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DESIGN OF MULTI-LAYER THIN FILM PHOTONIC FILTERS US
[ABCD] TRANSMISION MATRIX

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DESIGN OF MULTI-LAYER THIN FILM PHOTONIC FILTERS USING [ABCD] TRANSMISION MATRIX

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Abstract:

A design technique employing [ABCD] transmission matrix has been developed for multi-layer thin film photonic crystal (PC) optical filters. A computer aided design program has been developed for the design of the pass and stop bands of cascaded multi-layer thin film stack structures. Cascaded PC consists of two PC's each having periodic alternating layer thickness defined at different wavelengths.

The core computational routine is based on a matrix formulation that computes the input and reflected wave amplitudes given the amplitude of the output wave, unity, and amplitude of the wave reflected from the output dielectric medium, assumed as zero, that is no wave incident on the cascaded PC from the output. By varying alternating layers of the PC designed wavelength, the number of layers, layer refractive index and the coupling layer thickness, the variation of the number of layers in each PC gives the greatest control of the half maximum input and reflected power bandwidths. Design control over a range of ~127nm and ~129nm for the half maximum input and reflected power bandwidths has been obtained corresponding to an attenuation range of 28dB and 8.71dB for input and reflected powers respectively.

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1 Introduction

Photonic Crystals (PC's) are 1, 2 and 3-D structures that have periodic dielectric distributions, i.e. the refractive index of the dielectric medium is periodic in one or more dimensions. Modern thin film multi-layer optical filters can be fabricated with brick-wall like structures using X-ray lithography[1] and several hundreds of such layers can be stacked on the same substrate thus the challenging problem is how to design such structures so as to tailor the optical filter passband or cut-off bands.

When electromagnetic (EM) waves propagate through such structures they may do so, without attenuation, for certain waves whose wavelength lies within certain energy bands. To describe the propagation of EM waves in PC's Maxwell's equations are cast as an eigen-problem. Existing numerical methods and techniques can be used to solve the eigen-problem and determine the eigenvalues that correspond to those wave vectors that are allowed to propagate through the PC with minimum attenuation.

The eigen-problems that model 1, 2 and 3-vectorial PC systems can be quite complex and so numerical computation often requires large amounts of computing power and memory. The difficulties in using existing numerical programs, coupled with their complexity and the experience and knowledge required to operate them successfully, makes them an unattractive choice for use in the analysis of simple 1-D PC's. Considering the relative simplicity of 1-D PC's (periodic alternating layers of different refractive index) compared to 2 and 3-D PC's one possible alternative analysis method is the transmission or ABCD matrix method. The ABCD matrix is a square unity matrix than can be used to determine the output magnitude of a single wave as it crossed the interface between two different refractive index mediums. By incorporating appropriate terms the phase or propagation delay undergone by the wave as it travels through a medium can also accounted for. The method can also be used inversely to calculate the input waves needed to generate a specific output power. This method does not require the solution of complex eigen-problems or Maxwell's equations and as such is not as computationally intensive as the other time-domain and frequency-domain method that is the FDTD and eigen-

[1] P. Kemeny and L.N. Binh " LIGA X-ray lithography and integrated photonic crystal photonics", Invited paper ACOFT 2004, Canberra Australia

decomposition. Because the filters designed in this paper are 1-D they are consequently applicable.

In this paper an alternative theoretical formulation to describe the propagation of plane waves in 1-D PC's has been developed using ABCD transmission matrices. The ABCD transmission matrices model the reflections and transmissions at the interfaces between different refractive index dielectric mediums and the propagation or phase delay experienced by EM waves as they travel through the dielectric medium. The ABCD transmission matrices model small periodic sections of the PC and are cascaded together to construct a matrix that describes the entire PC. Using this theory a relatively simple numerical simulation program, 'PC-cas-sim', has also been developed. This program simulates a cascaded PC that consists of two PC connected coupled via a single dielectric coupling layer. Users of the program can alter the cascaded PC system parameters that include the relative refractive index of alternate layers in the PC (i.e. the refractive index of each alternate layer can be individually specified), the thickness of these layers, the number of alternate layers in the PC, the wavelength at which layer thickness is specified or the desired operating wavelength, the refractive index of the coupling layer and the thickness of the coupling layer. Once the filter system parameters are specified the program outputs the amplitude of plane waves in the range, $1401\text{nm} \leq \lambda \leq 1600\text{nm}$, incident on and reflected from the first dielectric interface at the input (left hand side) of the PC Figure 2-15). The input wave amplitudes are determined using transmitted output waves (see Figure 2-15b), over the same range of wavelengths, whose amplitudes are unity. No reflected waves are assumed from the cascaded PC output, i.e. the input and output dielectric mediums are assumed to be semi infinite. By systematically and individually altering the system parameters many input simulation plots were obtained. The filter characteristics are analyzed with the variation in half maximum input and reflected power bandwidths and signal attenuation. In each set of data one system parameter was varied. It is determined that altering the number of layers in each PC allowed greatest overall bandwidth control with reasonable signal attenuation.

This paper is organized into four sections. Section 2 contains three sub sections. The first is an explanation of the theory involved in PC design and a detailed discussion of the theoretical background. The second section explores the eigen-problem that results when Maxwell's equations are cast this way and discusses existing numerical solution techniques. The third section provides a detailed explanation of the motivation behind the ABCD transmission approach. The first section in Section 3 presents a rigorous treatment of the theory behind the ABCD transmission matrix method and section two illustrates the workings and development of the 'PC-cas-sim' cascaded PC simulator program. Collated and analyzed results, obtained using the simulation program, are presented in the first part of Section 3.1 followed by a summary of the main bandwidth and attenuation findings in the second part of this section. Section3.2 contains a detailed discussion of the results, comparing them with theory, and explores the sources of experimental anomalies observed. Section 4 then give some concluding remarks and major findings of the paper work and suggestions for further work.

2 Theoretical development of ABCD transmission matrix and the simulator

This section describes the theoretical development of the ABCD matrix method and how it is applied to model PC's. Section 2.1 contains a detailed explanation of the ABCD transmission matrix theory developed from simple transmission/reflection interface, propagation delay and signal flow graph theory. It then modifies and extends the basic transmission matrix to model interface transmission/reflection and dielectric medium propagation delay for the entire PC. Section 2.2 gives a detailed description of the development and functionality of the computer aided program 'PC-cas-sim' for simulation of cascaded PC.

2.1 Theoretical development of the ABCD matrix method

Consider a wave of amplitude, A, incident on the interface between two semi-infinite lossless mediums of refractive index n_1 and n_2:

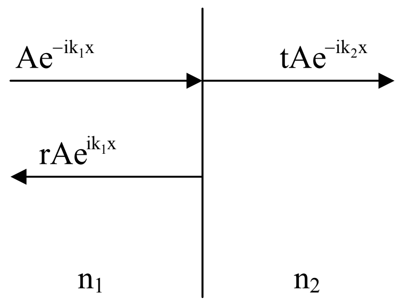


Figure 2-1 Transmission and reflection from an interface between two different dielectric media

The assumption that the mediums are semi-infinite implies that no wave is reflected from medium n_2. Part of the incident wave, Ae^{-ik_1x}, will be reflected by the interface between the two mediums giving the reflected wave, rAe^{ik_1x}, where r is the reflection coefficient, assuming normal incidence, given by:

$$r_{12} = \frac{n_1 - n_2}{n_1 + n_2} \tag{1}$$

Part of the incident wave will be transmitted, $t_{kl}Ae^{-jk_2x}$, where t_{kl} is the optical transmission coefficient from medium *k* to medium *l*, assuming normal incidence, given by:

$$t_{12} = \frac{2n_1}{n_1 + n_2} \tag{2}$$

Similarly, if the wave is incident from the other medium or their refractive indices are reversed (see Figure 2-2(a) and (b) below), the reflection and transmission coefficients, assuming normal incidence, become:

$$r_{21} = \frac{n_2 - n_1}{n_1 + n_2} \tag{3}$$

and

$$t_{21} = \frac{2n_2}{n_1 + n_2} \qquad (4)$$

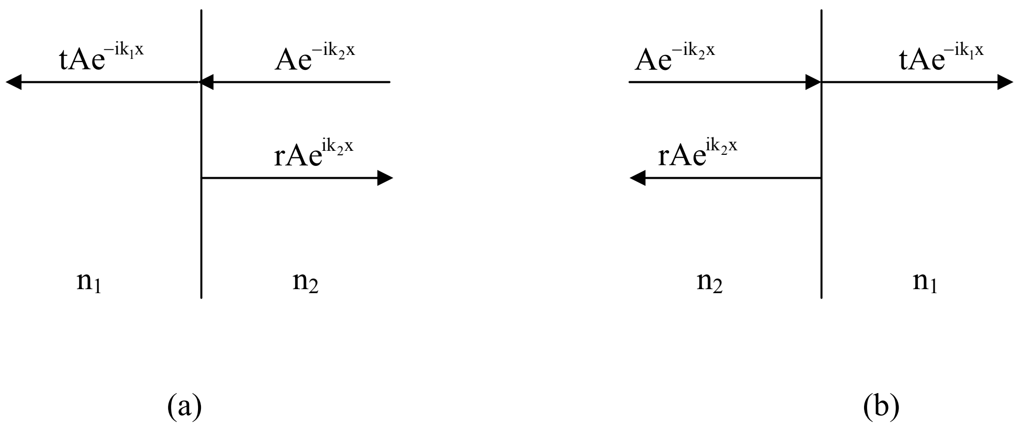


Figure 2-2 *The change in transmission and reflection coefficients when the direction of incidence is changes (a) or the refractive indices are reversed (b).*

If we introduce a third medium we have the structure shown below:

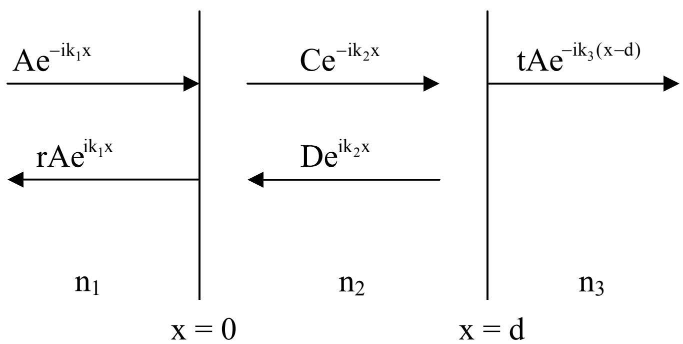


Figure 2-3 *Three medium dielectric structure showing reflections/transmissions and propagations of plane wave.*

At the interface located at x = 0 we have two incoming waves, Ae^{-ik_1x} and De^{ik_2x}, and two outgoing waves, rAe^{ik_1x} and Ce^{-ik_2x}. The amplitudes of these waves are given by the following relations:

$$C = t_{12}A + r_{12}D \qquad (5)$$

and

$$rA = r_{12}A + t_{21}D \qquad (6)$$

where r_{12}, r_{21}, t_{12}, t_{21} are the reflection coefficients representing reflections n_1 to n_2 and n_2 to n_1 and the transmission coefficients representing transmissions from n_1 to n_2 and n_2 to n_1 respectively.

Consider the interface at $x = d$ we find one incoming wave, Ce^{-ik_2x}, and two outgoing waves, De^{ik_2x} and $tAe^{-ik_3(x-d)}$. The relation between the amplitudes of these three waves is given by:

$$tA = t_{23}Ce^{-ik_2d} \qquad (7)$$

and

$$De^{ik_2d} = r_{23}Ce^{-ik_2d} \qquad (8)$$

where r_{23} is the reflection coefficients representing the reflection from n_2 to n_3 and t_{23} is the transmission coefficient representing transmission from n_2 to n_3.[i]

As the waves traveling through medium n_2 they undergo a phase change or propagation delay that is modeled as: Propagation delay or phase change = $e^{-i\phi}$ where $\phi = kL = \frac{2\pi}{\lambda}L$

The layer thickness, L, for a layer of refractive index, n, whose thickness is equal to one wavelength, λ of the incident wave, is given by:

$$L_{\lambda} = \frac{\lambda}{n} \qquad (9)$$

A layer thickness equal to half the wavelength of the incident wave is similarly given by:

$$L_{\frac{\lambda}{2}} = \frac{\left(\frac{\lambda}{n}\right)}{2} \qquad (10)$$

Consider a simple system (similar to Figure 2-1) consisting of two different mediums of different refractive index with two incoming and two outgoing waves:

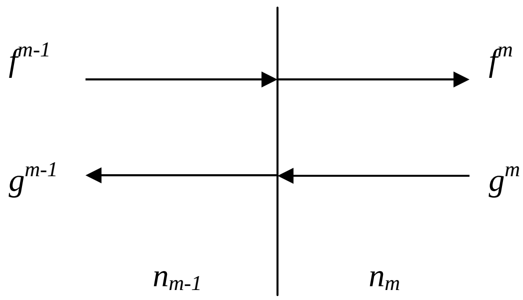


Figure 2-4 *Interface between two dielectric system with input waves f^{m-1} and g^m and output waves g^{m-1} and f^m*

The waves f^{m-1} and g^m are the waves incident on the interface from the $n_{(m-1)}$ *and* n_m refractive mediums respectively. The wave g^{m-1} is the sum of the portion of wave f^{m-1} reflected from *the* $n_{(m-1)}$ side of the interface and the portion of wave g^m transmitted through the interface from the n_m side of the interface. We can model this interaction quite easily using a signal flow graph similar to that used in digital signal processing[ii]:

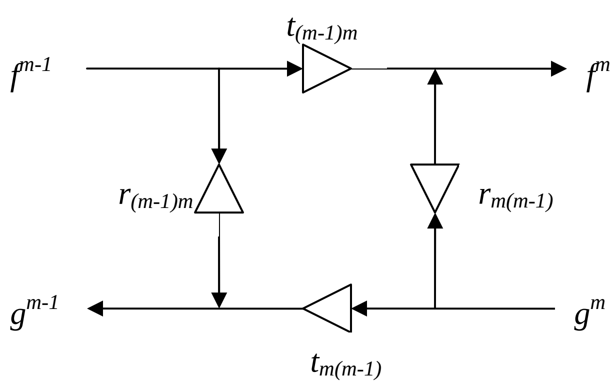


Figure 2-5 *Signal flow graph modeling interface transmission/reflection*

Where f^{m-1}, f^m, g^{m-1} *and* g^m are defined above; $t_{(m-1)m}$ *and* $t_{m(m-1)}$ are the transmission coefficients representing transmissions from $n_{(m-1)}$ to n_m and n_m to $n_{(m-1)}$ respectively; $r_{(m-}$

$_{1)m}$ and $r_{m(m-1)}$ are the reflection coefficients representing reflection from $n_{(m-1)}$ to n_m and n_m to $n_{(m-1)}$ respectively

Applying the signal flow graph technique [2] we can obtain the output waves as a function of the input waves as follows:

$$f^m = f^{m-1} t_{(m-1)m} + g^m r_{m(m-1)} \quad (11)$$

$$g^{m-1} = g^m t_{m(m-1)} + f^{m-1} r_{(m-1)m} \quad (12)$$

These equations can be rearranged to express the input waves as a function of the output waves:

$$f^{m-1} = \frac{f^m}{t_{(m-1)m}} - \frac{g^m r_{m(m-1)}}{t_{(m-1)m}} \quad (13)$$

$$g^{m-1} = g_m \left[t_{m(m-1)} - \frac{r_{m(m-1)} r_{(m-1)m}}{t_{(m-1)m}} \right] + f^m \frac{r_{(m-1)m}}{t_{(m-1)m}} \quad (14)$$

In matrix form we have:

$$\begin{bmatrix} f^{m-1} \\ g^{m-1} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{t_{(m-1)m}} & -\dfrac{r_{m(m-1)}}{t_{(m-1)m}} \\ \dfrac{r_{(m-1)m}}{t_{(m-1)m}} & \dfrac{t_{m(m-1)} t_{(m-1)m} - r_{m(m-1)} r_{(m-1)m}}{t_{(m-1)m}} \end{bmatrix} \begin{bmatrix} f^m \\ g_m \end{bmatrix} \quad (15)$$

The [ABCD] representing the transmission/reflection of plane waves at normal incidence to the interface that exists between two dielectric media that have refractive indices, n_{m-1} and n_m is thus given by:

$$[ABCD] = \begin{bmatrix} \dfrac{1}{t_{(m-1)m}} & -\dfrac{r_{m(m-1)}}{t_{(m-1)m}} \\ \dfrac{r_{(m-1)m}}{t_{(m-1)m}} & \dfrac{t_{m(m-1)} t_{(m-1)m} - r_{m(m-1)} r_{(m-1)m}}{t_{(m-1)m}} \end{bmatrix} \quad (16))$$

where the matrix parameters A, B, C and D of the transmission/reflection matrix are defined as:

$$A = \frac{1}{t_{(m-1)m}};\ B = -\frac{r_{m(m-1)}}{t_{(m-1)m}};\ C = \frac{r_{(m-1)m}}{t_{(m-1)m}} \text{ and } D = \frac{t_{m(m-1)}t_{(m-1)m} - r_{m(m-1)}r_{(m-1)m}}{t_{(m-1)m}}$$

Now consider the optical system in Figure 2-6

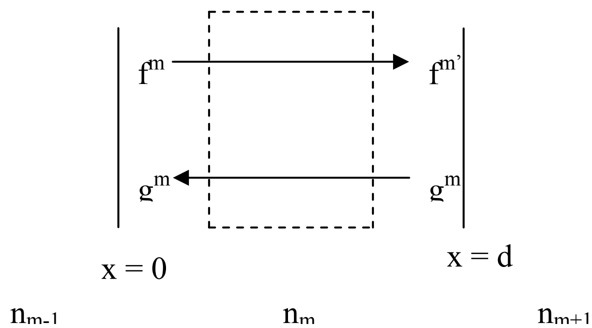


Figure 2-6 Schematic showing waves propagating through medium with refractive index n_m

The waves f^m and g^m are the waves leaving and entering (respectively) the n_m/n_{m-1} interface at $x = 0^+$. The waves $f^{m'}$ and $g^{m'}$ are the waves entering and leaving (respectively) the n_m/n_{m+1} interface at $x = d^-$. As waves propagate through the imaginary box (dashed line) drawn in medium n_m they experience a one way propagation delay: Propagation delay = $e^{-i\phi x}$ with $\phi = kL = \frac{2\pi}{\lambda} d$. As for the transmission/reflection interface we can model this propagation delay by signal flow graph as:

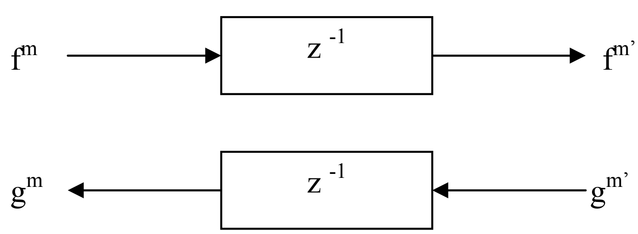


Figure 2-7 Signal flow graph model of the propagation delay experienced by a plane wave traveling though a uniform homogeneous dielectric medium. $z^{-1} = e^{-i\phi x}$

Assuming a lossless medium there are no reflections or absorptions as the wave propagates through a medium and so no coupling parameters Figure 2-7. Using the signal flow graph we can obtain the output waves as a function of the input waves as follows:

$f^{m'} = f^m z^{-1}$ (17)

$g^m = g^{m'} z^{-1}$ (18)

(18) can be used to express the input waves as a function of the output waves:

$$g^{m'} = \frac{g^m}{z^{-1}} \qquad (19)$$

These two equations can be expressed in matrix form as:

$$\begin{bmatrix} f^{m'} \\ g^{m'} \end{bmatrix} = \begin{bmatrix} z^{-1} & 0 \\ 0 & z^{1} \end{bmatrix} \begin{bmatrix} f^{m} \\ g_{m} \end{bmatrix} \qquad (20)$$

The ABCD matrix that describes the propagation delay or phase change undergone by plane waves of wavelength, λ, propagating through a dielectric medium of refractive index, n, and thickness, *L*, is thus given by:

$$[\text{ABCD}] = \begin{bmatrix} z^{-1} & 0 \\ 0 & z^{1} \end{bmatrix} \qquad (21)$$

where $z^{-1} = e^{-i\phi x}$ and $\phi = kL = \frac{2\pi}{\left(\frac{\lambda}{n}\right)} L$ and the matrix parameters, A, B, C and D, of the propagation delay matrix are defined as: $A = z^{-1}$; $B = 0$; $C = 0$ *and* $D = z^{1}$. We can now combine the signal flow graphs that model interface transmission/reflection and propagation delay to construct a larger signal flow graph that models both properties:

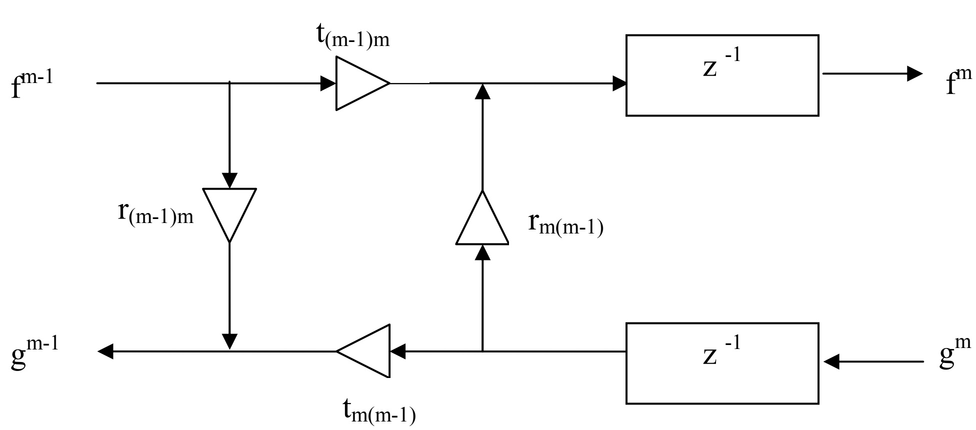


Figure 2-8 Signal flow graph representation of a transmission/reflection interface and the propagation delay undergone by a plane wave traveling through a dielectric medium.

This signal flow graph models the transmissions/reflections and the propagation delays experienced by plane waves propagating through the boxed section of the dielectric structure below:

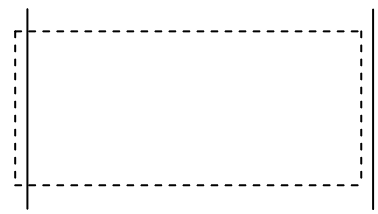


Figure 2-9 *Region of dielectric structure modeled by signal flow graph in figure 3.8) (dashed box). Note that the boxed section above extends from $x = 0^+$ to $x = d^-$.*

A system of equations can now be formed using the signal slow graph in Figure 2-8:

$$f^m = f^{m-1} t_{(m-1)m} + g^m r_{m(m-1)} z^{-1} \qquad (22)$$

$$g^{m-1} = g^m t_{m(m-1)} z^{-1} + f^{m-1} r_{(m-1)m} \qquad (23)$$

We can rearrange these equations to express the input waves as a function of the output waves:

$$f^{m-1} = \frac{f^m}{t_{(m-1)m}} - \frac{g^m r_{m(m-1)} z^{-1}}{t_{(m-1)m}} \qquad (24)$$

$$g^{m-1} = g_m \left[t_{m(m-1)} z^{-1} - \frac{r_{m(m-1)} r_{(m-1)m}}{t_{(m-1)m}} z^{-1} \right] + f^m \frac{r_{(m-1)m}}{t_{(m-1)m}} \qquad (25)$$

These two equations can be expressed in matrix form as:

$$\begin{bmatrix} f^{m-1} \\ g^{m-1} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{t_{(m-1)m}} & -\dfrac{r_{m(m-1)}z^{-1}}{t_{(m-1)m}} \\ \dfrac{r_{(m-1)m}}{t_{(m-1)m}} & \dfrac{t_{m(m-1)}t_{(m-1)m} - r_{m(m-1)}r_{(m-1)m}}{t_{(m-1)m}} z^{-1} \end{bmatrix} \begin{bmatrix} f^{m} \\ g_{m} \end{bmatrix} \qquad (26)$$

The ABCD matrix that describes the plane waves entering and leaving a system that consists of two dielectric mediums, of refractive index n_{m-1} and n_m, and contains one reflective/transmissive interface and a region of dielectric material, of refractive index n_m, through which the waves pass, and consequently undergo propagation delay, is thus given by:

$$[\text{ABCD}] = \begin{bmatrix} \dfrac{1}{t_{(m-1)m}} & -\dfrac{r_{m(m-1)}z^{-1}}{t_{(m-1)m}} \\ \dfrac{r_{(m-1)m}}{t_{(m-1)m}} & \dfrac{t_{m(m-1)}t_{(m-1)m} - r_{m(m-1)}r_{(m-1)m}}{t_{(m-1)m}} z^{-1} \end{bmatrix} \qquad (27)$$

A 1-D PC can be represented as follows:

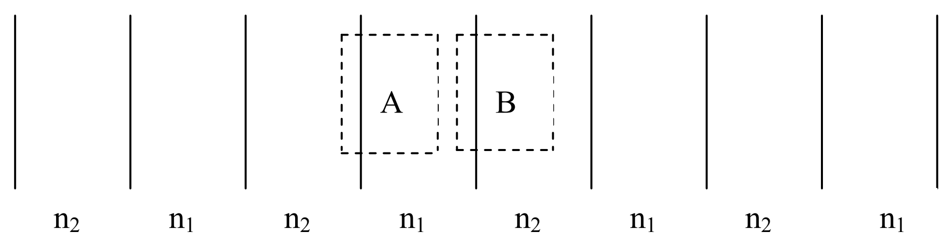


Figure 2-10 *Schematic representation of a 1-D PC showing repeated regions of interest (Dashed boxes).*

The imaginary box A drawn in the diagram above is a region of the PC whose transmission/reflection and propagation delay properties can be modeled by the ABCD transmission/reflection/propagation delay matrix, with a suitable choice of parameters, above. The region encompassed by imaginary box B in the above figure can similarly be modeled, using appropriately chosen parameters. If we denote f'' and g'' as the output and input on the right hand side of imaginary box B, *f'* and *g'* as the input and output respectively at the left hand side of imaginary box B and the output and input respectively on the right hand side of imaginary box A and f and g as the input and output respectively at the left hand side of imaginary box A (see Figure 2-11 below) we can show that:

$$\begin{bmatrix} f \\ g \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} f' \\ g' \end{bmatrix} \qquad \text{and} \qquad \begin{bmatrix} f' \\ g' \end{bmatrix} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \begin{bmatrix} f'' \\ g'' \end{bmatrix}$$

where $\begin{bmatrix} \mathrm{A} & \mathrm{B} \\ \mathrm{C} & \mathrm{D} \end{bmatrix}$ and $\begin{bmatrix} \mathrm{A'} & \mathrm{B'} \\ \mathrm{C'} & \mathrm{D'} \end{bmatrix}$ are the [ABCD] transmission/reflection/propagation delay matrices that describe the regions encompassed by imaginary boxes A and B in figure 3.10).

