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MULTIPLE QUANTUM WELL DIRECTIONAL COUPLER WITH PHOTOREFRACTIVE GRATING

E. Weinert-Rączka* and R. Iwanow†

Institute of Electronics, Telecommunication and Informatics
Technical University of Szczecin, Al. Piastów 17, 70-310 Szczecin, Poland

We analyse an asymmetric directional coupler with a thin photorefractive grating as a switching and demultiplexing element with memory. The grating is induced by two external beams interfering in the structure of AlGaAs/GaAs multiple quantum wells with an electric field applied along the quantum well planes.

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1. Introduction

Transfer of light between different waveguides is one of the crucial functions of the integrated optics systems. One of the most often used switching devices is a directional coupler consisting of two waveguides placed in a closed proximity. The power exchange between waveguides can be efficient when the light propagates in them with the same velocity. In case of different propagation constants the coupling can be obtained by means of a diffraction grating formed by periodic changes of the refractive index along the propagation direction [1–3]. The grating constant $K = 2\pi/\Lambda$ (where Λ is the length of the grating period) should be close to the difference between propagation constants of coupled modes ($K = \beta_A - \beta_B$). Such systems, called grating assisted couplers (GACs) are used as narrow frequency filters and demultiplexing elements. The grating in the traditional GAC has constant parameters, which limits the operation of the coupler to the defined frequency. A tuneable coupler can be realised when the grating is created by two external beams interfering in a nonlinear Kerr like medium [4]. Parameters of such a grating depend on the external waves properties and can be changed during the work of the device.

The directional coupler with photorefractive grating proposed in [5] has the same flexibility as a directional coupler with optically induced grating but does

*corresponding author; e-mail: ewar@arcadia.tuniv.szczecin.pl

†Present address: School of Optics and CREOL, University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816-2700, USA.

not require the permanent illumination by the external waves. The grating can be created by a short pulse of the external waves and can last until the arrival of the next pulse which can renew or erase it. Signals guided in the structure and being the subject of switching have lower frequencies than the external waves and their influence on the grating can be neglected.

Here we analyse the directional coupler with photorefractive grating induced in a semi-insulating multiple quantum well (MQW) structure operated with an external electric field applied along the quantum well planes [6].

2. Performance of the coupler

The coupler consists of two different channel waveguides parallel to the z-axis of the co-ordinate system (Fig. 1). Parameters of the channels differ enough to avoid a power exchange between them. The grating required to mediate coupling, is created by two external waves forming an interference pattern along the z-axis.

$$I = I_0(x,z,t)\exp(-\alpha_{\mathrm{ex}}y)[1 + m\cos(Kz)], \tag{1}$$

where I_0 denotes the intensity of the external beams at the surface of the coupler, α_{ex} describes the absorption coefficient, m is the modulation depth, and K — the grating constant. For strongly absorbed external waves the interference pattern

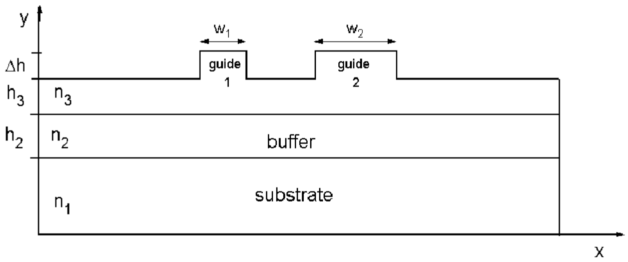

Fig. 1. Geometry of the coupler.

