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# A NOVEL STUDY OF ELECTRIC FIELDS FOR TE MODE IN A DOUBLE STEP-INDEX WAVEGUIDE

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***ABSTRACT***
*Alpha ( $\alpha$ ) method is a novel method for step-index waveguides depending on normalized propagation constant. In this work the electric fields in the active region and cladding layers (CLs) for a double symmetric step-index waveguide are studied. Having obtained equivalent normalized frequency, equivalent normalized propagation constant, equivalent barrier potential, equivalent abscissa and ordinate of the EEV and equivalent refractive index of double symmetric step-index waveguide we have equivalent step index waveguide of double symmetric step-index waveguide and found its some parameters are compared with the parameters of double symmetric step-index waveguide*

***Keywords*: *Normalized frequency, Normalized propagation constant, Barrier potential, Energy eigenvalue***

## *BIR İKİLİ ADIM KIRILMA İNDİSLİ DALGA KILAVUZUNDA TE MODU İÇİN ELEKTRİK ALAN ANALİZİ*

***ÖZET***
*Alfa metodu, adım kırılma indisli dalga kılavuzlarında normalize yayılım sabitine bağlı olan yeni bir hesaplama metodudur. Bu çalışmada bir ikili simetrik adım kırılma indisli dalga kılavuzu için aktif ve gömlek bölgelerindeki elektrik alanları incelenmiştir. İkili simetrik adım kırılma indisli dalga kılavuzunun eşdeğer normalize frekansı, eşdeğer normalize yayılım sabiti, eşdeğer çukur potansiyeli, enerji özdeğerinin eşdeğer apsis ve ordinatı ve eşdeğer kırılma indisi elde edilerek, ikili simetrik adım kırılma indisli dalga kılavuzunun eşdeğer adım kırılma indisli dalga kılavuzu elde edilmiş ve bulunan bazı parametreleri ikili simetrik adım kırılma indisli dalga kılavuzunun parametreleri ile karşılaştırılmıştır.*

***Anahtar Kelimeler:*** *Normalize frekans, Normalize yayılım sabiti, Çukur potansiyeli, Enerji özdeğeri*

## 1. INTRODUCTION

If thin layer of a narrower-band material, “region II”, which is called active region (AR), is sandwiched between two layers of a wider-band material, “regions I, III”, which are also called cladding layers (CLs), a asymmetric single step-index waveguide (ASSIWG) is obtained, as depicted in Figure-1. Here, $n_I$, $n_{II}$ and $n_{III}$ are refractive indices of the regions. The regions are formed dissimilar materials, such as p-GaAs (p-type Gallium Arsenide) and n-$Al_xGa_{1-x}As$ (n-type Aluminium Gallium Arsenide), with x being the fraction of aluminium being replaced by gallium in the GaAs material. GaAs and AlAs semiconductors have almost identical lattice constant [1]. Different values of refractive indices can be obtained by doping. It is also noted that the refractive indices of materials are depend on the wavelength of the field. The usual relationship between the refractive indices in the three regions in the ASSIWG shown in Figure-1 is given by $n_{II} \rangle n_I \rangle n_{III}$. If the refractive indices $n_I$, $n_{II}$ and $n_{III}$ are taken as $n_{II} \rangle\ n_I = n_{III}$ then the wave guide is called symmetric single step-index waveguide (SSSIWG).

Additional semiconductor layer can be accommodated in the AR in the ASSIWG in Figure-1. So, a double active regions in the ASSIWG can be constructed at the right and left hand sides of the region b as shown in Figure-2, which can called a double asymmetric step-index waveguide (DASIWG). Region b is second cladding layer (SCL) of the first (F) ASSIWG (FASSIWG) and first cladding layer (FCL) of second (S) ASSIWG (SASSIWG) from the left side to the right side. So, FASSIWG and SASSIWG give FSSSIWG and SSSSIWG if $n_{II} \rangle n_I = n_{III}$ in the double symmetric step-index waveguide (DSSIWG).

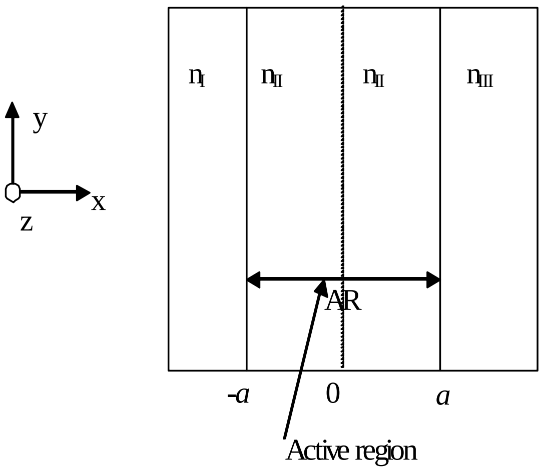



**Figure 1.** Regions of an asymmetric single step-index waveguide (ASSIWG)

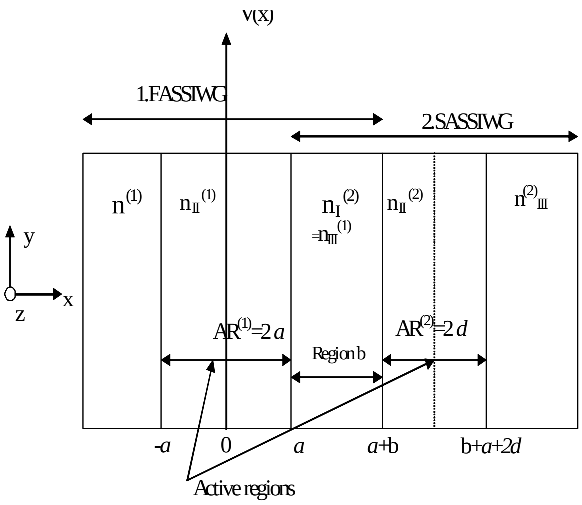



**Figure 2.** Active regions at the right and left hand sides of the region b in the DASIWG

The DASIWG has one-dimensional potential energy V(x) [1, 2] in the conduction and valence band, as shown in Figure-3. Active region of the DASIWG consists of the active region 1 ($AR^{(1)}$), which has refractive index $n_{II}^{(1)}$, and the active region 2 ($AR^{(2)}$), which has refractive index $n_{II}^{(2)}$ and $n_{III}^{(1)}$ or $n_I^{(2)}$ (region b). Note that refractive index $n_{III}^{(1)}$ for FASSIWG must be equal to refractive index $n_I^{(2)}$ for the SASSIWG. If any electron or hole exists in the DASIWG, whether thermally produced intrinsic or extrinsic as the result of doping, it attempts to lower their energy states. Solid circle and open circle in Figure-3 represent electron and hole, respectively. There is different barrier potentials [3] in the structure of DASIWG as $V_o^{(1)}$, $V_o^{(2)}$.

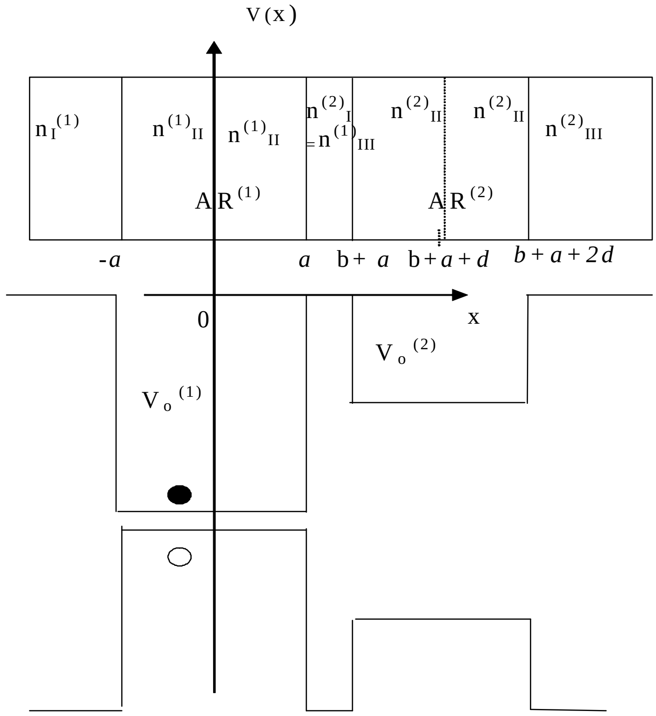



**Figure 3.** The one-dimensional potential energy V(x) in the conduction and valence band for the DASIWG

In this manner the electronic structure can be represented by the simple one-dimensional the Schrödinger wave equation. It can be shown that the solution of this equation is a plane electric field wave described an electron (or hole). For each of the layers I, II and III, the wave equation of electric field [1] is given by the scalar Hemholtz equation