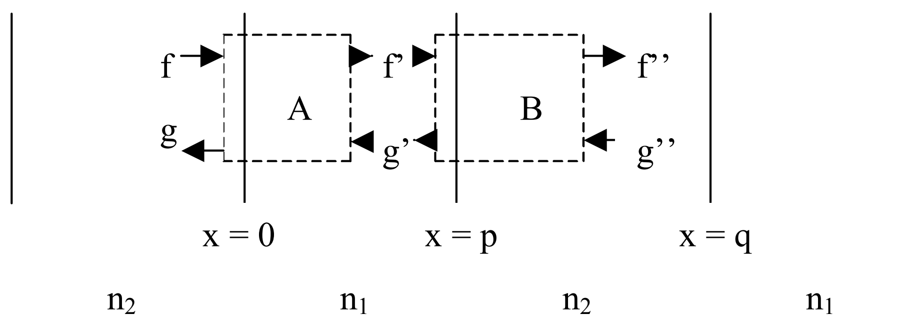


Figure 2-11 *The Input and output waves for sequential cascaded layers in a 1-D PC. (Note that imaginary box A extends from $x = 0^-$ to $x = p^-$ and imaginary box B extends from $x = p^-$ to $x = q^-$.*

Using these definitions we can show that the input, to the imaginary box A, can be expressed in terms of the output, of imaginary box B. Substituting in $\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \begin{bmatrix} f'' \\ g'' \end{bmatrix}$ for $\begin{bmatrix} f' \\ g' \end{bmatrix}$ in equation x) above we have:

$$\begin{bmatrix} f \\ g \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \begin{bmatrix} f'' \\ g'' \end{bmatrix} \qquad (28)$$

From this result it can be seen that the input to a PC, constructed by cascading regions similar to that encompassed by imaginary boxes A and B in Figure 2-10) above, can be expressed as a function of its output by multiplying the output by the product of all the ABCD transmission/reflection/propagation delay matrices for all regions in the PC.

Consider the six-layered PC structure shown below where the first and last layers are semi-infinite:

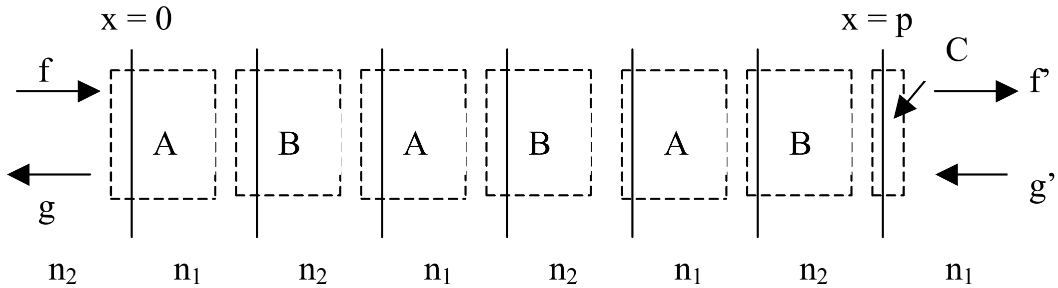


Figure 2-12 *Six layered 1-D PC showing input/output waves and repeated dielectric regions (dashed boxes A, B) and final dielectric interface (dashed box C).*

In this structure there is no reflection from the last layer, i.e. the amplitude of $g' = 0$. If we assume that the output wave amplitude, $f' = 1$ then using the ABCD matrix method devised above it can be shown that the input wave amplitudes, f and g, are given by:

$$\begin{bmatrix} f \\ g \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix}\begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix}\begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix}\begin{bmatrix} A'' & B'' \\ C'' & D'' \end{bmatrix}\begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (29)$$

where $\begin{bmatrix} A & B \\ C & D \end{bmatrix} =$ The *[ABCD]* modeling the region of the crystal encompassed by imaginary box A in figure 3.12) – that is the transmission/reflection/propagation delay matrix

$\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} =$ The *[ABCD]* modeling the region of the crystal encompassed by imaginary box B in Figure 2-12.

$\begin{bmatrix} A'' & B'' \\ C'' & D'' \end{bmatrix} =$ The *[ABCD]* modeling reflections/transmissions across the last n_2/n_1 interface on the right hand side of Figure 2-12 (the region of the crystal encompassed by imaginary box C)

Note that the ABCD transmission/reflection matrix modeling reflections/transmissions across the last n_2/n_1 interface on the right hand side of figure 3.12), $\begin{bmatrix} A'' & B'' \\ C'' & D'' \end{bmatrix}$, must be included in the calculation to only account for transmission/reflection. Since we take the output at $x = p^+$, and similarly the input at $x = 0^-$, no propagation delay needs to be accounted for.

In general, the inputs of an N layered PC structure can be expressed, as a function of its outputs, as:

$$\begin{bmatrix} f \\ g \end{bmatrix} = \left[\begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix}\right]^{\left(\frac{N}{2}\right)}\begin{bmatrix} A'' & B'' \\ C'' & D'' \end{bmatrix}\begin{bmatrix} f' \\ g' \end{bmatrix} \qquad \text{(where } N \geq 2\text{)} \qquad (30)$$

We can design a 100 layer PC, that has a structure similar to that in Figure 2-12 where $n_1 = 1.45$ and $n_2 = 1.46$, using $\frac{\lambda}{2}$ layer thicknesses at 1495nm. The input wave amplitudes to the PC, assuming an output of $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$(i.e. unity transmitted wave and no reflected wave), can be calculated using equation (30) above, for all wavelengths $1401nm \leq \lambda \leq 1600nm$ to obtain:

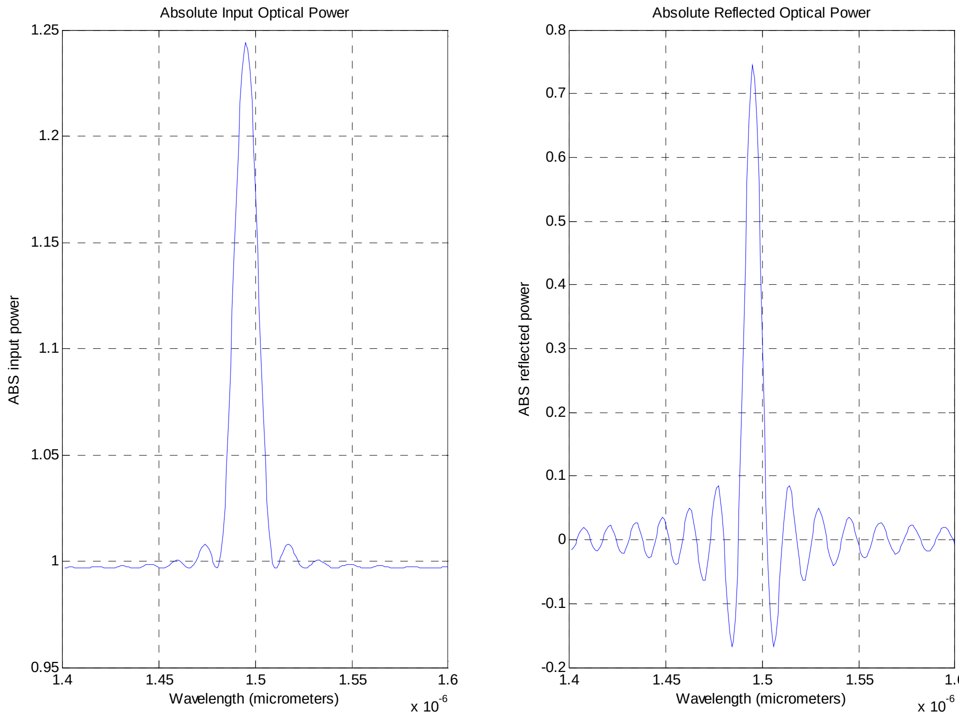


Figure 2-13 Pc-cas-sim simulation plot of PC with 100 layers, $n_1 = 1.45$ and $n_2 = 1.46$, and $\frac{\lambda}{2}$ layer thicknesses at 1495nm showing the input and reflected absolute power over the wavelength range $1401\text{nm} \leq \lambda \leq 1600\text{nm}$.

This figure illustrates that for wavelengths close to the wavelength used to design the $\frac{\lambda}{2}$ thick alternate layers we have increased reflection or reduced transmission. If we consider the wavelengths transmitted, the PC can be thought of as behaving like band reject filter; those wavelengths that lie close to the wavelength used to design the PC's layers are attenuated. If we examine the wavelengths reflected, the PC seems to behaving as a band pass filter; there is an attenuation of those wavelengths that lie away from the wavelength used to design the PC's layers.

It is now possible to design another 100 layer PC, that has the same structure but instead we design the $\frac{\lambda}{2}$ layer thickness at 1505nm and use $n_1 = 1.45$ and $n_2 = 1.46$. The input wave amplitudes, required to obtain output wave amplitudes of unity, and the reflected wave amplitudes, for $1401nm \leq \lambda \leq 1600nm$ are shown below:

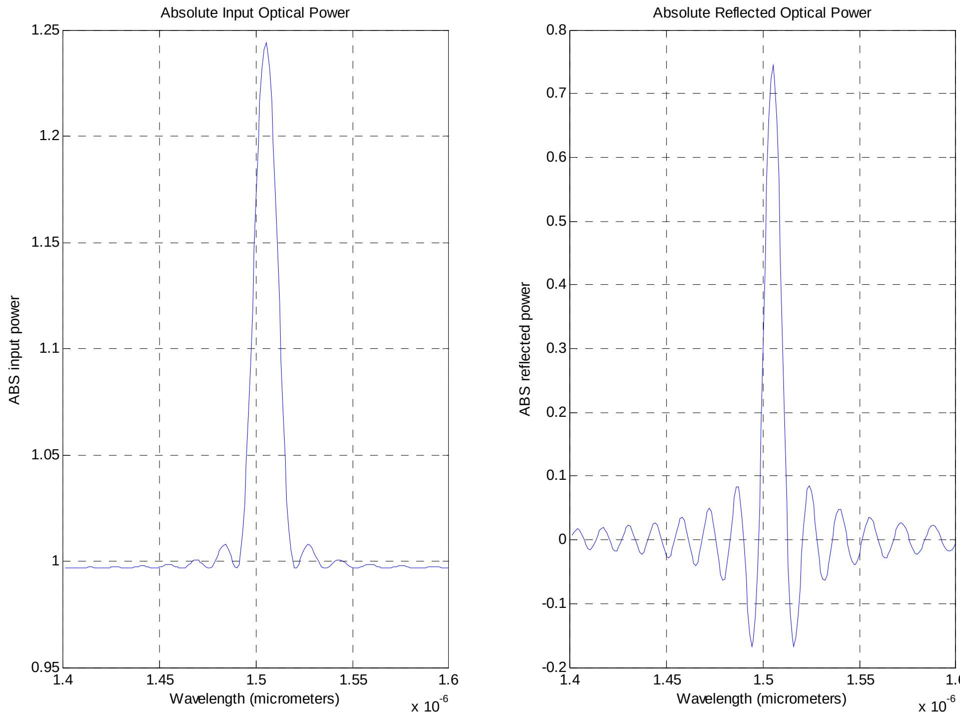
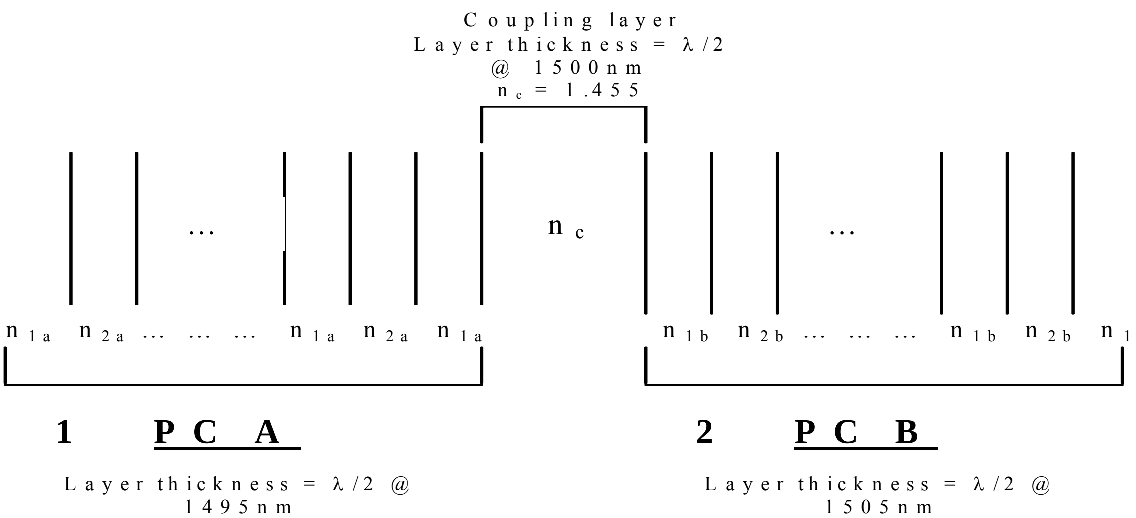


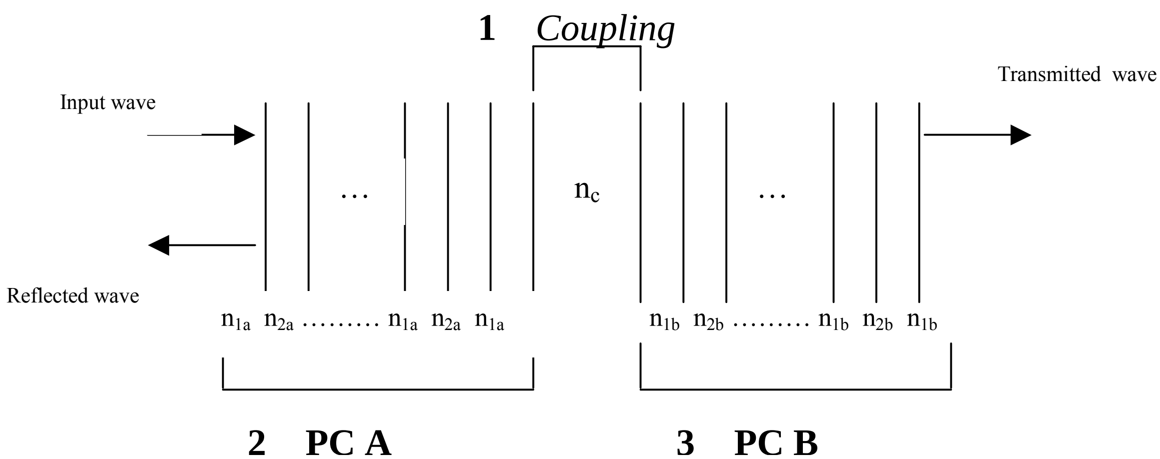
Figure 2-14 *Simulation plot of PC with 100 layers,* $\frac{\lambda}{2}$ *layer thickness at 1505nm,* $n_1 =$ *1.45 and* $n_2 = 1.46$ *showing the input and reflected absolute power over the wavelength range 1401nm* $\leq \lambda \leq$ *1600nm. Note that this figure has an identical form to that in figure 3.13) except that the center frequency has been shifted to 1505nm.*

We can cascade the two photonic crystals together using a coupling layer consisting of a single dielectric layer, of refractive index $n_c = 1.455$, that has a $\frac{\lambda}{2}$ layer thickness at 1500nm. For symmetry we add an extra n_1 layer to the right of the coupling layer and to the left of the first photonic crystal:



(a)

(a)



(b)

Figure 2-15a Symmetrical cascaded PC with coupling layer and (b) Definition of input and output waves for the cascaded PC.

This resultant cascaded PC has and input/reflected wave amplitudes (with unit amplitude output transmitted waves (over the region $1401nm \leq \lambda \leq 1600nm$)).

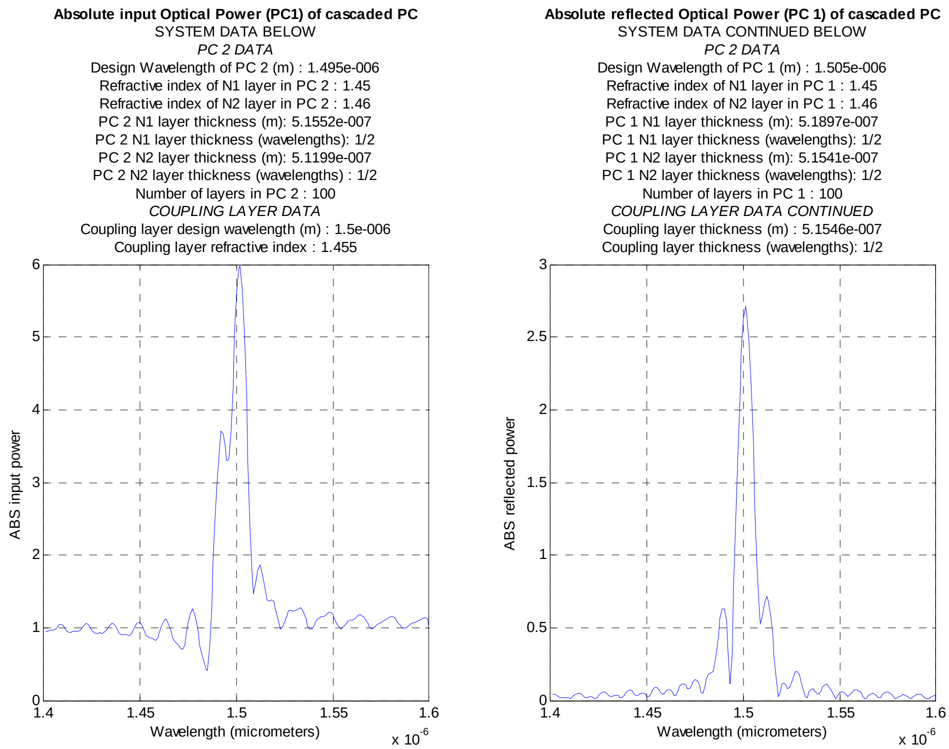


Figure 2-16 *Pc-cas-sim simulation plot of a cascaded PC, using the design specifications from figure 3.15a), showing the input and reflected absolute power over the wavelength range 1401nm* $\leq \lambda \leq$ *1600nm*

From Figure 2-16 we see that the range of wavelengths that undergo heavy attenuation upon reflection has been increased. Similarly the range of transmitted wavelengths that undergo significant attenuation has been increased. In other words, the cascaded PC has an increased bandwidth in the band pass reflected output and band reject transmitted output bands.

Half maximum power bandwidth measurements are made at half the power of the main peak in Figure 2-13, Figure 2-14 and Figure 2-16. This same measurement technique is used for all simulation plots obtained. The power of the main peak is taken relative to an absolute value of 1 for absolute input powers and 0 for absolute reflected powers. An example of the bandwidth measurement position is shown in Figure 2-17 below using the plot from Figure 2-14.

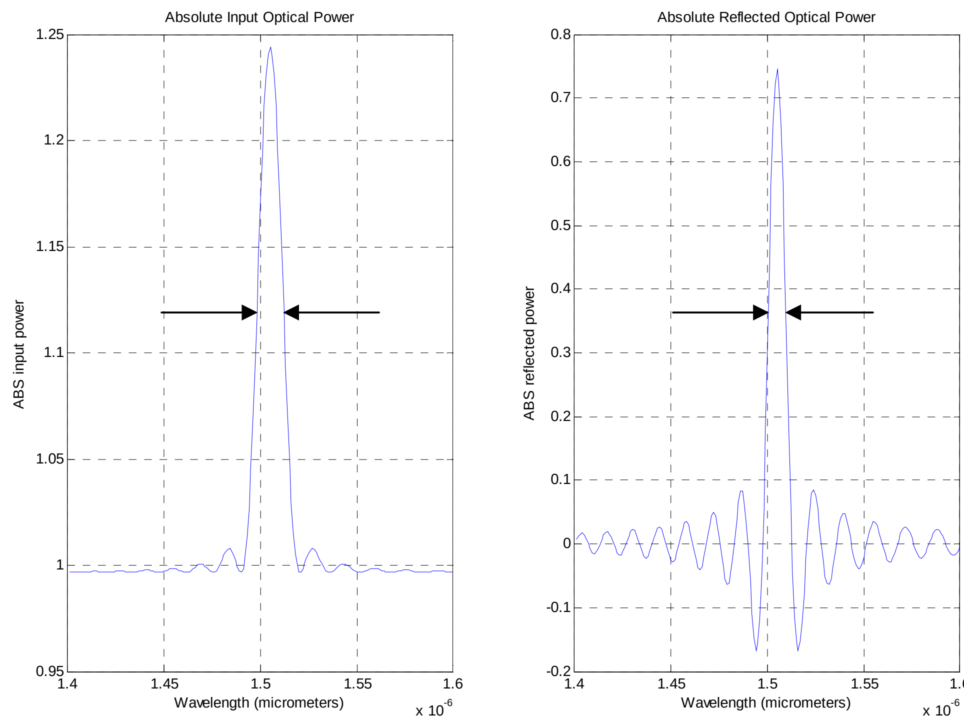


Figure 2-17 *Example of bandwidth measurements for absolute input and reflected power plots.*

Attenuation is determined for input absolute powers using the power of the main peak relative to the absolute power of the transmitted wave, unity. Attenuation is determined for reflected absolute powers using the power of the reflected absolute power main peak relative to the power of the main peak of the input absolute power.

2.2 Development of MATLAB simulation program, "PC-cas-sim"

The product of all ABCD matrices for each layer in a PC must be calculated before the input to the PC can be determined from its output. PCs being investigated may have 10's or 100's of layers and often we desire their input, for a given output, over a range of wavelengths. To avoid a disjoint and irregular curve input powers should be determined using wavelengths separated by ~1nm. For a 200nm range of wavelengths, for example, this equates to ~200 different calculations (using different wavelengths) of the system. The need to calculate the product of such a large number of transmission/reflection and propagation delay matrices, in addition to having to repeat the process a large number of time to account for each individual wavelength, means that task is not one to be performed manually. Such a computationally intensive task is well suited to evaluation using a computer. Since all calculations are essentially matrix multiplications a mathematics software package would be an invaluable tool to help solve the equations.

MATLAB can be used to perform matrix calculations, manipulate matrices, plot data and functions; design user interfaces and is capable of interfacing with computer programs written in other programming languages. MATLAB contains a Maple symbolic engine that makes a computer algebra system as well. MATLAB has pervaded industry and academia and is used by over one million people world wide.[iii] Because of its inherent strengths in calculating matrix equations MATLAB was the computing environment chosen to implement a PC simulation program.

