Optical and Quantum Electronics (2019) 51:368
https://doi.org/10.1007/s11082-019-2090-7

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Two-frequency laser with distributed feedback formed by a space charge wave

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Received: 14 August 2019 / Accepted: 22 October 2019 / Published online: 31 October 2019

Abstract
The regimes of amplification and generation of optical TE waves arising on a grating formed by a space charge wave (SCW) in a plane optical waveguide based on an n-GaAs semiconductor are considered. For the perturbed n-GaAs waveguide, the reflectance and transmittance of TE modes with the same indices ($m=n=0$) are calculated depending on the pump level and length of interaction between the optical and SCWs. It is shown that even with a relatively small depth of modulation of the dielectric constant ($\Delta\varepsilon \approx 10^{-5}$) under conditions of high optical pumping (with an amplification factor $\gamma \approx 150$ cm^{-1}) and corresponding SCW-optical interaction length, there is a possibility of not only amplification, but also generation of forward and backward optical modes at a wavelength of 10.6 μm. The results can be used to create tunable semiconductor laser generators based on the SCW-optical interaction and operating in the near and mid-IR range.

Keywords Semiconductor waveguide · Space charge wave · Laser generation · GaAs

1 Introduction

Space charge waves (SCW), or spatiotemporal perturbations of charge density, arise in semiconductors with negative differential mobility in strong electric fields (Barybin 1986; Shur 1987). The SCW propagation velocity is close to the carrier drift velocity, which makes it possible to use them to create thin-film traveling-wave amplifiers and active transmission lines implemented in semiconductor films (Barybin et al. 1979; Dean and Matarese 1972). It is known that in piezoelectric semiconductors SCWs are generated by sound waves and can have a significant effect on light diffraction (Proklov et al. 1972). The deviation of the concentration of free charge carriers n_1 from the equilibrium concentration n_0, arising during the propagation of an SCW in a crystal, leads to a periodic change in the dielectric permittivity with a modulation depth sufficient for effective SCW-optical interaction. The diffraction efficiency of the interaction increases in proportion to the square of the wavelength of light as its frequency approaches the plasma frequency, and therefore is most significant in the middle and far infrared range, as well as in the terahertz region

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(Proklov et al. 1974). The formation of the electron grating can be carried out in semiconductor structures based on n-GaAs or n-InSb in the predomain mode under conditions of the Gunn effect.

The theory of SCW and an effective method of their excitation, based on the illumination of the crystal by a traveling interference pattern, was considered in (Bryksin et al. 2003). In papers (Barybin and Mikhailov 2000; Chaika et al. 1996) the diffraction of light by an SCW in bulk crystals of a semiconductor is considered. In the series of works (Sannikov and Sementsov 2006a, b, 2007a, b) an analysis of the dispersion properties of an SCW in a semiconductor (gallium arsenide) waveguide is made and the possibility of effective collinear interaction of optical waveguide modes with traveling and amplifying in amplitude SCW under various boundary conditions is shown. The GaAs semiconductor and its compounds is one of the main materials for injection laser waveguides operating at the near infrared region of wavelengths (0.85–1.7 μm) (Svelto 1998). Recently, the direction associated with the creation of optical parametric generators with tunable in a wide range (middle IR and terahertz ranges) radiation wavelength using well-developed diode, solid-state and fiber lasers operating in the near infrared region has been successfully developing recently. They are based on nonlinear elements consisting of regular domain heterostructures in GaAs (orientation-patterned, or OP-GaAs) (Eyres et al. 2001; Vodopyanov et al. 2004, 2006). Such structures consist of alternating regions laterally located on the GaAs plate—domains that are situated at right angles relative to each other in the plane of the surface of the structure (Kazakov et al. 2017). In (Wueppen et al. 2016) it is reported that an optical parametric generator was created with OP-GaAs as a nonlinear medium and a 1.95 μm pulsed-pumped laser, which generates an idle wave at the output of about 10.6 μm. The disadvantage of such schemes is their bulkiness and the impossibility of tuning parameters of the OP element.

In this article, we study the conditions for amplification and generation of TE-type optical waves in an n-GaAs waveguide due to an SCW, which forms a periodic tunable grating and provides distributed feedback for the forward and backward waves with frequencies ω_{m} and ω_{n} corresponding to a wavelength of 10.6 μm. Unlike works (Sannikov and Sementsov 2007a, b), where an SCW amplifying in amplitude was used, we consider a traveling SCW without amplification and absorption and the case of external optical pumping. The conditions of phase mismatch and pumping are analyzed, which ensure the generation of forward and backward optical waves without end reflectors in the generation structure.

2 Statement of the problem and basic relations

The structure is formed by an optical waveguide consisting of a substrate (medium 1), a semiconductor film (medium 2) with a thickness t_{WG}, and a cover medium (medium 3) with permittivities $\varepsilon_j = n_j^2$ (j=1, 2, 3). The x-axis is perpendicular to the interface, the SCW and optical waves propagate along the z-axis. A constant electric field E_0 is applied to the waveguide section L, which, in the Gunn generation suppression regime, provides the appearance of a low-signal periodic inhomogeneity, i.e. SCW. Transparent materials such as, e.g. InGaBiAs: Si (Zhong et al. 2013) can be used as electrodes for creating the field (see Fig. 1).