is created only in a thin surface layer of a depth about $1/\alpha_{\mathrm{ex}}$. A high frequency light excites free carriers and by the photorefractive effect leads to the modulation of the refractive index. Coupling between modes of different waveguides in the presence of the grating is described by the following equations [4, 7]:

$$\mathrm{i}\mathrm{d}A_1/\mathrm{d}z = G_{12}A_2\exp\left[\mathrm{i}(\beta_1 - \beta_2)z\right]\exp(-\mathrm{i}Kz), \tag{2a}$$

$$\mathrm{i}\mathrm{d}A_2/\mathrm{d}z = G_{21}A_1\exp[-\mathrm{i}(\beta_1 - \beta_2)z]\exp\left(\mathrm{i}Kz\right), \tag{2b}$$

where β_ν are the propagation constants and A_ν — the amplitudes of modes. The coupling coefficients are

$$G_{\mu\nu} = (\omega\varepsilon/N)\int\int \Delta\varepsilon_G E_\mu E_\nu^* \mathrm{d}x\mathrm{d}y, \tag{3}$$

with $N = (N_\mu N_\nu)^{1/2}$ and $N_\nu = (2\beta_\nu/\omega\mu_0)\int\int E_\nu E_\nu^* \mathrm{d}x\mathrm{d}y$, where $\Delta\varepsilon_G$ describes the amplitude of the dielectric constant changes within the grating and E_ν is a transverse distribution of the ν-th mode electric field. When the grating constant

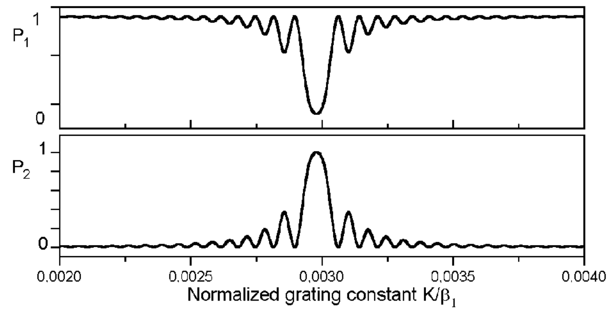

Fig. 2. Output power in the first and in the second waveguide as a function of the normalised grating constant.

is matched to the guided modes propagation vectors difference, $K = \beta_1 - \beta_2$, the periodic power exchange between modes occurs. The complete switching from one waveguide to another is obtained at a distance $L = \pi/2G_{\mu\nu}$ [1]. The above relation allows us to estimate the amplitude of the refractive index grating necessary to obtain a transfer of light in the coupler with chosen parameters. The output power distribution strongly depends on the grating constant. Figure 2 presents this relation for the optimal grating amplitude.

3. Dynamics of the grating

For high frequency external waves the main photorefractive mechanism in MQW layer relays on the interband excitation of electrons and holes, their movement due to the drift and diffusion and finally a recombination to the donor traps. The resulting space-charge electric field causes the change of the refractive index due to the electro-optic effect. Assuming that the planes of MQW are perpendicular to the x-axis and the electric field is applied along the z-axis the following equations based on a classical Kukhtarev–Vinetskii model [8] can be derived:

$$\frac{\partial n_{\mathrm{e}}}{\partial t} = \frac{\alpha}{h\nu} I - \gamma_{\mathrm{e}} n_{\mathrm{e}} N_{\mathrm{D}}^{+} + \frac{1}{e}\frac{\partial j_{\mathrm{e}}}{\partial z}, \tag{4a}$$

$$\frac{\partial n_{\mathrm{h}}}{\partial t} = \frac{\alpha}{h\nu} I - \gamma_{\mathrm{h}} n_{\mathrm{h}} (N_{\mathrm{D}} - N_{\mathrm{D}}^{+}) - \frac{1}{e}\frac{\partial j_{\mathrm{h}}}{\partial z}, \tag{4b}$$

$$j_{\mathrm{e}} = e\mu_{\mathrm{e}} n_{\mathrm{e}} E + \mu_{\mathrm{e}} k_{\mathrm{B}} T \frac{\partial n_{\mathrm{e}}}{\partial z}, \tag{4c}$$

$$j_{\mathrm{h}} = e\mu_{\mathrm{h}} n_{\mathrm{h}} E - \mu_{\mathrm{h}} k_{\mathrm{B}} T \frac{\partial n_{\mathrm{h}}}{\partial z}, \tag{4d}$$

$$\frac{\partial N_{\mathrm{D}}^{+}}{\partial t} = \gamma_{\mathrm{h}} n_{\mathrm{h}} (N_{\mathrm{D}} - N_{\mathrm{D}}^{+}) - \gamma_{\mathrm{e}} n_{\mathrm{e}} N_{\mathrm{D}}^{+}, \tag{4e}$$

$$\frac{\partial E}{\partial z} = \frac{e}{\varepsilon\varepsilon_0}(N_{\mathrm{D}}^{+} + n_{\mathrm{h}} - n_{\mathrm{e}} - N_{\mathrm{A}}). \tag{4f}$$

