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Modeling of All Nonlinear Guided Wave Including MQW Structure

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Abstract: The theoretical investigation of nonlinear optical waves in multi-layers systems and Multiple Quantum Well (MQW) structures have been made in this study. Numerical analysis for finding uniformity of amplitude-identical nonlinear field profile has been presented. Influence of structure parameter on optical power is also discussed.

Key words: Multiple quantum well, nonlinearity, bistability, field profile, effective refractive index, rms approximation, uniform core field

INTRODUCTION

In recent years, considerable attention and great effort have been focused on the theoretical investigation of nonlinear optical waves in multi-layers systems and Multiple Quantum Well (MQW) structures[1-4], because of potential application in all-optical signal processing devices, such as bistability[4-6], switching, upper and lower threshold devices, nonlinear directional coupler etc. The key concept on which all nonlinear guided wave optical devices are based is that the local intensity of the guided wave controls the propagation wave vector. Thus the profile and propagation constant can become power dependent when one or more of the layer are characterized by intensity dependent refractive index. For modeling of MQW structure, it is very important to analyze uniformity of amplitude-identical nonlinear field profile, to analyze the effect of structure parameters (e.g. core thickness, well number, the ratio of the well thickness to the periodic length) on optical power, effective index, field profile. It is also an important issue for analysis of non-linearity and bistability for given wave-guide parameters. For achieving the above goal, first it is needed to select the wave-guide structure and suitable materials for fabrication of optical devices. A number of studies[1-3] have been reported regarding modeling of MQW structure, consisted nonlinear cladding- substrate but with only linear core. The problem achieving uniform field profile in the core using all nonlinear optical wave guide structure shown in the Fig. 1. This structure consists of a guide core that contains M layers wells with nonlinear refractive index and M-1 layers barriers with nonlinear refractive index arranged alternatively and one nonlinear cladding and one nonlinear substrate beside the guide core.

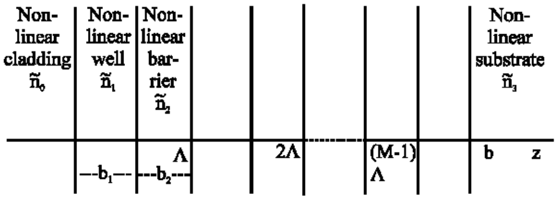

Fig. 1: Schematic diagram of all nonlinear wave-guides structure

In this study, numerical analysis for finding uniformity of amplitude-identical nonlinear field profile has been presented. Influence of structure parameter on optical power is discussed.

Analytical formalism: In one-dimensional medium with Kerr nonlinearity, the electric field component transverse to the propagation direction z satisfies the following one-dimensional nonlinear Helmholtz equation:

$$\frac{d^2E}{dz^2} - q_j^2 k_0{}^2 E + \alpha_j k_0{}^2 E^3 = 0 \qquad (1)$$

Where, $\alpha_j = c\varepsilon_0 n_j^2 \overline{n}_j$ and $q_j{}^2 = N_{eff}{}^2 - \tilde{n}_j{}^2$, j=0, 1, 2, 3, n_{1j} are the nonlinear coefficients, $k_0 = 2\pi/\lambda$, λ is the free space wave length. $\tilde{n}_j{}^2 = n_j{}^2 + \alpha_j E^2$ are the nonlinear refractive indexes; n_j are linear refractive index. E is the local field intensity. Index j indicates number of medium (layers). The thickness and the nonlinear refractive indices of the well and barrier layers are b_1 and $\tilde{n}_1$ and b_2 and $\tilde{n}_2$, respectively. Thus total core thickness is $b = Mb_1 + (M\text{-}1)b_2 = \{(M - 1) + R\}\Lambda$, where, $\Lambda = b_1 + b_2$ is the periodic length and $R = b_1/\Lambda$ is the ratio of the well thickness to the periodic length. Nonlinear refractive indexes $\tilde{n}_0$ and $\tilde{n}_3$ is the cladding and substrate,

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Corresponding Author: Dr. K.M. Rezanur Rahman, School of Science and Technology, Bangladesh Open University, Gazipur-1705, Bangladesh Tel: 88 02 9291111 Fax: 88 02 9291122 respectively. We consider nonsymmetrical cladding. Effective refractive index N_{eff} may be calculated using rms approximation:

$$N_{eff} = \left[\frac{1}{\Lambda}\int_0^{\Lambda} n^2(z)dz\right]^{1/2} = \sqrt{\left[\left[Rn_1{}^2 + (1-R)n_2{}^2\right] + \left[Rn_1{}^2 + (1-R)n_2{}^2\right]\alpha_{core}E_0{}^2\right]} \tag{2}$$

