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Numerical study of Two Photon Absorption effect on nonlinear directional couplers on coupled semiconductor waveguides

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Abstract

The nonlinear interactions of coupled semiconductor waveguides are important phenomena in ultrafast all-optical data processing of integrated photonic circuits. The coupling analysis of semiconductor couplers needs a careful study, because they produce large nonlinear optical responses such as Two Photon Absorption (TPA). In this work, the coupling process is studied by the evolution equations of the mode amplitude of coupled semiconductor waveguides. The formalism takes into account the effects of TPA by starting with Maxwell's equations and using the perturbation method. It is shown that free carriers produced by TPA lead to modification of refractive index. This, in turn, influences the coupling performance of semiconductor waveguides. Fast Fourier Beam Propagation Method (FFT-BPM) is used to investigate the problem, too. The inclusion of free carrier effects result in about one order of magnitude difference in the decoupling threshold.

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Keywords: Two Photon Absorption; Free carriers; Active nonlinear directional coupler; Fast Fourier Transform

1. Introduction

Active nonlinear waveguides have attracted a great deal of attention, because of the possibility of performing all-optical signal processing in integrated optical circuits. The experimental demonstration of ultrafast optical switching in short waveguides have almost been limited to those in semiconductor waveguides, where a variety of nonlinearity, including resonant (carrier induced) and nonresonant nonlinearities, can occur. Therefore, they are one of the attractive candidates among materials for integrated optical devices.

The inclusion of effects, due to an intensity-dependent refractive index in the description of a waveguide directional coupler, has revealed its potential as an all-optical signal processing device. Analysis of nonlinear intensity transmission characteristics has suggested its use as a logic gate [1], time delay in coupled resonator optical waveguide structures [2], small signal amplifier, transistor [3], and ultrashort, subpicosecond pulse generator [4,5]. Nonlinear transfer of light has been experimentally observed between two coupled GaAs/AlGaAs multiple quantum well waveguides [6] and in a two-core fiber [7]. The coherent nature of the nonlinear coupling has been disclosed by a full investigation of evolution along the coupler of the complex amplitudes of the two modes [8]. Although the optical nonlinearity in semiconductor material may be interpreted as a nonlinear refractive index through the Kramers–Kronig relation [9], this effect is always associated with nonlinear absorption such as Two Photon Absorption (TPA) and free carrier effects. TPA and free carrier effects are fundamental

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optical characteristics of semiconductors that describe intensity-dependent losses and refractive index variation of the semiconductor waveguides. Therefore, these nonlinear phenomena affect the operation of NLDC semiconductor waveguides.

Jensen [10] first discussed nonlinear directional couplers. Later, based on improved coupled mode formulations [11], Chen [12], Meng and Okomato [13] derived a more complete set of nonlinear coupled mode equations. But, these investigations have been limited to lossless Kerr law media. The nonlinear propagation of an optical pulse is normally described by the Nonlinear Schrödinger Equation (NLSE) [14], which includes the second order dispersion effect and self-phase modulation. Some researchers studied the active directional coupler by NLSE [15,16]. Some numerical studies on all-optical switching have been carried out in a three-slab NLDC with gain and loss [17], erbium doped fiber using transformed NLSE [18], and effect of saturation and loss on NLDC based on Jensen's relation [19]. Also, some theoretical methods are applied to the study of the active NLDC [20–25].

In this paper, we present a detailed derivation for nonlinear directional couplers using a perturbation method [26]. Our research takes into account some nonlinear optical effects of semiconductors for a system consisting of coupled waveguides. Those nonlinear effects include optical attenuation and intensity-dependent variation of the refractive index, due to free carriers and the Kerr effect. It is shown the free carriers affect the wave propagation in semiconductor couplers stronger than that of the Kerr effect. This provides a precise account of all approximations under which the evolution of nonlinear directional equations hold. This analysis generalizes for both conventional constant cross-section and refractive index semiconductor waveguides. In the last section, we treat an analytical approach by FFT-BPM simulation.

2. Nonlinear properties of semiconductors

When the time duration of the pulse is longer than free carrier life time, then the free carrier density will be stationary during the pulse propagation through a semiconductor in the presence of TPA. In a steady state, the carrier density generation ΔN_c can be approximated as [9]

$$\Delta N_c \cong \frac{\alpha_2 \tau_f}{2\hbar\omega} I^2, \tag{1}$$

where $\hbar\omega$ is the photon energy, I is the field intensity of light, and τ_f is free carrier life time. $\alpha_2 = 12\pi\,\mathrm{Re}[\chi^{(3)}]/n_l^2 \varepsilon_0 c\lambda$ is the two photon absorption coefficient and $\chi^{(3)}$ is the third order nonlinear susceptibility. n_l represents the usual weak-field refractive index, λ is the wavelength of light, ε_0 and c are vacuum permittivity and speed of light in free space, respectively. The free carriers generated by TPA, change the refractive index of semiconductors according to $\Delta n = -\sigma_r\,\Delta N_c$, where σ_r is the refractive volume of material. Therefore, the intensity-dependent refractive index of semiconductors will be given by [9]

$$n = n_l + (n_{nl} - n_{fc} I)I, \tag{2}$$

where $n_{nl} = 3\mathrm{Re}[\chi^{(3)}]/n_l^2 \varepsilon_0 c$ is the second order index of refraction (Kerr coefficient) and $n_{fc} = \sigma_r \alpha_2 \tau_f / 2\hbar\omega$ is the nonlinear refractive index of medium, due to free carriers. Similarly, the free carriers change the absorption coefficient of semiconductors according to the relation $\Delta\alpha = -\sigma_a\,\Delta N_c$, where σ_a is the free carrier absorption cross-section. The TPA coefficient will depend on intensity, according to the following relation:

$$\alpha = \alpha_0 + (\alpha_2 + \alpha_{fc} I)I, \tag{3}$$

where α_0 is the linear absorption and $\alpha_{fc} = \sigma_a \alpha_2 \tau_f / 2\hbar\omega$ is the nonlinear refractive index of the medium due to the free carriers. The attenuation of the field intensity along the propagation axis can be described by:

$$I(z) = I_0\, e^{-\alpha z}, \tag{4}$$

I_0 is the incident field intensity at $z = 0$. Since $I = n_0 \varepsilon_0 c |\mathbf{E}|^2$, one can conclude the electric field, $\mathbf{E}$, attenuates along the propagation distance by the factor of $Exp[-\alpha z/2]$ [9]. In this work, we consider the semiconductor waveguide GaAs-based system with $\alpha_0 = 10.20$/cm, $\alpha_2 = 24$ cm/GW, $\sigma_a = 1.5 \times 10^{-16}$ cm^2, $\tau_f = 50$ ps, and $\lambda = 1.55$ μm. When the applied intensity is smaller than $I = 10$ MW/cm^2, the absorption coefficient can be approximated by α_0 ($\alpha \cong \alpha_0$). In the next section, we will investigate the influence of free carriers on the refractive index in low intensities, which alters the coupling process of the semiconductor waveguides. This treatment is valid for some kinds of semiconductors, such as AlGaAs and InP, too.

3. Nonlinear directional coupler

We will solve the well-known wave equation,

$$\nabla^2 \mathbf{E} - \varepsilon(x, y, z)\mu_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0, \tag{5}$$

where the electric field is represented by $\mathbf{E} = \mathbf{E}(x,y,z)e^{-i\omega t}$ and ω is the frequency of light. The dielectric distribution of medium is defined by $\varepsilon(x,y,z) = n(x,y,z)^2 \varepsilon_0$. By using Eq. (2) in the expansion of square