The symbols in the above equations are: n_{e} — the free electron and n_{h} — the free hole concentrations, N_{D} — donors, N_{D}^{+} — ionised donors and N_{A} — acceptors concentrations, j_{e} — the electronic and j_{h} — the hole current densities, E — the total electric field ($E = E_0 + E_{\mathrm{sc}}$, where E_{sc} is a space-charge field and E_0 is an external field), I — the light intensity, γ_{e} and γ_{h} — the constants describing recombination of electrons and holes, μ_{e} — electron and μ_{h} — hole mobilities along the quantum wells, ε_0 — the permittivity of the vacuum, ε — the effective dielectric constant of MQW structure, e — the absolute value of the elementary charge, k_{B} — the Boltzmann constant and T — the absolute temperature. Thermal excitation of the carriers and transverse carrier mobility are not included in the above set of equations. The later condition is fulfilled due to the high difference between longitudinal and transverse carrier mobilities.

The example calculations were performed for the coupler with a photorefractive layer consisting of 75-Å-GaAs wells and 100-Å-$\mathrm{Al_{0.3}Ga_{0.7}As}$ barriers. The MQW structure, in accordance with previous studies [8, 9] was simulated by a strongly anisotropic homogeneous semiconductor with the parallel mobilities of the carriers much higher than the perpendicular ones. An efficient operation of the coupler is possible with high frequency external waves writing the grating and lower frequency guided modes reading it. The wavelengths ($\lambda_{\mathrm{ex}} = 630$ nm and $\lambda_{\mathrm{g}} = 845$ nm) were chosen on the basis of the spectral dependence of the absorption and electro-refraction coefficients presented in Fig. 3. Absorption curves consist of Gaussian peaks for light hole and heavy hole absorption and continuum contribution from absorption to free electron–hole pairs [10, 11] calculated in the presence of an external electric field and without the field.

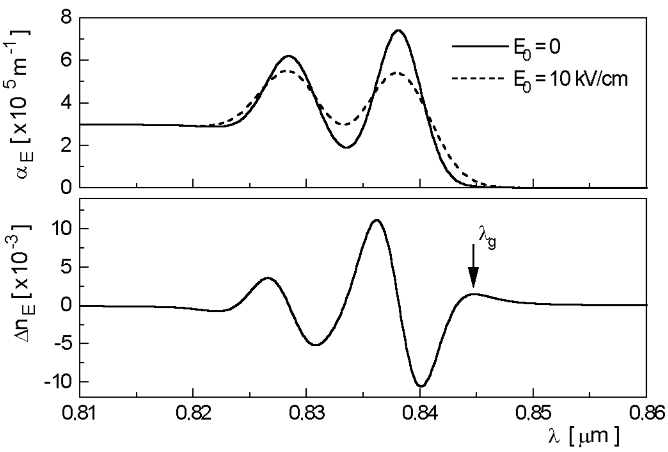

Fig. 3. Spectral dependence of absorption and electro-refraction.

The change of the refractive index, $\Delta n_E(\lambda)$, due to the absorption changes caused by the quantum confined Franz–Keldysh effect was calculated using Kramers–Krönig relations [12]. The parameters used in these calculations were taken from the paper of Wang et al. [13].