We define:

$$q_1 = k_0{}^2\left(n_1{}^2 - N_{eff}{}^2\right)$$
$$q_j = k_0{}^2\left(N_{eff}{}^2 - n_j{}^2\right),\ (j = 0,1,2,3)$$

$$\tilde{q}_j{}^2 = q_j{}^2 - k^2\alpha_j E^2(0)/2$$
$$\tilde{T}_j = \tilde{q}_j\ / q_1,\ \ (j = 0,1,2,3)$$
$$T_2 = \frac{q_1}{\tilde{q}_2}\ ,\ T^* = \frac{q_2}{q_1}$$

Where, E(0) is the boundary electric field intensity at x = 0. By solving Eq. 1 and by applying the boundary conditions successively at each interface, the nonlinear TE waves are derived. Using rms approximation, the field profile is given by:

$$\begin{aligned}
E(z)/E_0(0) &= [\cosh(q_0x) - (\tilde{q}_0/q_0)\sinh(q_0x)]^{-1}, \quad (x \le 0)\\
E(z)/E_0(0) &= A_j\cos\{q_1[x-(j-1)\Lambda]\} + \\
&\quad B_j(\tilde{q}_1/q_1)\sin\{q_1[x-(j-1)\Lambda]\},\\
&\quad ((j-1)\Lambda \le x \le (j-1)\Lambda + b_1,\ j = 1,2,......,n)\\
E(z)/E_0(0) &= C_j\cosh\{q_2[x-(j-1)\Lambda - b_1]\} + \\
&\quad D_j(\tilde{q}_2/q_2)\sinh\{q_2[x-(j-1)\Lambda - b_1]\},\\
&\quad ((j-1)\Lambda + b_1 \le x \le (j-1)\Lambda,\ j = 1,2,......,n-1)\\
E(z)/E_0(0) &= C_n\{\cosh[q_3(x-b)] + \\
&\quad (\tilde{q}_3/q_3)\sinh[q_3(x-b)]\}^{-1}, \quad (x \ge b),
\end{aligned} \tag{3}$$

Where, the coefficients A_j, B_j, C_j and D_j in the Eq. 3 are determined by the equations.

$$\begin{pmatrix} A_j \\ B_j \end{pmatrix} = (VU)^{-1}\begin{pmatrix} 1 \\ \tilde{T}_0 \end{pmatrix}, \quad (j = 1,2,3......,n)$$

$$\begin{pmatrix} C_j \\ D_j \end{pmatrix} = U(VU)^{j-1}\begin{pmatrix} 1 \\ \tilde{T}_0 \end{pmatrix}$$

$j = 1, 2, 3......, n$ for C_j) and ($j = 1,2,3......, n-1$ for D_j)

$$U = \begin{pmatrix} \cos(q_1b_1) & \sin(q_1b_1) \\ -T_2\sin(q_1b_1) & T_2\cos(q_1b_1) \end{pmatrix}$$

$$V = \begin{pmatrix} \cosh(q_1b_1) & \dfrac{1}{T_2\ T^*}\sinh(q_1b_1) \\ -\dfrac{T^*}{\tilde{T}_1}\sinh(q_1b_1) & \dfrac{1}{T_2{}^2\tilde{T}_1}\cosh(q_1b_1) \end{pmatrix}$$

Amplitude of uniform core field E and corresponding modal index N_{eff} can be determined by Eq. 3. Total optical power P for which field becomes uniform can be obtained

$$P = P_0 + P_{core} + P_3 \tag{4}$$

Power in cladding (P_0), core (P_{core}) and substrate (P_3) layers are calculated using:

$$\begin{aligned}
P_0 &= \frac{k_0N_{eff}}{4\omega\mu}\int_{-\infty}^{0} E^2dz\\
P_{core} &= \frac{k_0N_{eff}}{4\omega\mu}\int_{0}^{b} E^2dz\\
P_3 &= \frac{k_0N_{eff}}{4\omega\mu}\int_{-\infty}^{+\infty} E^2dz
\end{aligned} \tag{5}$$

The relation between the effective refractive index N_{eff} and the propagation power P can be obtained. Finally, the field profiles of the nonlinear TE waves can be plotted from the Eq. 3.

