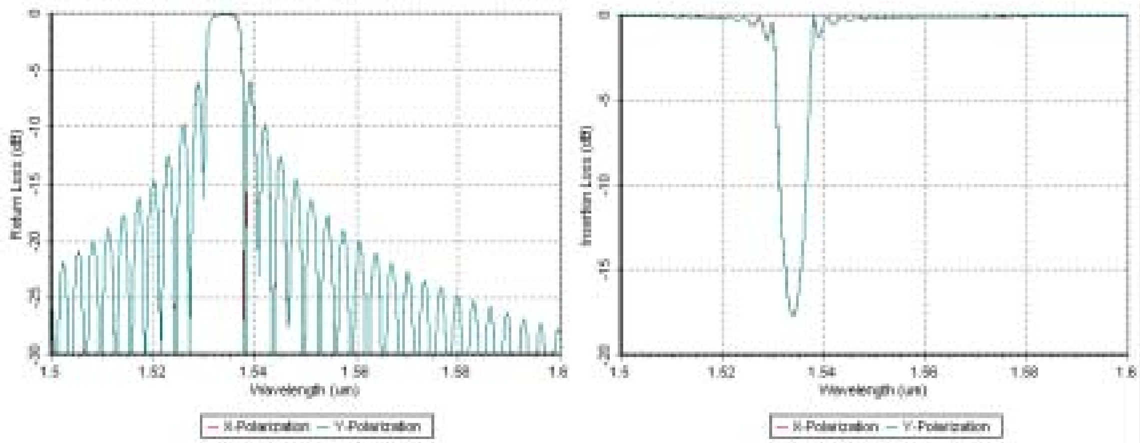



**(a) Reflection** **(b) Transmission**

**Figure 7 Spectra of the short Bragg Gratings**

Again, the mesh setting must be used correctly to achieve accurate results. To ensure the dielectric boundaries are coincident with the mesh boundaries, an integer number of meshes must be used in the Z-direction within each half period and quarter period for the grating at the two ends. A similar rule applies to meshes in the Y-direction. Finally, there can be no less than four meshes within the gratings at the two ends from the time that the incident is launched for simulation.

Figure 8 shows the spectra of a 265µm long grating that consists of 50 short gratings. The 3-dB bandwidth is about 6nm, the reflection peak is about –0.1dB, and the transmission notch is about -18dB.



(a) Reflection (b) Transmission

**Figure 8 Spectra of the cascaded grating with 50 short gratings**

## *3.5 Circuit design*

### 3.5.1 Layout

Figure 9 shows the APSS circuit project. As shown, a pair of long gratings, consisting of 50 short gratings each, are connected to 2x2 3-dB couplers on each side of the coupler. Because there must be room for optical fiber when the component is complete, a 250μm space is left between the two input/output terminals on each side. The gratings on the adjacent arms between the couplers are separated by 50μm to avoid any coupling in between. The offset/length ratio of S-bend connectors is set to 1/20, to ensure the bend loss is negligible.