The PC simulation program, "Pc-cas-sim" for a complete listing of the program code simulates the cascaded PC shown in Figure 2-15. It computes the input and reflected absolute optical power needed to obtain an output absolute optical power of unity. The program is used to determine the cascaded PC input over a range of operational wavelengths. With a minor modification the evaluation wavelength range can be changed. The cascaded PC consists of two different 1-D PC coupled by a coupling layer. Modifiable system parameters (and a brief description of each) include:

- Optical filter PC 1:
    - Specify the desired wavelength: Wavelength used to determine layer thickness
    - Layer refractive index: Refractive index of each periodic alternating layer in the PC ; n_{1a} can be varied to any value; n_{2a} can be varied to any value
    - Layer thickness: The thickness of each periodic alternate layer; Thickness is defined (e.g. $\lambda/2$, $\lambda/4$) and then the actual thickness is calculated using the design wavelength and layers refractive index.
    - Number of layers in the PC: Sets the number of stratified layers in the PC; E.g. one layer implements one layer of refractive index, n_1, stacked on one layer of refractive index, $n_{2;}$ NOTE: a 10 layer structure consists of 10 layers of the n_1/n_2 layer combination, i.e. PC consists of 20 layers of

dielectric mediums with alternating refractive index, $n_{1a}/n_{2a}/n_{1a}/n_{2a}/n_{1a}/n_{2a}/\ldots$ Etc.

- Optical filter PC 2
  - Design wavelength: Wavelength used to determine layer thickness
  - Layer refractive index: Refractive index of each periodic alternating layer in the PC ; n_{1b} can be varied to any value; n_{2b} can be varied to any value
  - Layer thickness: The thickness of each periodic alternate layer; Thickness is defined (e.g. $\lambda/2$, $\lambda/4$) and then the actual thickness is calculated using the design wavelength and the layers refractive index.
  - Number of layers in the PC: Sets the number of stratified layers in the PC: E.g. one layer implements one layer of refractive index, n_1, stacked on one layer of refractive index, n_2; NOTE: a 10 layer structure consists of 10 layers of the n_1/n_2 layer combination, i.e. PC consists of 20 layers of dielectric mediums with alternating refractive index, $n_{1b}/n_{2b}/n_{1b}/n_{2b}/n_{1b}/n_{2b}/\ldots$ Etc.; NOTE: Design wavelength, layer refractive indices, layer thicknesses and number of layers are specified independently for each PC; E.g. A design wavelength of 1450nm specified for PC 1 is NOT the design wavelength of PC 2, the two are specified independently; All other PC system parameters are similarly specified independently.
- Coupling layer
  - Design wavelength: The wavelength used to specify the coupling layers thickness
  - Refractive index: The refractive index of the dielectric medium used to construct the coupling layer
  - Coupling layer thickness: The thickness of the coupling layer, determined using the coupling layer design wavelength and refractive index

If no values for the above parameters are specified then the default values, shown below, are used: Default cascaded PC system parameter values

- Optical filter PC 1
  - Design wavelength: $\lambda = 1502nm$
  - Layer refractive index: $n_{1a} = 1.495$ and $n_{2a} = 1.505$
  - Layer thickness: $L_{1a} = \frac{\left(\frac{\lambda}{n_{1a}}\right)}{2}$ where λ = PC 1 design wavelength; $L_{2a} = \frac{\left(\frac{\lambda}{n_{2a}}\right)}{2}$ where λ = PC 1 design wavelength Number of layers in PC 1; N = 100 (200 stratified layers of alternating refractive index).
- Optical filter PC 2
  - Design wavelength: $\lambda = 1498nm$
  - Layer refractive index: $n_{1b} = 1.495$; $n_{2b} = 1.505$
  - Layer thickness : $L_{1b} = \frac{\left(\frac{\lambda}{n_{1b}}\right)}{2}$ where λ = PC 2 design wavelength; $L_{2b} = \frac{\left(\frac{\lambda}{n_{2b}}\right)}{2}$ where λ = PC 2 design wavelength Number of layers Number of layers in PC 2; N = 100 (200 stratified layers of alternating refractive index)
- Coupling layer
  - Design wavelength: $\lambda = 1500nm$
  - Refractive index: $n_c = 1.5$

- Coupling layer thickness: $L_c = \dfrac{\left(\dfrac{\lambda}{n_c}\right)}{2}$ where λ = coupling layer design wavelength

Once system parameters have been specified matrix multiplication, to calculate the input over the wavelength range, 1401nm $\leq\lambda\leq$ 1600nm, can be performed. The core matrix multiplication loop of the PC-cas-sim program calculates as follows: (i) Calculate the input just before a n_1/n_2 interface using the output just before the next n_2/n_1 interface (ii) Calculate the input just before a n_2/n_1 interface using the output (the input just calculated) just before the next n_1/n_2 interface (iii) Repeat N times and (iv) See Figure 2-11 above

Due to the extra layers required to make the cascaded PC symmetric (i.e. same refractive index material at input/output and either side of the coupling layer (see Figure 2-15) the matrix computational procedure is as follows: (i) Calculate the input to the first n_{2b}/n_{1b} interface (right hand side of Figure 2-15) using the output initial conditions (transmitted wave amplitude = 1, reflected wave amplitude = 0) (ii) Use the core matrix multiplication loop, described above, N times, using PC 2 parameter values (iii) Calculate propagation delay through N_{2b} layer (iv) Calculate transmission/reflection across N_{1b}/N_{2b} interface (v) Calculate propagation delay through N_{1b} layer (vi) Calculate transmission/reflection across N_c/N_{1b} interface and (vii) Calculate propagation delay through N_c layer (viii) Calculate transmission/reflection across N_{1a}/N_c interface (ix) Calculate propagation delay through N_{1a} layer (x) Use the core matrix multiplication loop, described above, N times, using PC 1 parameter values (xi) Calculate propagation delay through N_{2a} layer (xii) Calculate transmission/reflection across N_{1a}/N_{2a} interface.

The input matrix that results from this series of calculations is a 2×200 input matrix whose 1st row values are the absolute input powers required to obtain an absolute output power of unity for wavelengths separated by 1nm over the range 1401nm $\leq\lambda\leq$ 1600nm. Similarly, the 2nd row values are the absolute reflected power reflected from the cascaded PC, for wavelengths separated by 1nm over the range 1401nm $\leq\lambda\leq$ 1600nm, when the input power is that of the 1st row. These results can be plotted, for all wavelengths in the 1401nm $\leq\lambda\leq$ 1600nm range, to obtain plots similar to those of Figure 2-13, Figure 2-14 and Figure 2-15(a). The input and output waves for the cascaded PC are defined in Figure 2-159b).

3 Simulation Results

This section presents the collated findings of all the PC simulations performed. Section 3.1 contains data plots of the half maximum power bandwidths and input and reflected absolute power attenuation for each set of results, where one system parameter is varied as the others remain constant. A summary of the simulated results is given in Section 3.2. Typical simulated optical filters characteristics are included in the Appendix.

3.1 Cascaded PC Bandwidth and Attenuation simulation results

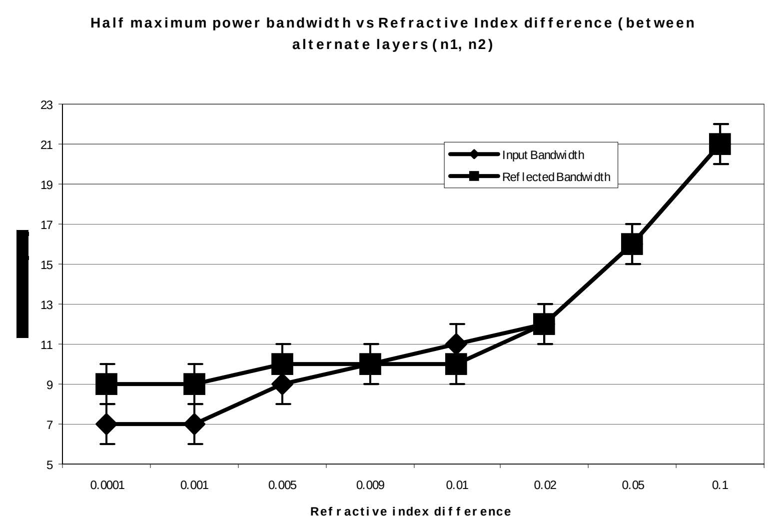


Figure 3-1 *A plot of the cascaded PC bandwidth, at half maximum input and reflected power, as the refractive index difference, between adjacent layers in each PC, is increased.*

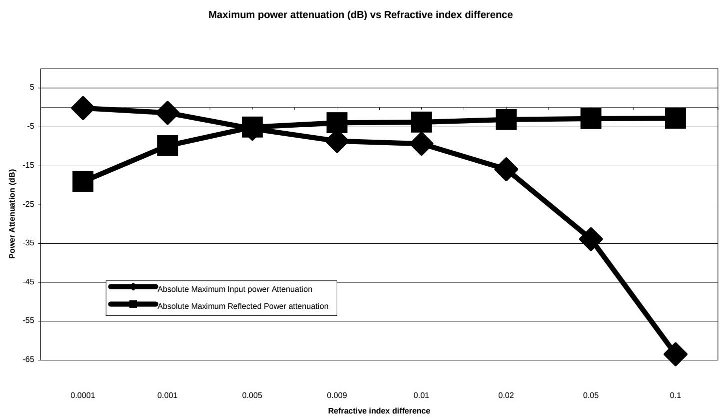


Figure 3-2 *Maximum power attenuation of input wave, relative to the transmitted wave absolute output power of 1, and reflected wave, relative to the absolute input power, as the refractive index difference, between adjacent layers in each PC, is increased.*

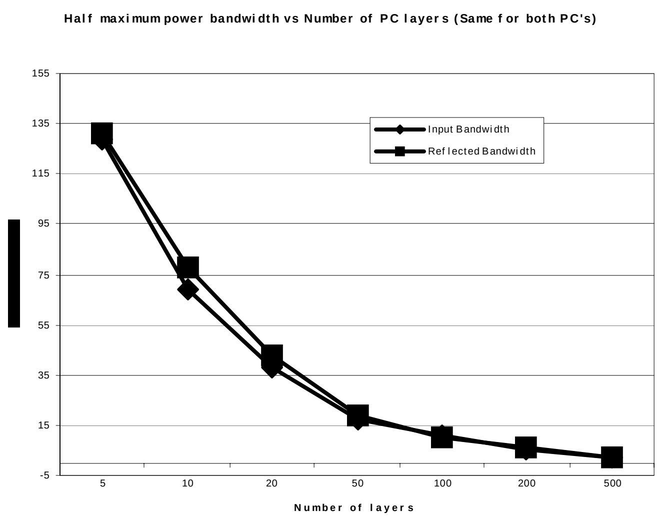


Figure 3-3 *A plot of the cascaded PC bandwidth, at half maximum input and reflected power, as the number of layers in each PC is increased.*

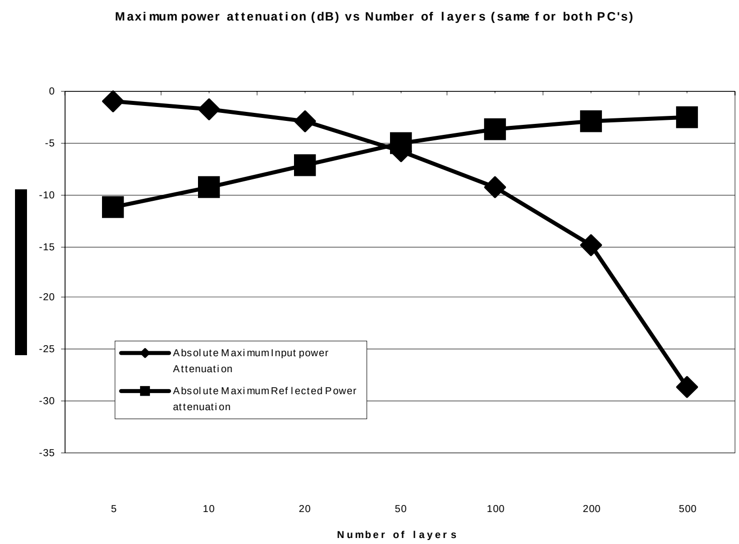


Figure 3-4 *Maximum power attenuation of input wave, relative to the transmitted wave absolute output power of 1, and reflected wave, relative to the absolute input power, as the number of layers in each PC is increased.*

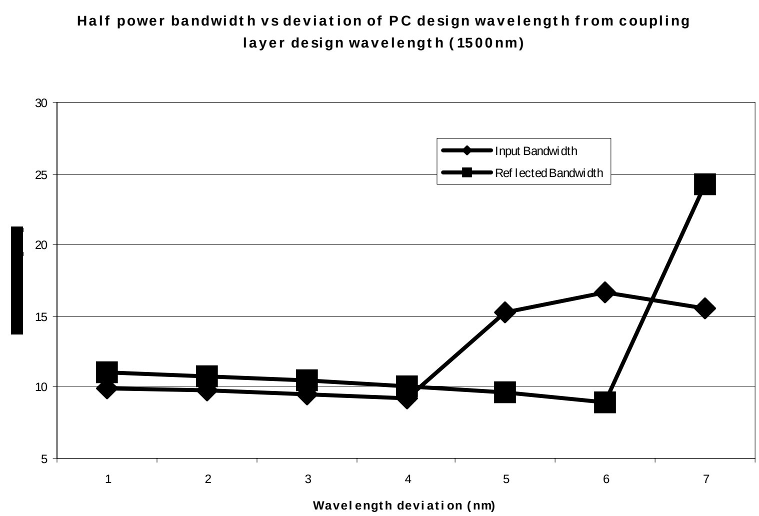


Figure 3-5 *A plot of the cascaded PC bandwidth, at half maximum input and reflected power, as the PC's design wavelength deviates from the design wavelength of the coupling layer (1500nm), i.e. a deviation of 4nm means that the design wavelength of PC 1 is 1504nm and the design wavelength of PC 2 is 1496nm.*

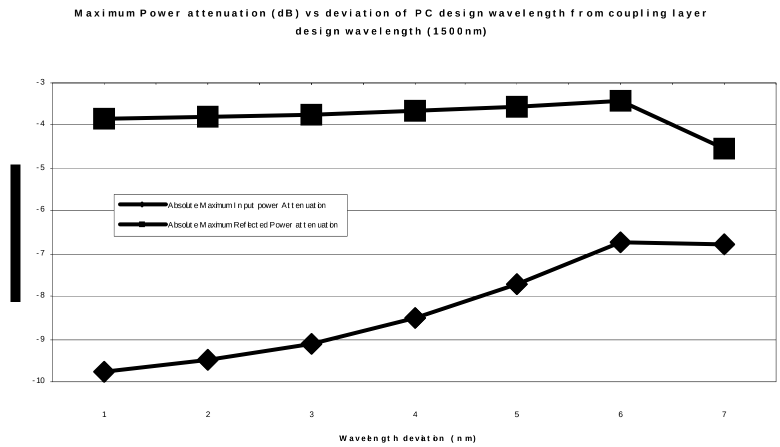


Figure 3-6 *Maximum power attenuation of input wave, relative to the transmitted wave absolute output power of 1, and reflected wave, relative to the absolute input power, as the PC's design wavelength deviates from the design wavelength of the coupling layer (1500nm).*

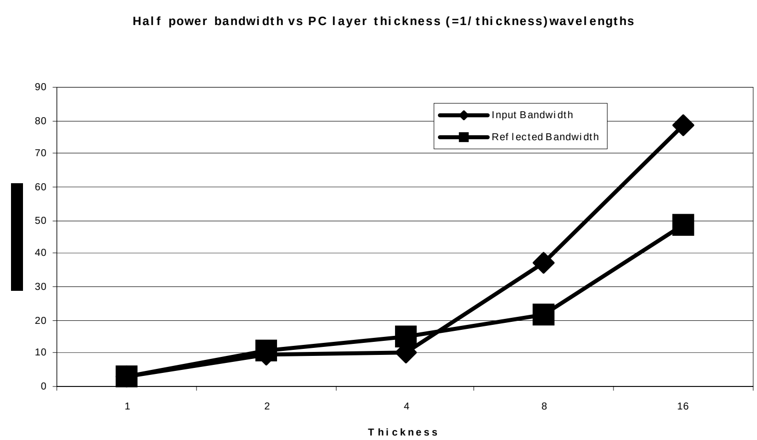


Figure 3-7 A plot of the cascaded PC bandwidth, at half maximum input and reflected power, as the thickness of each alternate layer in both PC's is decreased, i.e. each alternate dielectric layer, in either PC, has a thickness of: $L = \left(\frac{\lambda}{n_{sr}}\right)/t$ *where* λ *is the design wavelength of the PC, s is the dielectric layer number (1 or 2), r is the PC (a = PC 1, b = PC 2) and t is the thickness. For a thickness of 2 each layer is designed to be* $\lambda/2$ *thick at the specific PC design wavelength and refractive index of that layer.*

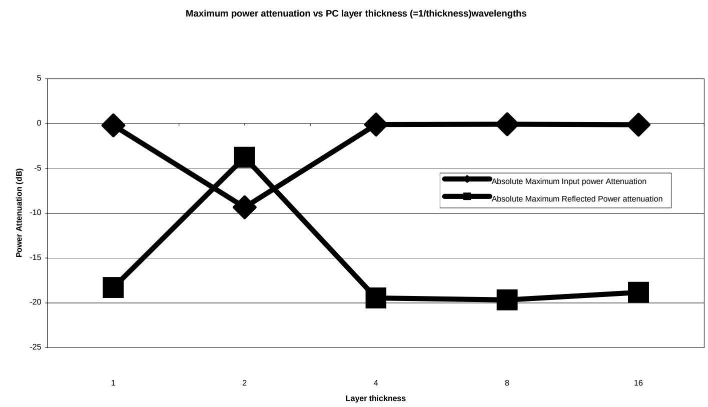


Figure 3-8 *Maximum power attenuation of input wave, relative to the transmitted wave absolute output power of 1, and reflected wave, relative to the absolute input power, as the thickness of each alternate dielectric layer, in each PC, is increased. Layer thickness is defined in the same way as in figure 4.7)*

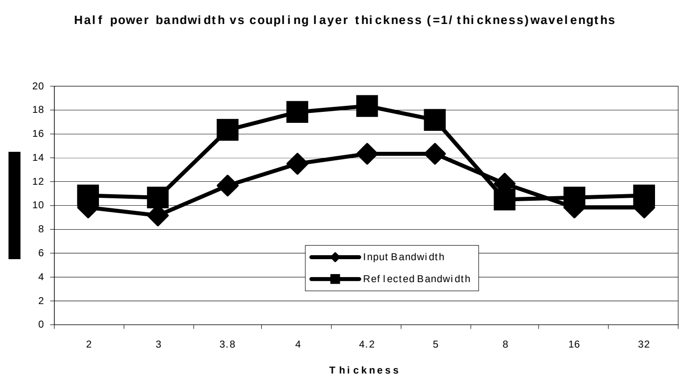


Figure 3-9 A plot of the cascaded PC bandwidth, at half maximum input and reflected power, as the thickness of the coupling layer is increased, i.e. the coupling layer thickness, L_c, is given by: $L_c = \left(\frac{\lambda}{n_c}\right)/t$, where λ is the design wavelength of the coupling layer, n_c is the refractive index of the coupling layer dielectric medium and t is the thickness. For a thickness of 2 the coupling layer is designed to be $\lambda/2$ thick at the coupling layer design wavelength and refractive index.

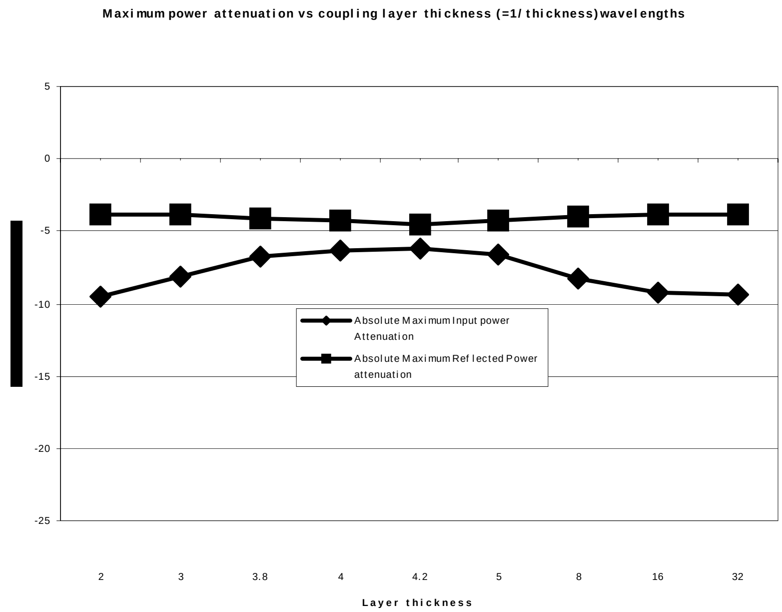


Figure 3-10 Maximum power attenuation of input wave, relative to the transmitted wave absolute output power of 1, and reflected wave, relative to the absolute input power, as the thickness of the coupling layer is increased. Coupling layer thickness is defined in the same way as in figure 25).

3.2 Summary of Cascaded PC Bandwidth and Attenuation simulation results

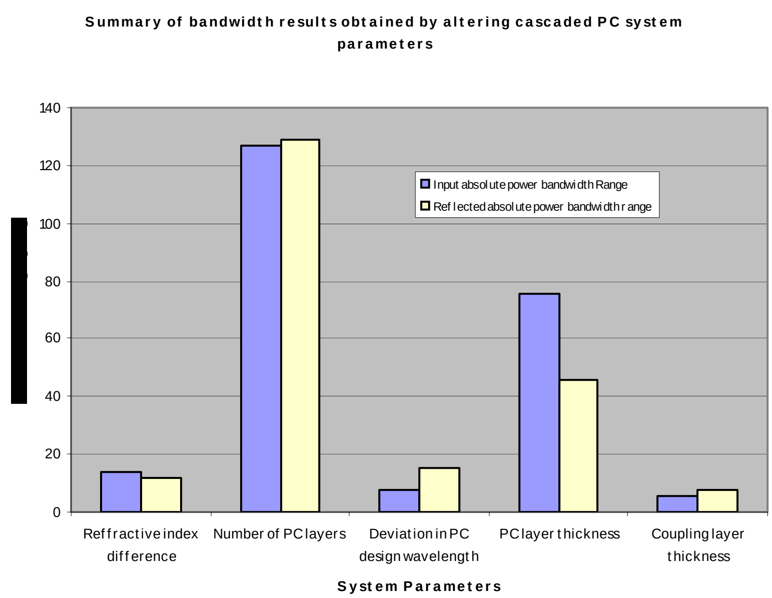


Figure 3-11 *Summary of the bandwidth control ranges obtained for the input and reflected half maximum power bandwidths as the system parameters are individually altered.*

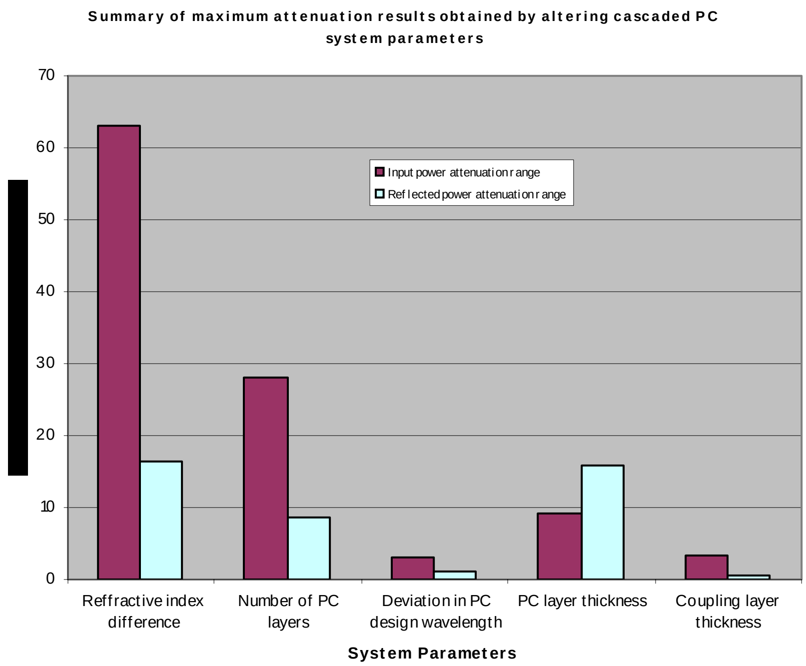


Figure 3-12 *Summary of the maximum attenuation ranges obtained for the maximum power attenuation of input wave, relative to the transmitted wave absolute output power of 1, and reflected wave, relative to the absolute input power as the system parameters are individually altered.*

There are two main characteristics of the cascaded PC that are of practical importance. The first is the bandwidth of the stop and pass bands for the input and reflected absolute power and the second is the amount of attenuation of transmitted and reflected waves. It is supposed that these 1-D photonic crystals would be used in optical fiber systems. A great degree of attenuation within a stop band is necessary to ensure that wavelengths inside the stop band are sufficiently attenuated and do not constitute much of the output signal power. Similarly, a very low attenuation within a pass band is required to ensure that desired wavelengths are transmitted and not attenuated like those outside the pass band. As such, it is desirable to obtain a high degree of control over the bandwidth of the pass and stop bands and a have a rapid roll-off at the ends of the bands. This would ensure that wavelengths outside a pass band are sufficiently attenuated, while not attenuating wavelengths in the pass band, and that the wavelengths inside a stop band are sufficiently attenuated while not attenuating those wavelengths outside the stop band. A transmitted wave absolute power plot can be obtained by inverting the results for an input wave absolute power plot. However, due to the similarity in bandwidth between the two plots the input absolute power plots we used to avoid the calculation and hasten data analysis. To ensure that the attenuation data is accurate the attenuation of the input wave absolute power is taken relative to the transmitted wave absolute power of unity.

