Optimization of optical waveguide structure

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Abstract-**Optical waveguides have been known as basic structure in integrated optics. The result of waveguide analysis is very useful to apply before fabrication process begins. The normalized propagation constant b, propagation constant β and effective refractive index n_{eff} conditions have been considered for the straight waveguide for single mode propagation. In this work, a mathematical approach was applied in order to model the waveguide structure and its ability to guide the light. Through this, the behavior of light propagation in a polymer based optical waveguide could be investigated and the characteristic of the optical waveguide can be simulated in order to obtain an optimum design.**

Keywords-Optical waveguide, normalized propagation constant, effective refractive index, computational time, optimum design

I. INTRODUCTION

An optical waveguide is a physical structure that guides electromagnetic waves in the optical spectrum. Waveguides used at optical frequencies are typically dielectric waveguides, structures in which a dielectric material with high permittivity, and thus high index of refraction, is surrounded by a material with lower permittivity. The structure guides optical waves by total internal reflection.

Optical waveguides are used as components in integrated optical circuitsor as the transmission medium in local and long haul optical communication systems. In 1960, Miller introduced the term 'Integrated Optics'[1]. It was involve the realization of the optical and electro optic elements which may be integrated in the large numbers on one chip means of the same processing techniques used to fabricate integrated electronic circuits.

Optical waveguides can be classified according to their geometry (planar, strip, or fiber waveguides), modestructure (single-mode and multi-mode), refractive index distribution (step or gradient index) and material (glass, polymer, semiconductor) [2].

Optic communication systems widely operate in the wavelength windows at 850nm, 1310nm and 1550nm. For a low loss transmission system, the optical loss due absorption from ultra violet (UV) and infrared (IR) region must minimize at operating wavelength and the system bandwidth will be increase. To choose the best wavelength, it depends to the transmission system.

There is several type of representative channel waveguide such as buried channel waveguide, strip-loaded waveguide, ridge waveguide and rib waveguide[3]. These four types of waveguides are usually termed rectangular waveguides with a thickness d in the x direction and a width w in the y direction, though their shapes are normally not exactly rectangular.

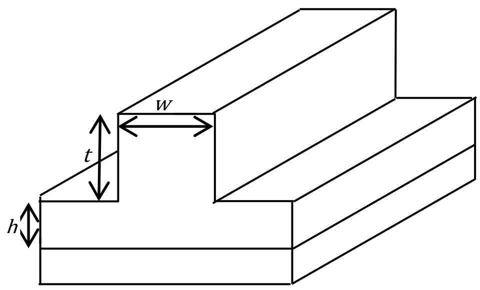

Figure 1: Rib channel waveguide

There are numerous types of technique to analyze the optical waveguide, and those techniques can divided into analytical and numerical methods [4]. In this project, we have concentrate to the numerical method. By using numerical method, there are several method are applicable such as scalar and vectorial finite element method, scalar and vectorial finite difference method, and beam propagation method. For this work, we have emphasis on scalar finite difference method.

MATLAB (R2010b) was used to carry out this project. MATLAB (R2010b) was easier application to simulate a single mode optical waveguide because the application was friendly user to engineering student. By using MATLAB (R2010b), we can calculate the normal propagation constant, propagation constant, effective index and computation time [5].

II. METHODOLOGY

The finite difference method (FDM) is a simple numerical technique used in solving problem that uniquely defined by three things, firstly partial differential equation such as Laplace's or Poisson' equation, a solution region Boundary and initial conditions [6]. The basic formulation that governs the propagation of light in the optical waveguide is a Maxwell's equations and it can be derived to get the electric field equation [7].

$$E(i,j) = \frac{E(i+1,j) + E(i-1,j) + \left(\frac{\Delta x^2}{\Delta y^2}\right)^2 \left(E(i,j+1) + E(i,j-1)\right)}{2\left(1 + \left(\frac{\Delta x^2}{\Delta y^2}\right)^2\right) - \Delta x^2\left(k_o^{\,2} n^2(i,j) - \beta^2\right)} \ldots (1)$$

Due to difficulties in interpreting small differences of effectives index values, a more sensitive comparison is made by introducing a normalized propagation constant [8]:

$$b = \frac{n_{eff}{}^2 - n_{substrate}{}^2}{n_{guide}{}^2 - n_{substrate}{}^2} \ldots\ldots\ldots\ldots\ldots (2)$$

