Validation Report

Name of Report	Group delay simulations – a comparison between OmniSim and FIMMWAVE
Performance Date	13th July 2005
Performed By	Stephen Day
Product Name	OmniSim
Product Version & Compile Date	
References	"Transmission, Group Delay and Dispersion in Single-Ring Optical Resonators and Add/Drop Filters – A tutorial Overview"; Otto Schwelb;Journal of Lightwave technology V22 N5 May 2004; p1380-1394

Group delay simulations – a comparison between OmniSim and FIMMWAVE

1. Report Summary

a) The aim of this study was to compare the phase response of a region of uniform refractive index, a straight waveguide, a grating filter and a ring resonator – comparing OmniSim using FDTD, FIMMWAVE using eigenmode expansion and analytical approaches

1.1. Summary

The validation tests have been performed on regions of uniform refractive index, straight waveguides, grating devices and ring resonators.

Test 1	Uniform region with plane wave excitor		
Test 2	Straight waveguide		
Test 3	1D grating		
Test 3	Waveguide grating		
Test 5	Ring Resonator		

1.2. Validation Tests Results

1.2.1. Test 1

The simplest structure that can be considered is a region of uniform refractive index. The phase change due to a plane wave propagating through a region of uniform refractive index is given by the following

$$\phi = \frac{2*\pi*n*L}{\lambda} \qquad (1)$$

where L is the distance from a reference plane, λ is the wavelength and n is the refractive index. Equation 1, give an analytical method for calculating the phase change.

A region was defined in OmniSim with refractive index of 3.42. A plane wave excitor with TM polarisation was used together with magnetic sidewalls and a step size of 50 nm. A reference sensor and an output sensor were created 6 um apart. In OmniSim, it is necessary to calculate the difference in phase between two sensors, as the input phase is not defined. The OmniSim device is shown schematically in figure 1.

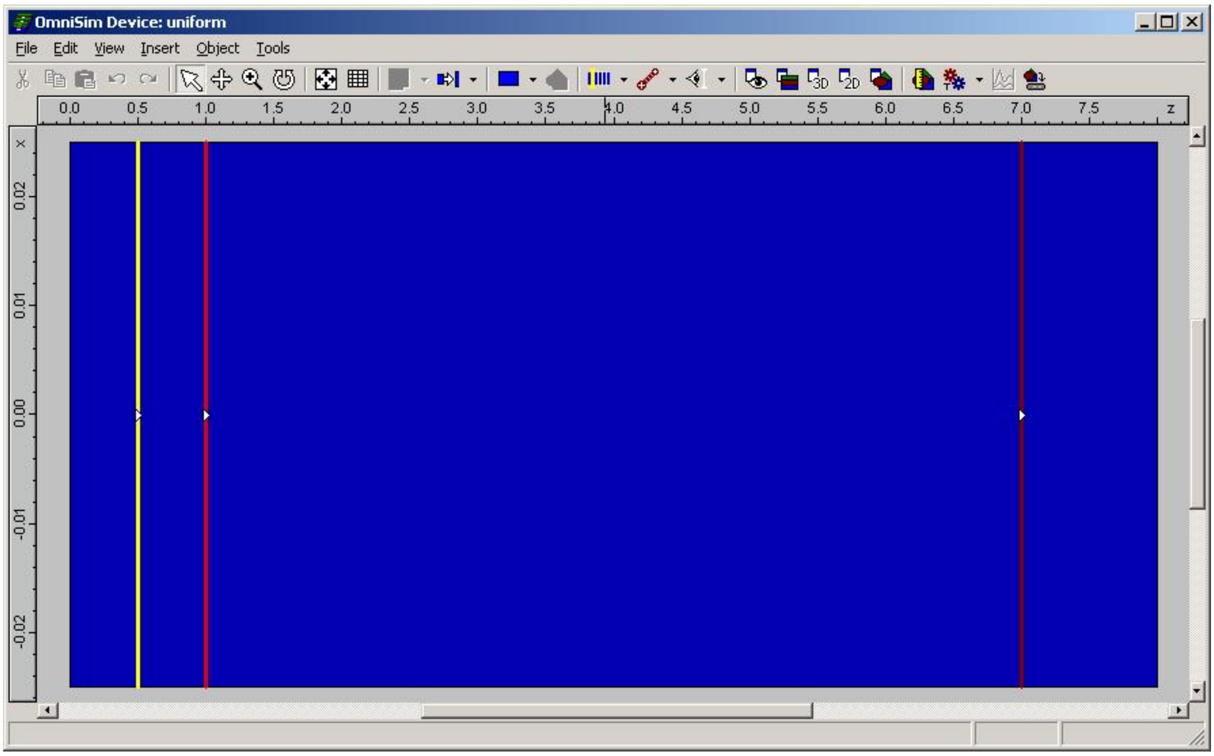

Figure 1: OmniSim device used in Test 1

The device was also simulated in FIMMPROP, by creating an MWG waveguide of uniform refractive index and then using this to define a FIMMPROP device 7 um long. A FIMMPROP scanner was defined to scan the wavelength from 1.3 to 1.9 um and the phase of the output was mode plotted using the arg function. In FIMMWAVE, only the output phase is required, as the input phase is zero for all wavelengths.

The phase calculations for the three methods are shown in figure 2.

