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THERMAL ANALYSIS IN OPTICAL WAVEGUIDES

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Abstract. A thermal analysis in optical waveguides structure is simulated in order to predict the temperature distribution over the waveguide cross-section, when heated by a heating element. A steady state heat equation is solved by using finite difference numerical method. It is observed that by applying different value of thermal conductivities for each waveguide element and further application of convection mechanism to the ambient, obvious differences with other researchers' work are recorded.

Keywords: Thermo-optic effect, thermal analysis, finite difference method

Abstrak. Analisis haba di dalam struktur pandu gelombang optik telah dijalankan untuk mengkaji taburan suhu keratan rentas apabila dipanaskan dengan elemen pemanas. Persamaan umum haba diprogramkan menggunakan kaedah berangka pembezaan terhingga. Perbezaan keputusan yang ketara telah diperoleh apabila nilai keberaliran haba yang berbeza bagi setiap elemen pandu gelombang dan mekanisma konveksi ke persekitaran dipertimbangkan.

Kata kunci: Kesan termo-optik, analisis terma, kaedah pembezaan terhingga

1.0 INTRODUCTION

One of the widely used approaches to control light beam and optical waves in optical waveguide devices is a thermo-optic (TO) effect. According to Nishihara *et al.* [1], TO effect is a mechanism in which the material refractive indices are temperature dependent. By applying considerable amount of heat to the waveguide devices, guided waves can be controlled which forms a basis of functional or active devices.

Many researchers have emphasized on developing functional devices based on thermo-optic effect, taking advantage of TO effect which can be found in all transparent dielectric materials [1]. In this development process, analysis of temperature distribution in the waveguide as a result of applied heat or known as thermal analysis need to be worked out. This temperature distribution will be used as indicator to the amount of refractive index change in the waveguide structure as demonstrated by Moller *et al.* [2], Sircilli *et al.* [3] and Wang *et al.* [4].

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The basic idea of thermal analysis is to solve the heat equation as described by Kokkas [5] in his work on multiple-layer structure. Various methods have been used to solve this equation which include the finite difference method [2], finite element method [3] and Fourier Transform method [4]. However, as the author's concern, all of them are only concentrating on conduction as heat transfer mechanism while ignoring the convection and radiation mechanism. The effect of radiation in waveguide thermal analysis can be completely ignored as proved by Abu Sahmah [6]. In contrast, the convection mechanism is hard to be ignored in waveguide thermal analysis as described by Ozisik [7] due to temperature gradient between waveguide structure and ambient air.

From literatures, it is found that to simplify the thermal analysis process, the assumption on thermal properties of the waveguide structure has been taken into consideration. For instance, thermal conductivity for core and cladding are assumed to be the same, as proposed by Hida *et al.* [8], Abu Sahmah [6], Wang *et al.* [4] and Mahmud [9]. As both core and cladding are made of materials with slightly different thermal properties, it is important to provide further investigation on this assumption.

In conjunction with the above issues, this paper is dedicated towards further investigating the thermal analysis process in a heated waveguide which considers conduction and convection as heat transfer mechanisms and different thermal conductivity for core and cladding. As such, this will definitely lead to more accurate design of functional optical devices which is based on thermal controlling effect.

2.0 THEORETICAL CONSIDERATION

According to Jaluria and Torrance [10], the heat conduction mechanism in a material is due to thermal motion of microscopic particles contained in the material and it is determined by temperature gradient that exists locally in the material. The governing equation for conductive heat transfer process is given by [10]:

$$\nabla.(k\nabla T) + \dot{Q} = pC\frac{dT}{dt} \tag{1}$$

where

$\dot{Q}$ = distributed thermal source per unit volume (W/m^3)
p = density of material (kg/m^3)
C = specific heat (J/kg.K)
t = time (s)
k = thermal conductivity (W/m.K)