Figure 3-11 displays the input half maximum power bandwidth of the cascaded PC against refractive index difference. Two data plots are provided, one for the input wave and one for the reflected wave. Input and reflected waves are determined using output initial conditions of unity, for the transmitted wave, and 0 for the wave reflected from the semi-infinite output dielectric medium n_{1b} (the input wave (not shown) at the cascaded PC output in Figure 2-15 . The general trend for both sets of data is an increase in bandwidth with increasing refractive index difference. Over the range of refractive index difference, ~3 orders of magnitude, the variation in bandwidth is 14nm for both sets of data. Measurements of the lower and upper bound wavelengths at half maximum power suffer an error of ~±1nm. Initial inspection of the data in Figure 3-11 reveals that variation of the refractive index difference gives a limited control in varying the bandwidth of the cascaded PC’s input and reflected power. Hence by varying the refractive index difference between alternate layers in each PC in the cascaded PC we can thus alter the bandwidth of the pass and stop bands

Figure 3-12 shows the plot of the maximum power attenuation of input wave absolute power, relative to the transmitted wave absolute output power of 1, and reflected wave absolute power, relative to the absolute input power, as the refractive index difference, between adjacent layers in each PC, is increased. The data plot of the attenuation of the input wave absolute power shows that the attenuation increases as the refractive index difference between adjacent layers is increased. Attenuation of the input wave absolute power ranges from a little less than ~0dB, for a refractive index difference of 0.0001, to its greatest value of ~-63 dB when the refractive index difference is 0.1. On the other hand, as the refractive index difference increases the attenuation of the reflected wave absolute power, relative to the input wave absolute power, decreases. The greatest attenuation of the reflected wave is ~-19dB, for a RI difference of 0.0001, decreasing rapidly to ~-5dB at a RI difference of 0.005. After this the decrease in attenuation slows, reaching it lowest value of ~-2.8dB for a RI difference of 0.1. The data in Figure 3-1 seems to suggest that varying the RI difference is way of obtaining limited control over the bandwidth of the input and reflected wave absolute power however, the data in Figure 3-2 demonstrates that the consequence of this variation is severe power attenuation of the transmitted wave. The attenuation of the reflected wave absolute power is not as severe and decreases as the RI difference is increased.

An explanation of the heavy attenuation of the input and reflected absolute powers can be found by examining the transmission and reflection coefficients of the interface between two different refractive index dielectric mediums. As the RI difference increases so does the reflection coefficient. The physical importance of this is that a greater portion of the power of a wave incident on the interface will be transferred to the reflected wave. Conversely, as the RI difference increases the value of the transmission coefficient will decrease causing a drop in the power of the output wave. If transmission was only through a few layers then the cumulative effect of changing the RI difference would not be as great as in the case of the simulation where transmission is through 100 layers in both PC. These effects are reflected in Figure 3-2. The great attenuation in input and reflected absolute power that results from altering the stop and pass band bandwidths via RI difference variation indicates that's this is not an efficient means for controlling bandwidth.

Figure 3-3 shows a plot of the cascaded PC bandwidth, at half maximum input and reflected power, as the number of layers in each PC is increased. As the number of layers in each PC is increased we see a decrease in the bandwidth of the cascaded PC. The rate of decrease is quite rapid for both input and reflected absolute power bandwidths from 5 layers to 50 layers. The bandwidth changes by about ~110nm over this range. As the number of layers is increased past 50 to 500 the change in bandwidth for both plots slows, covering a range of ~15nm. The total variation in bandwidth is ~130nm over the layer range of 5 to 500 layers. Both data sets seem to decrease at about the same rate starting at a maximum bandwidth of ~130, for a cascaded PC having 5 layers in each PC, to ~2nm for a cascaded PC with 500 layers in each PC.

Figure 3-4 displays the maximum power attenuation of the input wave absolute power, relative to the transmitted wave absolute output power of 1, and reflected wave absolute power, relative to the absolute input power, as the number of alternating layers in each PC is increased from 5 to 500 layers. As the number of alternate layers is increased we see an increase in the attenuation of the transmitted wave indicated by the attenuation of the absolute power of the input wave. Attenuation is at it smallest value, ~-1dB, for PC's with 5 layers increasing to it maximum value of ~-29dB for PC's with 500 layers. The attenuation varies by ~28dB over the entire range of the different number of PC layers. As the number of PC layers is increased the attenuation of the reflected wave absolute power is decreased. For a 5 layered PC the attenuation is at it's greatest value of ~-11dB decreasing to ~-2.5dB for a 500 layered PC structure. The attenuation varies over ~8-9dB over this range of the number of layers in each PC.

Figure 3-3 illustrates that the variation in bandwidth for PC's with between 5 to 50 alternating layers is ~110nm. Figure 3-4 illustrates that over this same number of layers range the attenuation of the input wave absolute power varies by ~5dB and the variation in attenuation of the reflected wave absolute power is ~6dB. Increasing the number of alternating PC layers beyond 50 results in a linear increase in attenuation of the input wave absolute power, with limited further bandwidth variation (~15 – 20nm) up to 500 layers, and a slowly decreasing attenuation for the reflected wave absolute power, with a ~15-20nm variation in bandwidth and ~2.5dB variation in attenuation for PC structures having between 50 to 500 layers. Compared to the data in Figure 3-1 and Figure 3-2, Figure 3-3 and Figure 3-4 illustrate that variation of the number of alternating layers in each PC gives a wider range of control over the half maximum power bandwidth, of the pass and stop bands of the input and reflected wave absolute power, with significantly less power attenuation over that range, 5 to 50 layers. As the number of layers increases more complete destructive interference occurs for wavelengths closer to the design wavelength of the coupling layer, the center wavelength. Consequently the half maximum power bandwidth decreases resulting in narrower pass and stop bands for the transmitted and reflected wave absolute power.

When the PC's design wavelength deviates from the design wavelength of the coupling layer (1500nm) we obtain a plot of the cascaded PC bandwidth, at half maximum input and reflected power, similar to that shows in Figure 3-5. As the wavelength deviation is increased the half maximum power bandwidth of the input wave absolute power decreases slowly from ~10 to 9 nm for a wavelength deviation ranging from 1 to 4nm, increases rapidly from ~9 to 17 nm for wavelength deviation between 4 to 6nm then decreases again after a 6nm wavelength deviation. The half maximum power bandwidth of the reflected wave absolute power decreases slowly from ~11 to 9nm from a wavelength deviation of 1 to 6nm and then rises sharply to ~24nm for a wavelength deviation of 7nm. Unlike the previous two sets of results this data does not seem to follow a clearly defined trend. Some explanation of the bizarre appearance of the data in Figure 3-5 can be found in the measurement technique and an analysis of the actual plotted data. Once the magnitude of this peak exceeds the half maximum power of the main peak there exist four crossings at this power. The bandwidth is measured at the widest point of these two curves. This is the source of the sudden increase in bandwidth of the half maximum power bandwidth of the input wave absolute power. The subsequent presence of a third peak that forms to the right of the main peak, as the design wavelength deviation is increased is the source of the following drop in bandwidth of the half maximum power bandwidth of the input wave absolute power. A similar effect is present in the results for the bandwidth of the half maximum power bandwidth of the reflected wave absolute power. Unlike the input wave absolute power plot, the reflected wave absolute power plot contains two main side lobes to the main power peak that grow, equally, as the wavelength deviation is increased. The bandwidth of the main peak decreases slowly and steadily as the side lobes grow in power. When they equal the half maximum power of the main peak, that is when the wavelength deviation reached ~7nm, the contribution to the measured value of the half maximum power bandwidth resulting in a sudden jump in measured bandwidth.

Figure 3-6, unlike Figure 3-5 does not contain such peculiar shaped data curved, with the exception of the final data point. Figure 3-5 contain as plot of the maximum power attenuation of input wave, relative to the transmitted wave absolute output power of 1, and reflected wave, relative to the absolute input power, as the PC's design wavelength deviates from the design wavelength of the coupling layer (1500nm). As the wavelength deviation is increased we se a slow but steady decrease in the attenuation of the maximum input and reflected wave absolute powers. The maximum attenuation of the maximum input wave absolute power is ~-9.5dB for a wavelength deviation of 1nm decreasing to ~–6.7dB at a wavelength deviation of ~6 to 7nm giving a attenuation range span of ~3dB over the entire range of wavelength deviations. Similarly, the maximum attenuation of the maximum reflected wave absolute power is ~-3.8dB for a wavelength deviation of 1nm decreasing to ~-3.4dB at a wavelength deviation of ~6nm giving a attenuation range span of ~0.4dB over this range of wavelength deviations. At a wavelength deviation of 7nm there is a sharp increase in attenuation to ~-4.5dB. It is difficult to obtain qualitative conclusions from results from this data due, partially to the reasons mentioned in the above paragraph. The cascaded PC essentially takes the two pass or stop bands of each PC and superimposes them on each other. As the wavelength deviation between both PC's increases the two different stop or pass bands begin to separate. Eventually the separation exceeds the bandwidth of an individual stop or pass band and qualitative measurements become difficult to make. Consequently, as the wavelength variation increased to and past a certain point the data becomes more erratic. The erratic nature of the data make qualitative conclusions regarding the efficiency with which changing the design wavelength variation can be used to alter the bandwidth of the pass and stop bands of the cascaded PC.

Figure 3-7 contains a plot of the cascaded PC bandwidth, at half maximum input and reflected power, as the thickness of each alternate layer in both PC's is decreased. The cascaded PC bandwidth is measured using layers that vary in thickness from λ to $\lambda/16$ of the design wavelength. As layer thickness is decreased we see increases in the half maximum input and reflected power bandwidths. The minimum bandwidth of the maximum input absolute power is ~3nm, for wavelength-thick layers, increasing to ~78nm for $\lambda/16$ wavelength thick layers. The bandwidth varies by ~75nm over this range of layer thickness. The minimum bandwidth of the maximum reflected absolute power is ~3nm, for wavelength-thick layers, increasing to ~49nm for $\lambda/16$ wavelength thick layers. The bandwidth varies by ~46nm over this range of layer thickness.

In Figure 3-8 a plot of maximum power attenuation of input wave, relative to the transmitted wave absolute output power of 1, and reflected wave, relative to the absolute input power, as the thickness of each alternate dielectric layer, in each PC, is increased is shown. With the exception of the data points obtained for ½ wavelength layers the maximum attenuation of the input and reflected wave absolute power does not seem to vary much over the other layer thickness. Two problems exist in the interpretation of this data; the first concerns the sudden increase/decrease in maximum attenuation of the input/reflected wave absolute powers (respectively, and the second concerns the small deviation in maximum attenuation over the other layer thickness... With the exception of the data plot where the layer thickness is a $\lambda/2$ wavelength, all others plots display what looks to be the output of a resonator. As the layer thickness is decreased the period of oscillation, and consequently the bandwidth, increases. Note that the maximum power measurements are made using the peak of greatest amplitude that lies closest, in wavelength, to the center wavelength, 1500nm. When the thickness of the layers is a ½ wavelength constructive/destructive interference occurs with minimal resonance. For all other layer thickness the coupling layer acts as a resonant cavity and this resonance effect dominates. For resonance to occur the must be little attenuation otherwise oscillations quickly damp out and cannot be sustained. Compared to the plot of the maximum reflected wave absolute power range for the ½ wavelength thick cascaded PC, all other plots have a much smaller range of maximum reflected wave absolute powers. This is a consequence of the cascaded PC acting as a resonator. While the data in Figure 3-7 seems to indicate that a good degree of control over the bandwidth, of the maximum input and reflected absolute powers, can be obtained by varying the layer thickness, the data in Figure 3-8 shows that the attenuation of wavelengths in the pass/stop bands is very small meaning that this method of bandwidth control, while allowing a wide range of bandwidth control, is not very practical due to its inability to significantly attenuate wavelengths within or outside a stop or pass band respectively.

Figure 3-9 shows the cascaded PC bandwidth, at half maximum input and reflected power, as a function of the thickness of the coupling layer. The coupling layer thickness, L_c, is varied from a $\lambda/2$ to $\lambda/32$ thick. Both sets of data showing the bandwidth for the input and reflected wave absolute power decrease initially, by less than ~1nm from ½ to

$\lambda/3$ wavelength thick coupling layers, then increase to a maximum for $\lambda/4$ to $\lambda/5$ thick coupling layers. From the minimum bandwidth at $\lambda/3$ thick layers, ~ 9.2nm and ~10.6nm for the half maximum input and reflected power bandwidths (respectively), the bandwidth increases to ~14nm and ~18nm, respectively, at these maximums. The bandwidth of both data plots then decreases again, though more slowly, reaching final bandwidths of ~10nm, for a $\lambda/16$ wavelength thick coupling layer for the half maximum input power bandwidth, and ~11nm for a $\lambda/8$ wavelength thick coupling layer for the half maximum reflected power bandwidth. The peak in bandwidth around the quarter wavelength thick coupling layer is probably due to the uniformity of the resonance that occurs, i.e. the resonance is more lossless at this particular coupling layer thickness. By examining the plot of input and reflected power for the cascaded PC where each PC has ¼ wavelength layers, we see a more uniform resonance in that the maxima and minima of the oscillations remain fairly constant over the plotted wavelength range. The position of the maximum bandwidth, lying slightly to the right of the $\lambda/4$ thick coupling layer, is assumed to be due to the asymmetry in the design wavelength of the cascaded PC.

Figure 3-12 shows that maximum power attenuation of the input wave, relative to the transmitted wave absolute output power of 1, and reflected wave, relative to the absolute input power, as the thickness of the coupling layer is increased. Around the same coupling layer thickness, a little greater than ~1/4 wavelength thick, a decrease, ~3dB, can be seen in the maximum attenuation of the input wave absolute power and a slight increase, ~0.5dB, in maximum attenuation is observed in the maximum attenuation of the reflected wave absolute power. The decrease in maximum attenuation observed in the data plot of maximum input wave absolute power may be explained by resonance. As the thickness of the resonant cavity, the coupling layer, approaches $\lambda/4$ wavelength the resonance within the cavity increases and so there may be a loss reduction of reflected and transmitted power causing the drop in transmitted power attenuation. Similarly, the increase in reflected power attenuation may be caused by a greater amount of power entering the resonant cavity to sustain the resonance. Altering the coupling layer thickness around ~$\lambda/4$ wavelength allows a bandwidth control of ~4nm in the half maximum power bandwidth of the maximum input wave absolute power and ~8nm in the half maximum power bandwidth of the maximum reflected wave absolute power, as can be seen in Figure 3-9. However, Figure 3-10 indicates that the maximum attenuation difference for wavelengths within this thickness range, ~10dB for the maximum input wave absolute power and ~1dB for the maximum reflected wave absolute power, may not be of much practical use, considering the limited bandwidth control, compared to the control afforded by altering the number of layers in each PC in the cascaded PC.

4 Concluding remarks

We have demonstrated the design of the pass and stop bands of a cascaded PC. The computer aided program has enabled the rapid computation of the initial input and reflected waves required to obtain a certain transmitted output waves using the [ABCD] matrix multiplication and inverse processes.

Various system parameters affect the stop and pass bands, of the input and reflected wave absolute powers respectively. A summary of the bandwidth control range and maximum attenuation range results obtained by individually altering cascaded PC system parameters is provided. Variation of the number of layers in each PC gives the greatest bandwidth range control, ~127nm and ~129 nm for the half maximum input and reflected power bandwidths respectively, corresponding to a reasonable attenuation of input and reflected power, a 28dB and 8.71dB attenuation range respectively. Variation of the number of the coupling layer thickness gives the lowest bandwidth range control, ~5.2nm and ~7.8nm for the half maximum input and reflected power bandwidths respectively, corresponding to an attenuation range of input and reflected power of 3.34dB and 0.69dB respectively. All other simulation results suffered from measurement difficulties due to asymmetrical pass and stop bands.

The designs of two PCs resonant circuits at two different cascaded optical filters to form a composite PC are described. This concept could easily be extended to form and simulate N-coupled PC’s where N >> 2. A cascaded PC consisting of many PC’s, designed at different wavelengths would have broader input and reflected half maximum power bandwidths. The addition of the extra PC, and subsequently increasing in variable system parameters, may allow for a greater and finer control of the pass and stop band characteristics.

One notable problem with the PC-cas-sim program is that at some wavelengths the input wave absolute power is less than unity. This is not physically possible because for all wavelengths the transmitted wave absolute power is unity. These results violate the conservation of energy law that implies that the power output of a system should always be less than power input of the system, for a physical system. This simulation program assumes a lossless system, however the input power still should be greater than or equal to one at all wavelengths. Due to time limitations the simulation program was unable to be modified to correct this fault. In spite of this problem results are fairly accurate considering that the maximum absolute input power is large compared to the maximum drop below unity input power of ~0.5. Another possible source of this apparent violation of the laws of physics could be that some power is being coupled from other modes to a particular wavelength thus requiring less than unity input power from that wavelength to provide unity output power. These are suppositions that should be further investigated in this author's opinion. Further experimental and analytical works should also be conducted to reduce the half-maximum power bandwidth and produce sharper roll-off at the cut-off bands for DWDM optical fiber systems.

Finally, the possibility of extending the ABCD transmission matrix theory to model 2 and 3-D PC's, so that the design of such structures may be facilitated more easily, should be investigated.

5 References

[1] P. Kemeny and L.N. Binh " LIGA X-ray lithography and integrated photonic crystal photonics", Invited paper ACOFT 2004, Canberra Australia

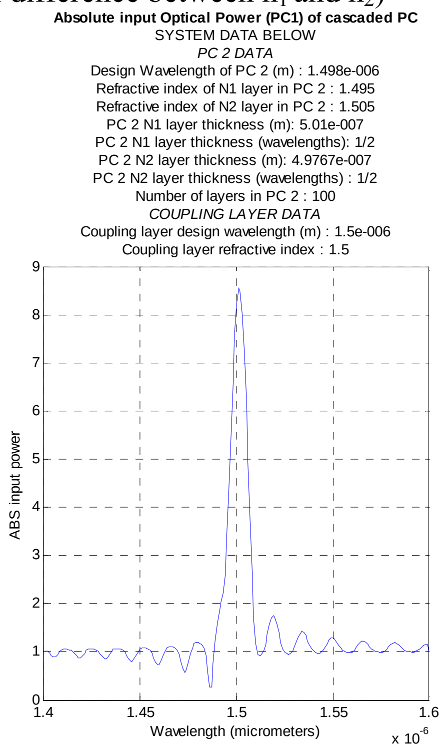
[2] P. Yeh, *Optical Waves in Layered Media,* John Wiley & Sons, New York (1988)

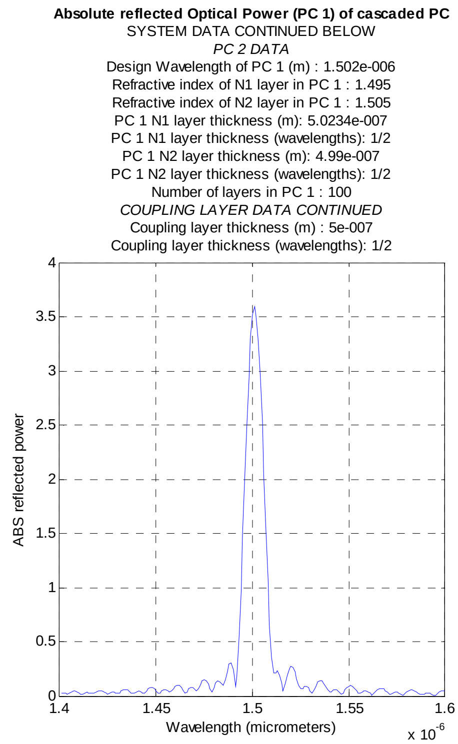
[3] WorkIQ, "Definition of MATLAB",

6 Appendix: Simulation data plots

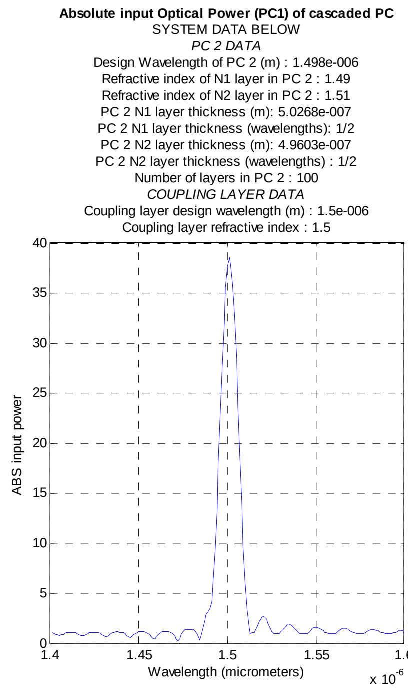
6.1 Part i) Simulation plots where the refractive index difference is varied.

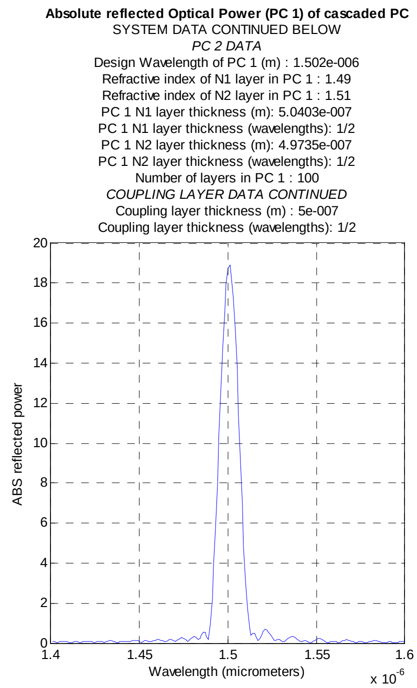
(0.01 RI difference between n_1 and n_2)



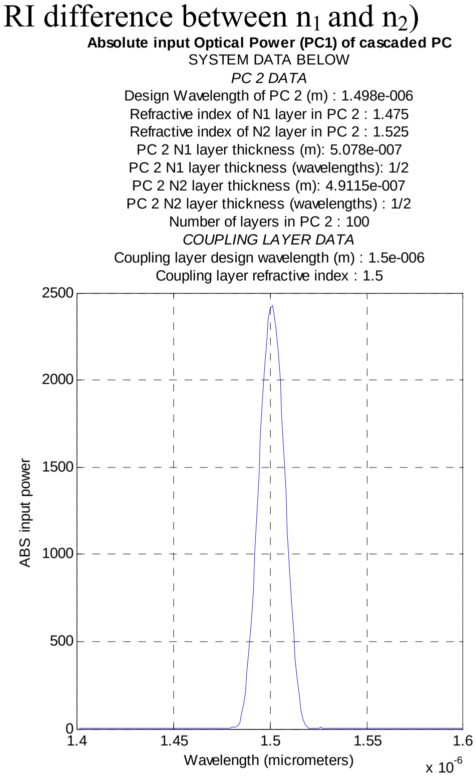


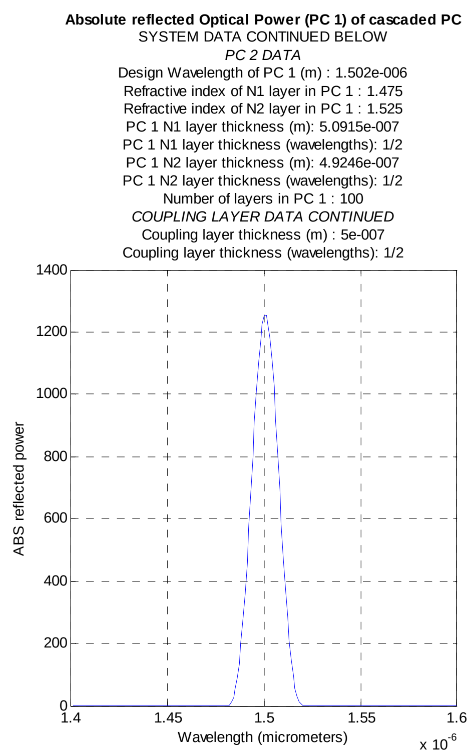
(0.02 RI difference between n_1 and n_2)