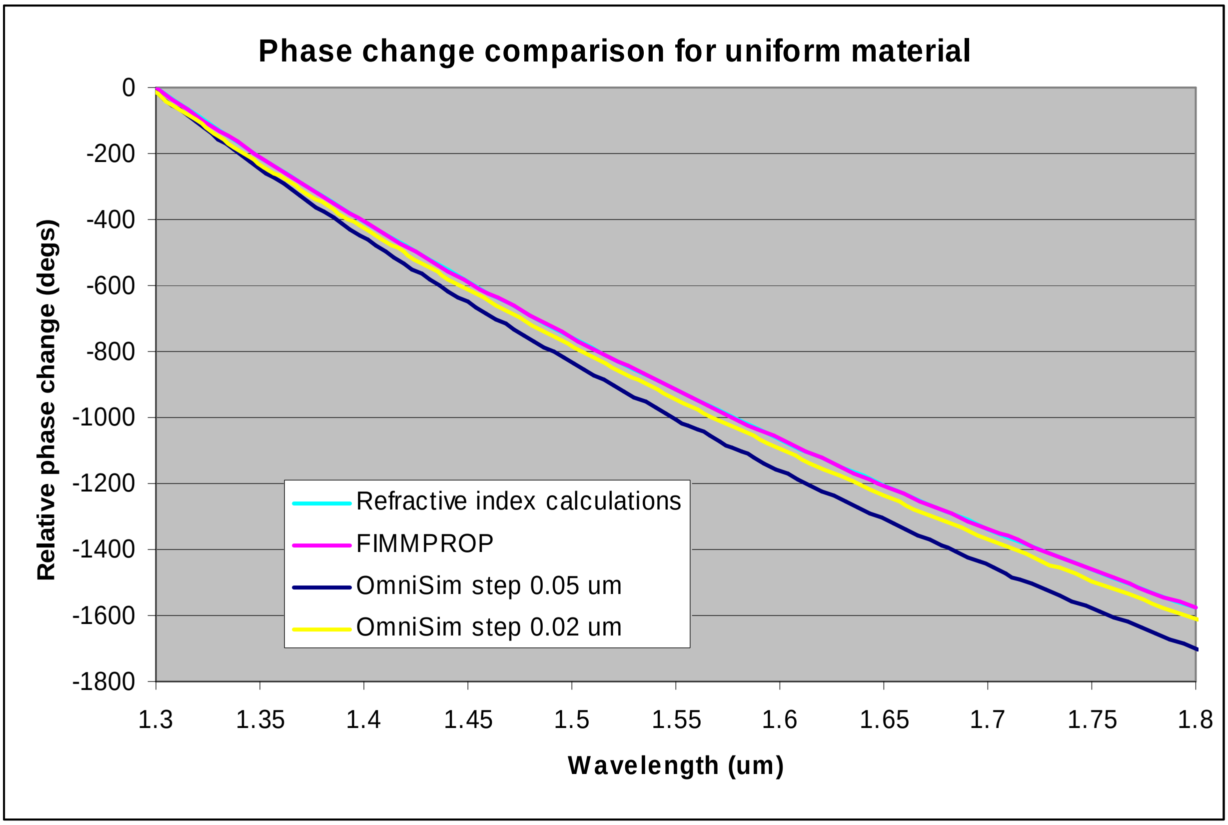

Figure 2: Phase calculations for propagation through uniform refractive index

The FIMMPROP and analytical calculations, show excellent agreement. OmniSim shows a slightly large phase change with wavelength, although reducing the step size from 50 nm to 20 nm, significantly reduces the error. An important calculation for filters is the group delay and the dispersion. The group delay is the change of phase with angular frequency (ω) and can be rewritten as

$$\tau_g = \frac{\lambda^2}{2*\pi*c}\frac{d\phi}{d\lambda} \qquad (2) \qquad \text{where c=speed of light}$$

Since this involves the differential of the phase with respect to wavelength, then it will also be a more sensitive method of comparing the different simulations. Figure 3 shows the group delay comparisons, for the initial OmniSim grid size of 50 nm and also for smaller OmniSim grid sizes

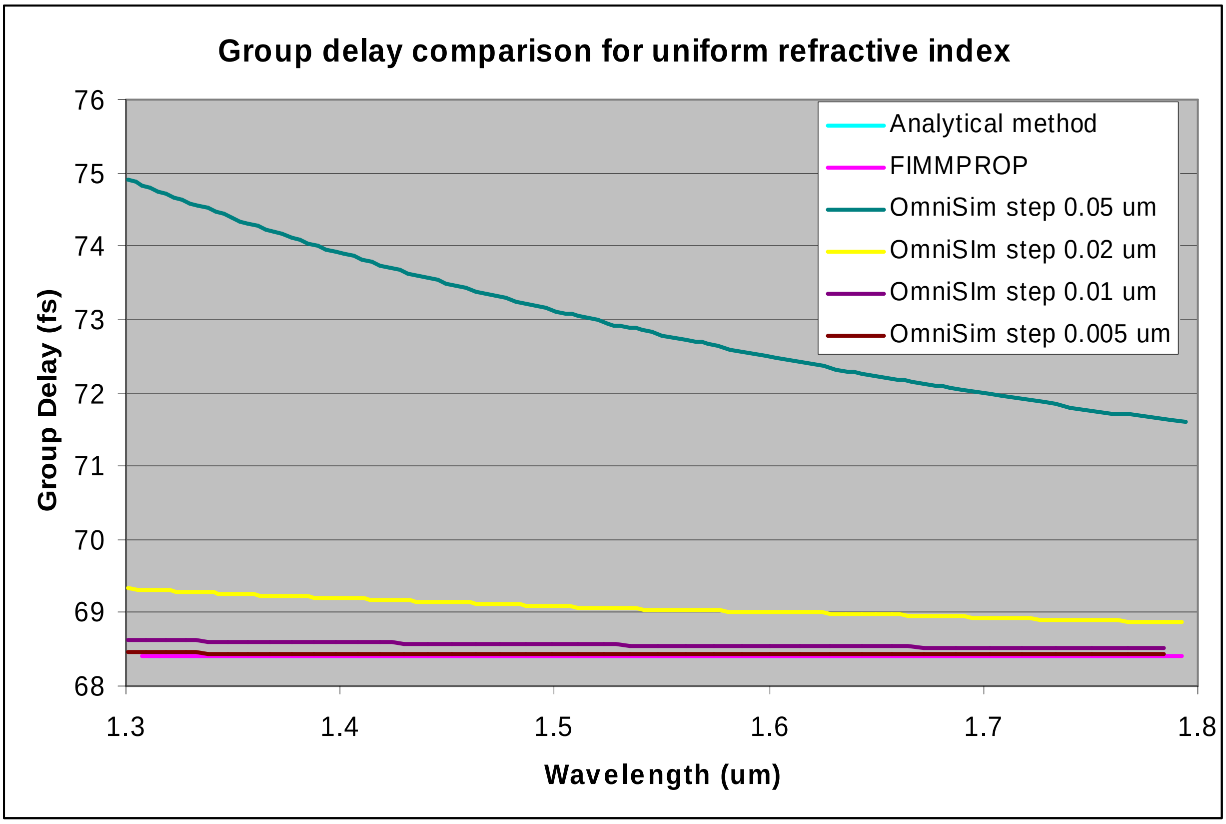

Figure 3: Group Delay comparisons

The group delay calculations show that the difference between the analytical method and OmniSim reduces as the step size is reduced. The average percentage error in group delay over the wavelength range 1.3 um to 1.9 um was calculated and is plotted in figure 4.

