BURIED WAVEGUIDE

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BURIED WAVEGUIDE POLYMETHYLMETHACRYLATE MODELING FOR REFRACTIVE INDEX SENSOR APPLICATION USING FINITE ELEMENT METHOD

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ABSTRACT

The purpose of this study is to obtain the optimum buried waveguide structure through modeling for refractive index sensor applications. The waveguide cladding material used as *Polymethylmethacrylate* (PMMA). The core cross-section size was 1×1 mm^2. The simulation was carried out at a wavelength of 650 nm using the Finite Element Method (FEM). The parameter of the buried waveguide optimized in this model was the core refractive index and the thickness of the upper cladding to obtain a high propagation constant and good sensitivity to refractive index. Modeling was done for various core refractive index values varied in the range of 1.52 to 1.59, which are the refractive index of various types of polymers. To optimize the sensitivity, the thickness of the upper cladding was varied between 0.125 mm to 0.5 mm. Besides, a simulation was also carried out for a waveguide without an upper cladding. The results show that the optimum waveguide is a waveguide without upper cladding using polyester as core material with a refractive index value of 1.57 and a sensitivity of 4.9×10^{-10}rad /m RIU.

Keywords: buried waveguide, refractive index sensor, finite element methods

INTRODUCTION

Fiber optic sensor technology has attracted much attention in various applications since it was more resistant to extreme weather conditions, anti-electromagnetic interference and it can be used for real-time and remote sensing. The detection principle that is widely used in fiber optic sensors is the detection of refractive index change from fiber optic's material or change of refractive index environment. Silica optical fiber is commonly used in fiber optic-based refractive index sensor [1-3]. However, for measurement of refractive index in liquid, optical sensor technology based on silica optical fiber has the disadvantage of causing absorption [4]. To overcome the problem, the light source needs to be replaced with visible light. However, visible light does not make it suitable for silica optical fiber. Fiber optic, which works with visible light is polymer optical fiber. However, the availability of polymer optical fiber, for now, is still limited. As an alternative, polymer optical fiber can be replaced with a waveguide with dimension and material which is suitable for visible light.

An optical waveguide sensor has been developed for the application of temperature sensor and refractive index. These sensors are developed using various technologies such as waveguide-prism system [5], Bragg grating [6] dan nano-silica waveguide [7]. However, the light sources used in the technique, as mentioned above, where the light source with a wavelength of 1260 nm - 1550 nm. Therefore, it will cause high absorption. Du & Zhao [4] and Hooda & Rastogi [8] have designed a waveguide refractive index sensor by using a visible light source (380 nm-760 nm). Du & Zhao [4] used silica carbide (SiC) as core material and SiO_2 as substrate and gold layer (Au) on the upper core.

Meanwhile, Hooda & Rastogi [8] used waveguide with Teflon-Cytop-Teflon material. However, the waveguide fabrications were quite complicated and need equipment with high technology, so the research was only done in simulations. Furthermore, the waveguide dimensions were very small (in nanometer and micrometer order) so that the sensor incompatible with polymer optical fiber with a diameter of 1 mm. This will cause a lot of power loss in connection with the light source.

In this research, we proposed a waveguide design for refractive index sensing for operation in visible light. Polymethylmethacrylate (PMMA) was used as a cladding material since PMMA has high transparency, low cost, and easy to fabricate. Furthermore, PMMA is also the material used in polymer optical fiber so it could minimize power loss when it is connected with polymer optical fiber. The design was optimized in terms of the core refractive index and its sensitivity to refractive index environment. The optimization was done by simulation using the Finite Element Method (FEM).