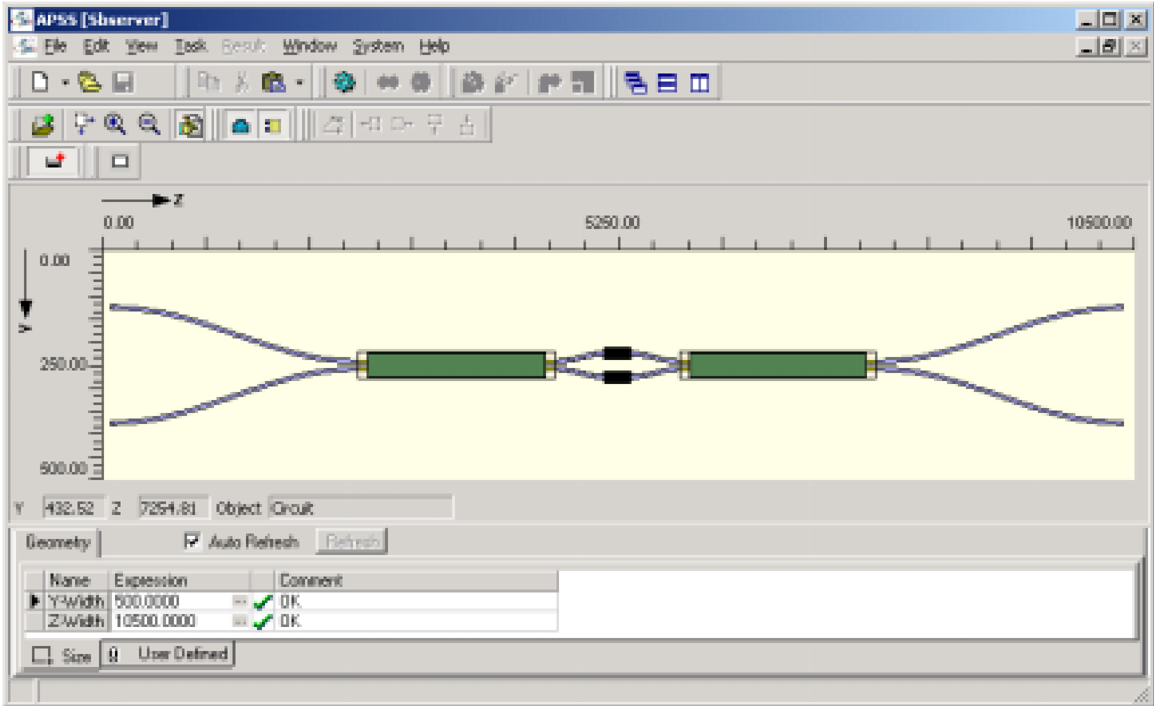



**Figure 9 Circuit project of the MZI add/drop filter**

### 3.5.2 Connectors

Two kinds of connections are used in this design:

- Direct connection – used between gratings
- S-bend connection – used between the gratings and the 3-dB couplers, as well as between the 3-dB couplers and input/output terminals.

### 3.5.3 Solver settings

The choices for circuit solver settings are logically limited because most settings, such as wavelength range, the number of wavelengths, and the available polarizations, are pre-determined by the loaded devices. However, there are many options for the connector solver settings. The default analytical solver is sufficient for most applications when the bend loss is low, because the connector's contribution is only a phase shift. However, a numerical solver or 3-D vector solver is recommended when the bend loss is high.

Because the measured loss of the connector is very low in the example design discussed here, contributing only a small phase shift, a designer might select the default fast analytical solver.

### 3.5.4 Simulation results

Figure 10 shows the reflected (dropped) signal and transmitted (pass through) signal for the two polarizations. In comparison to the spectra of the long grating (shown in Figure 8), this spectra has similar results, with the exception that there is increased loss due to the insertion loss of the 3 dB couplers. Polarization independence is also observed.