Wealso have calculated the cutoff thickness for each waveguide mode. By calculating the cutoff thickness, we can know the range of single mode. The basic formulationto calculate cutoff thickness [9]:

$$C_{th} = \frac{\lambda}{2\pi\sqrt{n_2{}^2 - n_3{}^2}}\left[m\pi + \tan^{-1}\left(\sqrt{\frac{n_3{}^2 - n_1{}^2}{n_2{}^2 - n_3{}^2}}\right)\right] \ldots (3)$$

In this project, a rib structure was used to obtain the optimum design of single mode optical waveguide. From the figure, the labels are described as below:

n_s=substrate refractive index
n_c=cladding refractive index
n_f=core refractive index
w= rib width
h=rib height
t=rib thickness

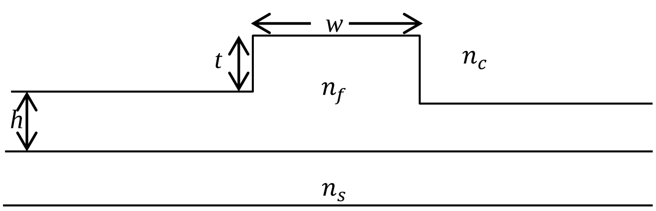

Figure 2: Rib structure

Figure 3 shows a flow process of optimization design step. The thickness, height and width of core will be affected in order to get the optimum design of single mode condition.

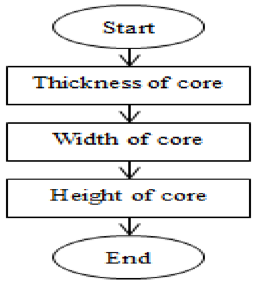

Figure 3: Flow process in optimizing the design of single mode condition

A. Thickness of core

By increasing or decreasing the thickness of core, it can affect the mode condition whether become single mode or multi mode. In this work, we need to create the optimum design of single mode condition by using rib representative channel waveguide.

B. Height of core

By reducing the height of core means reduces the overall size of the rib and weakens the lateral confinement.[10]The rib height has little effect on the anti-symmetric mode, and the effect is saturated very quickly. That is why by adjusting the height of core, it will affect the mode condition.

C. Width of core

According to waveguide processing technology, the waveguide width is the easiest parameter to vary after the wafer is ordered [10].Different width can be used anywhere on a wafer, so it makes sense to investigate width issues first. The width of core also affects to get the optimum design of single mode condition.

Figure 4 shows a flow chart of work progress of matlab code. It involves the declaration variable of material, shape of representative channel waveguide and operation of calculating normalized propagation constant, propagation constant, effective index and computation time.

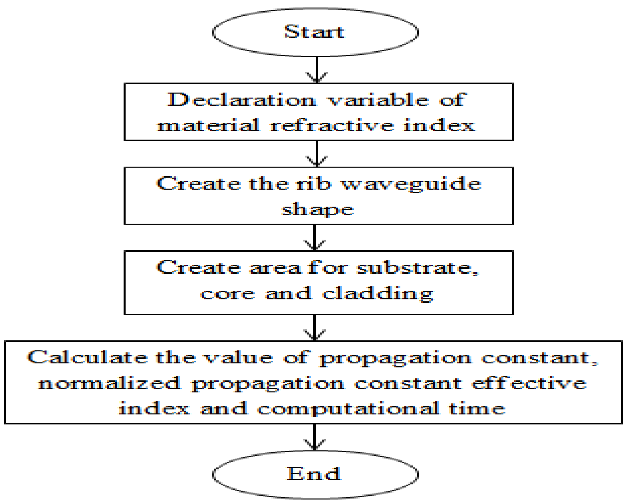

Figure 4: Flow chart of MATLAB operation

A. *Declaration of material refractive index*

For this project, the value of substrate and core refractive index are 1.545 and 1.57. For air refractive index are fixed which is 1.0. 1310nm wavelength were used in this project because it is suitable to get the optimum result.

B. *Create the rib waveguide shape*

Rib waveguide are usually termed rectangular waveguide with a thickness *t* in the *x* direction and*a* width *w* in the y direction. In this project, the values of thickness are varied to get the optimum result for the single mode optical waveguide. The value of the thickness and width will affect the normal propagation constant, propagation constant and effective index.