METHOD

The waveguide parameter was optimized to get the optimal parameter to be used as a refractive index sensor. Optimization was performed by varying the core refractive index value to get high propagation constant. The higher the value of propagation constant, then lower the waveguide power loss. After the optimum core refractive index was obtained, the next steps were performing a simulation of the effect of environment refractive index value on the propagation constant for various upper cladding thicknesses. The purpose of this simulation is to obtain an optimum upper cladding thickness, which results in high sensitivity. The waveguide structure used was buried waveguide structure as shown in FIGURE 1. The simulation was performed using a wavelength of 650 nm. The cladding material used in this simulation was PMMA with a refractive index value of 1.49, while the core material was polymer material with a refractive index value range between 1.52 to 1.59. The sensor sensitivity was determined by plotting refractive index vs. propagation constant.

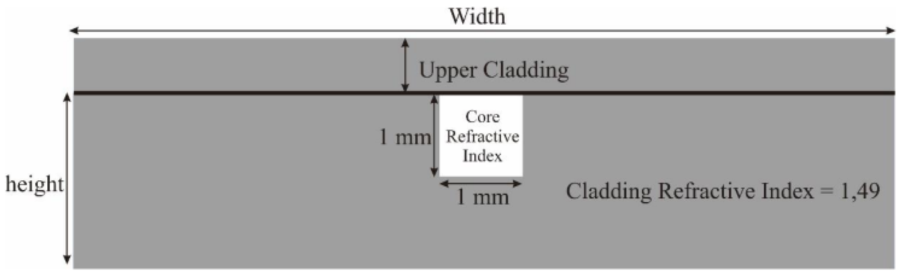

FIGURE 1. Buried waveguide parameter structure design.

Waveguide propagation constant (β) was simulated by solving the following Maxwell equations

$$\frac{\partial^2}{\partial x^2}E(x,y)+\frac{\partial^2}{\partial y^2}E(x,y)+\left[k_o^2 n(x,y)^2-\beta^2\right]E(x,y)=0 \quad (1)$$

where $E(x,y)$ is the electric field, k_o is propagation constant in a vacuum, and $n(x,y)$ is the waveguide material refractive index. Maxwell equations were solved by using numerical method FEM.

RESULT AND DISCUSSION

Program Validation

Before the simulation, the first steps were program validation. Program validation is required to show that the program and the steps were valid. The validation was done by performing simulation for waveguide structure which has been done by the researcher which was ridge waveguide structure [9]. In [9], the simulation was performed by using Finite Different Method (FDM). The simulation results obtained by FEM were compared with those obtained by FDM. The ridge waveguide which was simulated has core width and thickness of 10 µm and 50 µm, respectively.

Meanwhile, the core refractive index was 2.65, and the substrate thickness was 30 µm. The wavelength used was 650 nm. The mesh grid which was used in FEM was free triangular with a size of 4.4 µm. The results showed that the propagation constant was 1.02 rad/m. This value was different by 5.1% with the value obtained by FDM, which was 1.071 rad/m. With this small difference, it can be concluded that the FEM program used was valid and could be used for other waveguide structure simulation, in this case, it was the buried waveguide structure as shown in FIGURE 1.

Mesh grid Study

Before core refractive index optimization performed, the next step after program validation was mesh grid study. The size of the mesh grid is very important in modeling. The mesh grid that was used in this research was free triangular. It was selected since the free triangular provide fast computation [10]. The steps to obtained optimum mesh grid size were done by performing simulation using a large mesh size and decreased it until it reaches convergent propagation constant. The constant propagation value obtained from the variation of the mesh grid as shown in TABLE 1.

TABLE 1. The size of the mesh grid and waveguide propagation constant.