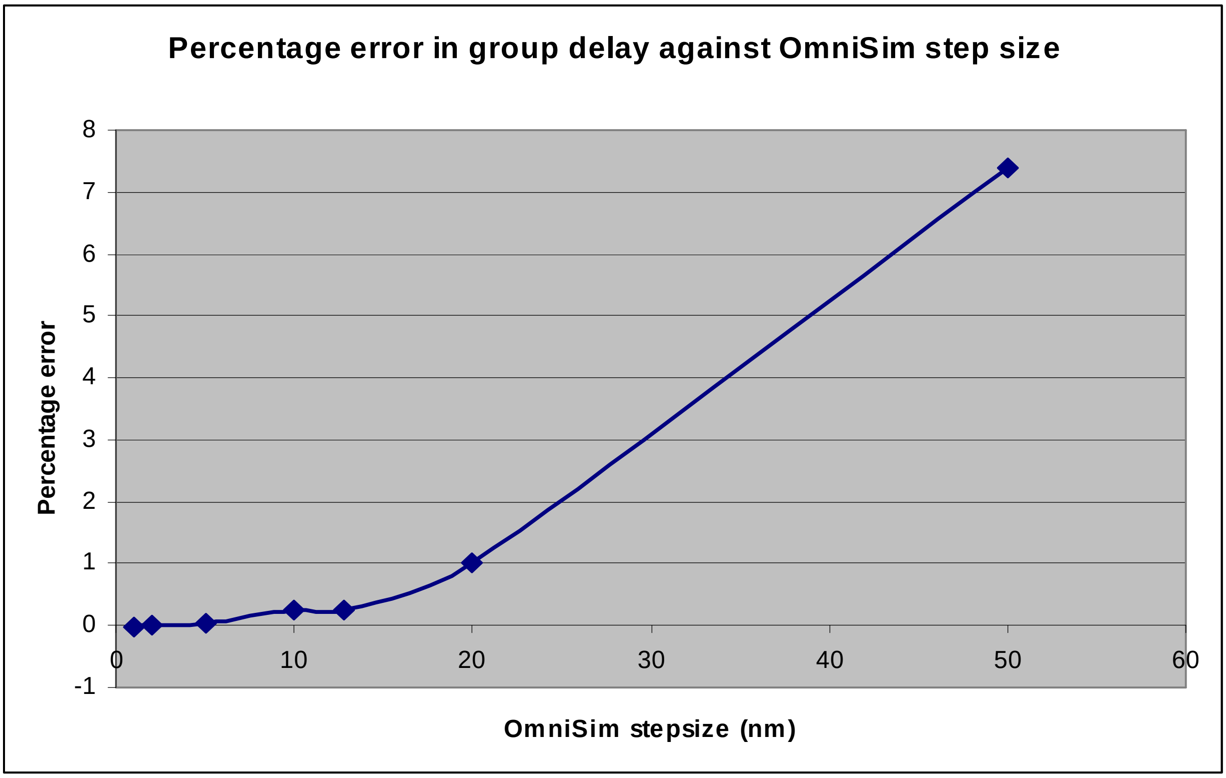

Figure 4: Effect of Stepsize on OmniSim error

The percentage error shows that to achieve an error of less than 1%, then a stepsize of 10 nm is required. Hence this stepsize was used for all further tests, unless stated. A 10 nm step size give an error of 0.24%.

1.2.2. Test 2

A waveguide was defined in FIMMWAVE with a 2 um wide core of refractive index 3.5 and cladding of refractive index 1.5. The effective index of the mode was calculated over the wavelength range 1.3 um to 1.9 um. Equation 1 was then used to calculate the phase response, replacing refractive index with the effective index of the mode. A 7 um long FIMMPROP device was defined using the waveguide cross section and a scanner was used to calculate the response from 1.3 um to 1.9 um. The phase was extracted using the arg(mode) function, to give a set of FIMMPROP results.

The waveguide was defined in OmniSim and simulated using 8192 points together with a grid spacing of 0.01um and a PML 64 grid points thick, two sensors were defined 7 um apart and the phase difference between them calculated as a function of wavelength.

The group delay was calculated for the three methods and the results are shown below in figure 5

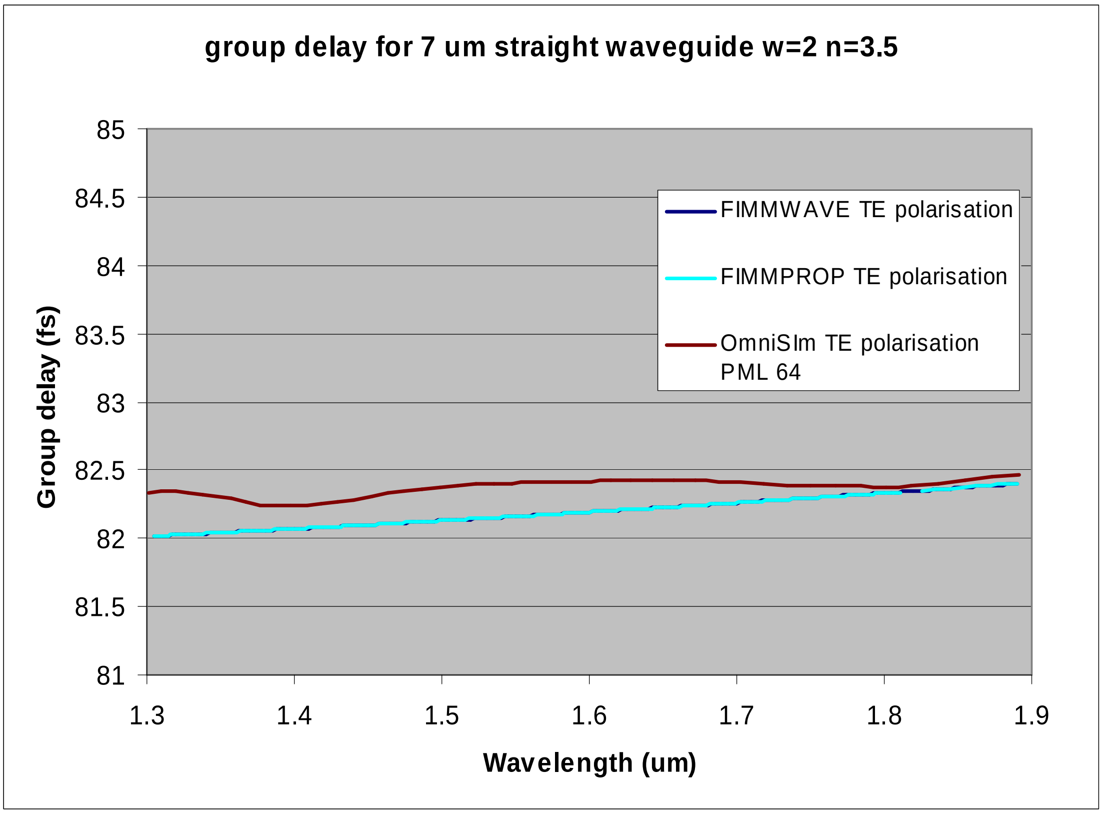

Figure 5: Group Delay calculations from FIMMWAVE / FIMMPROP and OmniSim

The group delay calculations show that the FIMMWAVE and FIMMPROP calculation agree very well. The OmniSim simulations show some low level ripple and gives reasonable agreement with FIMMPROP. The ripple is due to residual reflections and can be reduced by increasing the PML thickness. Future versions of OmniSim will have improved PML's. The error is quite small, the maximum error is 0.37%, which is comparable to the 0.24% observed with the uniform refractive index in test 1.

1.2.3. Test 3

In this test a one dimensional Bragg grating was considered. A Bragg grating was formed in a region of refractive index 3.6, by having 20 periods of refractive index 3.42, with a period of 0.256 um. The grating should reflect at

$$\lambda = (n_1 + n_2) * \Lambda \qquad (3)$$

where λ is the wavelength and Λ is the grating period

Hence a grating reflection should be expected at (3.42+3.6)*0.256=1.797 um. Figure 6 below shows the device schematically. Regions coloured blue have a refractive index of 3.6 and red regions are 3.42. The excitor was set to be a plane wave, using the same conditions as test 1. Each section in the grating has a length of 0.128 um, therefore the step size was set to 12.8 nm, so that there are an integer number of steps in each section.