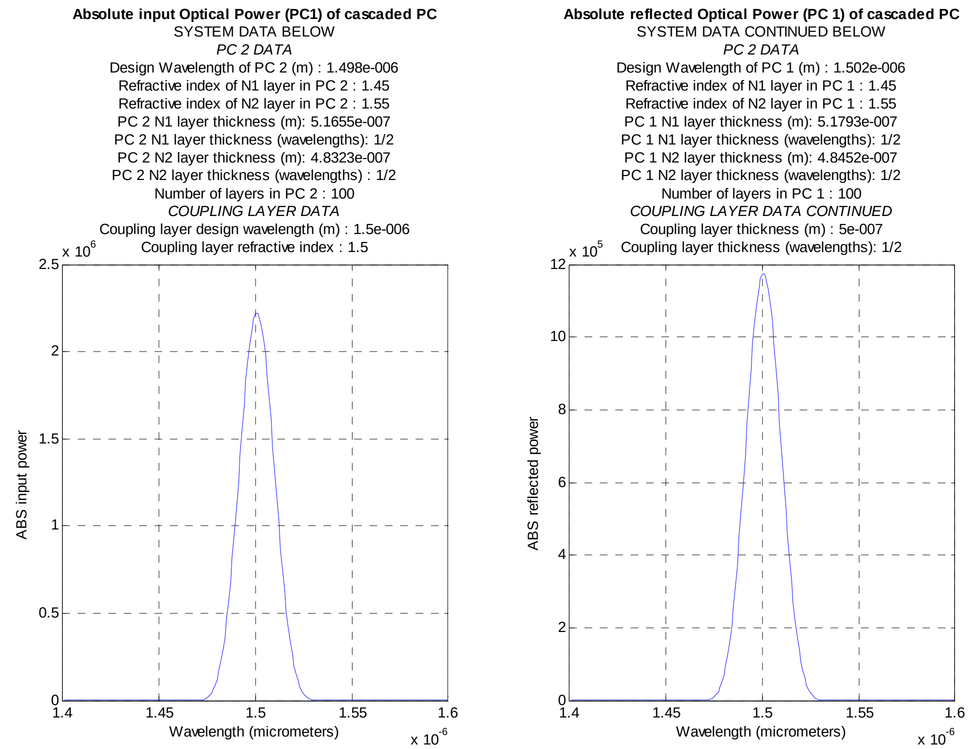


(0.05 RI difference between n_1 and n_2)

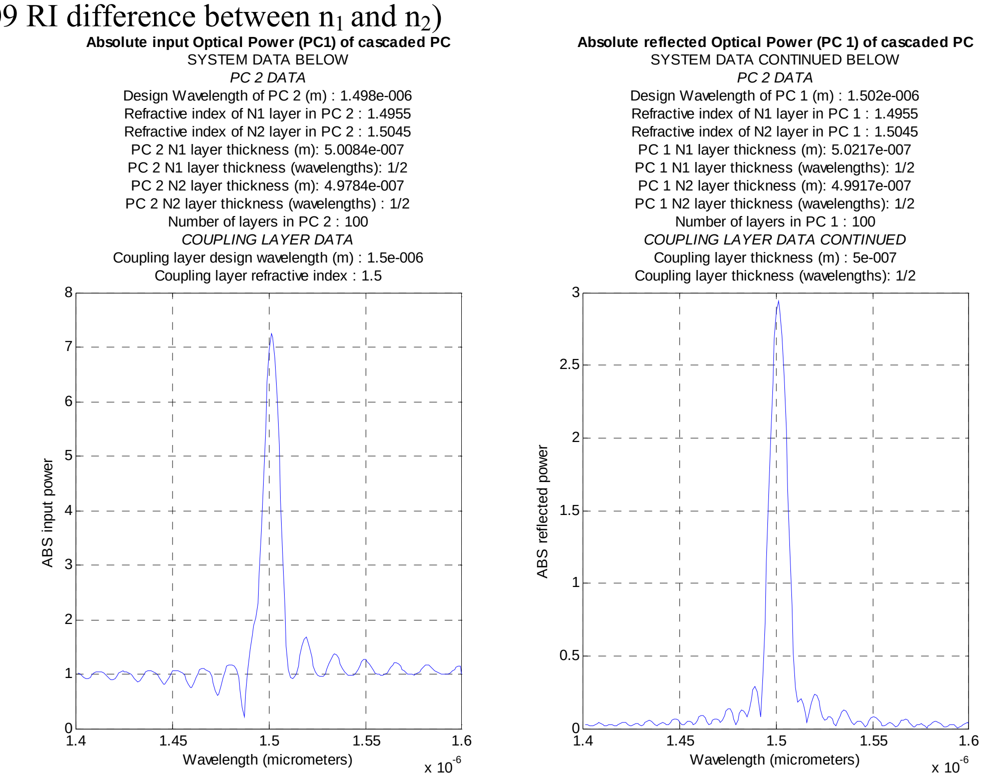




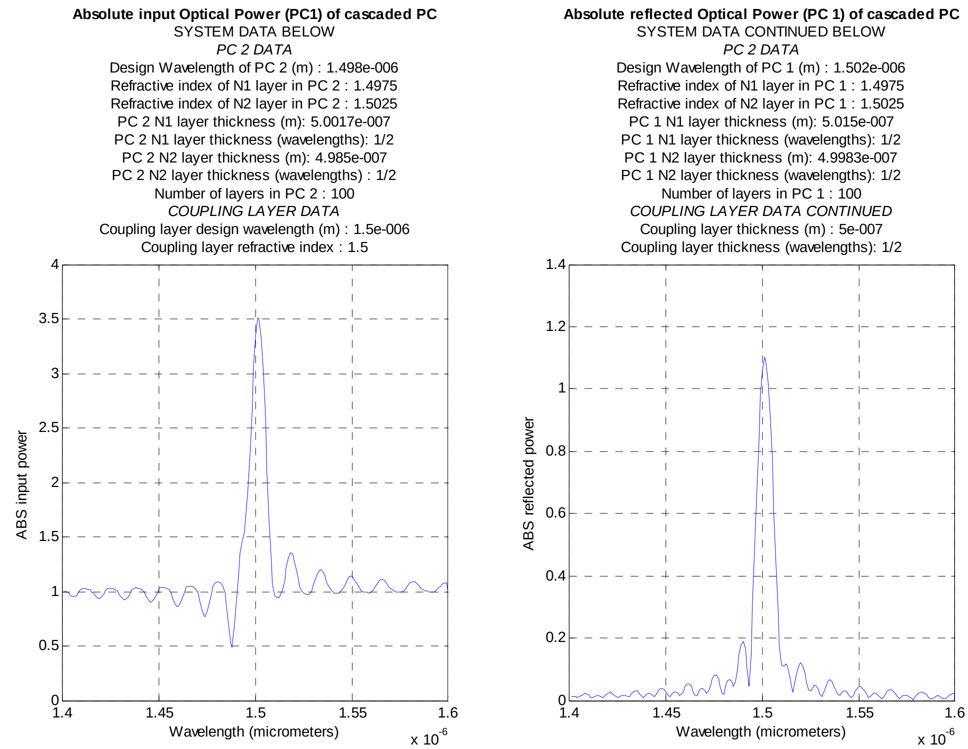
(0.1 RI difference between n_1 and n_2)



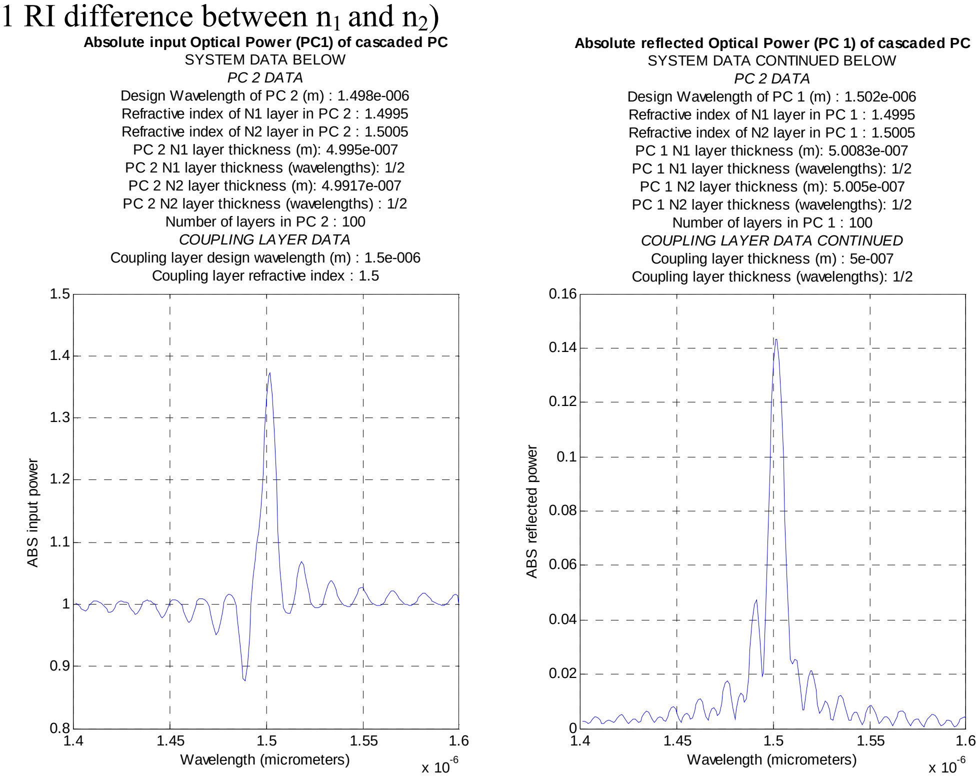
(0.009 RI difference between n_1 and n_2)



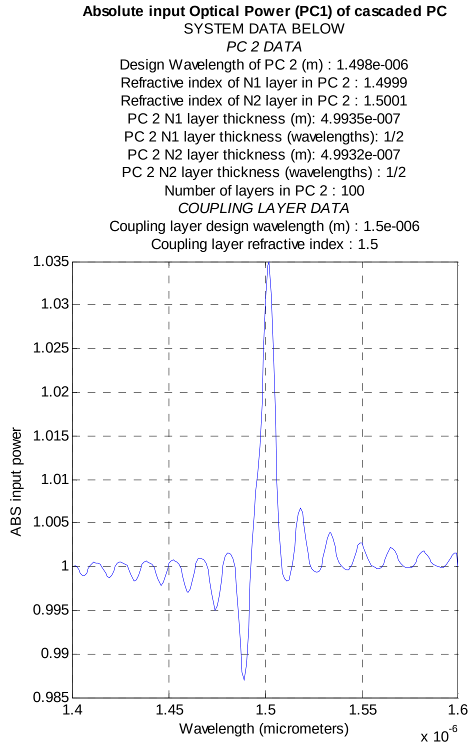
(0.005 RI difference between n_1 and n_2)

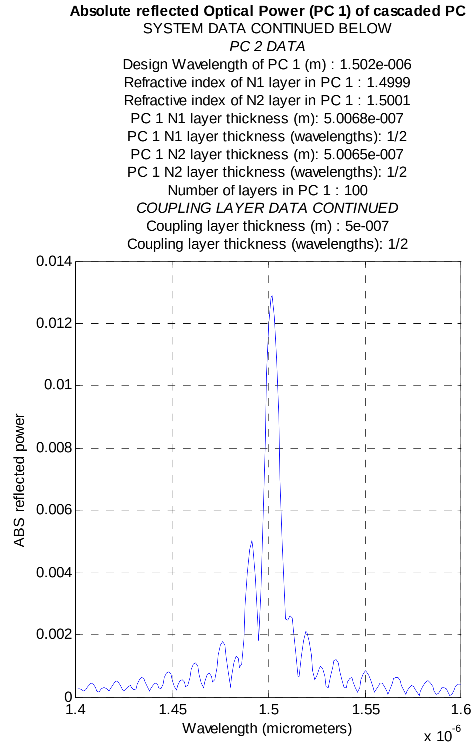


(0.001 RI difference between n_1 and n_2)

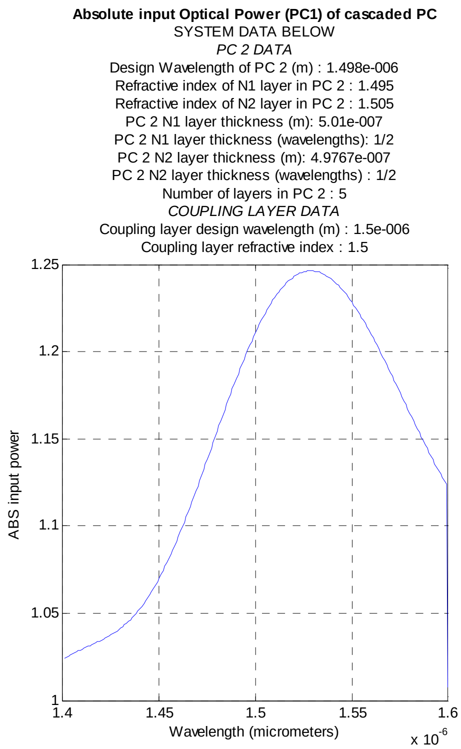


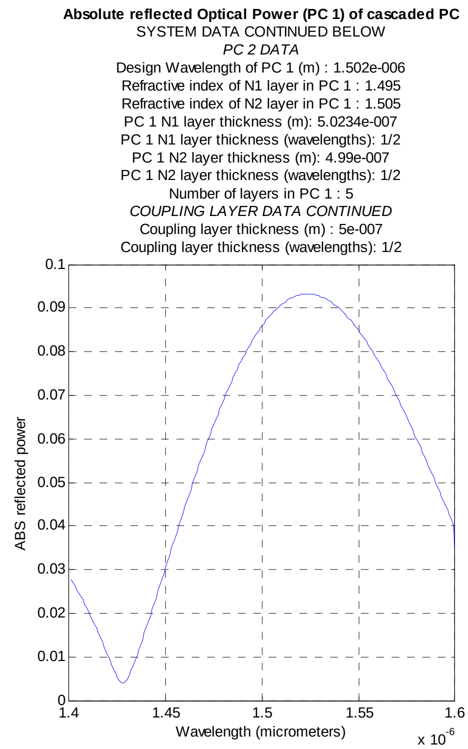
(0.0001 RI difference between n_1 and n_2)



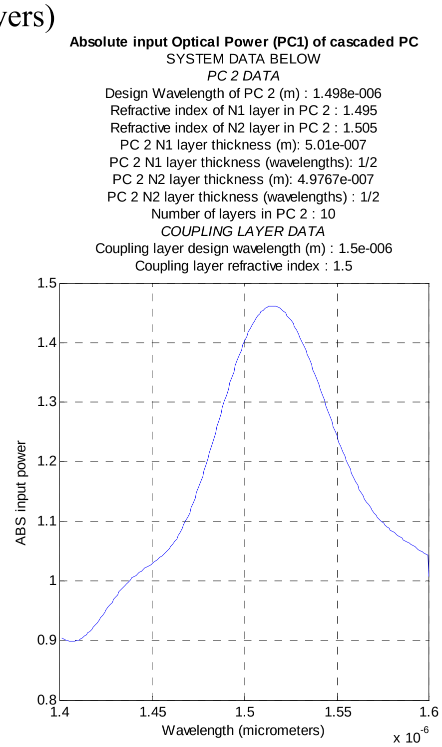


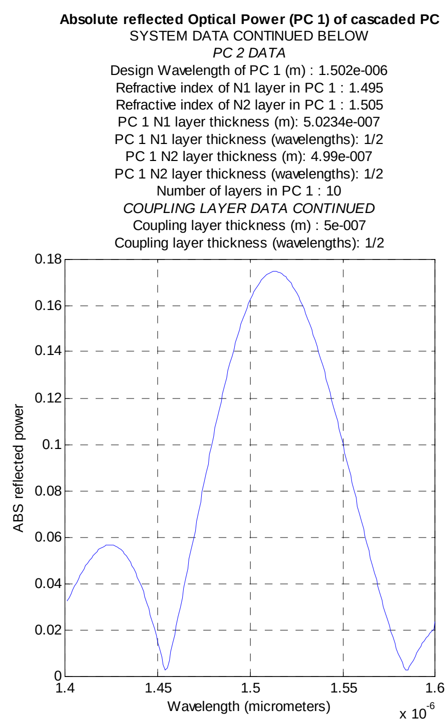
6.2 Part ii) Simulation plots where the number of layers in each PC is varied. (5 layers)



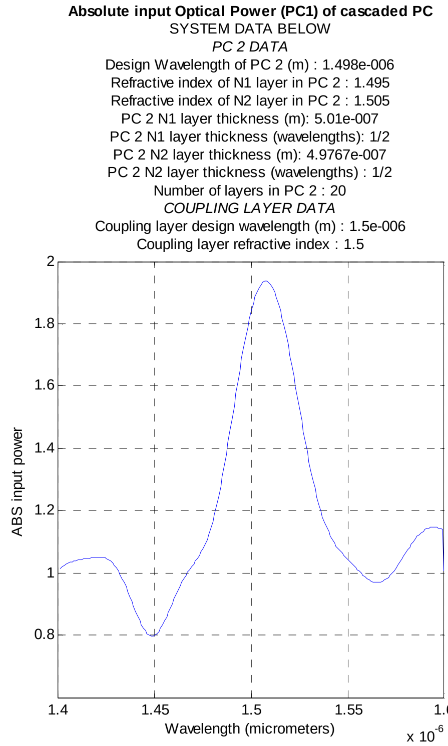


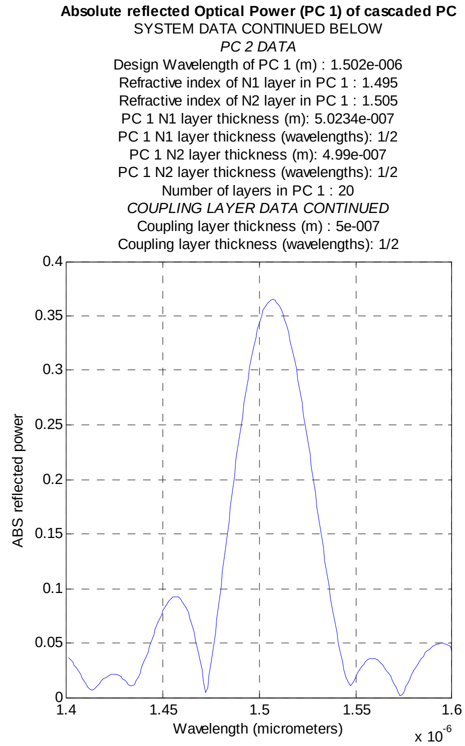
(10 layers)



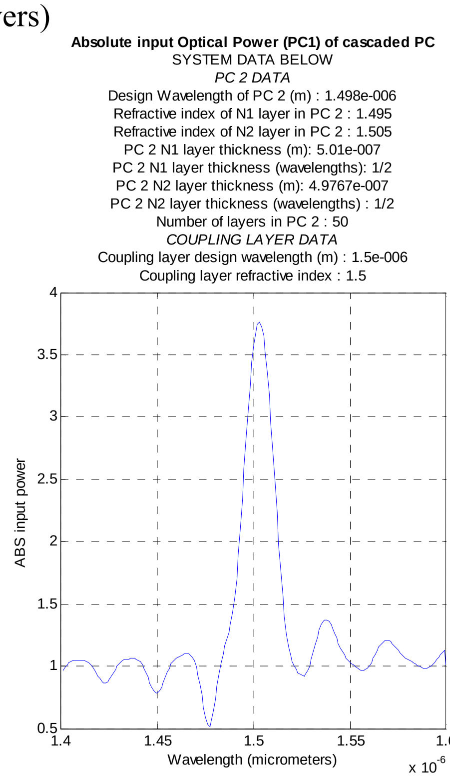


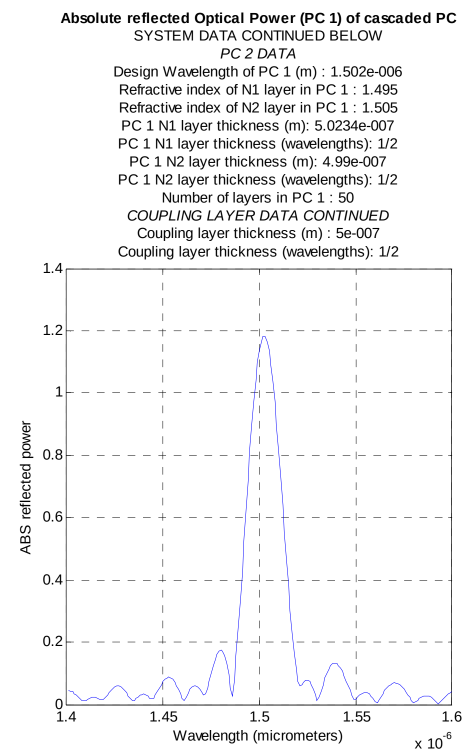
(20 layers)



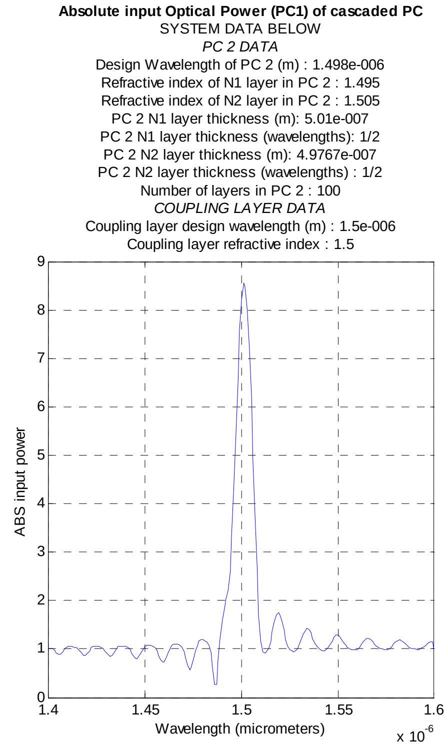


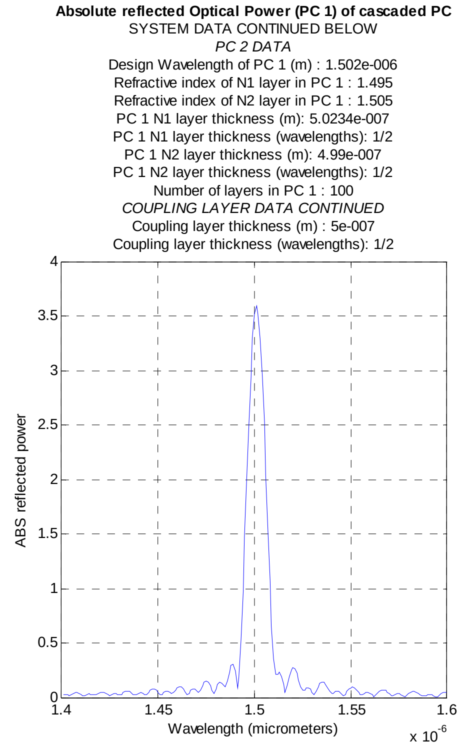
(50 layers)



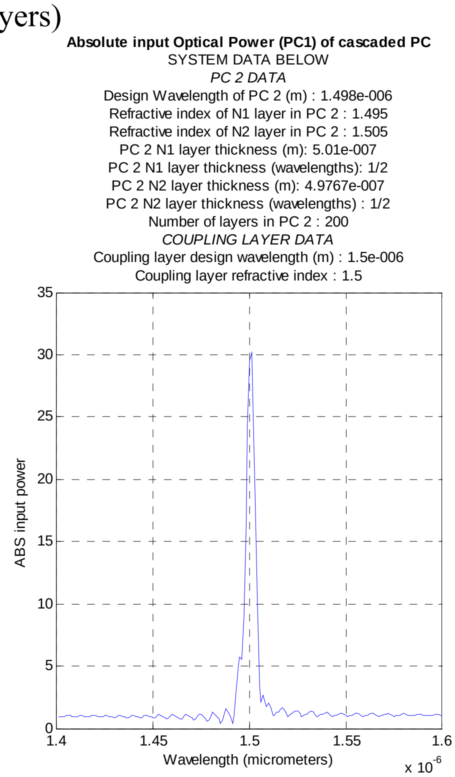


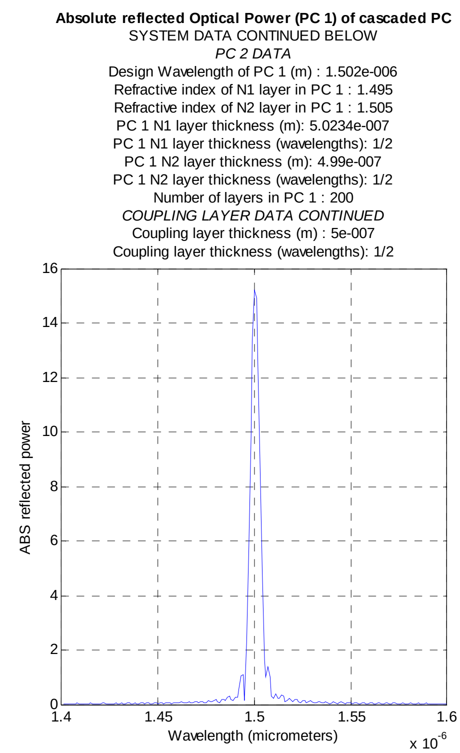
(100 layers)