C. *create area for substrate, core and air*

Rib waveguide consist of three layer which is substrate, core and cover. The top layer is called the cover layer. Air also can acts as a cover layer. Bottom layer is often a substrate. Core layer sandwiched between two layer of substrate and cover layer. The value of sabstrate and cover layer are lower refractive index. In this project, the value of core refractive index is 1.57 (hot plate polymer), substrate refractive index is 1.545 (oven baked polymer) and cover refractive index is 1.0(air).

D. *Operation of normalized propagation constant, propagation constant and effective index*

In numerical technique, there are three things need to do which is partial differential equation such as Laplace's or Poisson' equation, a solution region Boundary and/or initial conditions. By deriving maxwell's equation, electric field equation will be obtained. That equation is then applied to MATLAB code. By electric field equation, the normalized propagation constant, propagation constant, and effective index can be computed.

III. RESULT AND DISCUSSION

A. *Rib thickness*

In this project, we have varied the value of rib thickness with 0.5μm, 1.0μm, 2.0μm, 3.0μm, 4.0μm and 5.0μm. In this section, the value of width and height are fixed where the value of width and height are 6μm and 0μm respectively. Cover layer refractive index (air) = 1.0, core refractive index (hot plate polymer) = 1.57 and bottom layer refractive index (oven baked polymer) = 1.545. The results are listed in Table 1.

TABLE 1: MODE PROFILE CORE

Thickness (μm)	Normal propagation constant	Propagation constant	Effective index
0.5	-0.0474	$7.4046x10^6$	1.5438
1.0	-0.0278	$7.4070x10^6$	1.5443
2.0	0.3582	$7.4535x10^6$	1.5540
3.0	0.5641	$7.4782x10^6$	1.5592
4.0	0.6642	$7.4902x10^6$	1.5616
5.0	0.7193	$7.4968x10^6$	1.5630

From table 1, it shows that the value of normal propagation constant b, propagation constant β and effective refractive index neff. By increase the thickness, the value of normal propagation constant also increase. For the propagation constant and effective index also increase when the thickness are increase. For effective index, change of thickness does not affected so much. As state at table 1, value of effective index are almost is same for all thickness.A guided must satisfy the equation that$k_o n_s < \beta < k_o n_f$.In this case, the optimum thickness to get the optimum design by using 3μm where the waveguide is lied in the range for a guided wave which is $7.4102835x10^6 < \beta < 7.530191x10^6$.If the thickness was decrease less than 1μm, the electric field energy will radiate to the substrate.

B. *Rib height*

The six different height of rib were simulated at 0.0μm, 0.2μm, 0.4μm, 0.6μm, 0.8μm, and 1.0μm. For this section, width and thickness rib were set to be constant. In this case, width and thickness are 6μmand 3.0μm respectively. The result are show in table 2.

TABLE 2: MODE PROFILE HEIGHT

Height (μm)	Normal propagation constant	Propagation constant	Effective index
0.0	0.5641	$7.4782x10^6$	1.5592
0.2	0.5910	$7.4814x10^6$	1.5598
0.4	0.6149	$7.4843x10^6$	1.5604
0.6	0.6365	$7.4869x10^6$	1.5610
0.8	0.6561	$7.4892x10^6$	1.5614
1.0	0.6741	$7.4914x10^6$	1.5619

From table 2, by increasing the value of height, the normalized propagation constant, propagation constant and effective index will be increased.By varying the value of height, the normalized propagation constant, propagation constant and effective index does not affect to much.By varying small difference of height, it will affect to get the optimum design. In this project, the optimum height to get the optimum single mode condition is 0.2μm. by using 3μm of rib thickness and 0.2μm of height, the waveguide were lied in the range for a guided wave.

If the rib height is high, electric field energy still radiate into the core but in scatter condition. Figure 5 show the electric field in scatter condition.