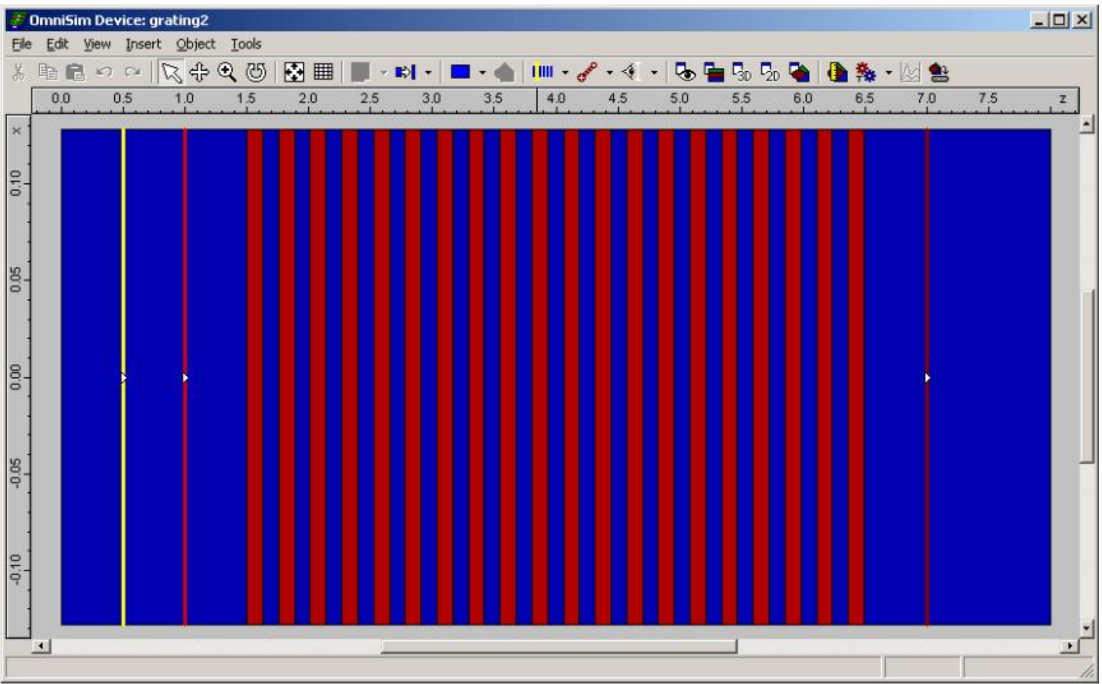

Figure 6: Device used for 1D Bragg grating

The transmission of the grating is shown in figure 7 and the group delay comparison is in figure 8.

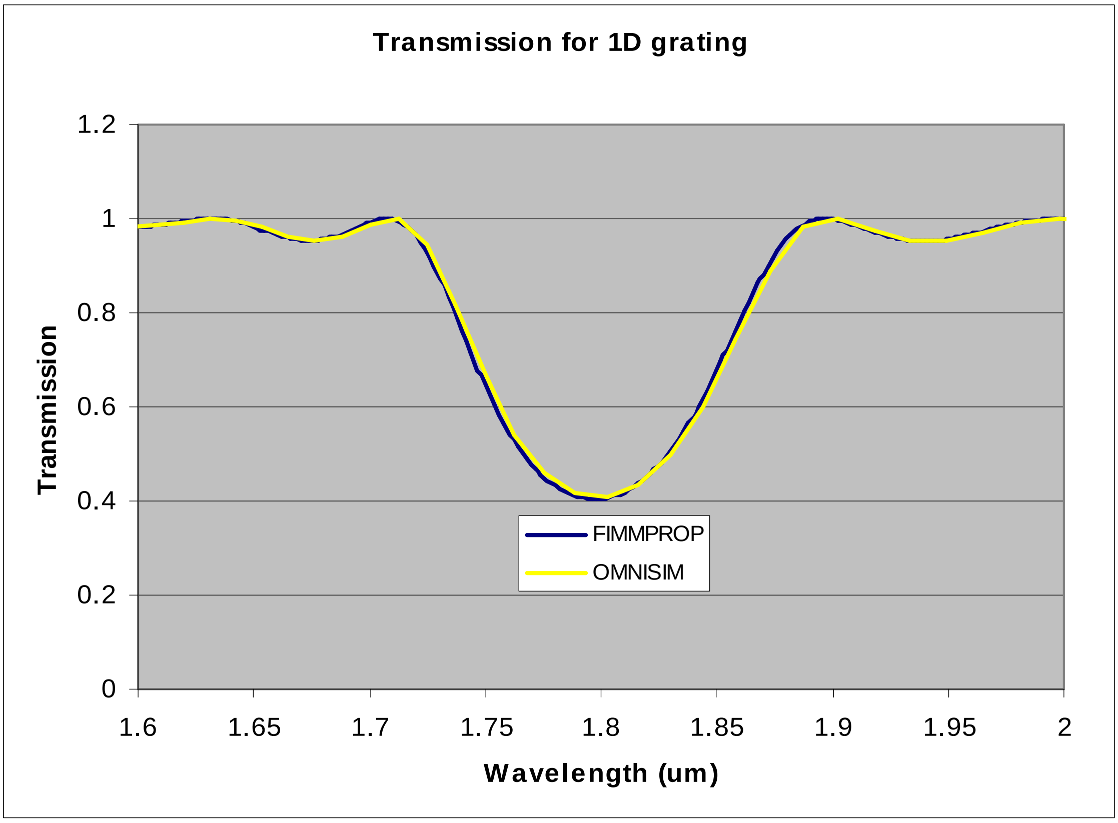

Figure 7: Transmission of 1D grating

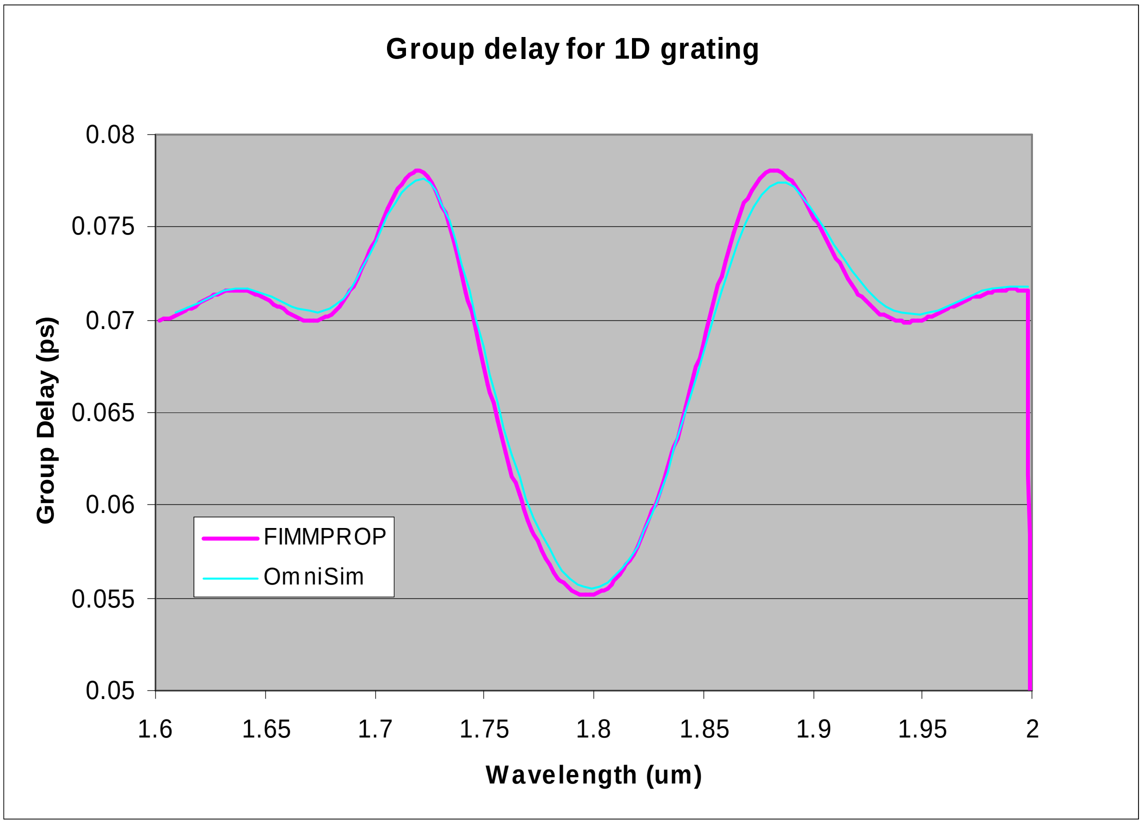

Figure 8: Group delay for 1D grating

There is very good agreement between OmniSim and FIMMPROP in both the transmission and the group delay of the grating and the reflection occurs at the expected wavelength of 1.797 um.