The propagation constants and field profiles of the modes for the chosen λ_g were determined using the effective index method and the transfer matrix approach [7]. The resulting grating amplitude necessary for transfer signals between the waveguides in the designed coupler (consisting of two 0.4-μm-high rib $Al_{0.5}Ga_{0.5}As$ waveguides of widths 0.4 μm and 0.7 μm separated by 0.6-μm-strip of AlAs and placed on MQW layer) is $\Delta n = 2.25 \times 10^{-4}$ per 1 cm of the device length and fringes spacing is $\Lambda = 84.5$ μm. Under the steady state conditions

$$\frac{\partial n_e}{\partial t} = \frac{\partial n_h}{\partial t} = \frac{\partial N_D^+}{\partial t} = 0. \tag{5}$$

The solutions of the equations can be approximated by

$$n_e(z) = n_{e0} + n_{e1} \exp(ikz), \tag{6a}$$

$$n_h(z) = n_{h0} + n_{h1} \exp(ikz), \tag{6b}$$

$$N_D{}^+(z) = N_{D0}^+ + N_{D1}^+ \exp(ikz), \tag{6c}$$

$$j_e(z) = j_{e0} + j_{e1} \exp(ikz), \tag{6d}$$

$$j_h(z) = j_{h0} + j_{h1} \exp(ikz), \tag{6e}$$

$$E_{sc}(z) = E_0 + E_1 \exp(ikz), \tag{6f}$$

where n_{e0}, n_{h0}, N_{D0}^+, j_{e0}, and j_{h0} describe the corresponding average values. The amplitudes of the exponential factors can have real and imaginary parts so that the solutions may have an arbitrary phase shifts comparing with the intensity pattern. According to [8] the space-charge field in a steady state for $\gamma_e = \gamma_h = \gamma$ is of the form

$$E_1 = 2m(A - iB)/(C + iD), \tag{7}$$

where

$$A = E_D(E_{Mh} - E_{Me}), \quad B = E_0(E_{Mh} + E_{Me}),$$

$$C = E_0/E_q(E_{Mh} - E_{Me}),$$

$$D = [E_D^2 + E_0^2 + E_D(E_{Mh} + E_{Me}) + 2E_q(E_{Mh} + E_{Me} + E_D)]/E_q,$$

$$E_{Me} = \gamma N/(4\mu_e k), \quad E_{Mh} = \gamma N/(4\mu_h k),$$

$$E_q = eN/(4k\varepsilon), \quad E_D = (k_B T/e)k.$$

The dependence of the space-charge field on the trap concentration is presented in Fig. 4a and on the intensity of the applied electric field in Fig. 4b.

The set of time dependent equations (4) was solved numerically for the initial conditions $E_0 = 10^6$ V/m and $N_D^+(0) = N_A = N_D/2$, trap density $N_D = 10^{23}$ m^{-3}, absorption coefficient $\alpha_{ex} = 10^5$ m^{-1} and other parameters as in [8]. The evolution of space-charge field depends on the energy of absorbed light per a unit of couplers

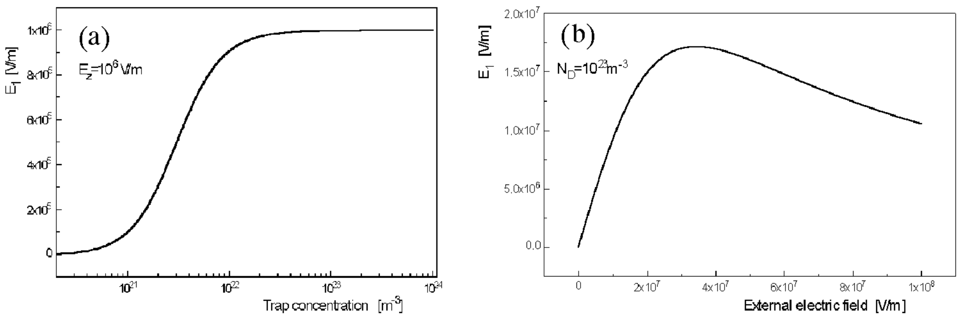

Fig. 4. Approximate analytical solutions for the space-charge field in the steady state (a) in dependence of trap concentration N_{D} and (b) in dependence of the applied electric field intensity E_0 for $N_{\mathrm{D}} = 10^{23}$ m^{-3}.