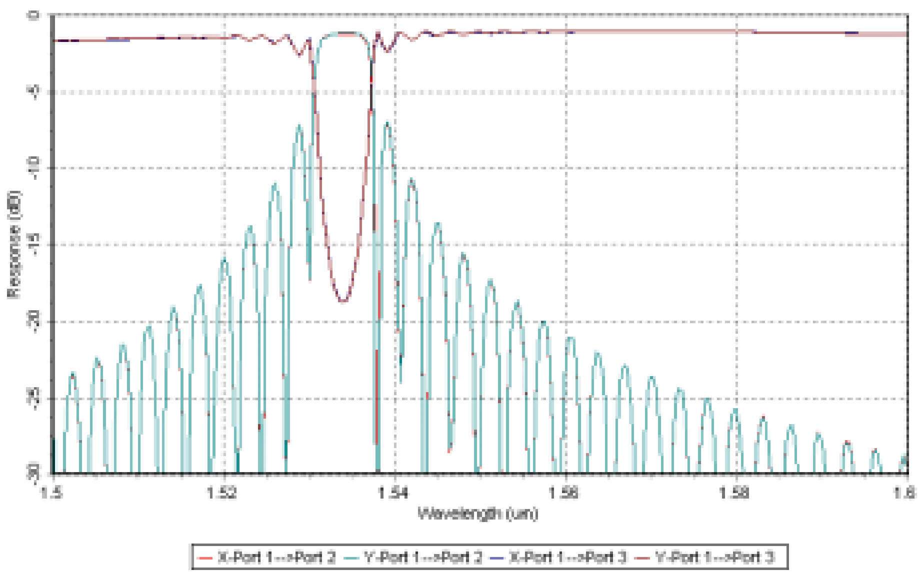



**Figure 10 Transmission and reflection spectra of the MZI-A/D filter**

Spatial cross-talks to the input terminal and the adding terminal is also monitored, and the spectra are shown in Figure 11. The cross-talk is about -30 dB for this design.

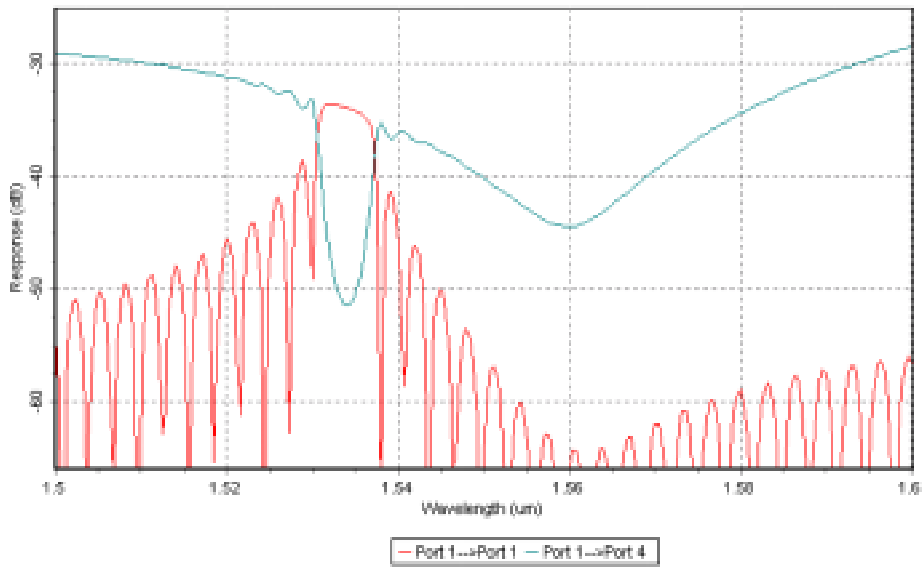



**Figure 11 Cross-talk spectra of the MZI-A/D filter**

### 3.5.5 Exporting projects and files

There are two ways to export: export the project or export the layout mask files.

To export the project, all the project information, including material, waveguide, and devices, can be exported to a APSS file "*.apx", which can be imported by APSS later.

When geometric layout mask files are exported, they are saved to an AutoCAD file "*.dxf", or a GDSII file "*.gds", which can be imported by some mask layout software, as shown in Figure 12.