$$[\nabla^2 + n^2 k_o^2] e(x, y, z) = 0 \quad (1)$$

in the Cartesian coordinate system. Here the electric field is $e(x, y, z) = E_i(x, y)\exp[j(\omega t - \beta_z z)]$, where i represents the I, II or III layer [1]. That is, the field has a time-harmonic dependence of the type $e^{j\omega t}$. In the harmonic variation Eq.(1) gives the following equation

$$[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + n_i^2(x, y)k_o^2 - \beta_z^2] E_i(x, y) = 0 \quad (2)$$

which describes the field for each of the three layers [3]. $E_i(x,y)$, $n_i(x,y)$, $k_o$ and $\beta_z$ in Eq.(2) are respectively transverse electric field phasor of the mode in the i[th] layer against axis z, index of refraction in the i[th] region, free space wave number for free space and phase constant of the electric field. TE mode for electromagnetic field in the AR and CLs obeys the same type of scalar wave equation. There is not more detail analysis in terms of the electric field in the DASIWG in the literature from point of view of the alpha method [4]. Therefore, in this paper the properties of the electric field in the DASIWG will be studied.

## 2. ELECTRIC FIELD COMPONENTS IN TE MODE IN THE AR AND CLS

The DASIWG in Figure-2 includes two wells at the right and left hand sides of the region b, each of these wells have the widths of 2*d* and 2*a*, respectively. The carriers are allowed to exist in a certain confined (bound) states within the wells in the DASIWG and are described by a wave function such as electric field wave. The quantum states for carriers can be described by solving the Schrödinger wave equation. The electric field waves for the regions and the energy eigenvalues (EEVs) in the AR$^{(1)}$ FSSIWG in DASIWG in Figure-2 for the SSSIWG getting $n_{II} \rangle\ n_I = n_{III}$ are [5,6,7] respectively

$$E_{yI}^{(1)} = A_I^{(1)} \exp\left[\alpha_I^{(1)}(x+a)\right] F(z,\omega,t) \quad (3)$$

$$E_{yII}^{(1)} = A^{(1)} \cos(\alpha_{II}^{(1)} x - \theta^{(1)})\ F(z,\omega,t) \quad (4)$$

$$E_{yIII}^{(1)} = A_{III} \exp\left[-\alpha_{III}^{(1)}(x-a)\right] F(z,\omega,t) \quad (5)$$

$$F(z,\omega,t) = \exp\left[j(\omega t - \beta_z z)\right], \quad (6)$$

$$E_n^{(1)} = \frac{n^2 \hbar^2 \pi^2}{8m^* a^2}, \qquad n=1, 2, 3, \ldots, \quad (7)$$

$$e_i^{(1)} = V_o^{(1)} - E_n^{(1)} \quad (8)$$

$$E_i^{(1)} = i^2 E_1^{(1)}, \quad E_1^{(1)} = \frac{\hbar^2 \pi^2}{8m^* a^2}, \quad i=1, 2, 3, \ldots \quad (9)$$

where n, i, m*, $V_o^{(1)}$ and $\hbar$ represent mode number of the field, quantum energy level in the well, effective mass of carrier in the conduction or valance band, barrier potential for AR$^{(1)}$ and the normalised Planck constant as $\hbar = 1.05459\text{x}10^{-34}$ Js. Propagation constants mentioned above in the fields for i=I, II, III, are defined by

$$\alpha_I^{(1)} = \sqrt{\beta_z^{(1)^2} - \left(\frac{\omega n_I^{(1)}}{c}\right)^2} = \sqrt{\beta_z^{(1)^2} - k_I^{(1)^2}} \quad (10)$$

$$\alpha_{II}^{(1)} = \sqrt{\left(\frac{\omega n_{II}^{(1)}}{c}\right)^2 - \beta_z^{(1)^2}}$$

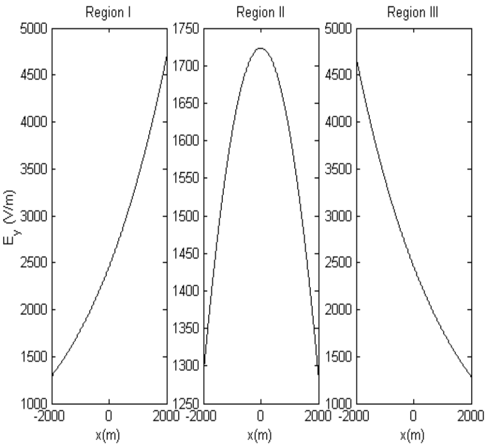
$$\alpha_{II}^{(1)} = \sqrt{k_{II}^{(1)^2} - \beta_z^{(1)^2}} \quad (11)$$

$$\alpha_{III}^{(1)} = \sqrt{\beta_z^{(1)^2} - \left(\frac{\omega n_{III}^{(1)}}{c}\right)^2} = \sqrt{\beta_z^{(1)^2} - k_{III}^{(1)^2}},$$

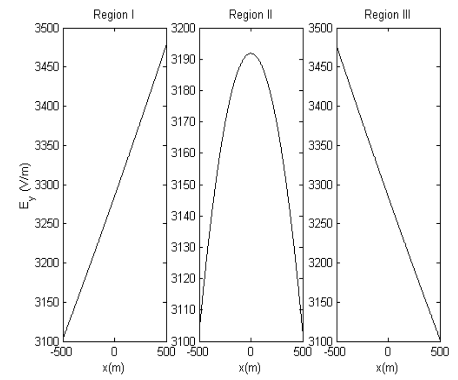
$$\omega = 2\pi c/\lambda,\ \zeta^{(1)} = \alpha_{II}^{(1)} a,\ \ \eta^{(1)} = \alpha_{I,III}^{(1)} a \quad (12)$$

where $k_i^{(1)}$, i=I,II,III $n_I$, $n_{II}$ and $n_{III}$ represent the wave number in the i[th] layer of the FSSIWG of DASIWG, the refractive indices of the regions I, II and III and c is the speed of the light [1]. We can calculate wave vectors, propagation constants, phase constant, effective indice, enery eigen value, barrier potential, zeta, eta and amplitude of the active region field for $\lambda = 1.55\text{x}10^{-6}$ m, $n_{I,III}$=4.5, $n_{II}$=4.7, 2*a*=6000 A$^o$ in the FSSSIWG, if we take $\alpha_I^{(1/2)} = \alpha_{III}^{(1/2)} = \alpha_{I,III}^{(1/2)}$ for the symmetric case (See Table I and Figure-6). Because of $\zeta^{(1)} < 1.57$ there is not solutions for odd electric field [8].

So, the evanescent electric fields in Eqs.(3) and (5) are obtained varying exponentially according to x in the CLs and the electric field in Eq.(4) travels in the z direction inside the AR$^{(1)}$ of the FSSIWG for $\theta = 2i\pi/2$ or $\theta = (2i+1)\pi/2$, i=0, 1, 2, 3,..., cosinusoidally or sinusoidally, respectively. Figures-4 and 5 show the variations of the fields of the regions of the FSSSIWG against the axis x.