The problem can be divided into two parts: the "solid state" part, associated with the description of the SCW, and the "optical" part, associated with the interaction of optical modes. It is known that in order to implement the SCW generation regime in a semiconductor

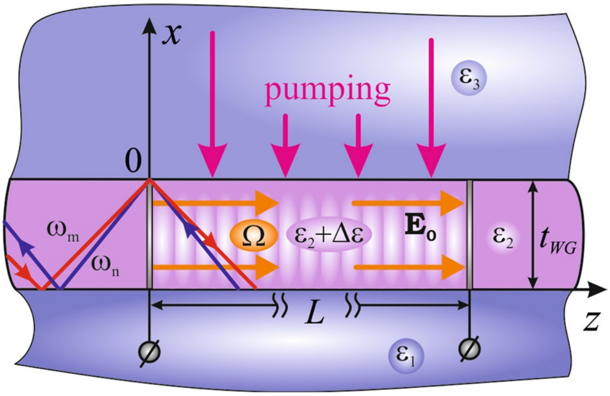

Fig. 1 Geometry of the structure. The interaction of the forward and backward optical waves and the SCW with the corresponding frequencies ω_m, ω_n and Ω

layer, the Kroemer condition has to be fulfilled (Shur 1987), which for GaAs has the form $10^{10} \le n_0 L \le 10^{12}$ cm^2, where n_0 is the equilibrium concentration of carriers, L is the length of the interaction region (Carroll 1970). By choosing the doping level of the waveguide layer, its length and thickness, and the value of the applied field E_0, which in n-GaAs should exceed the threshold value $E_t \approx 3$ kV/cm, it is possible, without going into the Gunn domain mode, to obtain a low-signal periodic inhomogeneity in the form of an electron grating formed by SCW (Chaika et al. 1996; Shur 1987).

The propagation of SCWs in the quasistatic approximation (rot $\mathbf{E}_1 = 0$) is described by the dispersion equation relating the parameters of the semiconductor layer with the frequency Ω and propagation constant Q (Sannikov and Sementsov 2006b; Shur 1987)

$$DQ^2 + i(\Omega - Qv_0) + \mu_d \omega_m = 0, \tag{1}$$

where $\mu_d = \mu_0^{-1}(dv/dE)$ is the negative (reduced) differential mobility, μ_0 is the mobility of "unheated" electrons, $\omega_m = 4\pi e n_0 \mu_0/\varepsilon_2$ is the Maxwell relaxation frequency corresponding to the time of electroneutrality loss of the semiconductor, e is the electron charge, v_0 is the drift velocity of the "hot" carriers. Two solutions of Eq. (1) correspond to forward (drift) and backward (diffusion) SCW. It is known (Barybin 1986), that the backward wave attenuates rapidly, therefore, further we consider only the forward SCW running along the z-axis without amplification, which creates a perturbation of permittivity. As can be seen from Eq. (1), the condition for the propagation of an SCW without absorption (or amplification) is satisfied at a frequency

$$\Omega = v_t Q = v_t \sqrt{-\mu_d \omega_m / D}, \tag{2}$$

where D is the diffusion coefficient. In this case, the coordinate dependence of the SCW-disturbance of permittivity in the semiconductor layer can be represented by the function:

$$\Delta\varepsilon(z) = \frac{1}{2}\Delta\varepsilon\{\exp[i(\Omega t - Qz) + c.c.\}. \tag{3}$$

As was shown in (Chaika et al. 1996; Sannikov and Sementsov 2006b), the permittivity modulation depth in the waveguide film

$$\Delta\varepsilon(x) = \Delta\varepsilon \approx \left| e\varepsilon_2 E_1 Q / m^* \omega^2 \right|, \tag{4}$$

where E_1 is the amplitude of the perturbing electric field in the semiconductor in the predomain mode, m^* is the effective mass of the electron, ω is the frequency of light. Numerical estimates of the value of Δε for a crystal (n-GaAs) at an optical wavelength $\lambda = 10.6$ μm at $m^* \approx 0.0063 m_0$ ($T = 300$ K), where m_0 is the mass of free electrons, $\varepsilon_2 \approx 12$, $E_1 \approx 300$ V/cm ($E_1 \ll E_0$) give values of $\Delta\varepsilon \approx 10^{-5}$. At a sufficiently high amplification level (of the order of hundreds cm^{-1}), this allows lasing to be performed, which will be shown below.