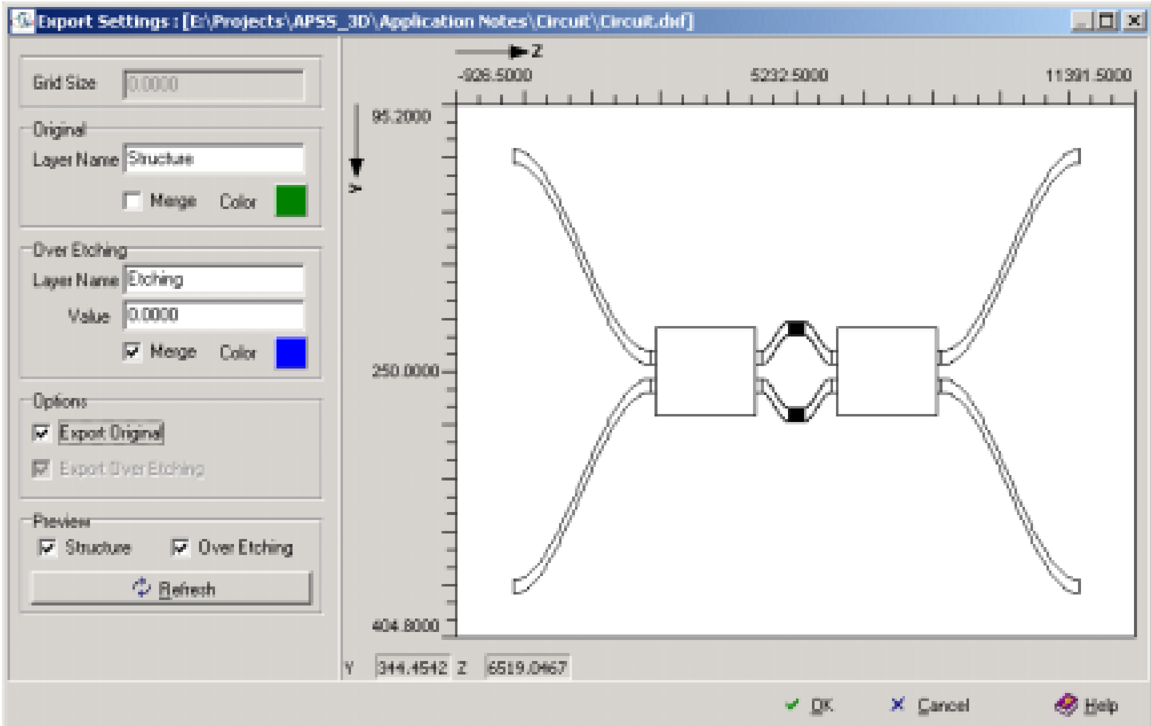



**Figure 12 Mash layout file export of the circuit**

***Note:*** Terminals are not exported to the mask layout file because they are only symbolically represented in the current example. If designers want to include terminals in the layout, straight waveguide devices or straight connectors must be used.

# 4 Discussion

The APSS-CM provides a convenient platform to disassemble a large and complex structure into smaller pieces. This process greatly facilitates the process of making the required calculations and performing the necessary analysis. How to optimize the design is a separate issue and is beyond the scope of this application note.

To improve the performance of the circuit, a designer could go back to the APSS Devices Module and/or the APSS Waveguide Module to fine-tune the waveguide structure and the gratings. The most critical issues are summarized as follows:

- Narrow bandwidth may be required in dense wavelength division multiplexing (DWDM) applications. In order to achieve this, the grating has to be long and weak. Therefore, we could reduce the grating height $H_g$ in the grating design to reduce the coupling strength, and then cascade more short gratings to form a longer grating.

- Grating apodization is an efficient way to suppress side lobes of the reflected spectrum. To achieve this, we could design several different gratings with different grating height $H_g$, and then cascade them so that gratings close to the center have stronger coupling, and gratings close to each end have weaker coupling.

# 5 Summary and conclusion

As demonstrated with a practical example, APSS offers designers a feasible and efficient way to design and simulate a large, complex, integrated component by disassembling the structure into discreet sub-components for separate analysis.

# 6 References

[1] T. Mizuochi, T. Kitayama, K. Shimizu, K. Ito, “Interferometric crosstalk-free optical add/drop multiplexer using Mach-Zehnder-based fiber gratings,**”** *IEEE J. of Lightwave Tech.*, vol. 16, pp. 265-276, Feb. 1998

[2] Y. Hibino, T. Kitagawa, K. O. Hill, F. Bilodeau, B. Malo, J. Albert, and D. C. Johnson, “Wavelength division multiplexer with photoinduced with phtoinduced Bragg gratings fabricated in a planar-lightwave-circuit-typle asymmetric Mach-Zehnder interferometer on Si,” *IEEE Photon. Technol. Lett,*. vol 8, pp. 84-86, Jan. 1996.

[3] T. Erdogan, “Fiber grating spectra,**”** *IEEE J. of Lightwave Tech.*, vol. 15, pp. 1277-1294, Aug. 1997

[4] B. E. Little and C. Wu, “Window functions for ideal response in distributed feedback reflection filters,” *IEEE Photon. Technol. Lett,*. vol 9, pp. 76-78, Jan. 1997.