1.2.4. Test 4

In this test the 1D grating in test 3 was changed for a waveguide which is 0.4 um wide. To obtain a correct reference phase, it is necessary to create a short straight waveguide with identical dimensions and with identical exciotrs and sensors. The reason being that the reference sensor in the device is distorted by reflections from the grating. The transmission and group delay obtained with OmniSim and FIMMPROP for TE and TM polarisation is shown in figures 9-12.

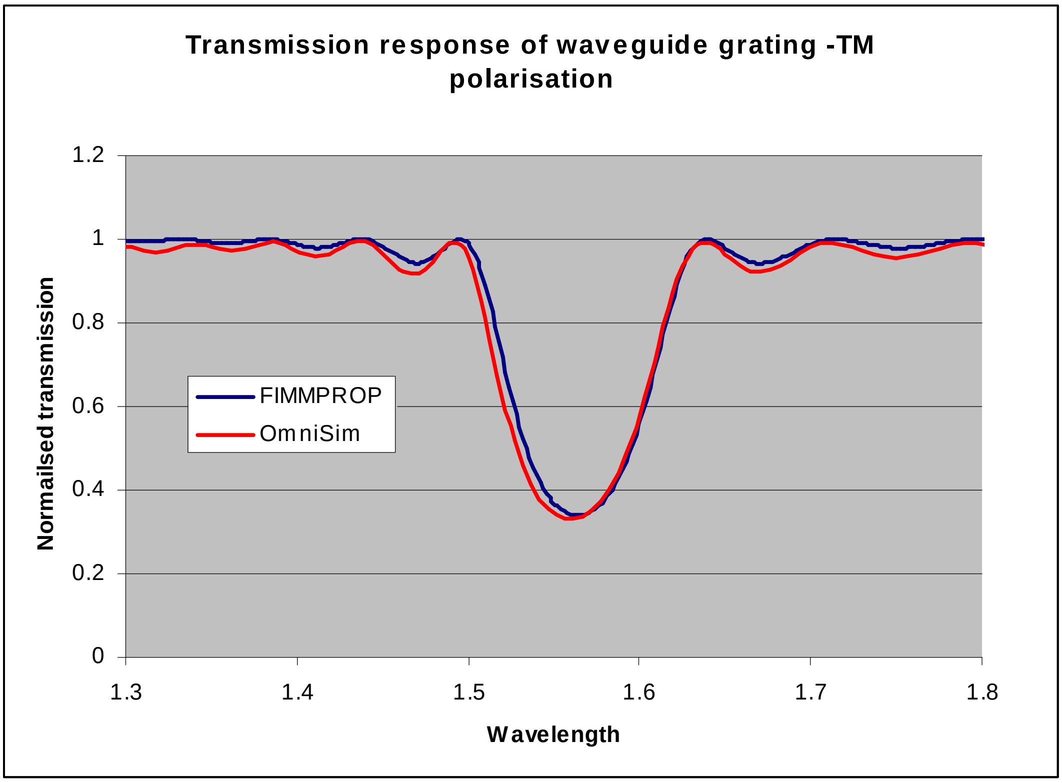

Figure 9: Transmission of 2D grating TM polarisation

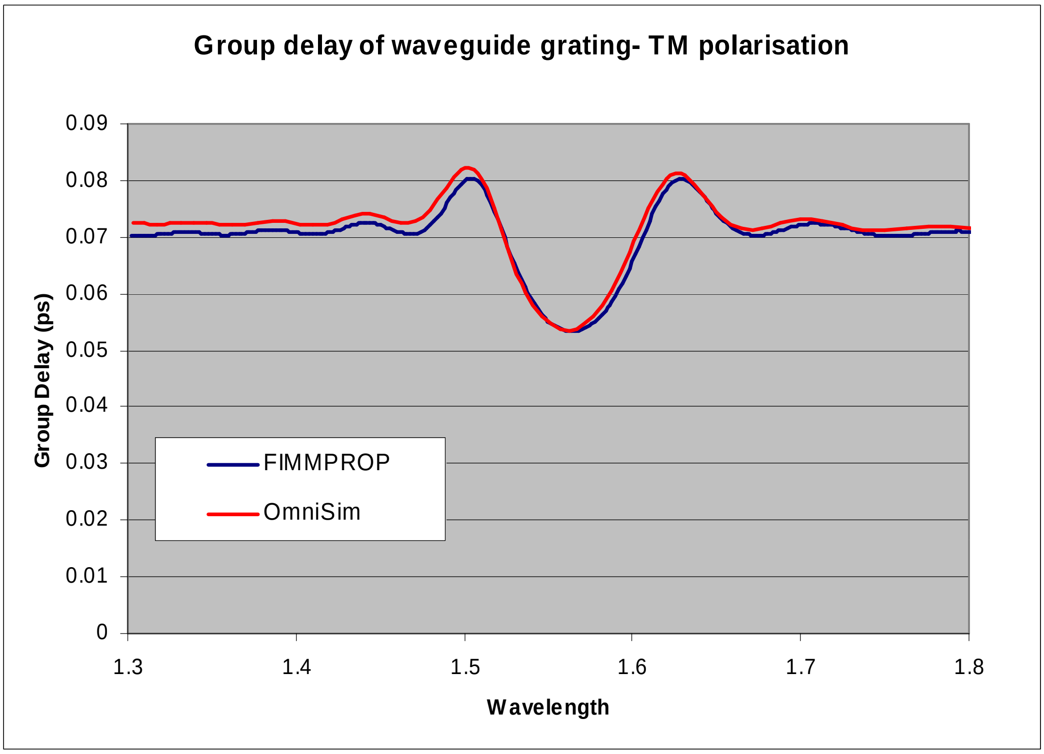

Figure 10: Group Delay of 2D grating TM polarisation

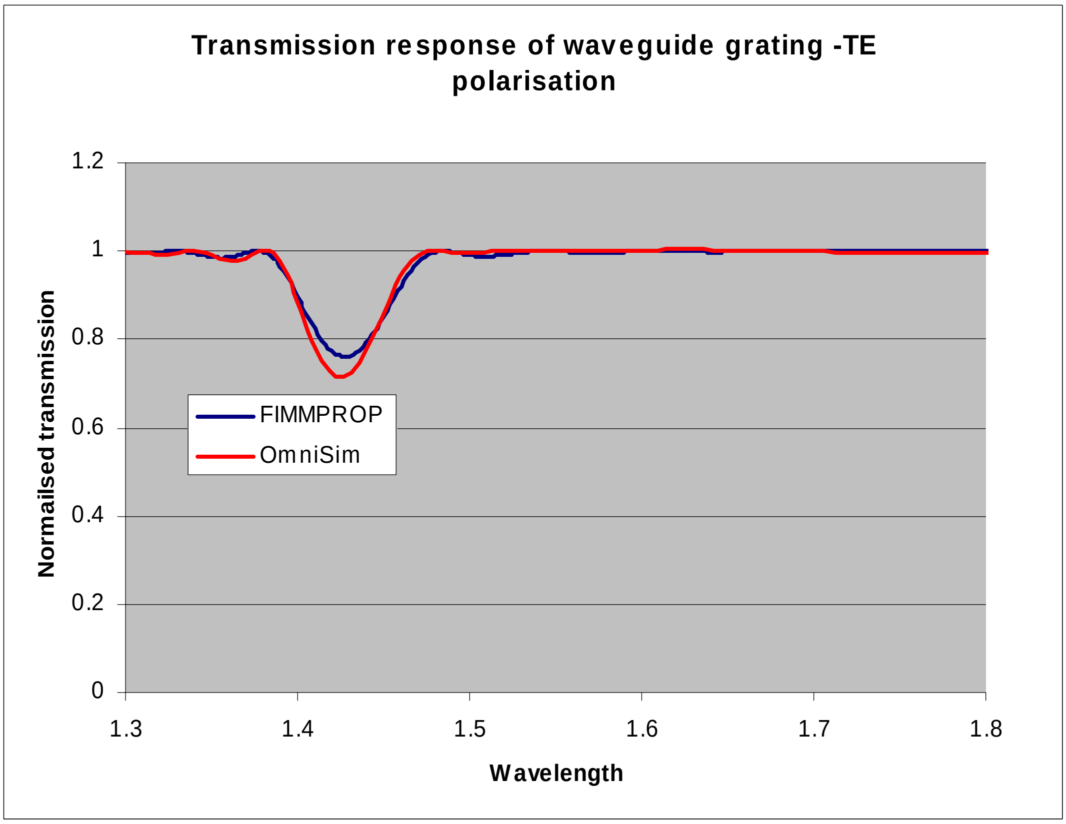

Figure 11: Transmission of 2D grating TM polarisation

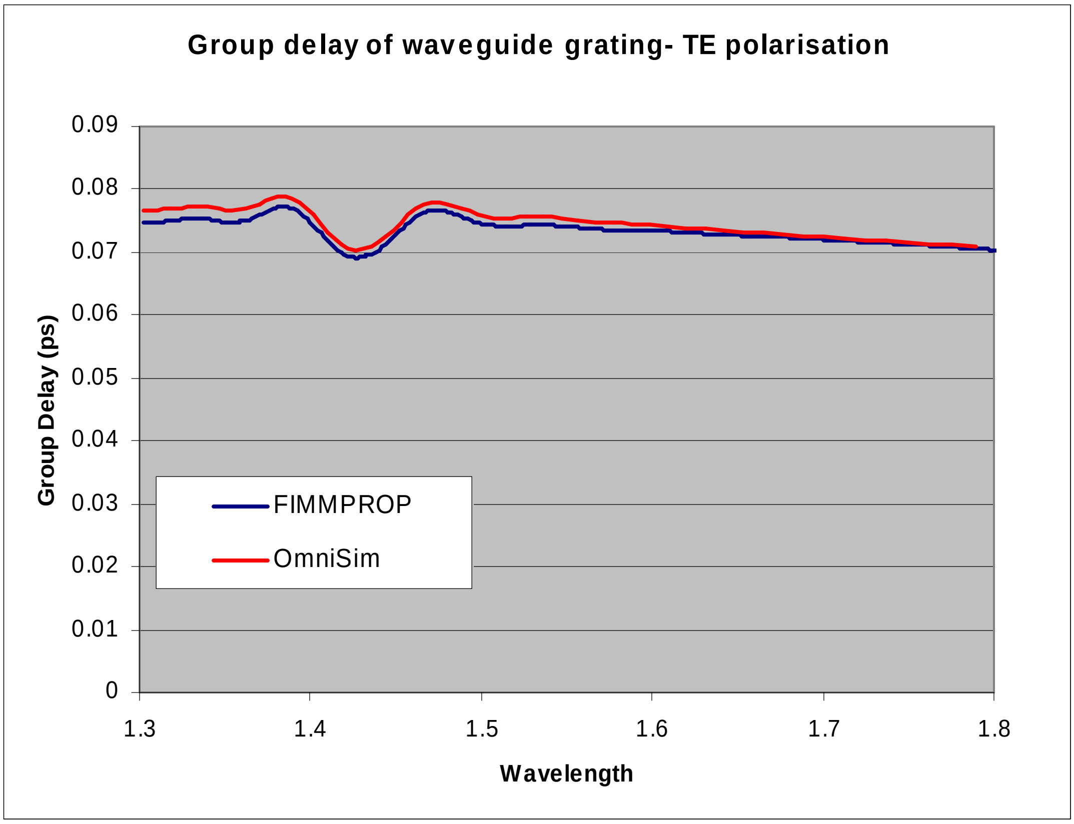

Figure 13: Group Delay of 2D grating TM polarisation

For TE polarisation, the agreement is very good and for TM polarisation there is reasonable agreement although the dip in transmission is slightly greater for OmniSim than for FIMMPROP.

1.2.5. Test 5.

This test uses a two port (all-pass) ring resonator, shown schematically in figure 13

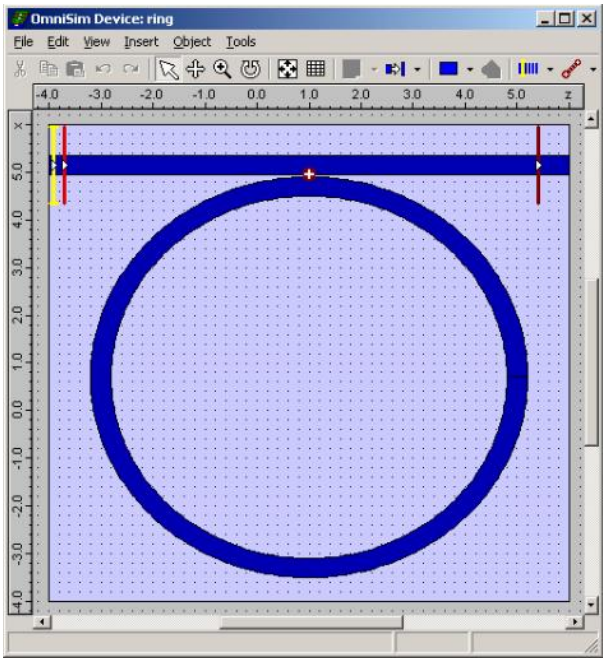

Figure 13: Schematic of ring resonator

In such a device, resonant frequencies, which are periodic become trapped in the ring. Since there is only one exit path out of the ring, then for a lossless ring, the resonant frequencies will slowly exit the ring so that the amplitude response will be unity, independent of frequency. However, the phase response is frequency dependent, which introduces a group delay enabling these devices can be used for dispersion compensation. Reference 2 describes the device in detail and also gives an analytical equation for the phase delay. For a lossless ring the phase delay is given by.

$$\phi = \tan^{-1}\left[\frac{K\sin(\theta)}{\sqrt{1-K}-(2-K)\cos(\theta)}\right] \quad (4)$$

where K is the coupling coefficient and

$$\theta = \frac{2*\pi*n_{eff}*2*\pi*R}{\lambda} \quad (5)$$

ie the phase due to propagation around the ring

The waveguide core was taken to have a refractive index of 3 and a width of 0.4 um. The ring radius was taken to be 4 um. These values were chosen to give a lossless ring to make the comparison easier. Couplers made with high refractive indices show a strong wavelength dependence of the coupling coefficient. OmniSim was first used to calculate the response of the coupler using the device shown in figure 14. A grid size of 50 nm was used and a PML thickness of 64 units.