If time is not an important consideration, steady-state condition is sufficient to describe the temperature profile as being demonstrated by Klunder [11]. In this particular assumption, all parameters that related with time will be vanished which lead to the simplified equation of:

$$\nabla.(k\nabla T) + \dot{Q} = 0 \tag{2}$$

From Equation (2), the temperature distribution by means of conduction mechanism can be obtained in a material having constant thermal conductivity, k with applied heat source $\dot{Q}$. The three dimensional (3D) solution of Equation (2) can be simplified into two dimensional (2D) solution by considering the case of conduction in long bars compared to the dimension of waveguide cross section [6]. Therefore, in 2D cases and considering the z-direction as the longitudinal direction, Equation (2) can be written as:

$$\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} + \frac{\dot{Q}}{k} = 0 \tag{3}$$

Convection mechanism is described by Ozisik [7] as heat transfer between the fluid flows and the solid surface as a consequence of the temperature gradient between the solid surface and the fluid. The heat transfer calculations between a hot surface at T_w and a cold fluid flowing over it at a bulk temperature T_f, with a heat transfer coefficient h, is defined as [7]:

$$q = h(T_w - T_f) \tag{4}$$

where q is defined as the convective heat flux (W/m^2) from the hot wall surface to the cold ambient air.

In order to solve for temperature distribution, the boundary conditions need to be defined. This will include the interface between the solid body and the ambient air, the interface between heater element and solid body, the interface between different waveguide materials and the boundary condition of waveguide corners. For instance, consider a waveguide cross section having heat source with a supply power of P and width, B and length of L as shown in Figure 1. The waveguide is made up of two materials having different thermal conductivities; k_A and k_C.

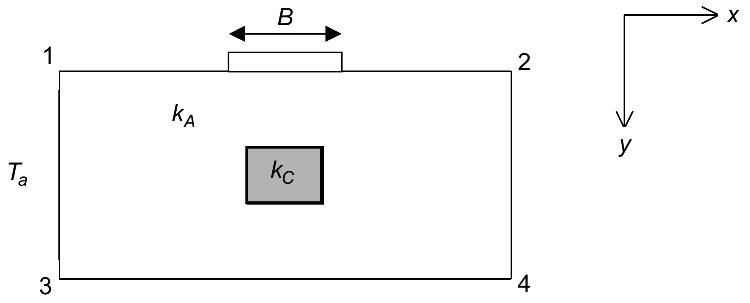

Figure 1 Waveguide cross section with heat source and T_a as ambient temperature

The following boundary condition can be deduced considering the effect of convection to the ambient air with h as the convection heat transfer coefficient of air:

Side plates (1-3) and (2-4)

$$-k\frac{dT}{dx} = h(T - T_a) \tag{5}$$

Bottom plate (3-4) and top plate without heat source element

$$-k\frac{dT}{dy} = h(T - T_a) \tag{6}$$

Top plate with heat source interface

$$-k\frac{dT}{dy} = \frac{P}{BL} \tag{7}$$

Interface between materials (k_A and k_C)

$$k_A\frac{dT}{dy} = k_C\frac{dT}{dy} \text{ (parallel to z-direction)} \tag{8a}$$

$$k_A\frac{dT}{dx} = k_C\frac{dT}{dx} \text{ (perpendicular to z-direction)} \tag{8b}$$

In order to obtain the waveguide temperature profile, Equation (3) and Equations (5)-(8) are solved using the finite difference numerical method [1].

3.0 ANALYSIS

In order to provide better understanding on the proposed method, thermal simulation by Wang *et al.* [4] using Fourier Transform method is adopted for initial comparison. The structure in [4] consists of silica glass waveguide, surrounded by silica glass material as cladding material with lower index on silicon (Si) substrate. A thin film heater is placed on top of the upper clad layer which provides an index change to the core material for optical switching purpose. The waveguide cross section is shown in Figure 2. The following parameters are taken into considerations during the simulation phase [4]:

- Thermal conductivity of Si = 150 (W/m.K)
- Thermal conductivity of silica glass = 1.40 (W/m.K)
- Thermal conductivity of air = 2.6×10^{-2} (W/m.K)

According to Wang *et al.* [4], consideration was only on the conduction as heat transfer mechanism while ignoring the convection and radiation. It has been assumed that the core and cladding layers have the same k value.