**(a)**

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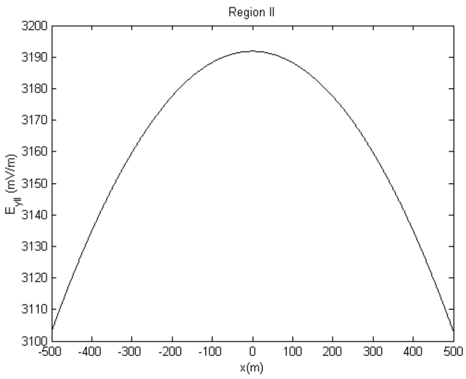
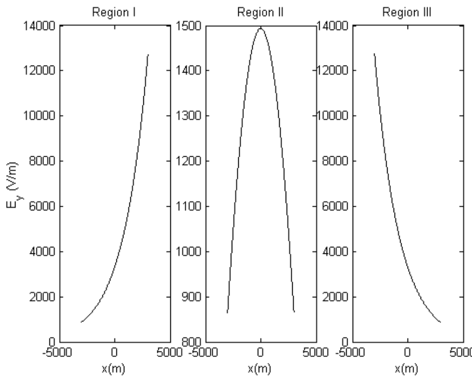



**(c)**




**(d)**

**Figure 4.** The variations of the fields of the regions of the FSSSIWG against the axis x**: (a)** for $\lambda$ =1.55x10$^{-6}$ m, $\theta_2$ =0, $n_I=n_{III}==n_{I,III}$ 3.5, $n_{II}$=3.7, 2*a*=4000 A$^o$, **(b)** $n_I=n_{III}=n_{I,III}$=3.5, $n_{II}$=3.7, 2*a*=1000 A$^o$, **(c)** The figure in only AR$^{(1)}$ at (b), **(d)** for $\lambda$ =1.55x10$^{-6}$ m, $n_I=n_{III}=n_{I,III}$=4.5, $n_{II}$=4.7, 2*a*=6000 A$^o$

Referring to Figure-3, in the x-V(x) coordinate system the electric fields in the AR$^{(2)}$ and CLs of the SASSIWG are given by

$$E_{y_I}^{(2)} = A_I^{(2)} \exp\{\alpha_I^{(2)}[(x-(b+a)]\}\ F(z,\omega,t)$$
$$= A_I^{(2)} \exp\{\alpha_{III}^{(1)}[(x-(b+a)]\}\ F(z,\omega,t) \qquad (13)$$

$$E_{yII}^{(2)} = A^{(2)}\cos\{\alpha_{II}^{(2)}[x-(b+a+d)]-\theta_2\}\ F(z,\omega,t) \qquad (14)$$

$$E_{yIII}^{(2)} = A_{III}^{(2)}\exp\{-\alpha_{III}^{(2)}[x-(b+a+2d)]\}\ F(z,\omega,t) \qquad (15)$$

$$E_\nu^{(2)} = \frac{\nu^2\hbar^2\pi^2}{8m^* d^2}, \qquad \nu = 1, 2, 3, \ldots, \qquad (16)$$

$$e_j^{(2)} = V_o^{(2)} - E_\nu^{(2)}, \qquad j=1, 2, 3, \ldots \qquad (17)$$

$$e_j^{(2)} = j^2 e_1^{(2)} \qquad (18)$$

$$e_1^{(2)} = \frac{\hbar^2\pi^2}{8m^* d^2} \qquad (19)$$

where

$$\alpha_I^{(2)} = \sqrt{\beta_z^{(2)2} - \left(\frac{\omega n_I^{(2)}}{c}\right)^2} = \sqrt{\beta_z^{(2)2} - k_I^{(2)2}} \qquad (20)$$

$$\alpha_{II}^{(2)} = \sqrt{\left(\frac{\omega n_{II}^{(2)}}{c}\right)^2 - \beta_z^{(2)2}} = \sqrt{k_{II}^{(2)2} - \beta_z^{(2)2}} \qquad (21)$$

$$\alpha_{III}^{(2)} = \sqrt{\beta_z^{(2)2} - \left(\frac{\omega n_{III}^{(2)}}{c}\right)^2} = \sqrt{\beta_z^{(2)2} - k_{III}^{(2)2}}, \qquad (22)$$

Here $k_i^{(2)}$, i=I,II,III, $\nu$, j and $V_o^{(2)}$ are respectively the wave number in the i$^{th}$ layer of the SSSIWG, mode number, quantum energy level and barrier potential for AR$^{(2)}$ in DASIWG. The figure of $E_{yII}^{(2)}$ in Eq.(14) for $\lambda$ =1.55x10$^{-6}$ m, $n_I=n_{III}==n_{I,III}$=4.5, $n_{II}$=4.76, 2*d*=5000 A$^o$ and $\theta_2$ =0 is shown in Figure- 5. Because of $\zeta^{(2)}$ <1.57 there is not solutions for odd electric field here also [8].

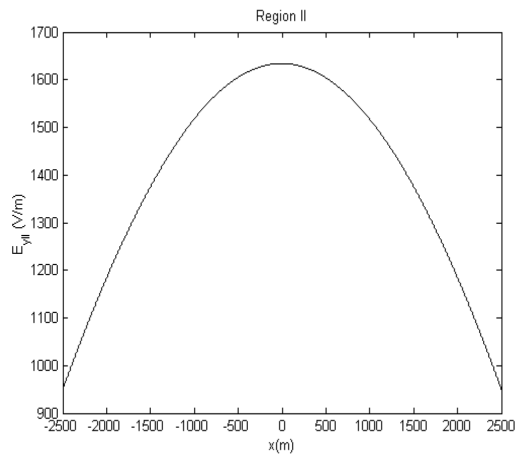



**Figure 5.** The variations of the fields of the regions of the SSSSIWG against the axis x variable

We can also calculate wave numbers, propagation constants, phase constants, effective indices, enery eigen values, barrier potentials, zetas, etas and amplitudes of the fields in $AR^{(1)}$ in the FSSSIWG and $AR^{(2)}$ in the SSSSIWG for the DSSIWG in Figure-6 for $\lambda=1.55\text{x}10^{-6}$ m, $n_{I,III}$=4.5, $n_{II}$=4.7, 2*a*=6000 A° and $n_{I,III}$=4.5, $n_{II}$=4.76, 2*a*=5000 A° respectively.

**Table I.** Wave vectors, Propagation constants, Phase constant, Equivalent indices, Enery eigen values, Barrier potential, Zetas, Etas and Amplitudes for $\lambda=1.55\text{x}10^{-6}$ m, $n_{I,III}$=4.5, $n_{II}$=4.7, 2*a*=6000 A° in the FSSSIWG and $\lambda=1.55\text{x}10^{-6}$ m, $n_{I,III}$=4.5, $n_{II}$=4.76, 2*a*=5000 A° in the SSSSIWG.

| Quantity | Symbol | Value | Symbol | Value |
|---|---|---|---|---|
| Wave number | $k_I^{(1)}$(1/m) | $1.824150573052138\text{x}10^7$ | $k_I^{(2)}$(1/m) | $1.824150573052138\text{x}10^7$ |
| Wave number | $k_{II}^{(1)}$(1/m) | $1.905223931854455\text{x}10^7$ | $k_{II}^{(2)}$(1/m) | $1.929545939495150\text{x}10^7$ |
| Wave number | $k_{III}^{(1)}$(1/m) | $1.824150573052138\text{ x}10^7$ | $k_{III}^{(2)}$(1/m) | $1.824150573052138\text{x}10^7$ |
| Propagation constant | $\alpha_I^{(1)}$ (1/m) | $4.485684534194733\text{x}10^6$ | $\alpha_I^{(2)}$ (1/m) | $5.058758055697320\text{x}10^6$ |
| Propagation constant | $\alpha_{II}^{(1)}$ (1/m) | $3.180239927133927\text{x}10^6$ | $\alpha_{II}^{(2)}$ (1/m) | $3.737805356020452\text{x}10^6$ |
| Propagation constant | $\alpha_{III}^{(1)}$ (1/m) | $4.485684534194733\text{x}10^6$ | $\alpha_{III}^{(2)}$ (1/m) | $5.058758055697320\text{x}10^6$ |
| Phase constant | $\beta_z^{(1)}$ (1/m) | $1.878493803708062\text{x}10^7$ | $\beta_z^{(2)}$ (1/m) | $1.892996472217334\text{x}10^7$ |
| Effective index | $n_{ef}^{(1)}$ | 4.63405940362834 | $n_{ef}^{(2)}$ | 4.66983606003808 |
| Phase velocity | $v^{(1)}$ (m/s) | $6.473805660866337\text{x}10^7$ | $v^{(2)}$ (m/s) | $6.424208390680713\text{x}10^7$ |
| Enery eigen value | $E_1^{(1)}$ (μeV) | 0.92510857713645 | $E_1^{(2)}$ (μeV) | 1.33355981930746 |
| Barrier potential | $V_o^{(1)}$ (μeV) | 1.02133197399615 | $V_o^{(2)}$ (μeV) | 1.33639068510496 |
| Zeta | $\zeta^{(1)}$ | 0.95407197814018 | $\zeta^{(2)}$ | 0.93445133900511 |
| Eta | $\eta^{(1)}$ | 1.34570536025842 | $\eta^{(2)}$ | 1.26468951392433 |
| Impedance | $Z^{TE}{}_{yxII}^{(1)}$(Ω) | 17.55528665775979 | $Z^{TE}{}_{yxII}^{(2)}$ (Ω) | 17.28732711454359 |
| Amplitude | $A^{(1)}$ | $1.493437127025004\text{x}10^3$ | $A^{(2)}$ | $1.626783325125536\text{x}10^3$ |
| Maximum Intensity of Poynting vector | $S^{(1)}$(W/m$^2$) | $6.352372638104545\text{x}10^4$ | $S^{(2)}$ (W/m$^2$) | $7.654231245153252\text{x}10^4$ |