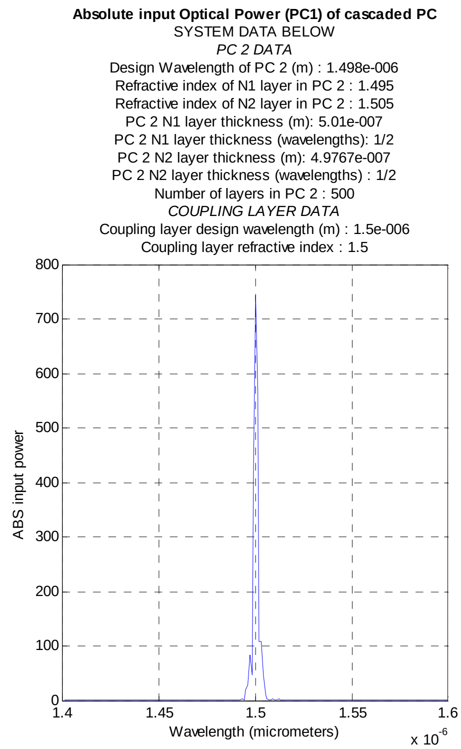


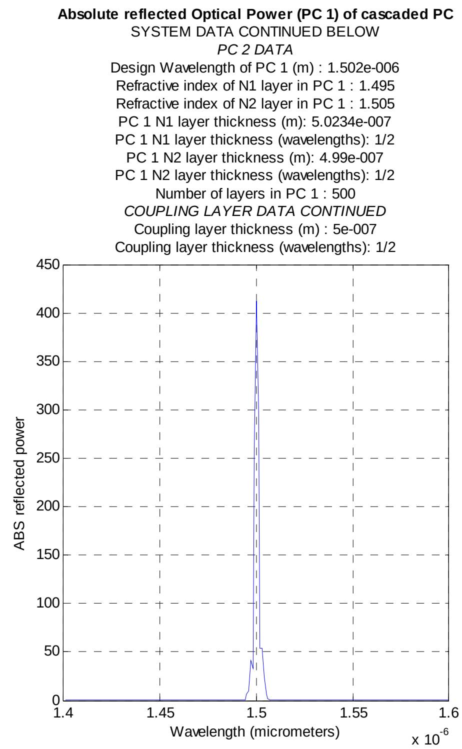
(200 layers)





(500 layers)

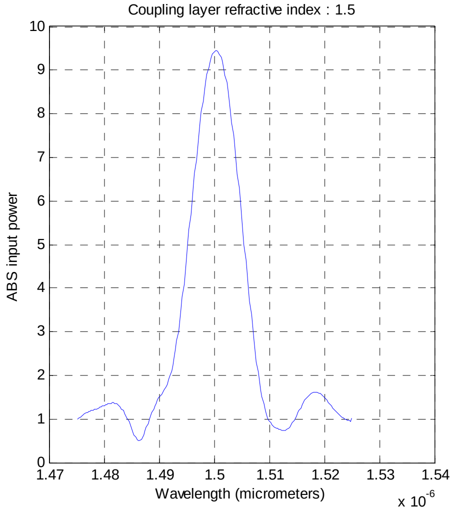

Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 500
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5
ABS input power
Wavelength (micrometers)
x 10^-6
0
100
200
300
400
500
600
700
800
1.4
1.45
1.5
1.55
1.6


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 500
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2
ABS reflected power
Wavelength (micrometers)
x 10^-6
0
50
100
150
200
250
300
350
400
450
1.4
1.45
1.5
1.55
1.6

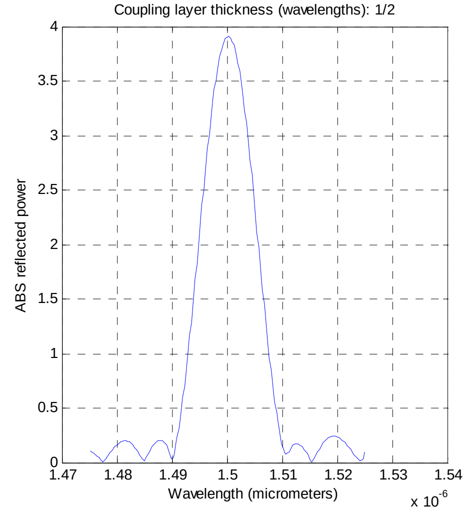
6.3 Part iii) Simulation plots where PC design wavelength is varied.

(± 1nm (PC2 = 1499, PC1 = 1501))

Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.499e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.0134e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9801e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5

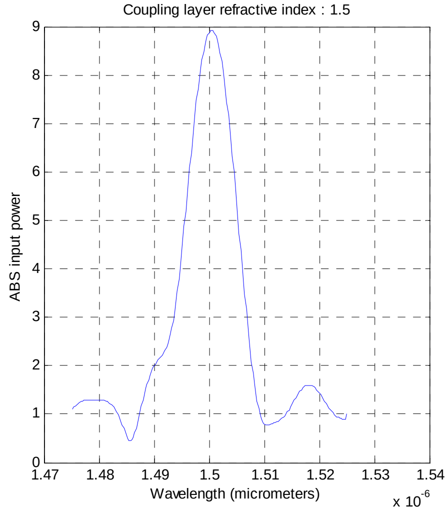


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.501e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0201e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.9867e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2

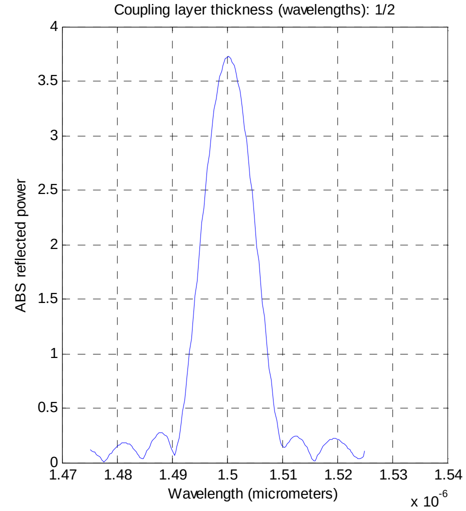


(± 2nm (PC2 = 1498, PC1 = 1502))

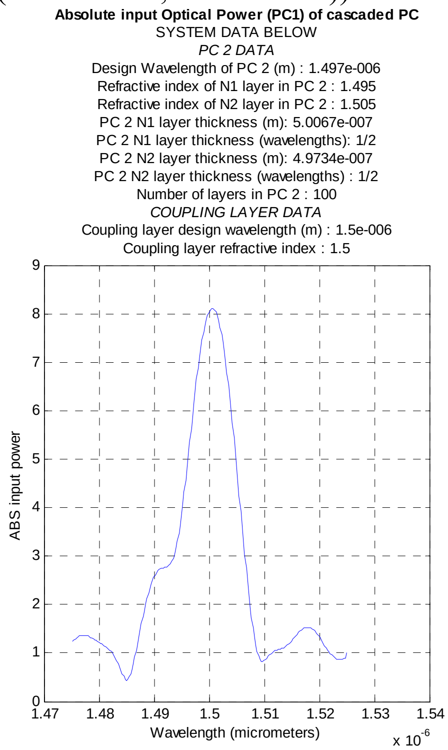
Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5

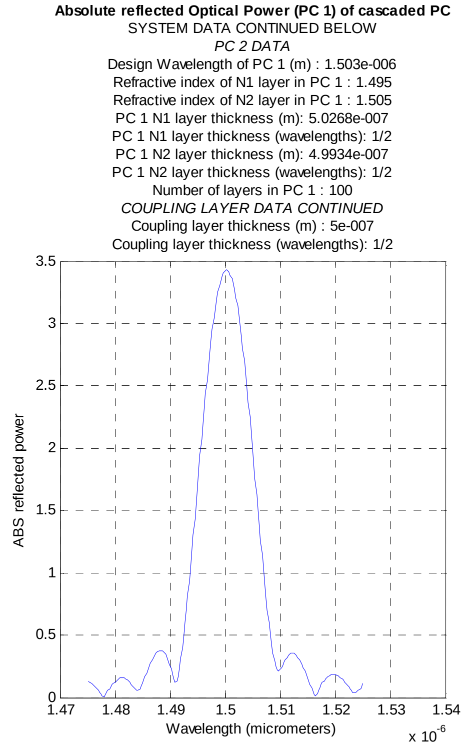


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2

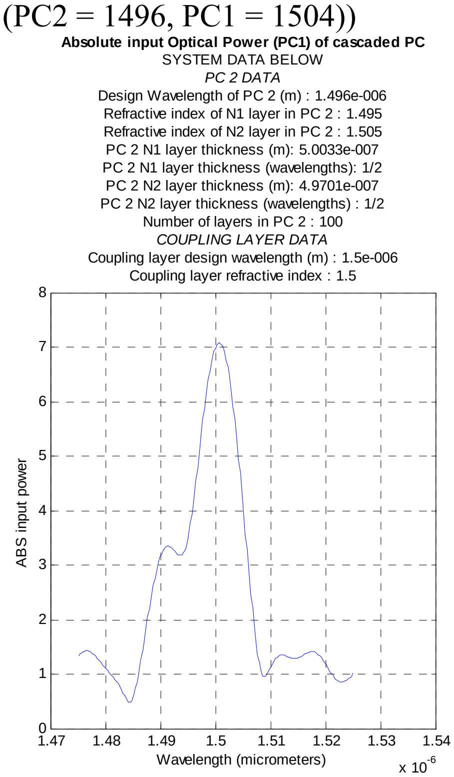


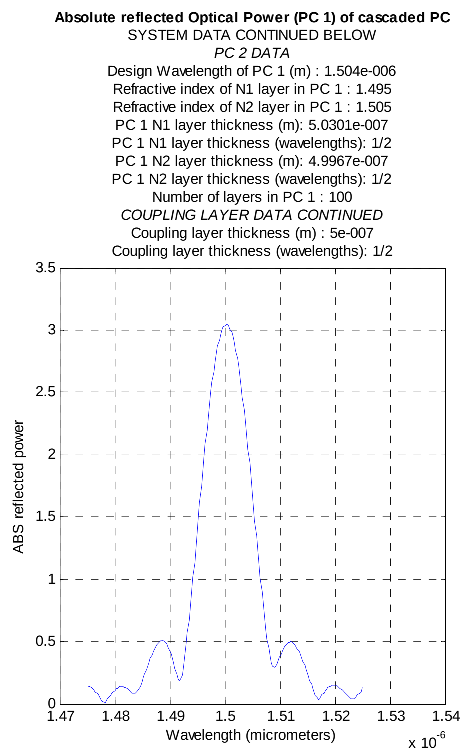
(± 3nm (PC2 = 1497, PC1 = 1503))



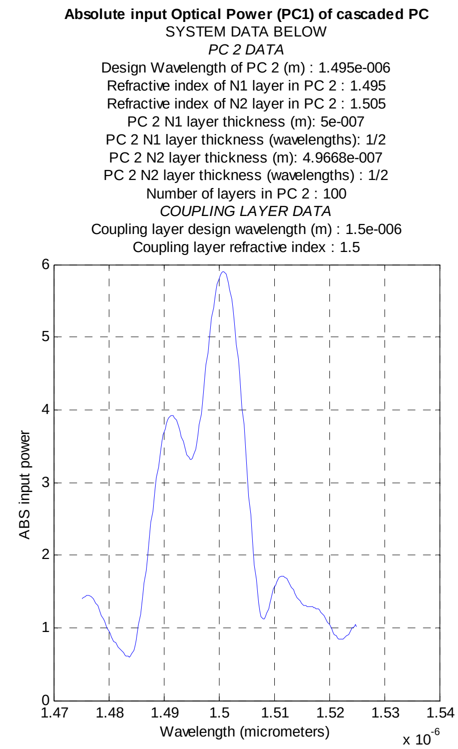


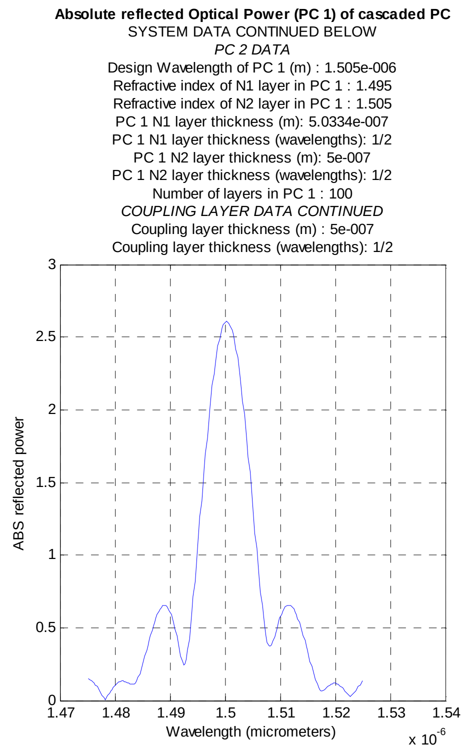
(± 4nm (PC2 = 1496, PC1 = 1504))



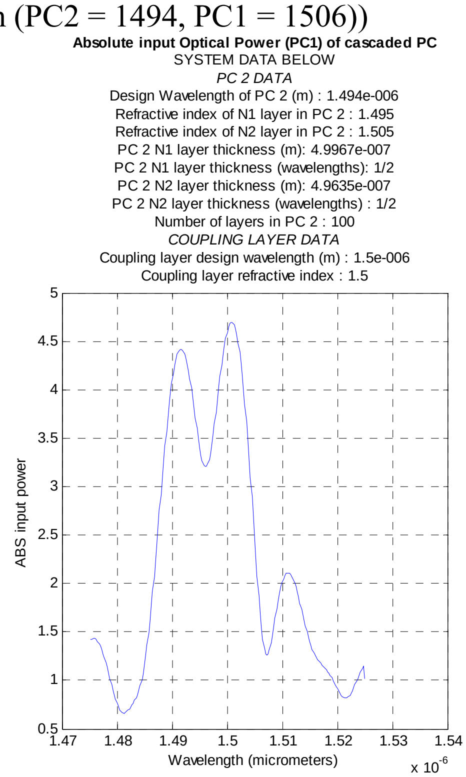


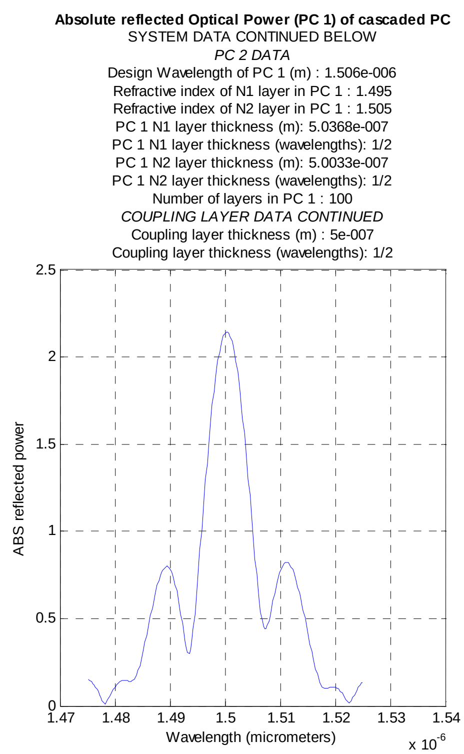
(± 5nm (PC2 = 1495, PC1 = 1505))





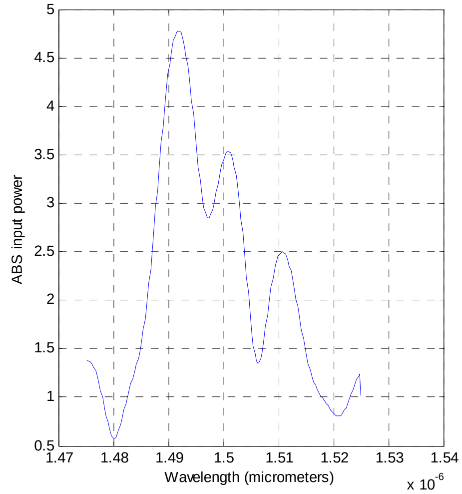
(± 6nm (PC2 = 1494, PC1 = 1506))



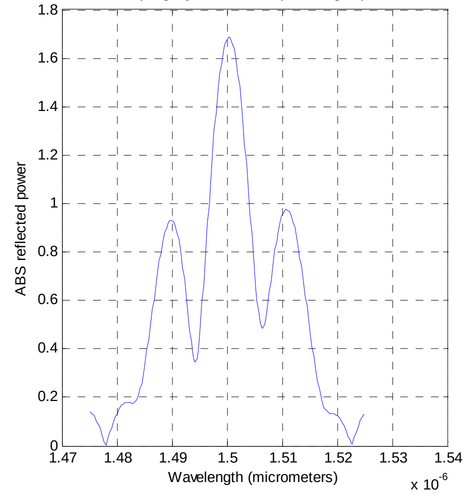


(± 7nm (PC2 = 1493, PC1 = 1507))

Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.493e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 4.9933e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9601e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5

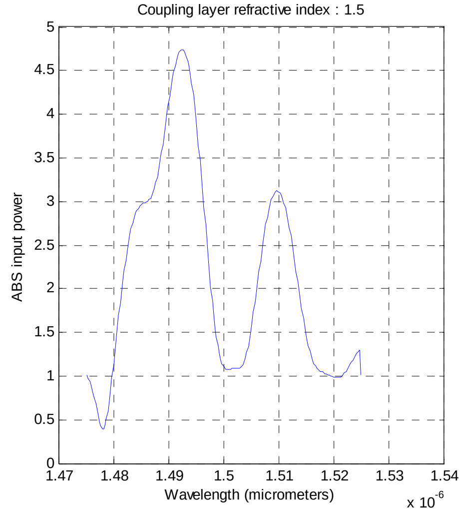


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.507e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0401e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 5.0066e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2

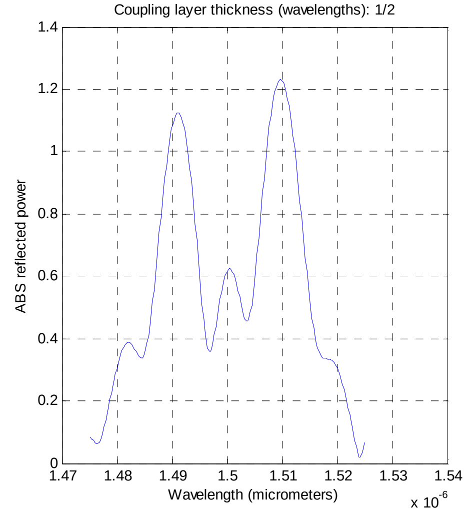


(± 10nm (PC2 = 1490, PC1 = 1510))

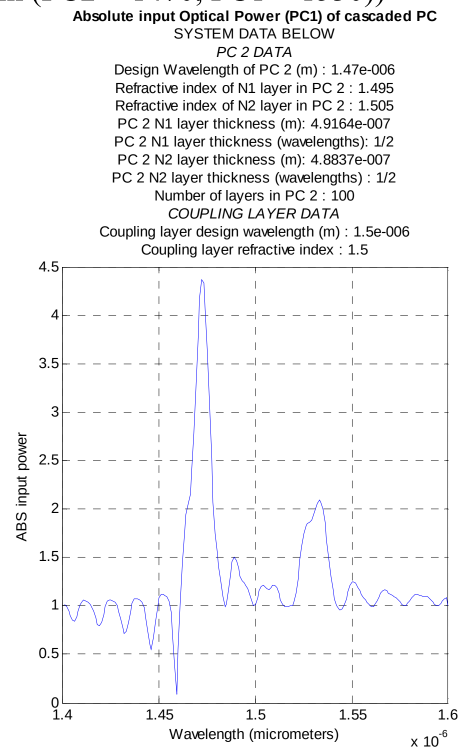
Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.49e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 4.9833e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9502e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5

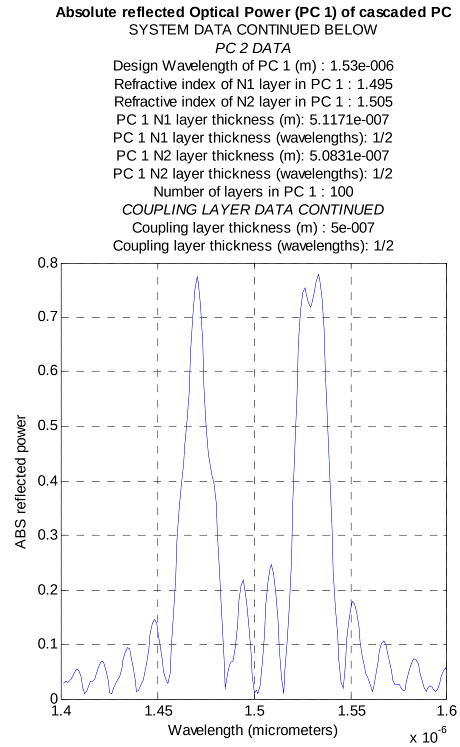


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.51e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0502e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 5.0166e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2



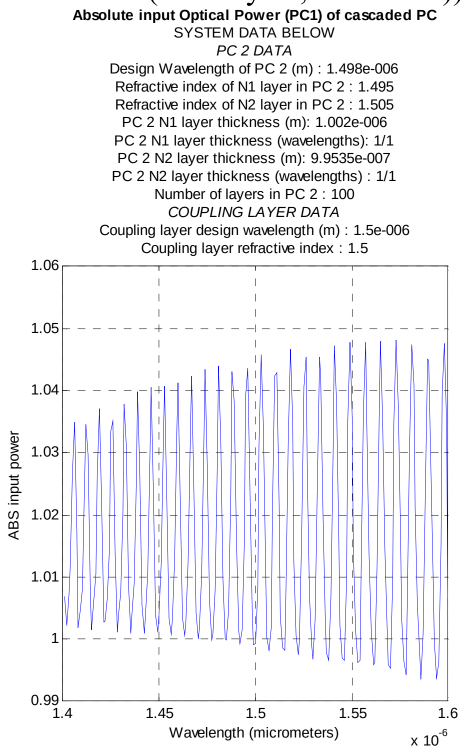
(± 30nm (PC2 = 1470, PC1 = 1530))

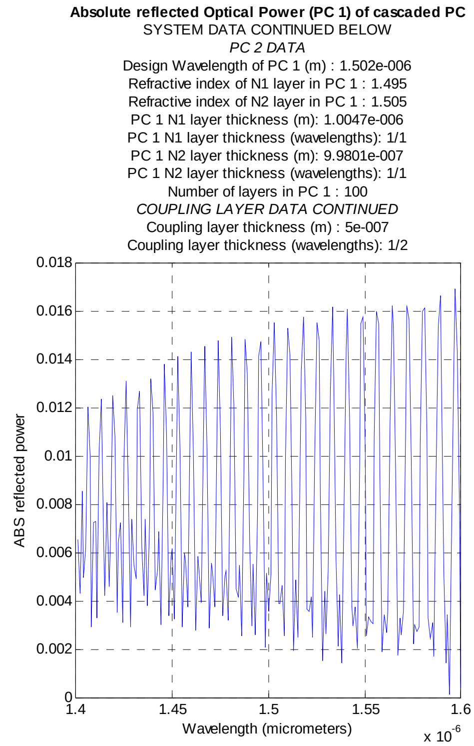




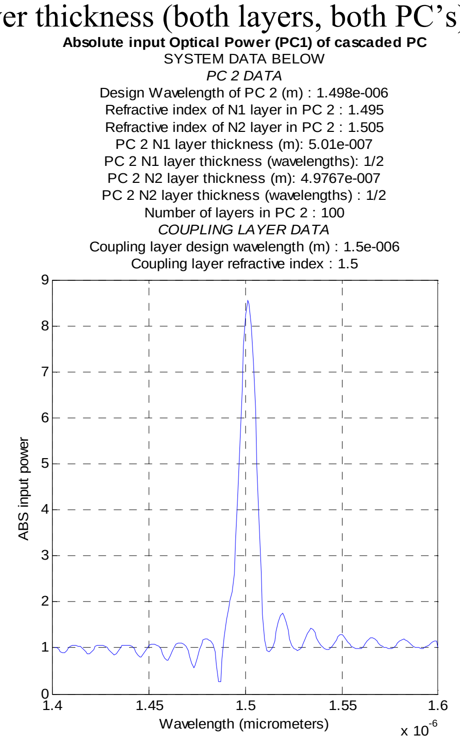
6.4 Part iv) Simulation plots where PC layer thickness is varied.