In this paper, we will investigate the combined approach of convection and conduction mechanisms in the thermal analysis and evaluate the effect of different k for both the core and cladding, based on the above structure and dimensions. The significance of the thermal conductivities is simulated up to the difference of 0.0001 (W/m.K). It has been assumed that k for the core is higher compared to the cladding, which has a k value of 1.40 W/m.K.

$$\Delta k = k_{\text{core}} - k_{\text{clad}} \quad ; \quad k_{\text{clad}} = 1.40 \text{ W/m.K} \tag{9}$$

The differences are manifested by the average induced temperature in the core and waveguide's effective index difference, Δn_{eff} as an implication of temperature induced refractive index change of the core layer. This simplification is based on the work by Klunder [11] which assumes that only the refractive index of the core layer changes by the change in the temperature. Thus, Δn_{eff} can be calculated by calculating the change in the refractive index of the core and calculating the resulting change in propagation constant [11]. From [11], it is shown that change in propagation constant, $\Delta\beta$ when heat is applied can be simplified to be:

$$\Delta\beta = k_o \Delta n_{eff} = \frac{k_o{}^2 n_{core}}{2\omega\mu_o} \left(\int\limits_{core}\int |E|^2 \; dxdy \right) \left[\frac{\partial n}{\partial T} T_{avg} \right] \tag{10}$$

which consider the change in propagation constant to be mostly contributed by the core structure. In Equation (10), k_o is the free space wavenumber, ω is the angular frequency, T_{avg} is the average temperature in the core, $\partial n / \partial T$ is the thermo optic coefficient of the core material and bracketed term is the modal field in the core. The difference in effective index value can be calculated using Equation (10).

4.0 RESULTS

Referring to Figure 2 and ignoring any optical leakage to the substrate, the waveguide's effective index is 1.5013, obtained using effective index method [13]. As a result of heat excitation, the effective index is changed according to the induced temperature in the core, as stated in Equation (10). The Δn_{eff} and average temperature in the core are used as a key comparison in this paper.

For validation purposes, the thermal analysis is done according to the works by Wang *et al.* [4]. By adopting several assumptions as stated in the previous section, the temperature distribution obtained from the finite difference simulation is identical to [4] and is shown in Figure 3. It can be deducted that the maximum temperature at the interface of heater electrode and cladding top surface is around 160°C.

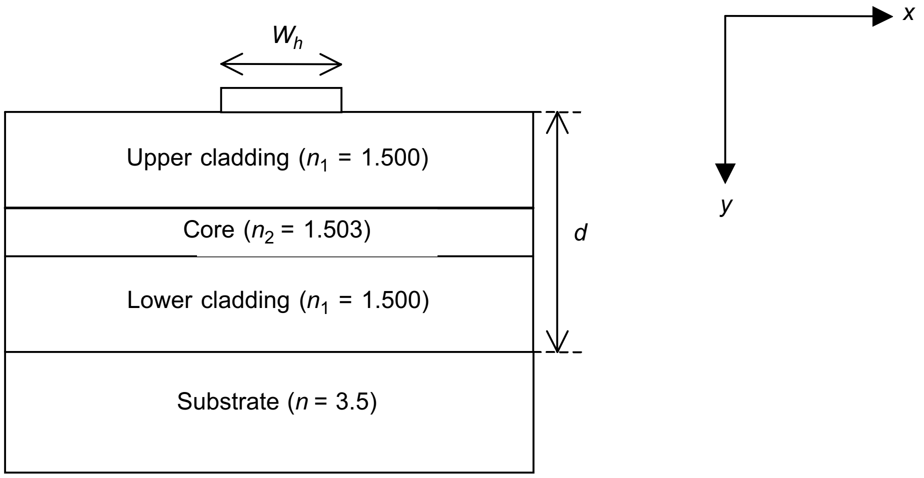

Figure 2 Waveguide cross section from [4] with $d = 25\ \mu$m, heater width, $W_h = 10\ \mu$m and power applied per unit heater length, $P_h/L_h = 0.25$ W/mm