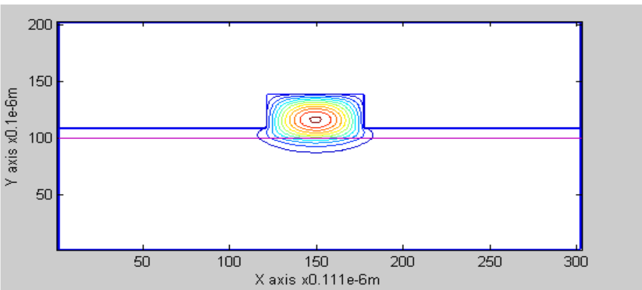

Figure 5: High rib height

C. *Rib width*

In the previous section, the optimum design value of thickness and height are 3.0µm and 0.2µm respectively. To get the optimum value of width, the value of thickness and height are fixed. In this section, we need to obtain the optimum value of width to get the optimum design of single mode optical waveguide.

TABLE 3: MODE PROFILE WIDTH

Width (µm)	Normal propagation constant	Propagation constant	Effective index
3.0	0.2478	$7.4402x10^6$	1.5512
4.0	0.4344	$7.4626x10^6$	1.5559
5.0	0.5330	$7.4745x10^6$	1.5584
6.0	0.5910	$7.4814x10^6$	1.5598
7.0	0.6279	$7.4858x10^6$	1.5607
8.0	0.6529	$7.4888x10^6$	1.5614

According to table 3, it shows the value of normalized propagation constant, propagation constant and effective index with varies the value of width. Refer to the result, by using 6.0µm rib width was the best to get the optimum design to get the single mode optical waveguide. Figure 6 and figure 7show the comparison between high and low rib width.

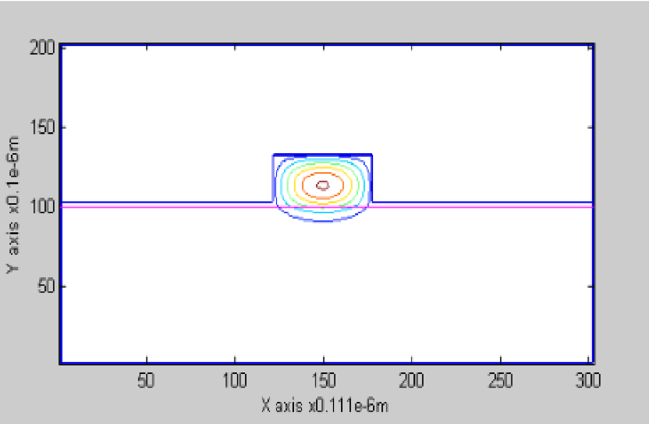

Figure 6: High rib width

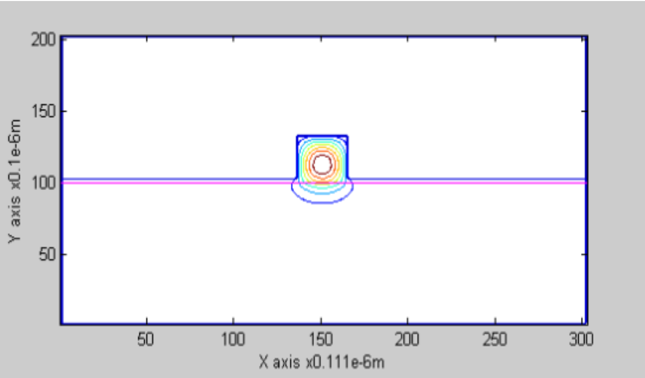

Figure 7: Low rib width

D. *Computational time*

By using intel(R) core(TM) i3 530@2.93GHz with 2.00 GB of DDR3 RAM the computational time taken for optimum design was calculated in this project. Optimum design of single mode optical waveguide with 3µm rib thickness, 0.2µm rib height and 6µm rib width. The result shown in table 4.

TABLE 4: COMPUTATION TIME

Height(µm)	x=0.111µmy=0.1µm
0.0	10.9883 s
0.2	11.4649 s
0.4	12.8919 s
0.6	12.9728 s
0.8	13.2716 s
1.0	13.3609 s

According to all simulation result in this project, the optimum design for single mode optical waveguide by using 3µm rib thickness, 0.2µm rib height and 6µm rib width. Table 4 show the computational time. For our optimum design, computational time taken is 11.4649s. From the table 4,the computational time is increased when the value of height is increased. It is because the area of field at dielectric interface are increased.

E. *Cutoff thickness*

The cutoff thickness for three layer which is cover layer, substrate and core. The value of cover layer(air)=1.0, substrate layer (oven baked polymer)=1.545 and core layer(hot plate polymer)=1.57 at wavelength of 1310nm. The results are shown in table 5.