RESULTS AND DISCUSSION

Numerical calculations have been performed for the wave-guide model described in Stegeman *et al.*[6]. We take λ = 0.515 μm (Ar+laser), the linear value of the refractive indexes of the nonlinear cladding and substrate are $n_0 = 1.55$, $n_3 = 1.53$, respectively; the linear refractive index of the nonlinear well layers is n_1=1.57 and nonlinear barrier layers is n_2= 1.52; nonlinear coefficients are $\bar{n}_0 = \bar{n}_1 = \bar{n}_2 = \bar{n}_3 = 10^{-10} m^2/W$, respectively. These values for the material parameters are taken from the data given by Ma[1]. To show the way in which the uniform core field of TE mode occurs, we plot the field profiles for different values of effective index N_{eff}. The value of effective index varies from 1.562 to 1.570 with precision 0.001 and total core thickness b = 2 μm, the well number n = 10 and the ratio R = 0.9 are taken for our calculation. In Fig. 2 we plot the electric filed profiles for different value of N_{eff}. As the value of N_{eff} increases from 1.564 to 1.570, the shape of field profile of the TE wave in the guide core changes from

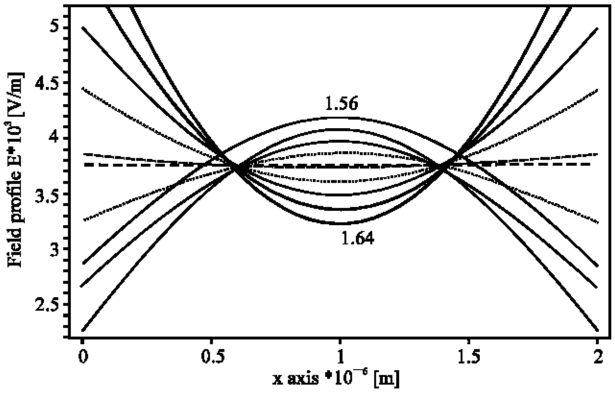

Fig. 2: Field profiles of the nonlinear TE wave for different values of the effective refractive index. Dashed curve corresponds to the uniform filed for refractive index $N_{eff} = 1.56623$

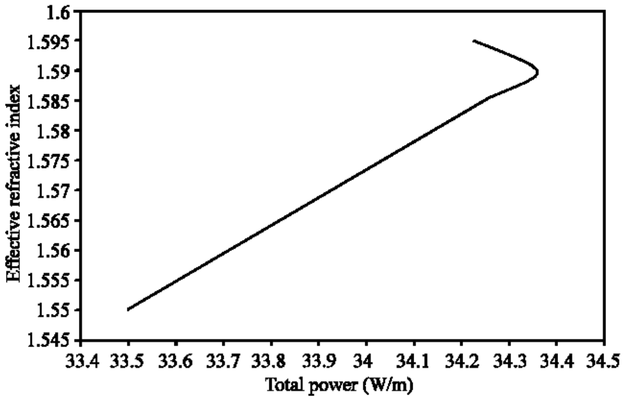

Fig. 3: Dependence of modal refractive index N_{eff} on total power P for core width $b = 2\ \mu m$, $R = 0.9$, $\lambda = 0.515\ \mu m$, $n_0 = 1.55$, $n_1 = 1.57$, $n_2 = 1.52$, $n_3 = 1.53$, $\bar{n}_I = 1\times10^{-10}\ m^2/W$.

peak to a valley. When the value of N_{eff} is chosen as $N_{eff} = 1.56623$, the amplitude-identical nonlinear TE wave (uniform core field) is formed. Indeed, three shapes (convex, concave and uniform) are formed. This result is in agreement with Ma[1] and Liu Wu *et al.* [3]. Figure 3 shows that optical bistability becomes stronger when the thickness is increased.

CONCLUSIONS

Simulation results are presented for modeling all-nonlinear MQW structure. Existence of uniform field in the core layer for this structure is also demonstrated. Producing uniform core field profile in wave guides would be of some importance in applications, such as, optical coupling between two wave guides and coupling between optical fiber and wave guides and may be used in fabrication of various guided wave devices.

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