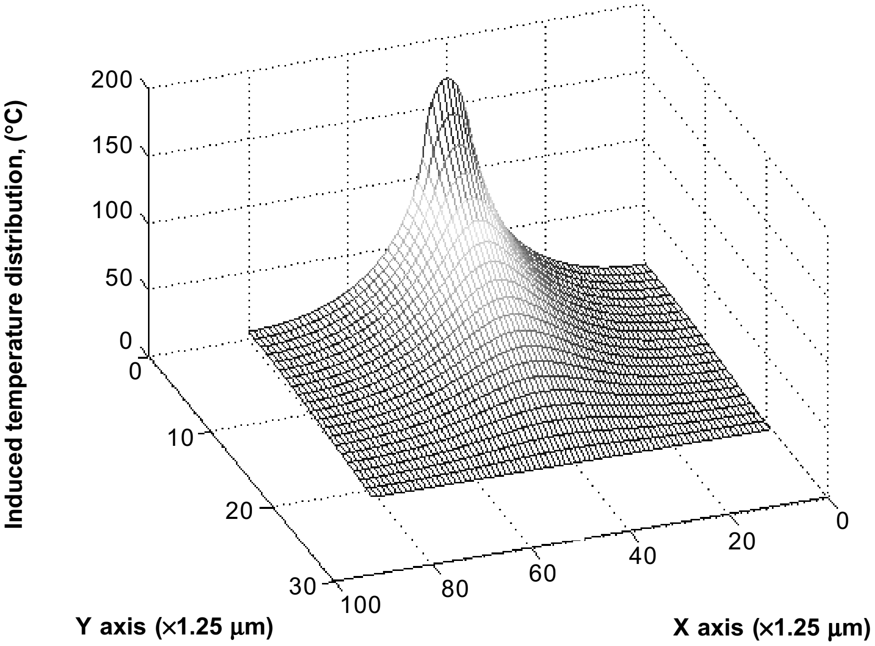

Figure 3 Temperature distribution plot

Further work on the proposed method in this paper which combines heat conduction and convection mechanism has been done and the results are tabulated in terms of average core temperature and Δn_{eff} as shown in Table 1.

Table 1 Average core temperature and effective index difference for distinct approach of heat transfer mechanism

Type	Average induced core temperature (°C)	Δn_{eff}
Waveguide heating [2]	26.1507	1.7423×10^{-4}
Waveguide heating (proposed method)	26.1390	1.7415×10^{-4}

In order to validate the assumption of using the same k value for both core and cladding, simulations are initiated which provide the value of average core temperature and Δn_{eff} for Δk as small as 0.0001 W/mK. The graphical form of this simulation is shown in Figures 4 and 5. From the figures, it clearly shows that the assumption of using the same thermal conductivity for both core and cladding is hardly acceptable due to significant difference up to the smallest Δk value of 0.0001 W/m.K. The average core temperature and Δn_{eff} are shown to vary linearly with the difference in thermal conductivities.