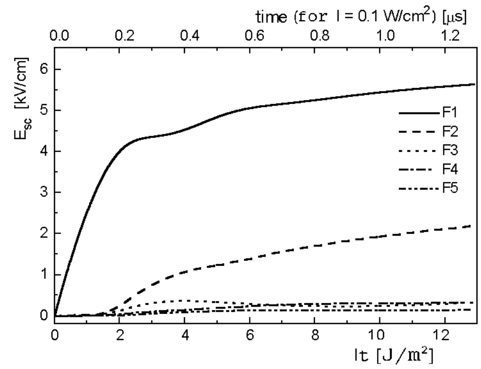

Fig. 5. The first five Fourier components of space-charge field as functions of external waves energy per square meter (bottom axis) and their dependence on time for continuous waves of intensity $I = 0.1$ W/cm^2 (top axis).

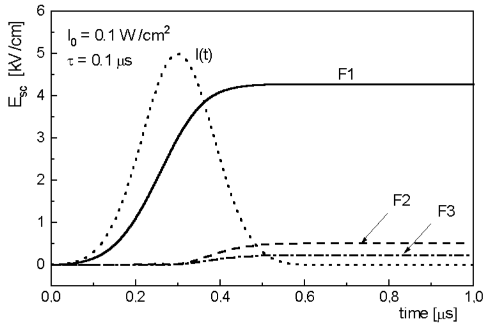

Fig. 6. The time evolution of the first three Fourier components of the space-charge field for a short pulse of external waves, $I = I_0 \exp[-(t - t_0)^2/2\tau^2)]$.

surface. Figure 5 presents the space-charge field dependence on external waves energy per square meter (bottom axis) and its evolution in time for continuous waves of intensity $I = 0.1$ W/cm^2 (top axis). The evolution of the space-charge

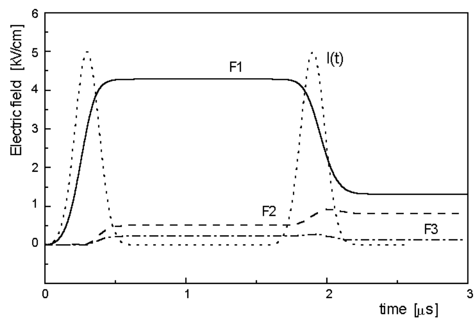

Fig. 7. The time evolution of the first three Fourier components of the space-charge field for two pulses. The first one consisting of two interfering beams and the second one being a single uniform beam.

field generated by the short pulse of light is presented in Fig. 6. The grating life-time depends mainly on the materials dark conductivity and in the absence of free carriers can be very long. The time evolution of the space-charge field for two pulses, the first one consisting of two interfering beams and the second one being a single uniform beam, is presented in Fig. 7.

The refractive index changes in the semi-insulating MQW structures are given by $\Delta n(E) = (-1/2)n_0^3 sE^2$, where s is a quadratic electro-optic coefficient [7] and E — the total electric field. According to our calculations the s coefficient due to the Franz–Keldysh effect for $\lambda_g = 845$ nm is in the range of 7×10^{-13} cm^2/V^2. Hence the achieved electric field causes an index change of about 3×10^{-4} and can provide a switching in a 0.8-cm-long device.

5. Conclusions

It has been shown that a thin photorefractive grating in semi-insulating MQW material can be used to control an asymmetric directional coupler. A choice of the output guide and of the wavelength of the switched signals depends on the grating parameters and can be varied during the work of the device. The grating does not require a permanent presence of the external waves. Pump pulses are necessary only for writing, refreshing or erasing the grating. Signal waves at low frequency do not destroy the grating which makes a potential application of the system as an all-optical switching element with memory possible. The switching time of the coupler depends on the intensity of the external waves and can be below 0.1 μs which allows potential applications for routing groups of signals.

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