Mesh Grid (mm)	Effective Refractive Index	Propagation Constant (rad/m)	ΔPropagation Constant ($\times 10^{-10}$) (rad/m)
0.49	1.56999993555735	1.51753085031098	0.17
0.48	1.56999993559270	1.51753085034513	0.22
0.47	1.56999993569573	1.51753085044474	0.65
0.46	1.56999993551485	1.51753085026988	1.15
0.45	1.56999993554293	1.51753085029702	0.18
0.44	1.56999993553089	1.51753085028539	0.07
0.43	1.56999993549058	1.51753085024642	0.25
0.42	1.56999993544357	1.51753085020097	0.29
0.41	1.56999993495646	1.51753084973012	3.1

From TABLE 1, the mesh grid size which was considered as the most convergent was a mesh grid with a size of 0.44 mm. Besides its convergence, the meh grid size was selected by considering the computer memory specification. The smaller the mesh grid, the more memory needed and the longer the computation time will be. Therefore, although reducing mesh grid size smaller from 0.44 mm still changes the propagation of constant value, but the change was very small (in the order of 10^{-11}). Therefore, the mesh grid of 0.44 mm was selected to be used in the simulation. The form and mesh grid size used in the simulation is shown in FIGURE 2.

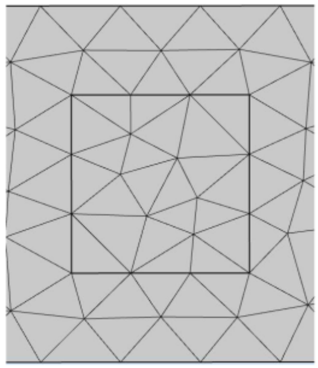

FIGURE 2. Mesh grid type that was used in the simulation (free triangular).

Waveguide Parameter Optimization

The buried waveguide that was used has a cross-sectional core of 1×1 mm, cladding width of 4 cm, cladding height of 2 mm, and cladding length of 5 cm.

Core Refractive Index Optimization

The value of the core refractive index determines the light propagation constant guided in the waveguide. The simulation was performed for various core refractive index values as shown in TABLE 2. PMMA selected because they have high transparency and low density [11].

TABLE 2. Polymer material waveguide core

Core Material	Refractive Index
Poly(methacrylonitrite) [12]	1.52
Poly(N-2-methoxyethyl)methacrylamide [13]	1.524
Poly(2,3-dimethylbutadiene) [13]	1.525
Benzocyclobutene [14]	1.54
Poly(2-vinyltetrahydrufuran) [12]	1.55
Poly(methyl m-chlorophenyl siloxane) [15]	1.56
Poly(benzyl methacrylate) [13]	1.568
Polyester [16]	1.57
Poly(1,2-diphenylethyl methacrylate) [17]	1.58
Poly[2,2-propane bis[4-(2-chlorophenyl)]carbonate] [18]	1.59

FIGURE 3 shows the graph of core refractive indexes variation vs. propagation constants. As shown in the graph, the higher the refractive, the higher the propagation constant is. It occurred since the refractive index linear with propagation constant, which caused propagation.

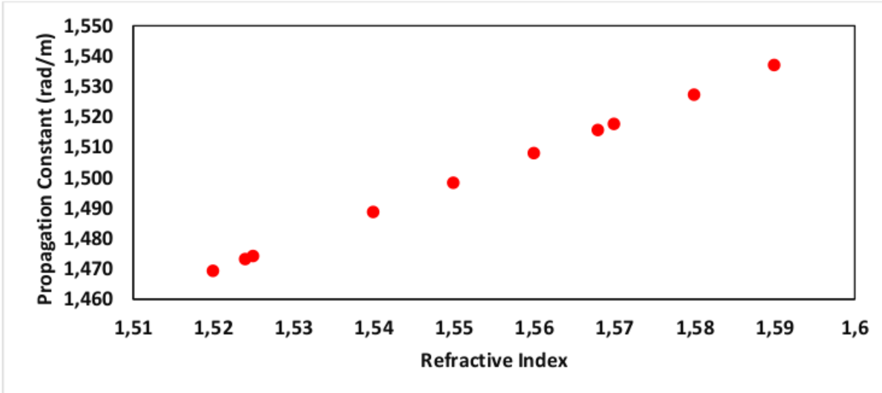

FIGURE 3. Graph of the relation of core refractive index to the propagation constant.