$$[\alpha_I^{(1)^2}+\alpha_{II}^{(1)^2}=k_{II}^{(1)^2}-k_{II}^{(1)^2}=3.0235291734450\text{x}10^{13},$$

$$\alpha_I^{(2)^2}+\alpha_{II}^{(2)^2}=k_{II}^{(2)^2}-k_I^{(2)^2}=3.9562221945577\text{x}10^{13}]$$

If b=0 then $E_{yIII}^{(1)}=0$, $E_{yI}^{(2)}=0$ and we get the electric field waves $E_{yI}^{(1)}$, $E_{yII}^{(1)}$, $E_{yII}^{(2)}$ and $E_{yIII}^{(2)}$ for Figure-7 as

$$E_{yI0}^{(1)}=A_{I0}^{(1)}\exp\left[\alpha_{I0}^{(1)}(x+a)\right]F(z,\omega,t) \tag{23}$$

$$E_{yII0}^{(1)}=A^{(1)}{}_0\cos(\alpha_{II0}^{(1)}x-\theta^{(1)})\ F(z,\omega,t) \tag{24}$$

$$F(z,\omega,t)=\exp\left[j(\omega t-\beta_z z)\right], \tag{25}$$

$$E_{yII0}^{(2)}=A^{(2)}{}_0\cos\{\alpha_{II0}^{(2)}[x-(a+d)]-\theta_2\}\ F(z,\omega,t) \tag{26}$$

$$E_{yIII0}^{(2)}=A_{III0}^{(2)}\exp\{-\alpha_{III0}^{(2)}[x-(a+2d)]\}\ F(z,\omega,t) \tag{27}$$

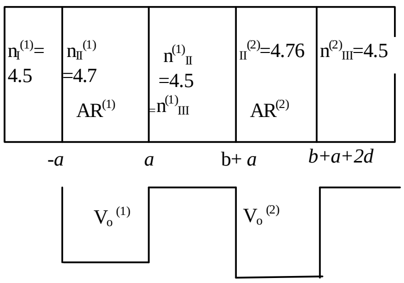



**Figure 6.** Energy-band diagram for $\lambda=1.55\text{x}10^{-6}$ m, $n_{I,III}^{(1)}$=4.5, $n_{II}^{(1)}$=4.7, 2*a*=6000 A° in the FSSSIWG and $\lambda=1.55\text{x}10^{-6}$ m, $n_{I,III}^{(2)}$=4.5, $n_{II}^{(2)}$=4.76, 2*a*=5000 A° in the SSSSIWG.

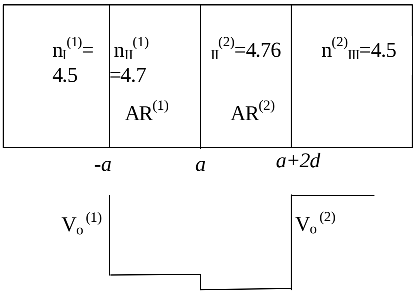



**Figure 7.** Energy-band diagram for $\lambda$=1.55x10$^{-6}$ m, $n_I^{(1)}$=4.5, $n_{II}^{(1)}$=4.7, 2$a$=6000 A$^o$ in the FSSSIWG and $\lambda$=1.55x10$^{-6}$ m, $n_{III}^{(2)}$=4.5, $n_{II}^{(2)}$=4.76, 2$a$=5000 A$^o$ in the SSSSIWG

## 3. CONTINUITY OF THE FIELDS CONDITIONS

For continuity of the fields at the boundaries $x=\pm a$, and $x = b + a + d$ in Figure-3, the parameters can be taken [6,7] as

$$\zeta^{(1)} = \alpha_{II}^{(1)} a = \frac{a}{\hbar}\sqrt{2m^*(V_o^{(1)} - E_n^{(1)})} = \frac{a}{\hbar}\sqrt{2m^* e_i^{(1)}} \quad (28)$$

$$\zeta^{(2)} = \alpha_{II}^{(2)} d = \frac{d}{\hbar}\sqrt{2m^*(V_o^{(2)} - E_v^{(2)})} = \frac{d}{\hbar}\sqrt{2m^* e_j} \quad , (29)$$

which are the optical phase changes across the widths $a$ and $d$ of the AR$^{(1)}$ and AR$^{(2)}$ in the DASIWG respectively. The amplitudes [5,6,7] $A_I^{(1)}$, $A_I^{(2)}$, $A_{III}^{(1)}$ and $A_{III}^{(2)}$ can be found in terms of $\alpha_{II}^{(1)}, \alpha_{II}^{(2)}$, $\theta^{(1)}$, $\theta^{(2)}$, $a$, $d$, $A^{(1)}$ and $B^{(2)}$. We obtain $A_I^{(1)}$ and $A_I^{(2)}$ from boundary conditions for Eq.(3), Eq.(4) and Eq.(13), Eq.(14) at x=-$a$ and x=b+$a$ as

$$A_I^{(1)} = A^{(1)}\cos(\alpha_{II}^{(1)} a + \theta^{(1)}) = A\cos(\zeta^{(1)} + \theta^{(1)}) \quad (30)$$

$$A_I^{(2)} = A^{(2)}\cos(\alpha_{II}^{(2)} d + \theta^{(2)}) = A^{(2)}\cos(\zeta^{(2)} + \theta^{(2)}) \quad (31)$$

and $A_{III}$ and $B_{III}$ boundary conditions for Eq.(4), Eq.(5) and Eq.(11), Eq.(12) at x=$a$ and x=b+$a$+$2d$

$$A_{III}^{(1)} = A^{(1)}\cos(\alpha_{II}^{(1)} a - \theta_1) = A^{(1)}\cos(\zeta^{(1)} - \theta_1) \quad (32)$$

$$A_{III}^{(2)} = A^{(2)}\cos(\alpha_{II}^{(2)} d - \theta^{(2)}) = A^{(2)}\cos(\zeta^{(2)} - \theta^{(2)}). \quad (33)$$

If we take for even field [6,7]

$$\theta_{1(2)} = m\pi/2 \text{ , m=0, 2, 4, 6,..., m=2i, i=0, 1, 2, 3,...,} \quad (34)$$

where m is mode number, then the coefficients in Eqs.(3)-(5) and Eqs.(13)-(15) become:

$$A_I^{(1)e} = A^{(1)e}\cos(\zeta^{(1)} + m\pi/2) = A^{(1)e}\cos(\zeta^{(1)} + i\pi) = (-1)^i A^{(1)e}\cos\zeta^{(1)} = A^{(1)e}\cos\zeta^{(1)}\cos(m\pi/2) = A^{(1)e}\cos\zeta^{(1)}\cos(i\pi) \quad (35)$$

$$A_I^{(2)e} = A^{(2)e}\cos(\zeta^{(2)} + m\pi/2) = A^e\cos(\zeta^{(2)} + i\pi) = (-1)^i A^{(2)e}\cos\zeta^{(2)} \quad (36)$$

or

$$A_I^{(2)e} = A^{(2)e}\cos\zeta^{(2)}\cos(m\pi/2) = A^{(2)e}\cos\zeta^{(2)}\cos(i\pi) = (-1)^i A^{(2)e}\cos\zeta^{(2)} \quad (37)$$

$$A_{III}^{(1)e} = A^{(1)e}\cos(\zeta^{(1)} - m\pi/2) = A^{(1)e}\cos(\zeta^{(1)} - i\pi) = (-1)^i A^{(1)e}\cos\zeta^{(1)} = A^{(1)e}\cos\zeta\cos(m\pi/2) = A^{(1)e}\cos\zeta^{(1)}\cos(i\pi) = A_I^{(1)e} = A_{III}^{(1)e} = A_{I,III}^{(1)e} \quad (38)$$

$$A_{III}^{(2)e} = A^{(2)e}\cos(\zeta^{(2)} - m\pi/2) = A^{(2)e}\cos(\zeta^{(2)} - i\pi) = (-1)^i A^{(2)e}\cos\zeta^{(2)} \quad (39)$$

$$A_{III}^{e} = A^{(2)e}\cos\zeta^{(2)}\cos(m\pi/2) = A^{(2)e}\cos\zeta^{(2)}\cos(i\pi) = A_I^{(2)o} = A_{III}^{(2)o} = A_{I,III}^{(2)o} \quad (40)$$