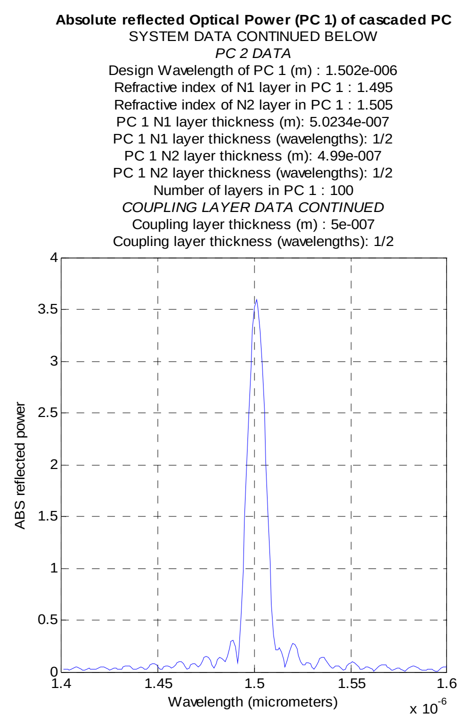
(λ layer thickness (both layers, both PC's))





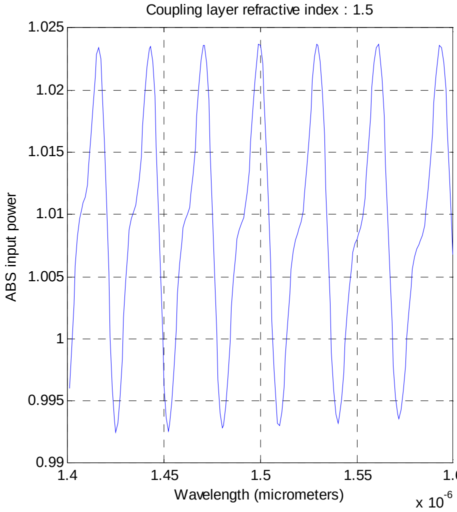
($\lambda/2$ layer thickness (both layers, both PC's))



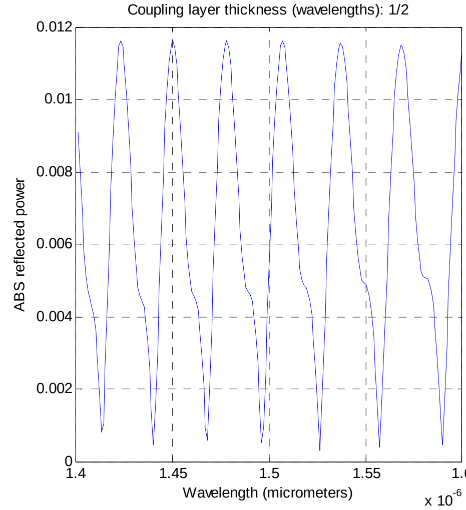


(λ/4 layer thickness (both layers, both PC's))

Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 2.505e-007
PC 2 N1 layer thickness (wavelengths): 1/4
PC 2 N2 layer thickness (m): 2.4884e-007
PC 2 N2 layer thickness (wavelengths) : 1/4
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5

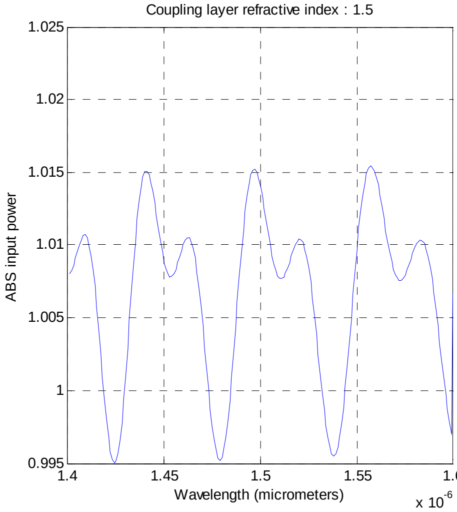


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 2.5117e-007
PC 1 N1 layer thickness (wavelengths): 1/4
PC 1 N2 layer thickness (m): 2.495e-007
PC 1 N2 layer thickness (wavelengths): 1/4
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2

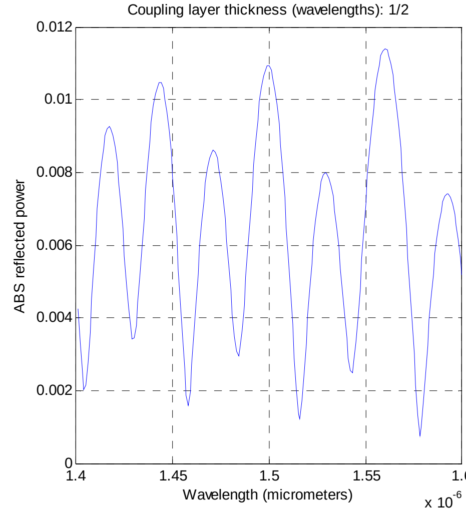


(λ/8 layer thickness (both layers, both PC's))

Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 1.2525e-007
PC 2 N1 layer thickness (wavelengths): 1/8
PC 2 N2 layer thickness (m): 1.2442e-007
PC 2 N2 layer thickness (wavelengths) : 1/8
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5

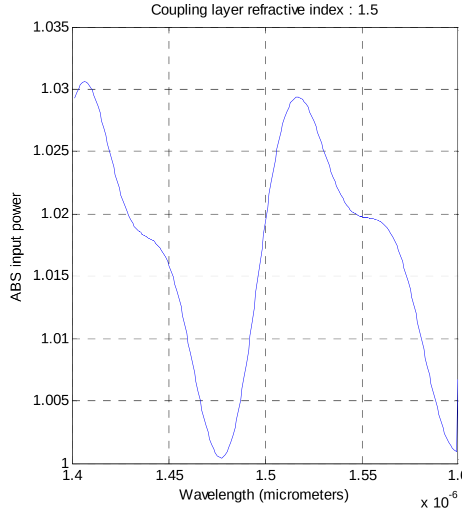


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 1.2559e-007
PC 1 N1 layer thickness (wavelengths): 1/8
PC 1 N2 layer thickness (m): 1.2475e-007
PC 1 N2 layer thickness (wavelengths): 1/8
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2

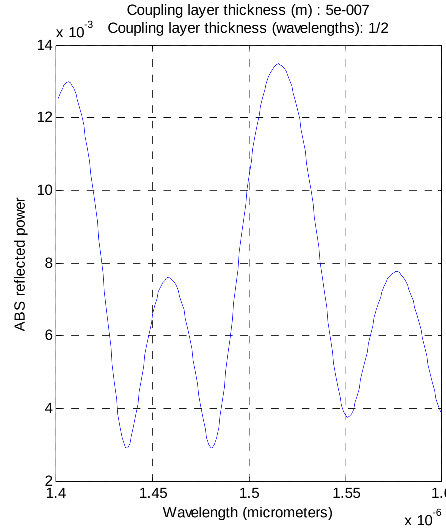


(λ/16 layer thickness (both layers, both PC's))

Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 6.2625e-008
PC 2 N1 layer thickness (wavelengths): 1/16
PC 2 N2 layer thickness (m): 6.2209e-008
PC 2 N2 layer thickness (wavelengths) : 1/16
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5

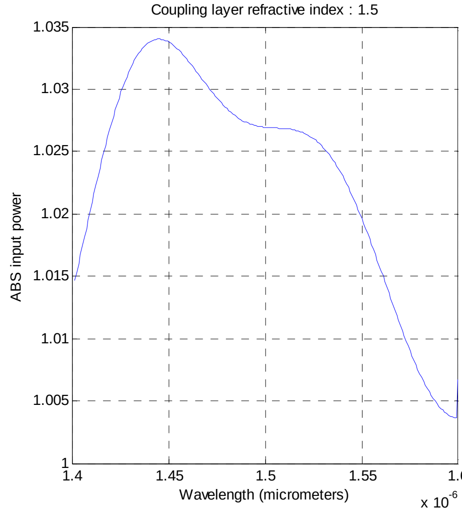


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 6.2793e-008
PC 1 N1 layer thickness (wavelengths): 1/16
PC 1 N2 layer thickness (m): 6.2375e-008
PC 1 N2 layer thickness (wavelengths): 1/16
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2

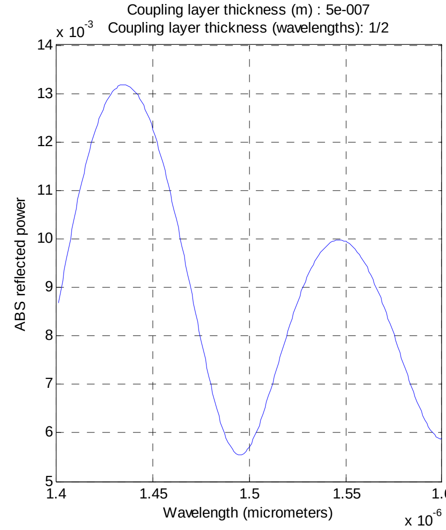


(λ/32 layer thickness (both layers, both PC's))

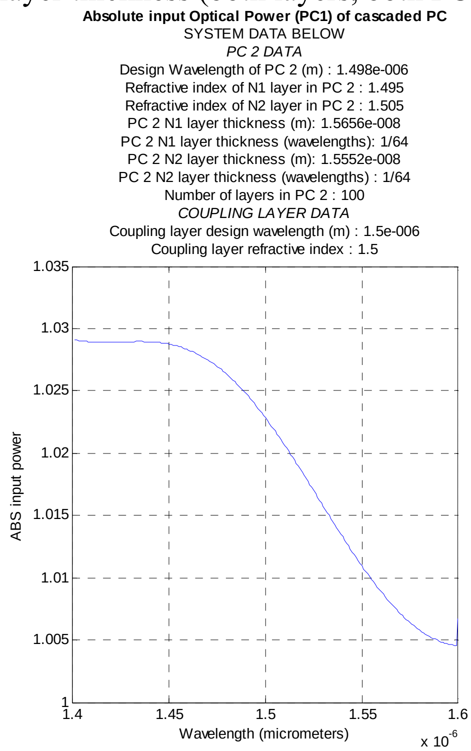
Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 3.1313e-008
PC 2 N1 layer thickness (wavelengths): 1/32
PC 2 N2 layer thickness (m): 3.1105e-008
PC 2 N2 layer thickness (wavelengths) : 1/32
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5

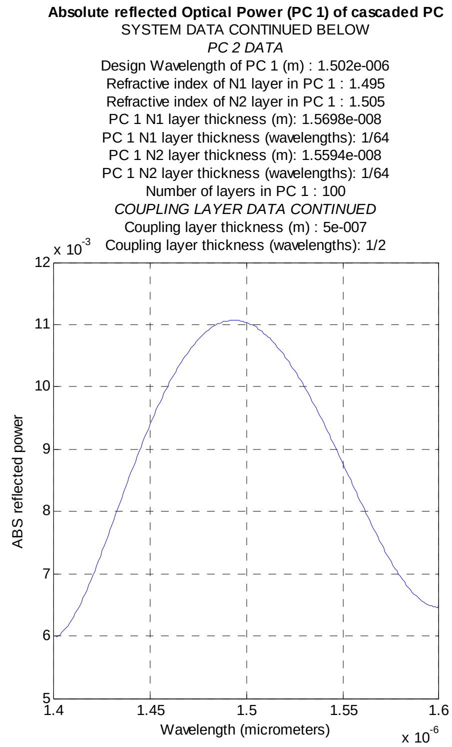


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 3.1396e-008
PC 1 N1 layer thickness (wavelengths): 1/32
PC 1 N2 layer thickness (m): 3.1188e-008
PC 1 N2 layer thickness (wavelengths): 1/32
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2



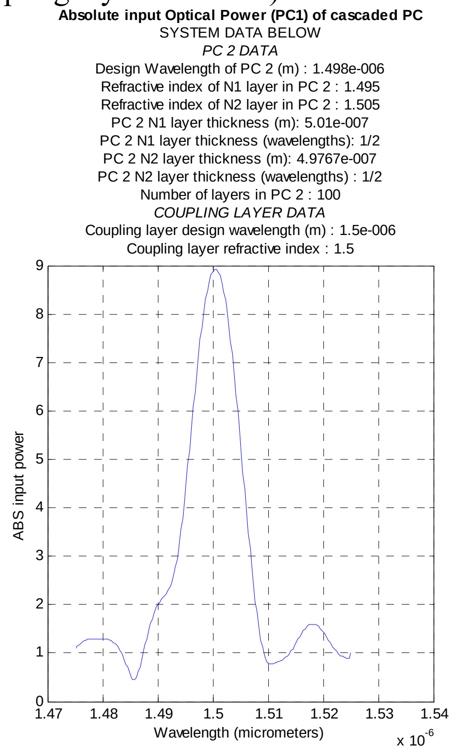
(λ/64 layer thickness (both layers, both PC's))

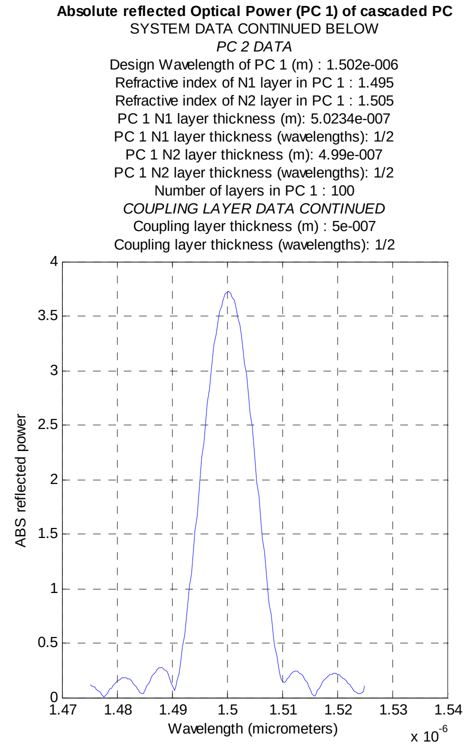




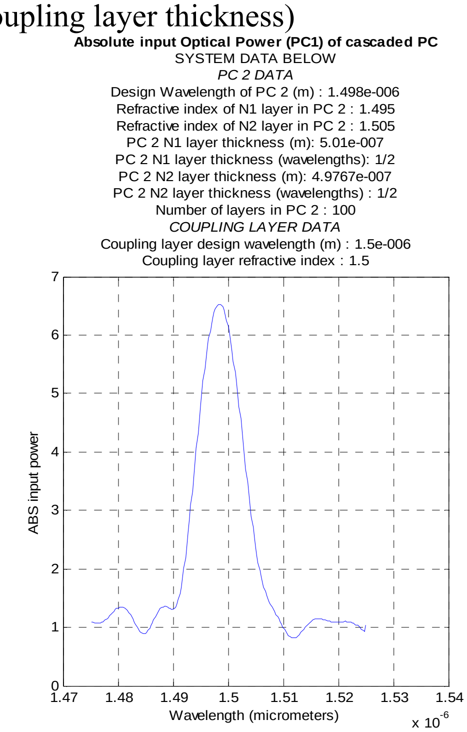
6.5 Part v) Simulation plots where the coupling layer thickness is varied.

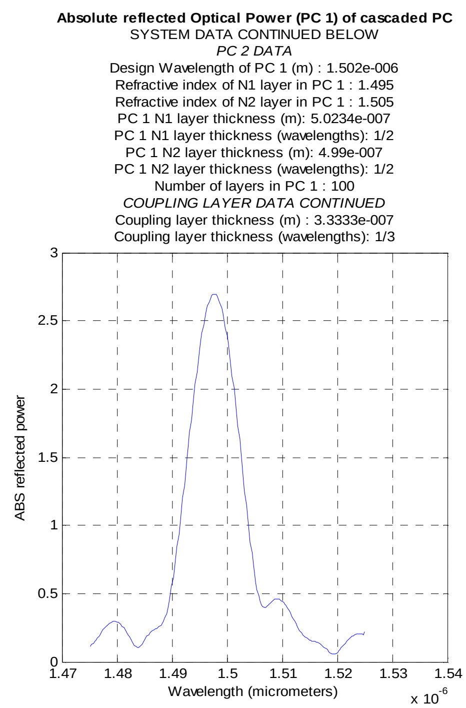
(λ/2 coupling layer thickness)



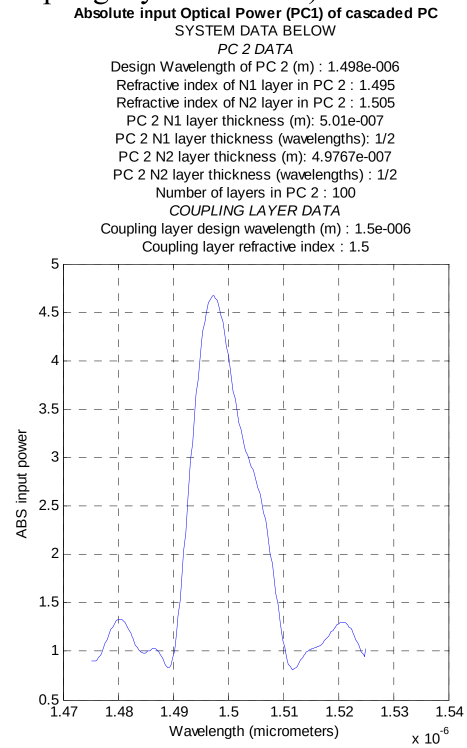


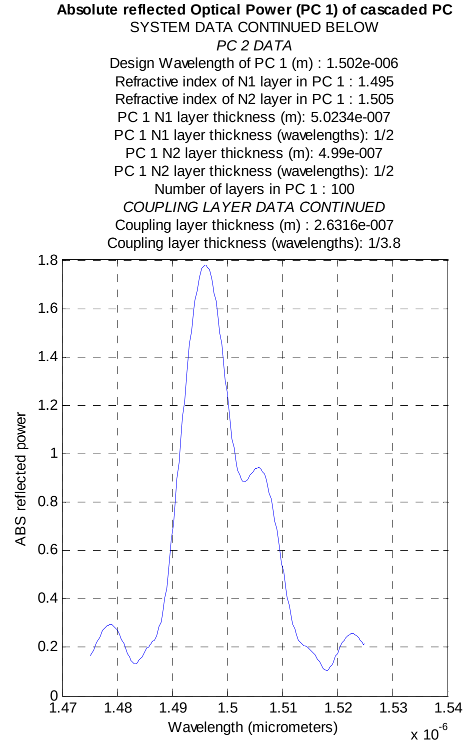
(λ/3 coupling layer thickness)



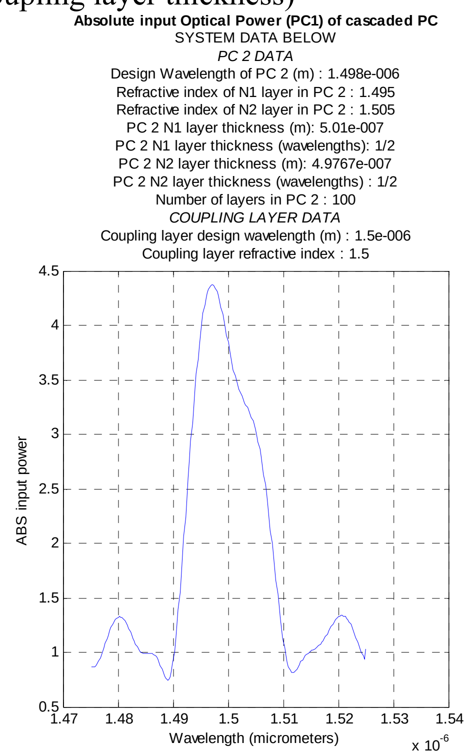


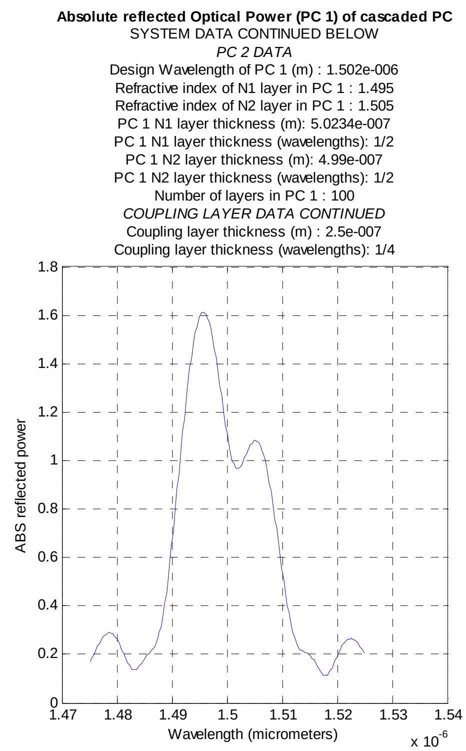
(λ/3.8 coupling layer thickness)



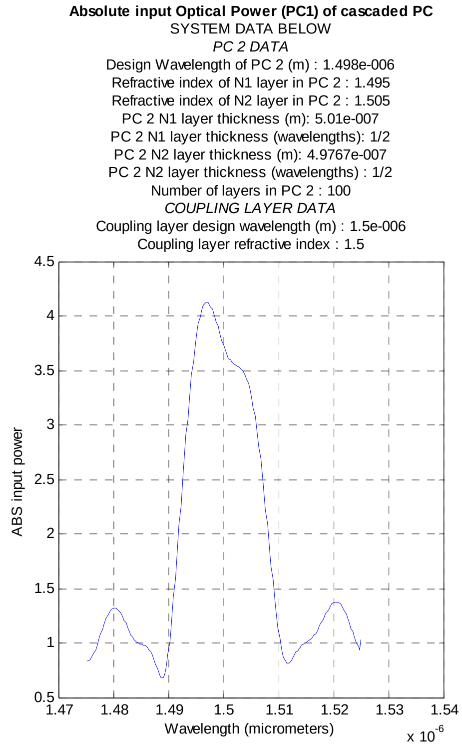


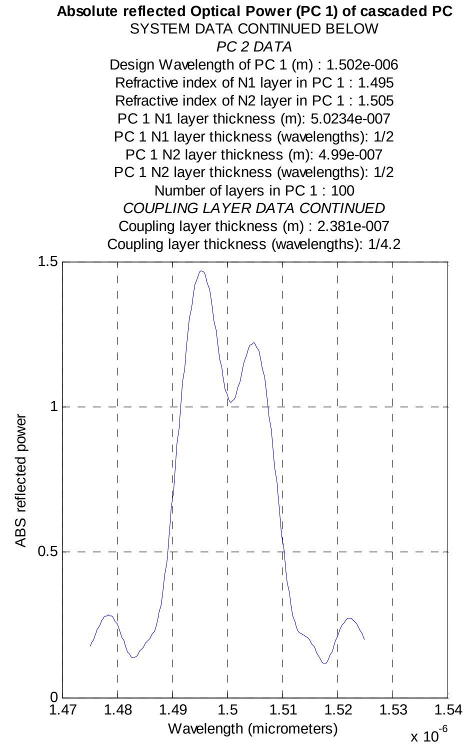
(λ/4 coupling layer thickness)



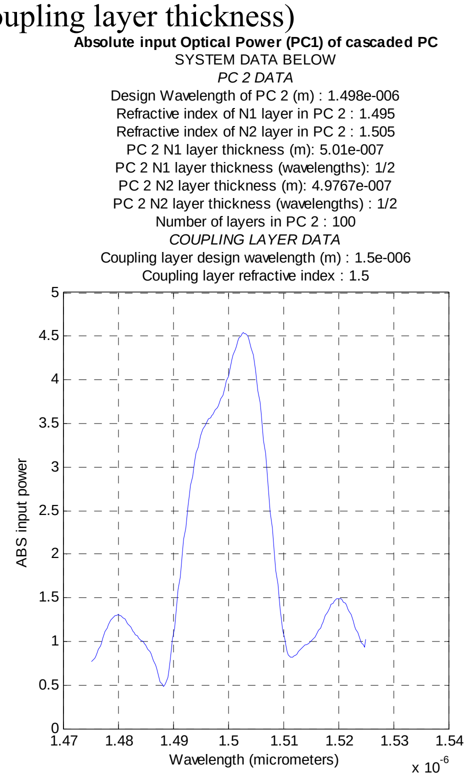


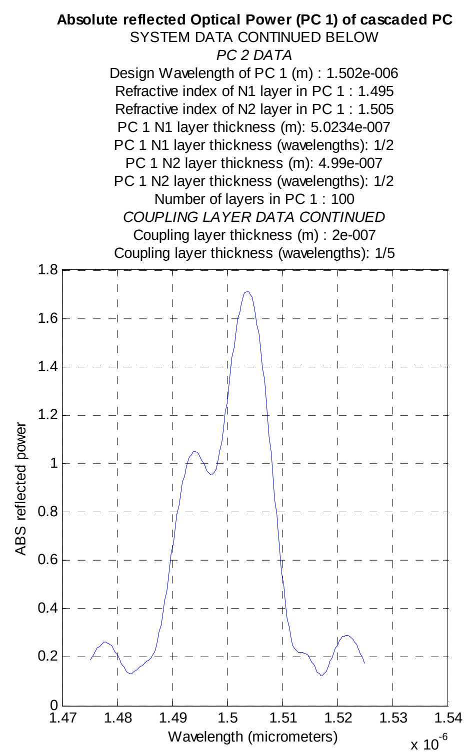
(λ/4.2 coupling layer thickness)