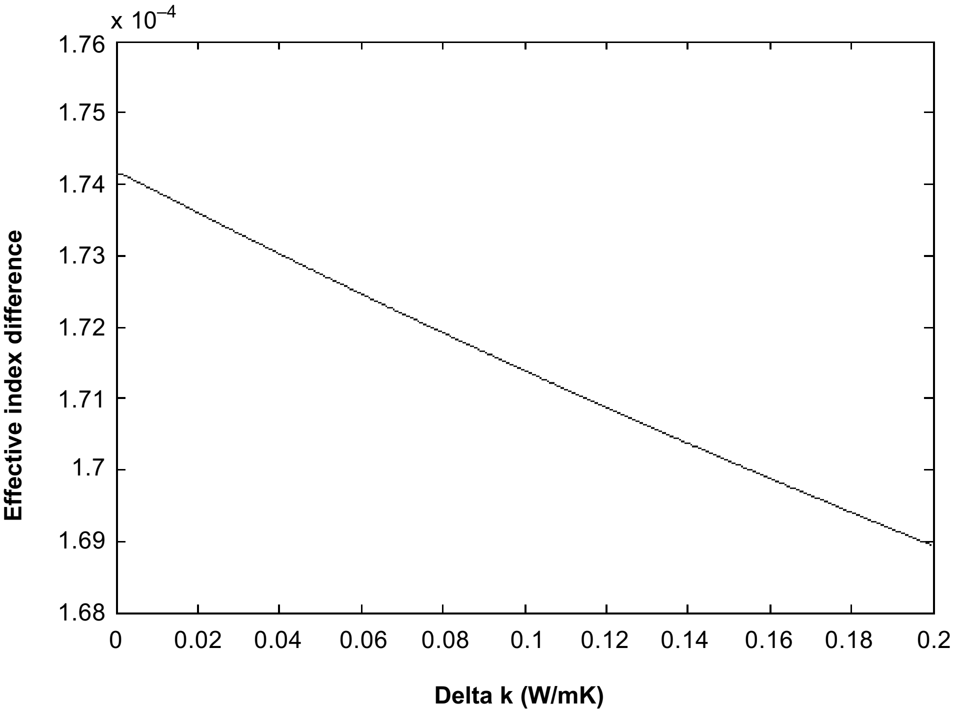

Figure 4 Effective index difference against thermal conductivity difference of core and cladding

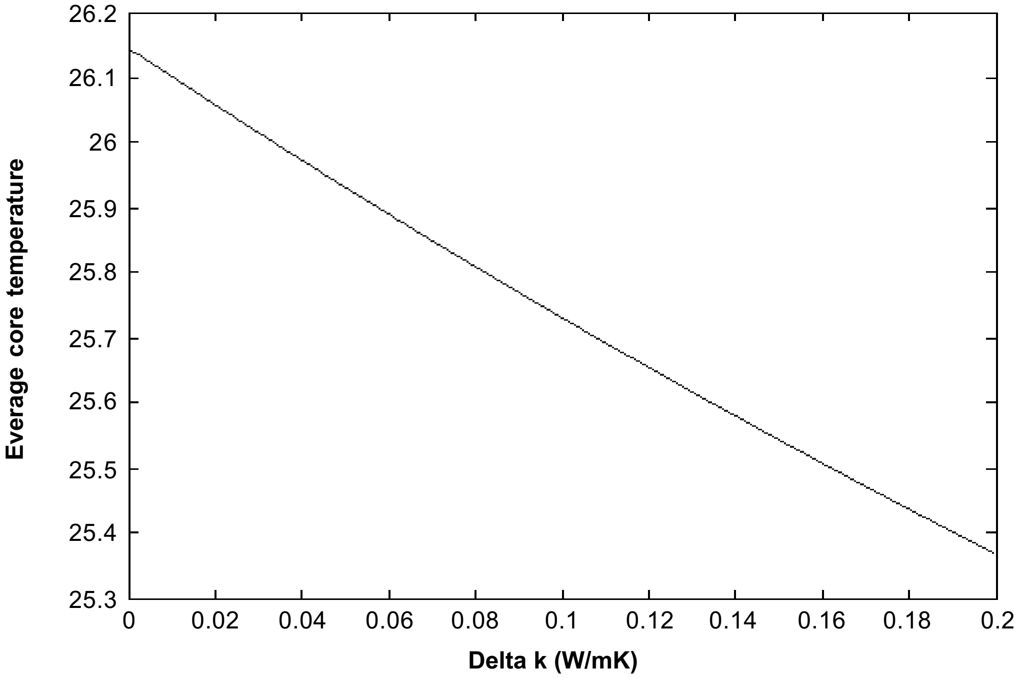

Figure 5 Average induced core temperature against thermal conductivity difference of core and cladding

5.0 CONCLUSION

It was found that the convection heat transfer mechanism has significant effect in the temperature distribution and waveguide's effective index. For proper optical waveguide thermal modelling, the effect of conduction and convection mechanism needs to be integrated. Knowing that both core and cladding have different values of refractive indices, the thermal properties between them may have a little difference. It is manifested by simulating different thermal conductivity differences (Δk), between core and cladding. From the simulation, the temperature distribution is varied, even for small Δk, up to 0.0001 W/m.K. These findings will be an initial step for further research related to thermal analysis in various optical waveguides and device development, particularly an active device which requires thermal control.

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