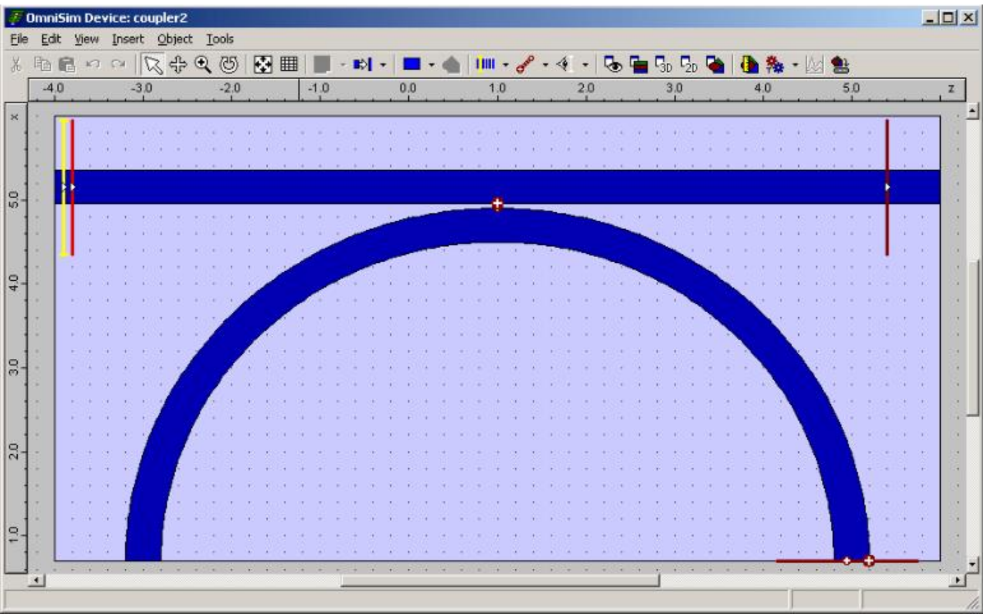

Figure 14: Device to calculate coupler response.

The output response of a coupler can be represented by K=cos^2(α) where α is given by

$$\alpha = \frac{\pi}{4}\left(\frac{\lambda}{\lambda_0}\right)^a \quad (6)$$

where λ_0 is the 50% coupling wavelength and a defines how fast the coupling changes with wavelength.

The coupler simulation together with the fitted data using equation 6 is shown in figure 15.

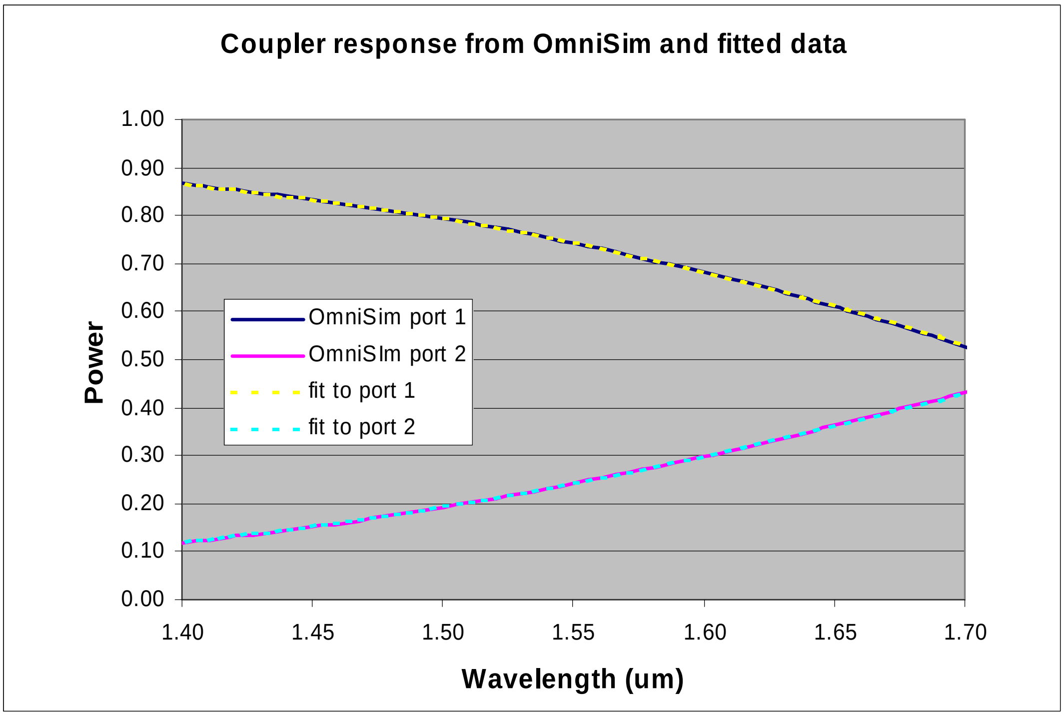

Figure 15: Coupler resonse from OmniSim and resulting fitted data

The effective index of the waveguide was calculated using FIMMWAVE. The effective index and the coupling coefficient can then be used in equation 4 to analyitically calculate the group delay of the ring resonator. The ring resonator has also been simulated using OmniSim and the phase response from OmniSim used to calculate the group delay. The comparison between the two sets of results is shown in figure 16.