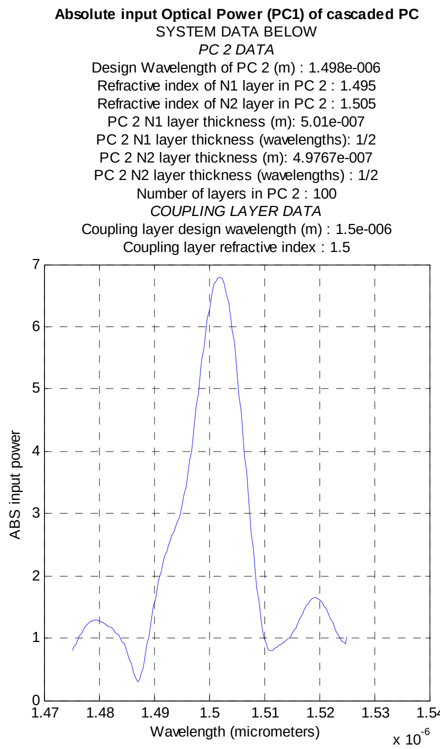


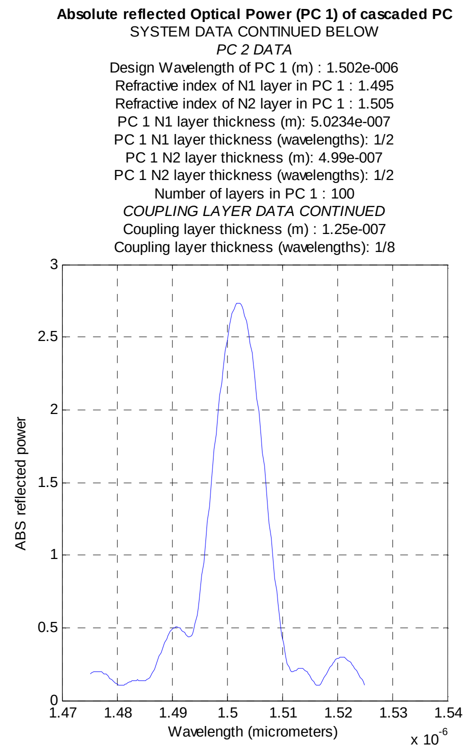
(λ/5 coupling layer thickness)



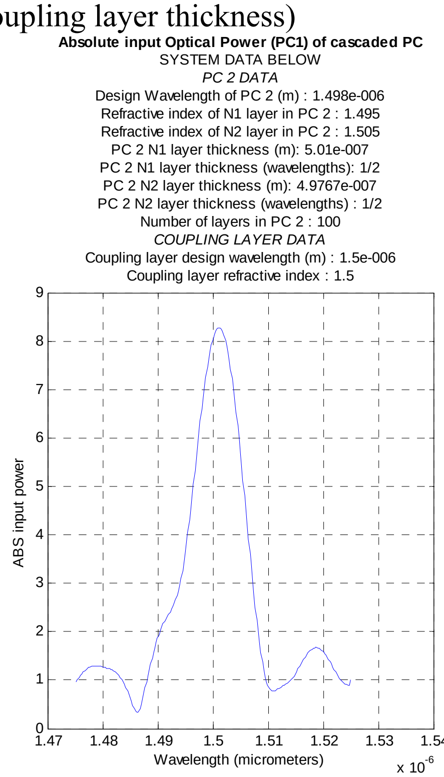


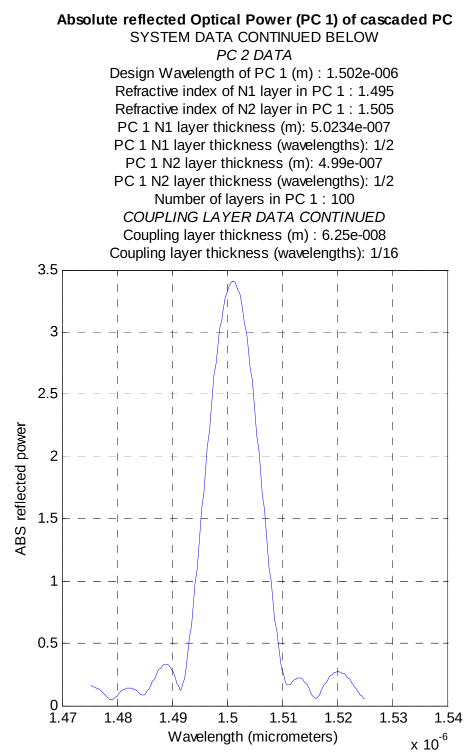
(λ/8 coupling layer thickness)



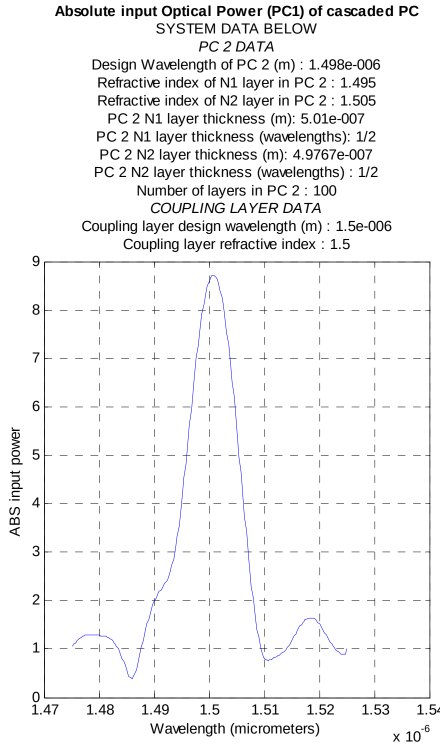


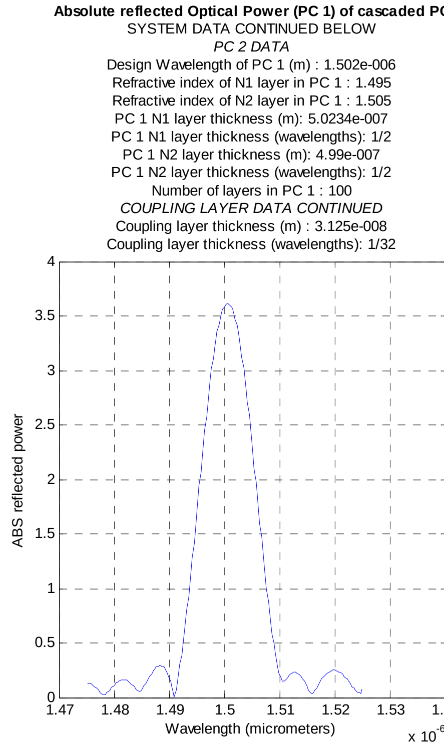
(λ/16 coupling layer thickness)



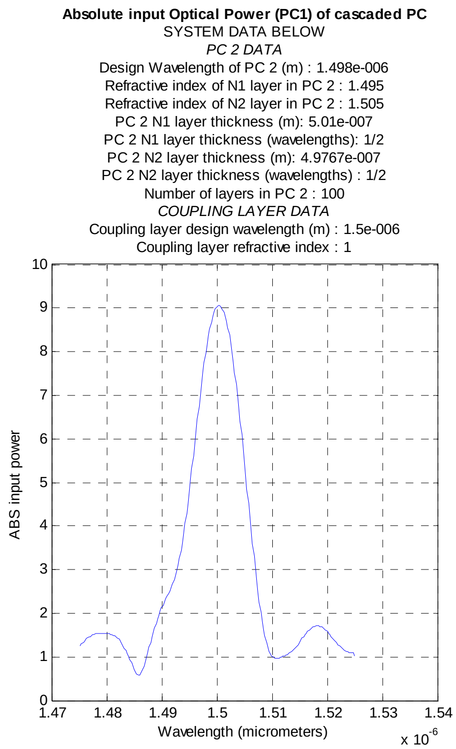


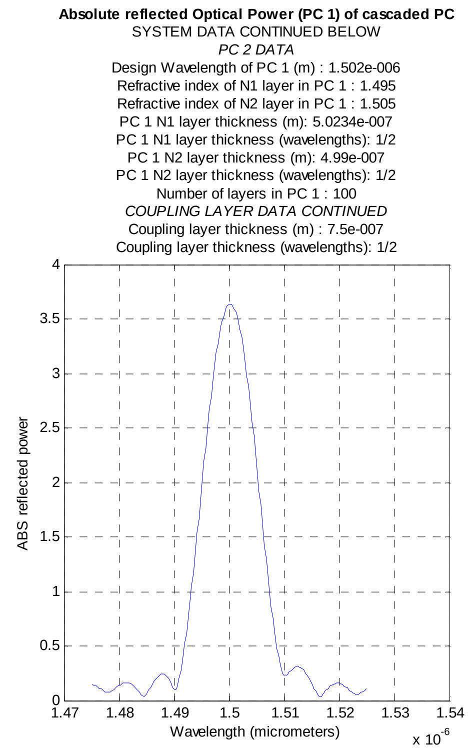
(λ/32 coupling layer thickness)



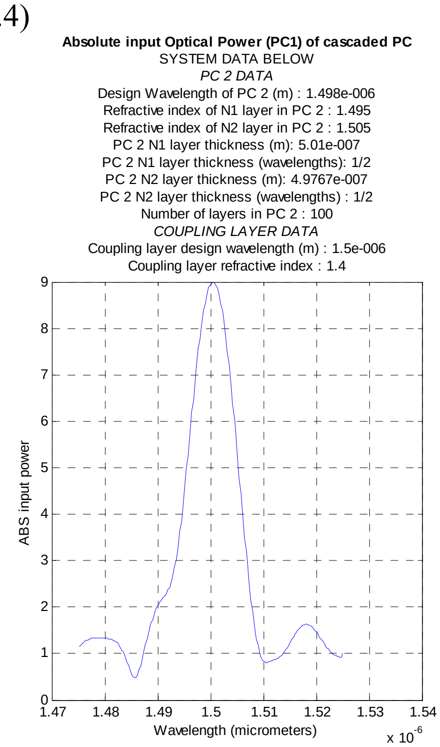


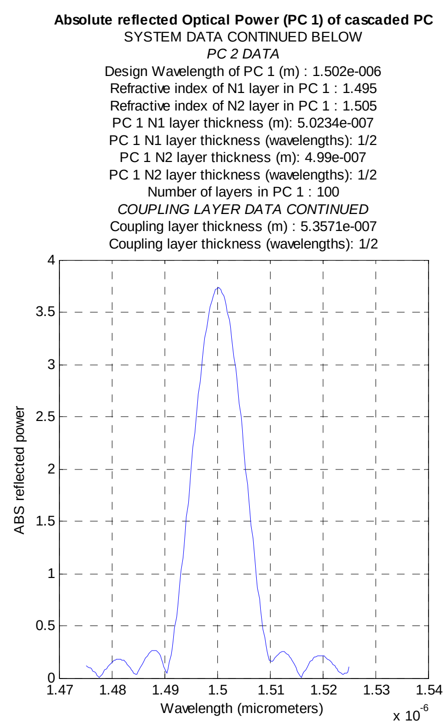
6.6 Part vi) Simulation plots where the coupling layer refractive index is varied. ($n_c = 1$)


Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1
ABS input power
Wavelength (micrometers)
x 10-6


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 7.5e-007
Coupling layer thickness (wavelengths): 1/2
ABS reflected power
Wavelength (micrometers)
x 10-6

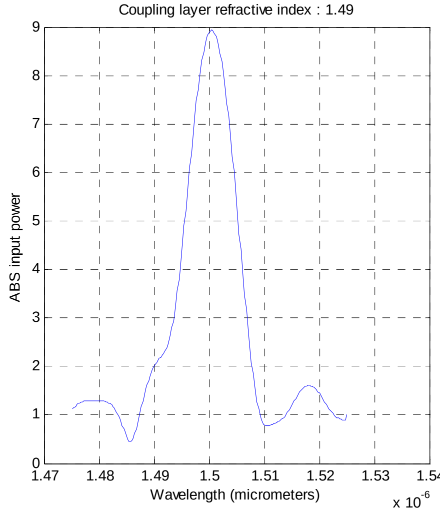
(n_c = 1.4)


Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.4
ABS input power
Wavelength (micrometers)
x 10-6

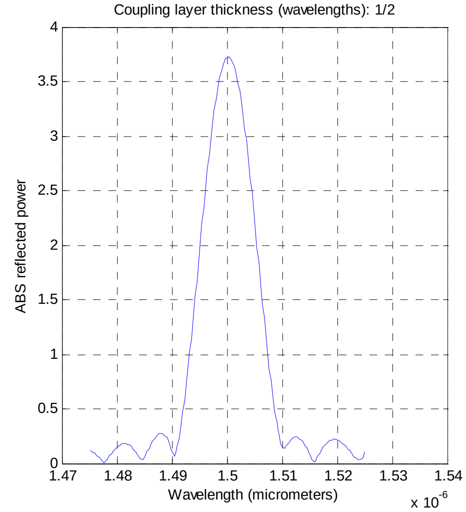

Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5.3571e-007
Coupling layer thickness (wavelengths): 1/2
ABS reflected power
Wavelength (micrometers)
x 10-6

(n_c = 1.49)

Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.49

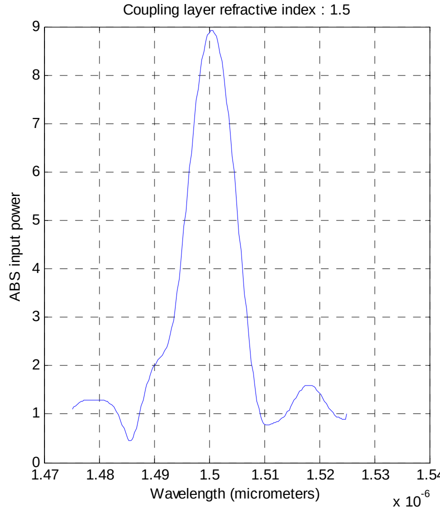


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5.0336e-007
Coupling layer thickness (wavelengths): 1/2

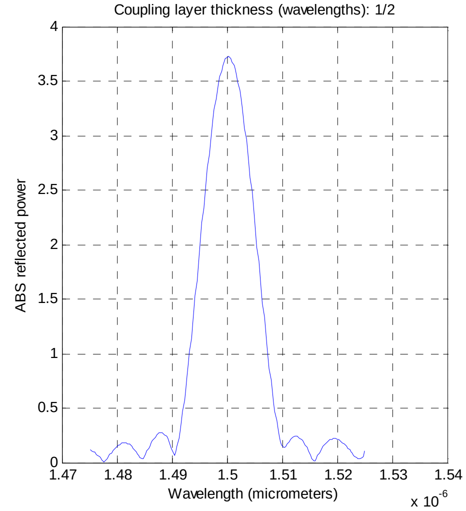


($n_c = 1.5$)

Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.5

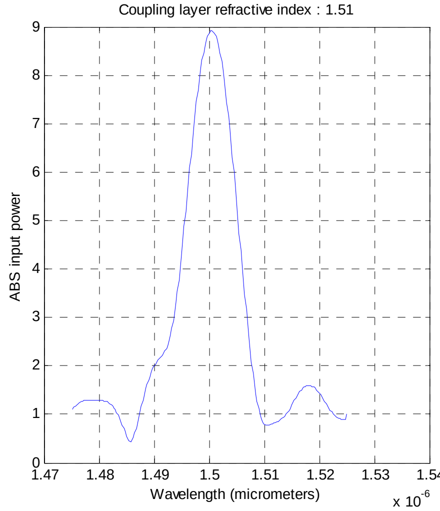


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 5e-007
Coupling layer thickness (wavelengths): 1/2

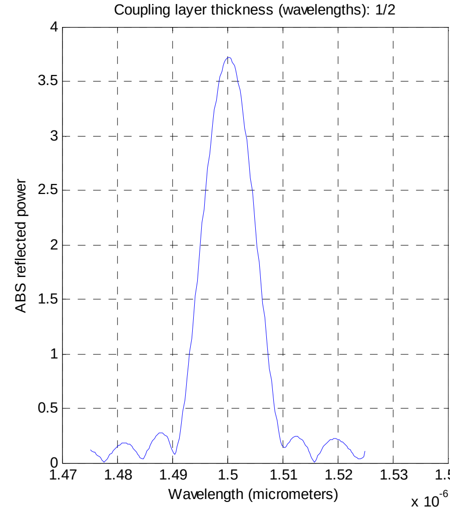


(n_c = 1.51)

Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.51

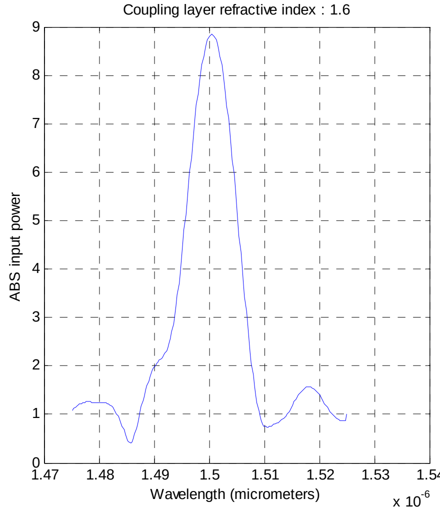


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 4.9669e-007
Coupling layer thickness (wavelengths): 1/2

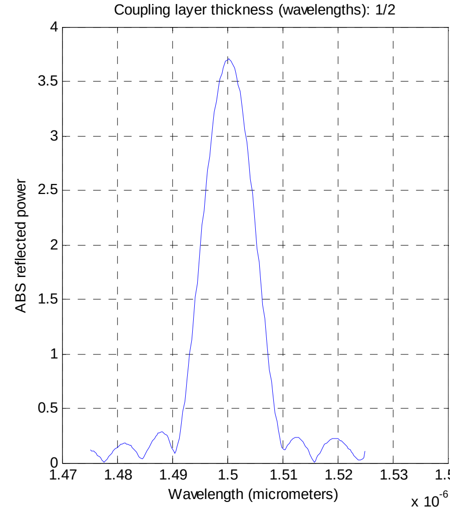


(n_c = 1.6)

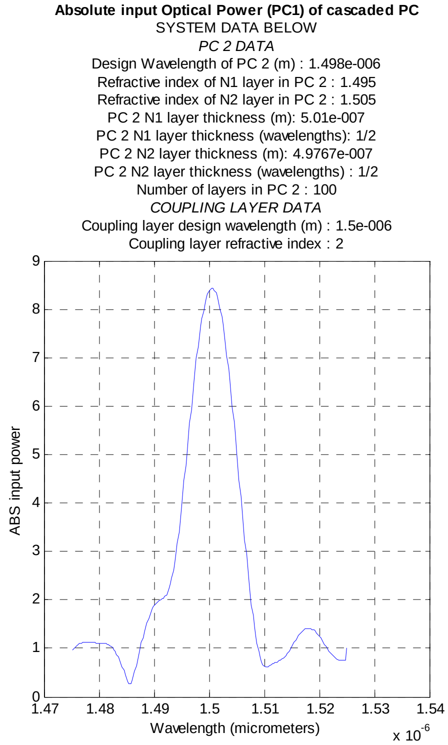
Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.6

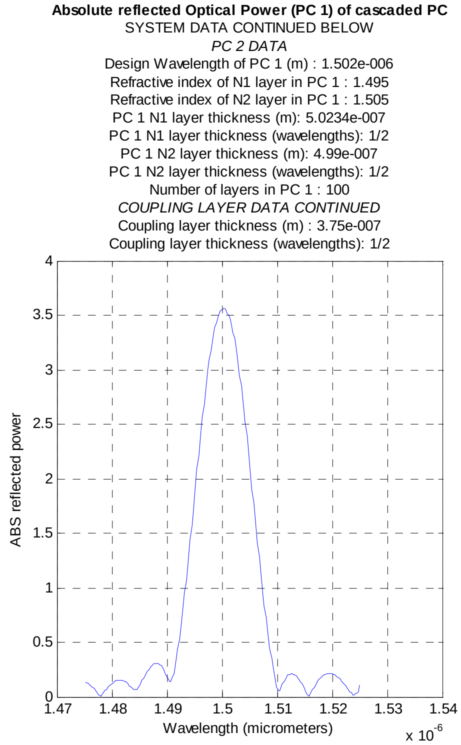


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 4.6875e-007
Coupling layer thickness (wavelengths): 1/2

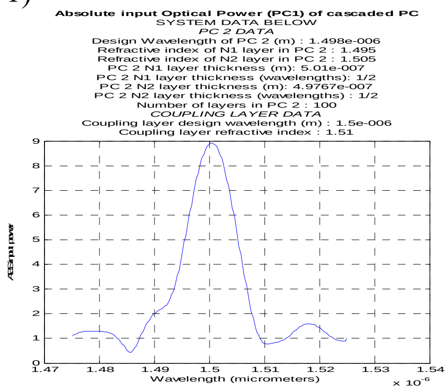


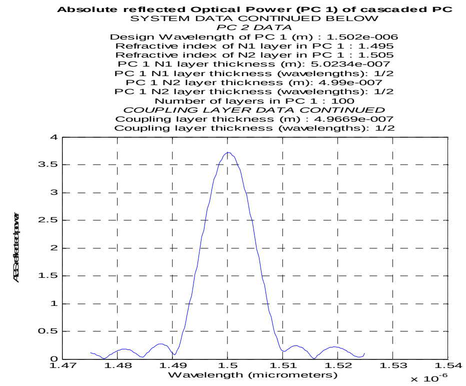
($n_c = 2$)


Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 2
ABS input power
Wavelength (micrometers)
x 10^-6

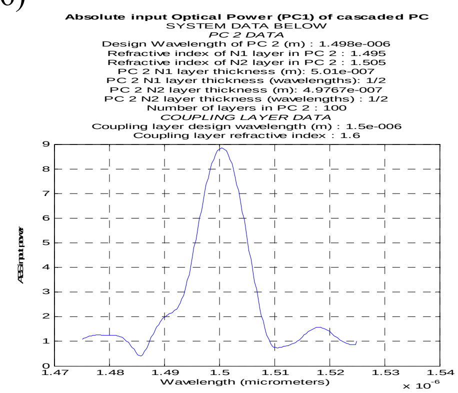

Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 3.75e-007
Coupling layer thickness (wavelengths): 1/2
ABS reflected power
Wavelength (micrometers)
x 10^-6

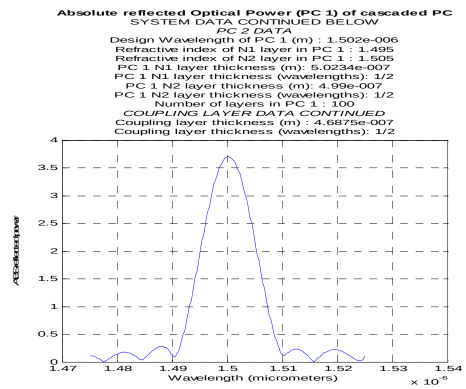
(n_c = 1.51)


Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.51
Wavelength (micrometers)
x 10-6

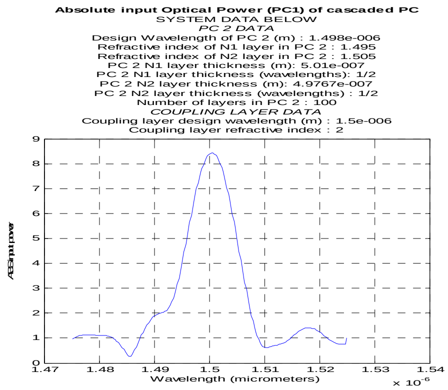

Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 4.9669e-007
Coupling layer thickness (wavelengths): 1/2
Wavelength (micrometers)
x 10-6

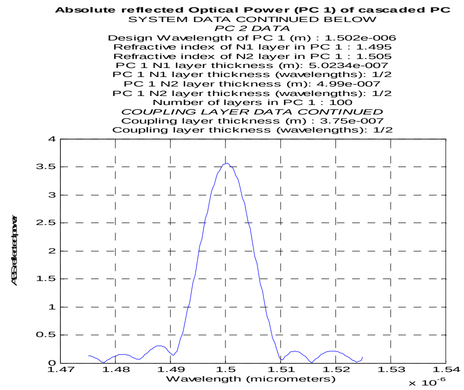
(n_c = 1.6)


Absolute input Optical Power (PC1) of cascaded PC
SYSTEM DATA BELOW
PC 2 DATA
Design Wavelength of PC 2 (m) : 1.498e-006
Refractive index of N1 layer in PC 2 : 1.495
Refractive index of N2 layer in PC 2 : 1.505
PC 2 N1 layer thickness (m): 5.01e-007
PC 2 N1 layer thickness (wavelengths): 1/2
PC 2 N2 layer thickness (m): 4.9767e-007
PC 2 N2 layer thickness (wavelengths) : 1/2
Number of layers in PC 2 : 100
COUPLING LAYER DATA
Coupling layer design wavelength (m) : 1.5e-006
Coupling layer refractive index : 1.6
Wavelength (micrometers)
x 10-6


Absolute reflected Optical Power (PC 1) of cascaded PC
SYSTEM DATA CONTINUED BELOW
PC 2 DATA
Design Wavelength of PC 1 (m) : 1.502e-006
Refractive index of N1 layer in PC 1 : 1.495
Refractive index of N2 layer in PC 1 : 1.505
PC 1 N1 layer thickness (m): 5.0234e-007
PC 1 N1 layer thickness (wavelengths): 1/2
PC 1 N2 layer thickness (m): 4.99e-007
PC 1 N2 layer thickness (wavelengths): 1/2
Number of layers in PC 1 : 100
COUPLING LAYER DATA CONTINUED
Coupling layer thickness (m) : 4.6875e-007
Coupling layer thickness (wavelengths): 1/2
Wavelength (micrometers)
x 10-6

($n_c = 2$)





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i P. Yeh, *Optical Waves in Layered Media,* John Wiley & Sons, New York (1988)
ii SIGNAL FLOW BOOK
iii WorkIQ, “Definition of MATLAB”, http://www.wordiq.com/definition/MATLAB