$A_{III}^{e} = A^{(2)e}\cos\zeta^{(2)}\cos(m\pi/2) = A^{(2)e}\cos\zeta^{(2)}\cos(i\pi)$

$$A_{I}^{(2)o} = A_{III}^{(2)o} = A_{I,III}^{(2)o} \qquad (41)$$

and by taking for odd field [6,7] $\theta_{1(2)} = m\pi/2$

$m=1, 3, 5,...,$ or $m=(2i+1)$, $i=0, 1, 2, 3,...,$ (42)

$$\begin{aligned} A_{I}^{(1)o} &= A^{(1)o}\cos(\zeta^{(1)} + m\pi/2) \\ &= A^{(1)o}\cos[\zeta^{(1)} + (2i+1)\pi/2] \\ &= A^{(1)o}\sin\zeta^{(1)}\sin[(2i+1)\pi/2] \end{aligned} \qquad (43)$$

$$\begin{aligned} A_{I}^{(2)o} &= A^{(2)o}\cos(\zeta^{(2)} + m\pi/2) \\ &= B^{(2)o}\cos[\zeta^{(2)} + (2i+1)\pi/2] \\ &= A^{(2)o}\sin\zeta^{(2)}\sin[(2i+1)\pi/2] \end{aligned} \qquad (44)$$

$$\begin{aligned} A_{III}^{(1)o} &= A^{(1)o}\cos(\zeta^{(1)} - m\pi/2) \\ &= A^{(1)o}\cos[\zeta^{(1)} - (2i+1)\pi/2] \\ &= A^{(1)o}\sin\zeta^{(1)}\sin[(2i+1)\pi/2] \\ &= A^{(1)o}\sin\zeta^{(1)}\sin[(2i+1)\pi/2] = A_{I}^{(1)o} \\ &= A_{III}^{(1)o} = A_{I,III}^{(1)o} \end{aligned} \qquad (45)$$

$$\begin{aligned} A_{III}^{(2)o} &= A^{(2)o}\cos(\zeta^{(2)}) - m\pi/2) \\ &= A^{(2)o}\cos[\zeta^{(2)} - (2i+1)\pi/2] \\ &= A^{(2)o}\sin\zeta^{(2)}\sin[2i+1)\pi/2] = A_{I}^{(2)o} \\ &= A_{III}^{(2)o} = A_{I,III}^{(2)o}. \end{aligned} \qquad (46)$$

The coefficients [5,6] $A^{(1)}$, $A^{(1)e}$ and $A^{(1)o}$ are respectively given by

$$A^{(1)} = \sqrt{\frac{2\alpha_{II}^{(1)}}{2\alpha_{II}^{(1)}a + \sin(2\alpha_{II}^{(1)}a)\mathrm{Cos}2\theta^{(1)}}} = \sqrt{\frac{2\zeta^{(1)}/a}{2\zeta^{(1)} + \sin2\zeta^{(1)}\mathrm{Cos}2\theta^{(1)}}} \qquad (47)$$

$$A^{(1)e} = \sqrt{\frac{2\zeta^{(1)}/a}{2\zeta^{(1)} + \sin2\zeta^{(1)}}},\ A^{(1)o} = \sqrt{\frac{2\zeta^{(1)}/a}{2\zeta^{(1)} - \sin2\zeta^{(1)}}}. \qquad (48)$$

The coefficients $A^{(2)}$, $A^{(2)e}$ and $A^{(2)o}$ are also respectively given by

$$A^{(2)} = \sqrt{\frac{2\alpha_{II}^{(2)}}{2\alpha_{II}^{(2)}d + \sin(2\alpha_{II}^{(2)}d)\mathrm{Cos}2\theta^{(2)}}} = \sqrt{\frac{2\zeta^{(2)}/d}{2\zeta^{(2)} + \sin2\zeta^{(2)}\mathrm{Cos}2\theta^{(2)}}} \qquad (49)$$

$$A^{(2)e} = \sqrt{\frac{2\zeta^{(2)}/d}{2\zeta^{(2)} + \sin2\zeta^{(2)}}},\ A^{(2)o} = \sqrt{\frac{2\zeta^{(2)}/d}{2\zeta^{(2)} - \sin2\zeta^{(2)}}} \qquad (50)$$

We can calculate the ratio of the field amplitude $A^{(1)}$ in the $AR^{(1)}$ of FSSSIWG to the field amplitude $A^{(2)}$ in the $AR^{(2)}$ of SSSSIWG for $\lambda=1.55\mathrm{x}10^{-6}$ m, $n_I=n_{III}=n_{I,III}=4.5$, $n_{II}=4.7$, $2a=6000$ A$^o$ and $n_I=n_{III}=n_{I,III}=4.5$, $n_{II}=4.76$, $2d=5000$ A$^o$ respectively in the DSSIWG as $A^{(1)}/A^{(2)}=0.91803075674491$.

## 4. EFFECTIVE INDEX AND PHASE VELOCITY

Eqs. (10)-(12) and Eqs. (20)-(22) state a very important point about each electric field in the regions of the DSSSIWG, which have guided field distributions. One expects a high peak transverse electric field in the immediate vicinities of the $AR^{(1)}$ and $AR^{(2)}$. These properties are obtained for condition $n_{I,III}^{(1/2)} \langle n_{ef}^{(1/2)} \langle n_{II}^{(1/2)}$ which makes the right-hand sides of the Eqs.(39)-(41) real [1]. Here $n_{ef}^{(1/2)}$ is effective index of refraction and given by $n_{ef}^{(1/2)} = \beta_z/k_o$, which is also effective index of refraction. In the case of symmetry $n_{I,III}^{(1/2)}$ stands for $n_{I}^{(1/2)}$ or $n_{III}^{(1/2)}$, ($n_{I}^{(1/2)} = n_{III}^{(1/2)} = n_{I,III}^{(1/2)}$). $k_o$ and $\lambda$ are the wave number of the free space and wavelength of the interested in field. Here (1/2) means that $(1/2)\rightarrow(1)$ or (2) such as $n_{I,III}^{(1)}\langle n_{ef}^{(1)}\langle n_{II}^{(1)}$ or $n_{I,III}^{(2)}\langle n_{ef}^{(2)}\langle n_{II}^{(2)}$ and $n_{ef}^{(1)} = \beta_z/k_o$ or $n_{ef}^{(2)} = \beta_z/k_o$. Effective indices for inside the $AR^{(1)}$ and $AR^{(2)}$ in FSSSIWG and SSSSIWG are respectively $n_{ef}^{(1)}=4.63405940362834$ and $n_{ef}^{(2)}=4.66983606003808$ which obey actually that $4.5\langle 4.63405940362834\langle 4.7$ and

$4.5 \langle 4.66983606003808 \langle 4.76$ respectively for $n_{II}^{(1)}=4.7$ and $n_{II}^{(2)}=4.76$. Effective indices, phase constants and the phase velocities of insides the AR$^{(1)}$ and AR$^{(2)}$ can also be calculated [8] by the other formulas $n_{ef}=n_{II}\sqrt{1-2\Delta(1-\alpha)}$ , $\beta_z=k_o n_{ef}$, and $v=c/n_{ef}$.