Besides propagation constant, the Numerical Aperture (NA) and V-Number were also calculated for each core refractive index. NA value obtained from equation (2)

$$NA = \frac{1}{n_0}\sqrt{n_i^2 - n_{cl}^2} \quad (2)$$

Meanwhile, V-Number values were obtained from equation (3) as below

$$V = \frac{2\pi}{\lambda} aNA = \frac{2\pi}{\lambda} a\sqrt{n_i^2 - n_{cl}^2} \quad (3)$$

where n_0 is the refractive index of the medium around the waveguide, which is close to 1 in case of air, n_i core refractive index of waveguide, n_{cl} cladding refractive index of waveguide, λ is the light wavelength and a is the radius of the waveguide. TABLE 3 shows the value of NA and V-Number from each material which used for core refractive index optimization. It can be seen from TABLE 3 that all waveguides with various core materials have NA value greater than 0.3 and V-Number greater than 2.405.

TABLE 3. Numerical Aperture and V-Number value of Polymer material waveguide core

Core Material	Refractive Index	Numerical Aperture (NA)	V-Number
Poly(methacrylonitrite)	1.52	0.3	2900
Poly(N-2-methoxyethyl)methacrylamide	1.524	0.32	3090
Poly(2,3-dimethylbutadiene)	1.525	0.325	3140
Benzocyclobutene	1.54	0.389	3760
Poly(2-vinyltetrahydrufuran)	1.55	0.427	4130
Poly(methyl m-chlorophenyl siloxane)	1.56	0.462	4470
Poly(benzyl methacrylate)	1.568	0.488	4720
Polyester	1.57	0.495	4780
Poly(1,2-diphenylethyl methacrylate)	1.58	0.526	5080
Poly[2,2-propane bis[4-(2-chlorophenyl)]carbonate]	1.59	0.555	5360

Based on the optimization of the core refractive index, the core materials that were selected were benzocyclobutene which has a refractive index of 1.54 and polyester, which has a refractive index of 1.57. The materials were selected since they were compatible with PMMA, have high transparency, simple fabrication, and low price [14,16].

Upper Cladding Optimization

The last step in parameter optimization was performing upper cladding optimization. The material used as upper cladding was PMMA with a refractive index of 1.49. The upper cladding thickness was varied for 0.5 mm, 0.25 mm, and without upper cladding. To obtain the waveguide sensitivity to refractive index change, the environment refractive index was varied for 1.333, 1.3403, 1.3479, 1.3557, 1.3639, 1.3723, 1.3811, 1.3902, 1.3997, 1.4096, and 1.42. The sensitivity for the three different waveguide thicknesses is tabulated on TABLE 4. It can be seen that the waveguide sensitivity to the refractive index was in the order of 10^{-10} rad/m.RIU for waveguide without upper cladding and in the order of 10^{-12} rad/m.RIU for a waveguide with upper cladding. For waveguide with the same cladding thickness, the sensitivity of waveguide with Benzocyclobutene material is higher than that of Polyester material. However, Polyester has a lower price and a more simple fabrication process than Benzocyclobutene [14]. Therefore, waveguide without upper cladding with Polyester material is more optimum than waveguide with Benzocyclobutene material.

TABLE 4. Buried waveguide sensitivity to the refractive index for several upper cladding.

Material	Refractive Index	Thickness (mm)	Sensitivity ($\times 10^{-10}$ rad/m.RIU)
Benzocyclobutene	1.54	0.5	0.03
		0.25	0.04
		0.125	0.01
		Without upper cladding	5
Polyester	1.57	0.5	0.02
		0.25	0.04
		0.125	0.01
		Without upper cladding	4.9

CONCLUSION

Buried waveguide PMMA simulations have been performed. The optimum waveguide for refractive index sensor application is waveguide without upper cladding with a core material of polyester with a refractive index of 1.57. The refractive index sensitivity was 4.9×10^{-10} rad/m.RIU.

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