TABLE 5: CUTOFF THICKNESS FOR THE WAVEGUIDE STRUCTURE

Mode number	Guide thickness (µm)
0	1
1	3.35
2	5.70
3	8.50
4	10.39
5	12.74
6	15.08
7	17.43

From this table, only the lowest order TE mode can propagate in the waveguide. By using the value of cover layer (air)=1.0, substrate layer (oven baked polymer)=1.545 and core layer(hot plate polymer)=1.57 at wavelength 1310nm, the thickness must lie in the range:

$$1\mu m < t < 3.35\mu m$$

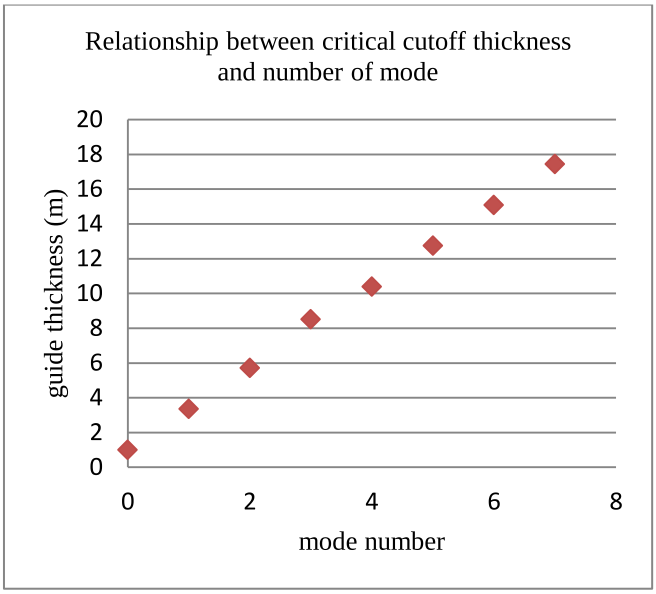

Figure 8: Relationship between critical cutoff thickness and number of mode.

F. *Optimum design*

From the simulation in varying the rib thickness, rib height and rib width, we be able to get the optimum design of rib channel waveguide.the optimum design is 3µm (rib waveguide), 0.2µm (rib height) and 6µm (width). Figure 9 show the contour of electric field for optimum design.

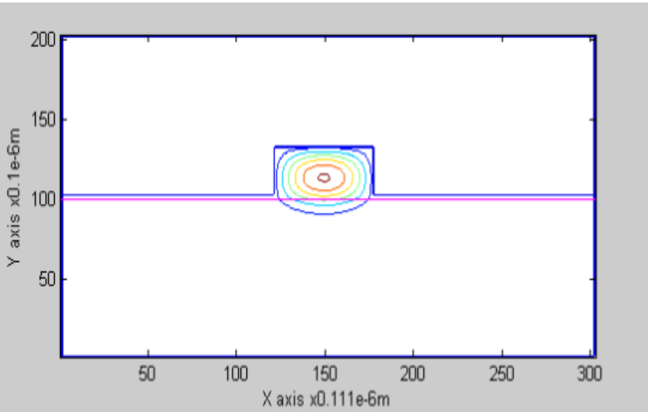

Figure 9: Optimum design of rib channel waveguide

IV. CONCLUSION

The iterative method applying of the numerical method using iterative technique in analyzing is optical waveguide can be search for electric field distribution. In the integrated optical circuit, the optimum design of rib channel waveguide should support with low loss and strongly optical confinement for practical implementation. A good design of the rib channel waveguide is intended to limit propagation loss and the transition losses. The propagation loss on straight waveguide depends on the declaration value of refractive index used between core and cladding waveguide. Besides that, the parameters that affect the performance of rib waveguide are rib thickness, rib height and rib width. These parameters will distress the value of normalized propagation constant, propagation constant β and also effective refractive index. The normalized propagation constant b is usually adopted to characterize this type of waveguide because it shows more sensitivity than the value of propagation constant β itself the variations with respect to geometric changes of the structure. To get the single mode the thickness must lie in the range 1µm < *t*< 3.35µm.

V. ACKNOWLEDGEMENT

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VI. REFERENCE

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