## 5. EVEN AND ODD FIELDS

If the phase angles of $\theta_1$ and $\theta_2$ in the electric fields in Eqs.(4) and (11) are taken as zero, then these electric fields in the DASIWG become the least even and odd mode. By ignoring $F(z,\omega,t)$, we have the least even mode ($\theta_1$ corresponds to m=0 and upper latter (e) denotes even). When $\theta_1=\theta_2=0$ occurs for the even field, then we obtain $\alpha_I^{(1/2)}=\alpha_{III}^{(1/2)}=\alpha_{I,III}^{(1/2)}$ for the symmetric case. We have the even fields, ignoring $F(z,\omega,t)$,

$$E^e{}_{yI}{}^{(1)} = A^e{}_I{}^{(1)} \exp\left[\alpha_{I,III}{}^{(1)}(x+a)\right] \tag{51}$$

$$E^e{}_{yII}{}^{(1)} = A^e \cos(\alpha_{II}{}^{(1)}x) \tag{52}$$

$$E^e{}_{yIII}{}^{(1)} = A^e{}_{III}{}^{(1)} \exp\left[-\alpha_{I,III}{}^{(1)}(x-a)\right], \tag{53}$$

where $A^e_I{}^{(1)}$ and $A^e_{III}{}^{(1)}$ are given by $E^e{}_{yI}(x)^{(1)}=E^e{}_{yII}(x)^{(1)}$ at $x=-a$ and $E^e{}_{yII}(x)^{(1)}=E^e{}_{yIII}(x)^{(1)}$ at $x=a$ boundaries as

$$A^e I = A^e III = A^e I, III = A^e \cos\zeta^{(1)} \tag{54}$$

in the AR$^{(1)}$ and CLs for the FSSSIWG.

In the AR$^{(2)}$ and CLs for the SSSSIWG we obtain the even fields as, ignoring $F(z,\omega,t)$,

$$E^e{}_{y_I}{}^{(2)} = A^e{}_I{}^{(2)} \exp\{\alpha_{I,III}{}^{(2)}[(x-(b+a)]\} \tag{55}$$

$$E^e{}_{yII}{}^{(2)} = A^e{}_I{}^{(2)} \cos\{\alpha_{II}{}^{(2)}[x-(b+a+d)]\} \tag{56}$$

$$E^e{}_{yIII}{}^{(2)} = A^e{}_{III}{}^{(2)} \exp\{-\alpha_{I,III}{}^{(2)}[x-(b+a+2d)]\} \tag{57}$$

where $A^e_I{}^{(2)}$ and $A^e_{III}{}^{(2)}$ are given by $E^e{}_{yI}(x)^{(2)}=E^e{}_{yII}{}^{(2)}(x)$ and $E^e{}_{yII}(x)^{(2)}=E^e{}_{yIII}{}^{(2)}(x)$ at $x=b+a$ boundaries as

$$A^e{}_I{}^{(2)} = A^e{}_{III}{}^{(2)} = A^e{}_{I,III}{}^{(2)} = A^{e(2)}\cos(\alpha_{II}{}^{(2)}d) = A^{e(2)}\cos\zeta^{(2)} \tag{58}$$

in the AR$^{(1)}$ and CLs for the FSSSIWG.

## 6. CONTINUITY CONDITIONS ON THE EVEN AND ODD FIELDS

If the phase angles of $\theta_1$ and $\theta_2$ in the electric fields in Eqs.(4) and (13) are taken as $\pi/2$, then these electric fields become the least odd mode ($\theta_1$ corresponds to m=$\pi/2$ and upper latter (o) denotes odd). When $\theta_1=\theta_2=90^o$ occurs for the odd fields, then you obtain $\alpha_I^{(1/2)}=\alpha_{III}^{(1/2)}=\alpha_{I,III}^{(1/2)}$ for the symmetric case also. Ignoring $F(z,\omega,t)$ we have

$$E^o{}_{yI}{}^{(1)} = A^o{}_I{}^{(1)} \exp\left[\alpha_{I,III}{}^{(1)}(x+a)\right] = A^{o(1)}\sin\zeta^{(1)} \exp\left[\alpha_I{}^{(1)}(x+a)\right] \tag{59}$$

$$E^o{}_{yII}{}^{(1)} = A^{o(1)}\sin(\alpha_{II}{}^{(1)}x) \tag{60}$$

$$E^o{}_{yIII}{}^{(1)} = A^o{}_{III}{}^{(1)} \exp\left[-\alpha_{I,III}{}^{(1)}(x-a)\right] \tag{61}$$

where $A^o_I{}^{(1)}$ and $A^o_{III}{}^{(1)}$ are given by

$E^o{}_{yI}(x)^{(1)}=E^o{}_{yII}(x)^{(1)}$ and
$E^o{}_{yII}(x)^{(1)}=E^o{}_{yIII}(x)^{(1)}$ at $x=a$ boundaries as

$$A^o{}_I{}^{(1)} = A^o{}_{III}{}^{(1)} = A^o{}_{I,III}{}^{(1)} = A^o\sin(\alpha_{II}{}^{(1)}a) = A^{o(1)}\sin\zeta^{(1)} \tag{62}$$

in the AR$^{(1)}$ and CLs for the FSSSIWG

$$E^o{}_{y_I}{}^{(2)} = A^o{}_I{}^{(2)} \exp\{\alpha_{I,III}{}^{(2)}[(x-(b+a)]\} \tag{63}$$

$$E^o{}_{yII}{}^{(2)} = A^{o\,(2)}\sin\{\alpha_{II}{}^{(2)}[x-(b+a+d)]\} \tag{64}$$

$$E^o{}_{yIII}{}^{(2)} = A^o{}_{III}{}^{(2)} \exp\{-\alpha_{I,III}{}^{(2)}[x-(b+a+2d)]\} \tag{65}$$

where $A^o_I{}^{(2)}$ and $A^o_{III}{}^{(2)}$ are given by $E^o{}_{yI}(x)^{(2)}=E^o{}_{yII}(x)^{(2)}$ and $E^o{}_{yII}(x)^{(2)}=E^o{}_{yIII}(x)^{(2)}$ at $x=a$ boundaries as

$$A^o{}_I{}^{(2)} = A^o{}_{III}{}^{(2)} = A^o{}_{I,III}{}^{(2)} = A^{o(2)}\sin(\alpha_{II}{}^{(2)}a) = A^{o(2)}\sin\zeta^{(2)} \tag{66}$$

in the AR$^{(2)}$ and CLs for the DSSIWG.

When $\theta_1=\theta_2=0$ occurs for the even field, then we obtain $\alpha_I^{(1/2)}=\alpha_{III}^{(1/2)}=\alpha_{I,III}^{(1/2)}$ for the DASIWG. We have following expressions, ignoring $F(z,\omega,t)$,

$$E^{e}{}_{yI0}{}^{(1)} = A^{e}{}_{I0}{}^{(1)} \exp\left[\alpha_{I0}{}^{(1)}(x+a)\right] \quad (67)$$

$$E^{e}{}_{yII0}{}^{(1)} = A^{e(1)}{}_{0}\cos(\alpha_{II0}{}^{(1)}x) \quad (68)$$

$$E^{e}{}_{yII0}{}^{(2)} = A^{e(2)}{}_{0}\cos\{\alpha_{II0}{}^{(2)}[x-(a+d)]\} \quad (69)$$

$$E^{e}{}_{yIII0}{}^{(2)} = A^{e}{}_{III0}{}^{(2)}\exp\{-\alpha_{III0}{}^{(2)}[x-(a+2d)]\} \quad (70)$$

where the coefficients $A^{e}{}_{I0}{}^{(1)}$ and $A^{e(1)}{}_{0}$ have relations

$$A^{e}{}_{I0}{}^{(1)} = A^{e(1)}{}_{0}\cos\zeta_{II0}{}^{(1)} \quad (71)$$

$$A^{e(1)}{}_{0} = A^{e(2)}{}_{0}\frac{\cos\zeta_{II0}{}^{(2)}}{\cos\zeta_{II0}{}^{(1)}} \quad (72)$$

which are respectively found at the boundaries x=-$a$ and x=$a$+$d$ of the equations $E^{e}{}_{yI0}(x)^{(1)} = E^{e}{}_{yII0}(x)^{(1)}$ and $E_{yII0}{}^{(2)} = E_{yIII0}{}^{(2)}$