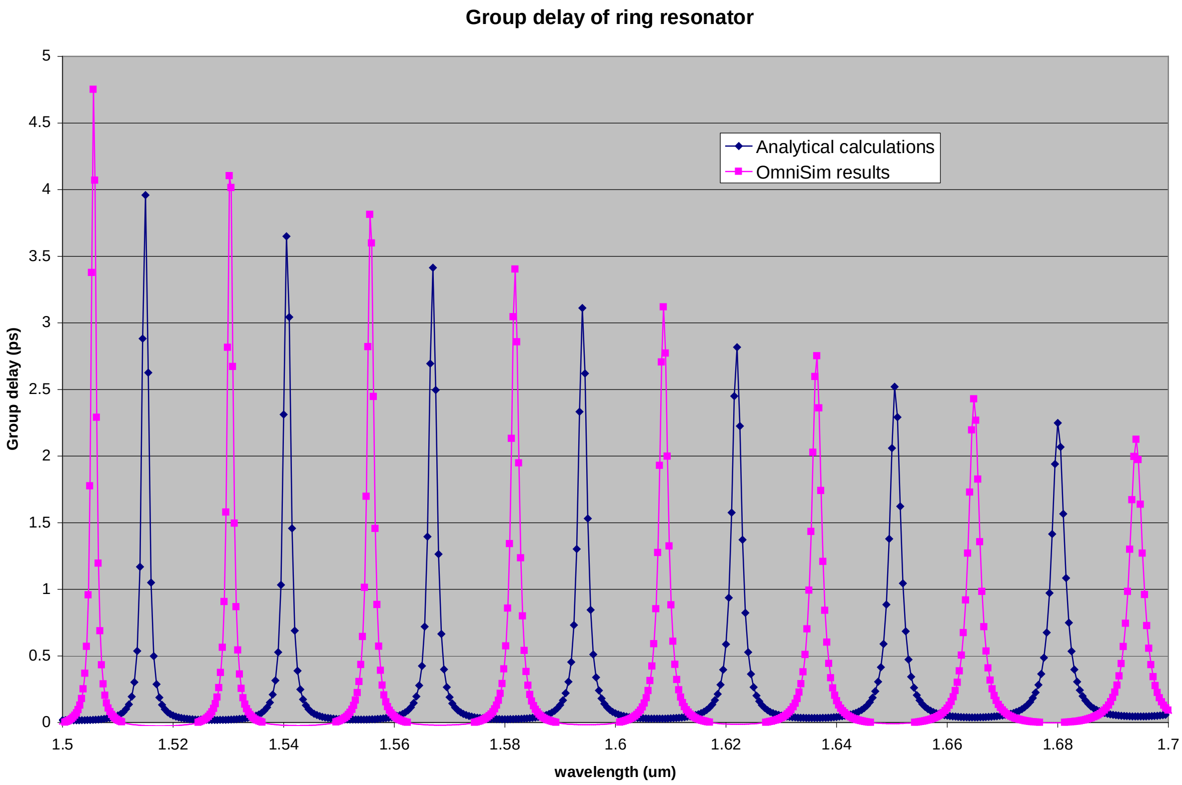

Figure 16: Comparison between OmniSim and analytical method for group delay of ring resonator

Although the OmniSim results show the same general trends as the analytical results, ie the peak width is similar and the peak decreases with wavelength, due to the increase in coupler response, there is very poor agreement in the peak position. In the analytical model, the radius of the ring was adjusted until the difference between the two curves was minimised. This required the ring radius to be increased to 4.058 um, which is comparable with the grid size of 0.05 um. The fit shown in figure 17 was obtained.

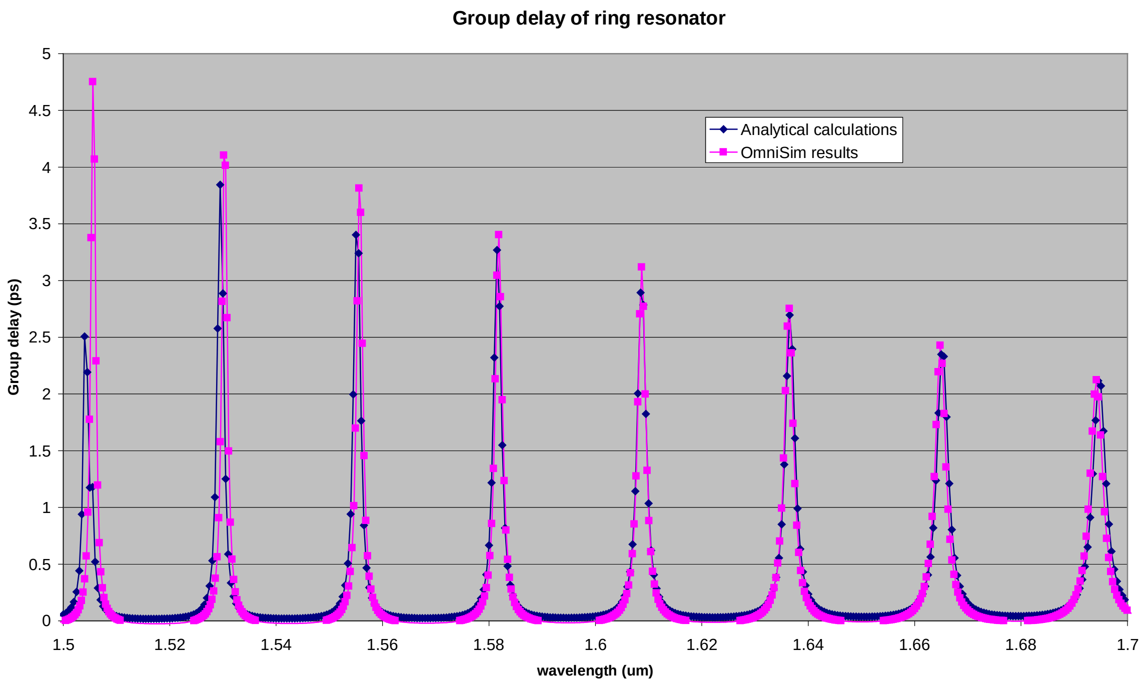

Figure 17: Comparison between OmniSim and analytical method after ring radius increased to 4.058 um

There is now excellent agreement across several free spectral ranges in both the height, width and position of the peak. To confirm that the discrepancy is due to the grid, the simulation was repeated using a 25 nm grid size. These simulations gave the result shown in figure 18, which were achieved using a ring radius of 4.018 um in the analytical model.

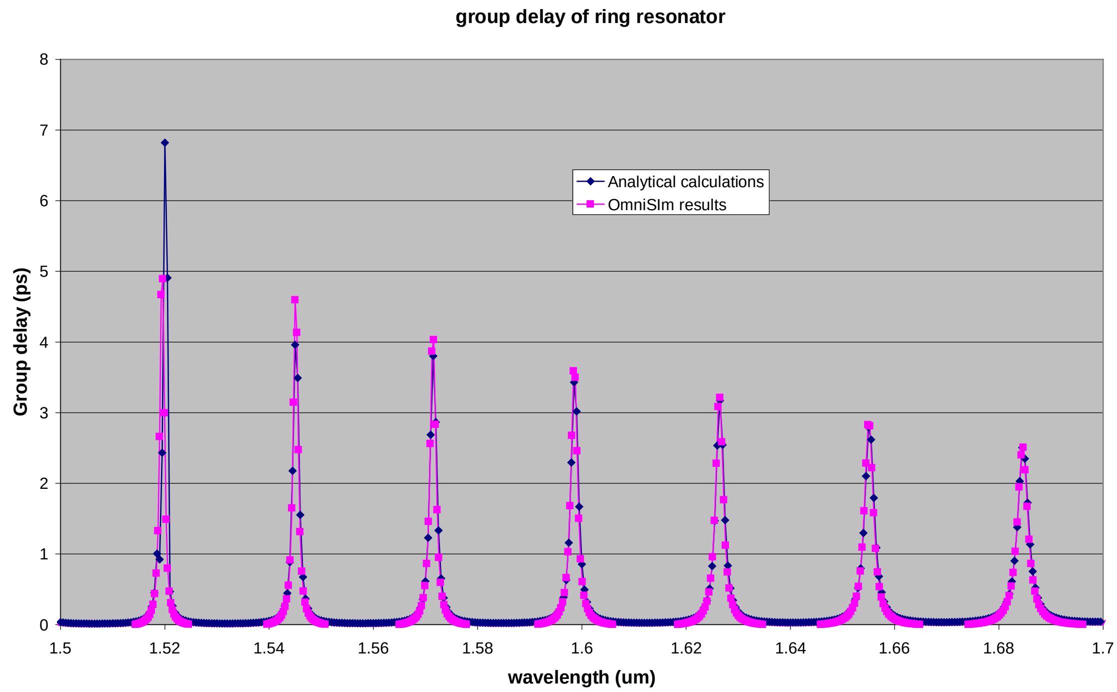

Figure 18: Comparison between using 25 nm step size and 4.018 um ring radius

Conclusions

The phase calculations and hence group delay calculations in OmniSim have been validated against FIMMWAVE, FIMMPROP and an analytical method for a range of test devices.

Provided that care is taken with the grid size and the PML settings, then it is possible to get excellent agreement for all of the test devices.