When $\theta_1=\theta_2=90^{o}$ occurs for the odd fields, then you obtain $\alpha_{I}{}^{(1/2)}=\alpha_{III}{}^{(1/2)}=\alpha_{I,III}{}^{(1/2)}$ for the DASSIWG also, ignoring $F(z,\omega,t)$,

$$E^{0}{}_{yI0}{}^{(1)} = A^{0}{}_{I0}{}^{(1)}\exp\left[\alpha_{I0}{}^{(1)}(x+a)\right] \quad (73)$$

$$E^{0}{}_{yII0}{}^{(1)} = A^{0(1)}{}_{0}\sin(\alpha_{II0}{}^{(1)}x) \quad (74)$$

$$E^{0}{}_{yII0}{}^{(2)} = A^{0(2)}{}_{0}\sin\{\alpha_{II0}{}^{(2)}[x-(a+d)]\} \quad (75)$$

$$E^{0}{}_{yIII0}{}^{(2)} = A^{0}{}_{III0}{}^{(2)}\exp\{-\alpha_{III0}{}^{(2)}[x-(a+2d)]\} \quad (76)$$

Here the equations $E^{0}{}_{yI0}{}^{(1)} = E^{0}{}_{yII0}{}^{(1)}$ and $E^{0}{}_{yII0}{}^{(1)} = E^{0}{}_{yII0}{}^{(2)}$ at the boundaries x=-$a$ at x=$a$ and x=$a$+$d$ give respectively the cofficients $A^{0}{}_{I0}{}^{(1)}$ and $A^{0(1)}{}_{0}$ as

$$A^{0}{}_{I0}{}^{(1)} = A^{0(1)}{}_{0}\sin\zeta_{II0}{}^{(1)} \quad (77)$$

$$A^{0(1)}{}_{0} = A^{0(2)}{}_{0} = \frac{\sin\zeta_{II0}{}^{(2)}}{\sin\zeta_{II0}{}^{(1)}} \quad (78)$$

**7. EQUIVALENCE OF DSSIWG AS A SSSIWG**

Parametric coordinates $\zeta$ and $\eta$ of the EEVs for carriers such as electrons or holes in the normalized coordinate system $\zeta$-$\eta$, the normalized frequency (NF) V and normalized propagation constant (NPC) $\alpha$ [8-9] are important parameters in the DSSIWG.

The normalized frequencies (NFs) $V^{(1)}$ and $V^{(2)}$ in FSSSIWG and SSSSIWG of the DSSIWG can be respectively defined [7] by

$$V^{(1)} = \frac{a}{\hbar}\sqrt{2m^{*}V_{o}{}^{(1)}} = ak_{o}\sqrt{n_{II}{}^{(1)^2} - n_{I,III}{}^{(1)^2}} \quad (79)$$

$$V^{(2)} = \frac{a}{\hbar}\sqrt{2m^{*}V_{o}{}^{(2)}} = dk_{o}\sqrt{n_{II}{}^{(2)^2} - n_{I,III}{}^{(2)^2}} = k_{o}d\sqrt{n_{II}{}^{(2)^2} - n_{I,III}{}^{(2)^2}} \quad (80$$

and equivalent normalized frequency for DSSIWG by

$$V=\frac{1}{2}(V^{(1)}+V^{(2)}) = \frac{1}{2}ak_{o}\sqrt{n_{II}{}^{(1)^2} - n_{I,III}{}^{(1)^2}} + \frac{1}{2}dk_{o}\sqrt{n_{II}{}^{(2)^2} - n_{I,III}{}^{(2)^2}} \quad (81)$$

or

$$V = \frac{1}{2}\frac{a}{\hbar}\sqrt{2m^{*}V_{o}{}^{(1)}} + \frac{1}{2}\frac{d}{\hbar}\sqrt{2m^{*}V_{o}{}^{(2)}} = \frac{1}{\hbar}\sqrt{\frac{1}{2}(m^{*}V_{o}{}^{(1)}a^{2} + m^{*}V_{o}{}^{(2)}d^{2})}\ . \quad (82)$$

and equivalent normalized propagation

$$\alpha=\frac{\eta^{2}}{V^{2}} = \frac{\left[\frac{a}{\hbar}\sqrt{\frac{1}{2}m^{*}V_{o}{}^{(1)}} + \frac{d}{\hbar}\sqrt{\frac{1}{2}m^{*}V_{o}{}^{(2)}}\right]^{2} - \left[\frac{m^{*}a^{2}}{2\hbar^{2}}e_{i} + \frac{2m^{*}d^{2}}{2\hbar^{2}}e_{j}\right]}{ak_{o}\sqrt{n_{II}{}^{(1)^2} - n_{I,III}{}^{(1)^2}} + ak_{o}\sqrt{n_{II}{}^{(2)^2} - n_{I,III}{}^{(2)^2}}} \quad (83)$$

and equivalent barrier potential Referring to Eqs.(28) and (29) equivalent abscissa of the EEV is given by

$$\zeta = \frac{1}{2}\frac{a}{\hbar}\sqrt{2m^{*}(V_{o}{}^{(1)} - E_{n}{}^{(1)})} + \frac{1}{2}\frac{d}{\hbar}\sqrt{2m^{*}(V_{o}{}^{(2)} - E_{n}{}^{(2)})} = \frac{a}{\hbar}\sqrt{\frac{1}{2}m^{*}e_{i}{}^{(1)}} + \frac{d}{\hbar}\sqrt{\frac{1}{2}m^{*}e_{j}{}^{(2)}} \quad (84)$$

or

$$\zeta = \sqrt{\frac{1}{2}\left[\frac{m^* a^2}{\hbar^2} e_i + \frac{m^* d^2}{\hbar^2} e_j\right]} \qquad (85)$$

and equivalent ordinate

$$\eta^{(1)} = \frac{1}{2}\sqrt{\frac{1}{4}[\eta^{(1)^2} + \eta^{(2)^2}]} = \sqrt{\frac{1}{2}\left(\frac{a^2}{\hbar^2} m^* E_i^{(1)} + \frac{d^2}{\hbar^2} m^* E_i^{(2)}\right)} \qquad (86)$$

or

$$\eta = \sqrt{V - \zeta^2} =$$

$$\sqrt{\left[\frac{a}{\hbar}\sqrt{\frac{1}{2} m^* V_o^{(1)}} + \frac{d}{\hbar}\sqrt{\frac{1}{2} m^* V_o^{(2)}}\right]^2 - \left[\frac{m^* a^2}{2\hbar^2} e_i + \frac{m^* d^2}{2\hbar^2} e_j\right]} \qquad (87)$$

$$V_o = \frac{V^2 h^2}{2m^*(a+d)^2} \qquad (88)$$

and equivalent refractive index of the AR

$$n_{II} = \sqrt{\frac{V^2}{k_o^2 (a+d)^2} + n_{I,III}^2} \qquad (89)$$

for the DSSIWG in Figure-7. Note that Note that $V^{(1)} = V^{(2)}$ gives $V = V^{(1)}$ or $V = V^{2)}$, $\zeta^{(1)} = \zeta^{(2)}$ gives $\zeta = \zeta^{(1)}$ or $\zeta = \zeta^{(2)}$ and $\eta^{(1)} = \eta^{(2)}$ gives $\eta = \eta^{(1)}$ or $\eta = \eta^{(2)}$. For example, from Table 1 for abscissas, ordinates we can obtain the following values V=0.5( $V^{(1)} + V^{(2)}$ )=1.61103074702189, $\zeta$=0.94426165857265, $\eta$ =1.30519743709137, and normalized propagation constant $\alpha$=0.656330381679475 and $n_{II} = 4.55764618707711$.

A new equivalent step index wave guide (ESIWG) of the DSSIWG is defined by these normalized frequencies, equivalent abscissa, equivalent ordinate, and normalized propagation as shown in Figure- 8.

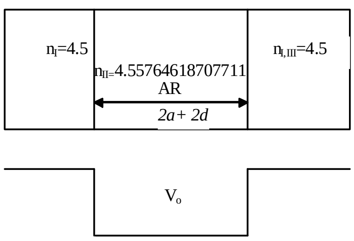



**Figure 8.** Equivalent step index wave guide

## 8. EXPRESSINS OF FIELDS FOR ESIWG

Field expressions and EEV for carriers of the ESIWG are given by

$$E_{yI} = A\exp\left[\alpha_I (x + a + d)\right] F(z,\omega,t) \qquad (90)$$

$$E_{yII} = A\cos(\alpha_{II} x - \theta)\ F(z,\omega,t) \qquad (91)$$

$$E_{yIII} = A_{III}\exp\left[-\alpha_{III}[x - (a+d)]\right] F(z,\omega,t) \qquad (92)$$

$$E_{n0} = \frac{n^2\hbar^2\pi^2}{8m^* a^2},\ \ n=1, 2, 3, \ldots, \qquad (93)$$

The ESIWG contains the normalized frequency V=1.61095326736701, normalized propagation constant $\alpha$ =0.65633038167949, normalized abscissa $\zeta$=0.944394637337171, normalized ordinate $\eta$ =1.30510122159518, refractive index $n_{II}$=4.55764067749070 for AR, EEV $E_1$=0.27443539876539 eV, barrier potential $V_o$=0.28864647569620. The variations of Eqs.(90)-(92) for the ESIWG against to axis x are in Figure-9 and Figure-10.

Our results of this work are suitable found results in ref. [10]. Because, for values $\lambda$=0.5145x10$^{-6}$ m, $n_{I,III}$=1.55, $n_{II}$=1.57, 2*a*=1 μm=10000 A$^o$ in ref. [10], we have achieved normalized frequency as V=3.0506106640935 in our method. Whereas, V has given by Popescu as 3.05061, as shown in ref. [10]. It is seen that the normalized frequency V found in our method is more sensitive than the normalized frequency in ref [10].

## 9. RESULTS AND DISCUSSIONS

In this novel study the variations of the fields of the regions of the FSSSIWG, SSSSIWG of the DSSIWG are studied and wave vectors, propagation constants, phase constant, equivalent indices, energy eigen values, barrier potentials, zetas, etas and amplitudes are obtained. Continuity conditions at the boundaries in the DSSIWG are investigated and then we have constituted the ESIWG getting equivalent refractive index for AR of the ESIWG. We have seen that V=0.5( $V^{(1)} + V^{(2)}$ ), $k_I$=0.5[$k_I^{(1)}$+$k_I^{(2)}$], $k_{III}$=0.5[$k_{III}^{(1)}$+$k_{III}^{(2)}$], here.

Impedance $Z^{TE}_{yxII}$ and phase velocity of the AR field for ESIWG are larger than the impedances $Z^{TE}_{yxII}{}^{(1)}$, $Z^{TE}_{yxII}{}^{(2)}$ and phase velocities $v^{(1)}$, $v^{(2)}$ of the AR $^{(1)}$, AR $^{(2)}$ for the DSSIWG, respectively.

On the other hand, the amplitude of the electric field, A, the effective index $n_{ef}$ , phase constant $\beta_z$ , the EEV $E_1$, barrier potential $V_o$ and maximum intensity of Poynting vector [8] in the AR of ESIWG are smaller than the amplitudes $A^{(1)}$, $A^{(2)}$, of the electric fields, the effective index $n_{ef}^{(1)}$, $n_{ef}^{(2)}$, the phase constants $\beta_z^{(1)}$, $\beta_z^{(2)}$, the EEVs $E_n^{(1)}$, $E_n^{(2)}$, barrier potentials $V_o^{(1)}$, $V_o^{(2)}$ and maximum intensities $S^{(1)}$, $S^{(2)}$ of Poynting vectors in the $AR^{(1)}$, $AR^{(2)}$ of the DSSIWG, respectively.

Consequently, the AR width 2*a* of step-index wave guide larger is, transferred energy in travel direction smaller is. Therefore, to great the transferred energy in travel direction like quantum well laser AR width must be small. The importance of the quantum well arises from this subject.

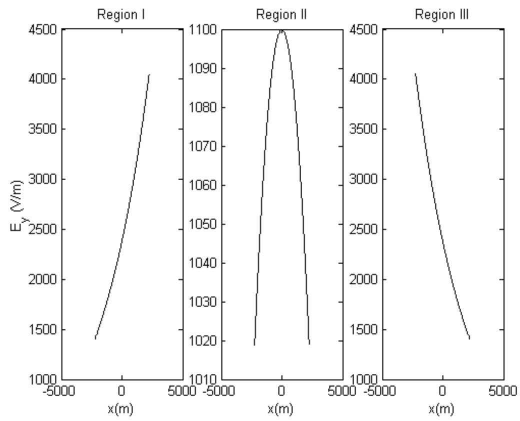



**Figure 9.** The variations of the fields of the regions of the ESIWG against to axis x for $n_{II} = 4.55764618707711$, $\alpha$=0.656349097706842, $\zeta$=0.944414341349384 and $\eta$=1.3051826001382, $E_1$=0.27443539876539. V=1.61103074702189

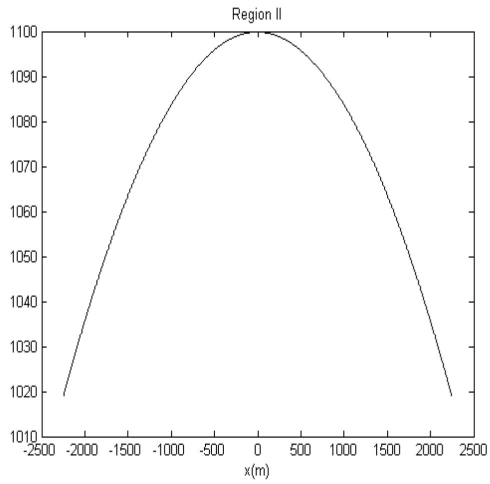



**Figure 10.** The variation of the only AR field of the ESIWG against to axis x.

**Table II:** Wave vectors, Propagation constants, Phase constant, Equivalent indice, Enery eigen value, Barrier potential, Zeta, Eta and Amplitudez for $\lambda$ =1.55x10$^{-6}$ m, $n_{I,III}$=4.5, $n_{II}$=4.55764618707711, 2*a*=5500 A$^o$ in the ESIWG.

| Quantity | Symbol | Value |
|---|---|---|
| Wave number | $k_I$ (1/m) | 1.824150573052138x10$^7$=0.5[$k_I^{(1)}+k_I^{(2)}$] |
| Wave number | $k_{II}$ (1/m) | 1.847518423094579x10$^7$=0.5[$k_{II}^{(1)}+k_{II}^{(2)}$ with %4 error] |
| Wave number | $k_{III}$(1/m) | 1.824150573052138x10$^7$=0.5[$k_{III}^{(1)}+k_{III}^{(2)}$] |
| Propagation constant | $\alpha_I$ (1/m) | 2.373059272978546x10$^6$ |
| Propagation constant | $\alpha_{II}$ (1/m) | 1.717116984271607x10$^6$ |
| Propagation constant | $\alpha_{III}$ (1/m) | 2.373059272978546x10$^6$ |
| Phase constant | $\beta_z$ (1/m) | 1.839521518302283 x10$^7$ |
| Effective index | $n_{ef}$ | 4.53791860970661 |
| Phase Velocity | v | 6.610960349934436x10$^7$ |
| Enery eigen value | $E_1$(μeV) | 0.27443543900888 |
| Barrier potential | $V_o$ (μeV) | 0.28867428390716 |
| Zeta | $\zeta$ | 0.944414341349384 =0.5[$\zeta^{(1)}+\zeta^{(2)}$] |
| Eta | $\eta$ | 1.3051826001382=0.5[$\eta^{(1)}+\eta^{(2)}$] |
| Amplitude | A | 1.099908675780402x10$^3$ |
| Impedance | $Z^{TE}_{yxII}(\Omega)$ | 18.30702245219 |
| Maximum Intensity of Poynting vector | S(W/m$^2$) | 3.304194055085877x10$^4$ |

$\alpha_I^2 + \alpha_{II}^2 = k_{II}^2 - k_I^2$=8.57990105074348x10$^{12}$

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## VITAE

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