For the optical TE modes (H_x, E_y, H_z) of the waveguide under consideration, the electric field in the transverse direction (profile function) is given by the expression (Hunsperger 2009; Yariv 1989)

$$E_{ym}(x) = C_m \cdot \begin{cases} \exp(-qx), & x \geq 0, \\ \left[\cos hx - \frac{q}{h} \sin hx\right], & -t_{WG} \leq x \leq 0, \\ \left[\cos ht_{WG} + \frac{q}{h} \sin ht_{WG}\right] \exp[p(x + t_{WG})], & x \leq -t_{WG}. \end{cases} \tag{5}$$

Here the transverse components of the wave vector in each of the three layers are $p^2 = \beta_m^2 - k_0^2\varepsilon_1$, $h^2 = k_0^2\varepsilon_2 - \beta_m^2$ and $q^2 = \beta_m^2 - k_0^2\varepsilon_3$, where $k_0 = \omega/c$ is the wave number, β_m is the propagation constant and c is the speed of light. Without loss of generality, we restrict ourselves to considering the case of TE modes, which usually have higher coupling coefficients than TM modes (Streifer et al. 1976). The constant C_m is determined from the condition for the power normalization of the m-th order mode in the structure:

$$\frac{\beta_m c a_y}{8\pi k_0} \int_{-\infty}^{\infty} \left[E_{ym}(x)\right]^2 dx = P_0, \tag{6}$$

where $a_y = 1$ cm is the length along the y-axis corresponding to unit power ($P_0 = 1$ erg/s) carried by the mode. The dispersion equation for TE modes of a 3-layer unperturbed waveguide in the general form (see, e.g. Adams 1981; Hunsperger 2009):

$$\tan[h\, t_{WG} - \pi m] - \frac{(q + p)h}{h^2 - pq} = 0 \tag{7}$$

allows one to find the effective refractive index of the m-th waveguide mode $n_m^* = \beta_m / k_0$.

In order to obtain amplification, a forward optical wave can be introduced into the waveguide (from outside the interaction region L) using prism or grating coupling elements that allow the selective excitation the m-th waveguide mode by changing the incidence angle of the laser beam. Similarly, we can carry the backward wave (amplified or generated) out of the structure. The frequencies of the forward and backward optical waves and the SCW moving along the z-axis are related by $\omega_{\mathrm{m}} = \omega_{\mathrm{n}} + \Omega$. Using the theory of coupled modes (Nakamura et al. 1973), for a periodic perturbation of permittivity of the form (3), one can write the coupling coefficient for waveguide TE modes with the same indices ($m = n$):

$$\kappa_{mm} = \frac{a_y \omega \Delta\varepsilon}{32\pi P_0} \int_{-t_{WG}}^{0} E_{ym}^2(x)\, dx. \tag{8}$$

The system of coupling equations for guided counterpropagating modes of a perturbed waveguide in the presence of amplification γ (cm^{-1}) has the form:

$$
\begin{aligned}
dA/dz &= -i\,\kappa_{mm}B\exp[2i\Delta\beta z] + \gamma A,\\
dB/dz &= i\,\kappa_{mm}A\exp[-2i\Delta\beta z] - \gamma B.
\end{aligned}
\tag{9}
$$

Here, the dimensionless amplitudes $A(z)$ and $B(z)$ correspond to optical modes traveling in the forward and backward directions, respectively, and $2\Delta\beta = 2\beta_m - Q$ is the propagation constants detuning. The wave number of the SCW is inversely proportional to the grating period Λ, i.e. $Q = 2\pi/\Lambda$. Introducing an auxiliary parameter $S = \sqrt{\left|\kappa_{mm}\right|^2 + (\gamma - i\Delta\beta)^2}$, one can write down the energy coefficients of reflection and transmission of modes in the waveguide in the form (Yariv 1976, 1989):

$$
\begin{aligned}
R &= \left|\frac{\kappa_{mm}\sinh SL}{(\gamma - i\Delta\beta)\sinh(SL) - S\cosh(SL)}\right|^2,\\
T &= \left|\frac{S}{(\gamma - i\Delta\beta)\sinh(SL) - S\cosh(SL)}\right|^2.
\end{aligned}
\tag{10}
$$

Note that these relations correspond to the reflection and transmission coefficients of waves in a corrugated waveguide laser and allow one to study the conditions for the generation of corresponding waves in the case of SCW-optical interaction. Due to the pumping in the waveguide film, the section of the waveguide plays the role of an amplifier for reflected and transmitted waves.

3 Numerical analysis and discussion

For the numerical analysis of the SCW-optical interaction, the structure parameters at room temperature $T = 300$ K were selected. An n-GaAs film was chosen as the guiding layer with the refractive index dispersion (Skauli et al. 2003)

$$
n_2(\lambda) = \sqrt{5.372514 + \frac{5.466742\ \lambda^2}{\lambda^2 - 0.4431307^2} + \frac{0.0242996\ \lambda^2}{\lambda^2 - 0.8746453^2} + \frac{1.957522\ \lambda^2}{\lambda^2 - 36.9166^2}},
\tag{11}
$$

where λ is the current wavelength in μm. The $Al_xGa_{1-x}As$ (x = 0.7) semiconductor substrate and covering layer have a refractive index of $n_1 \approx 3$ and relatively low losses in the working region of wavelengths of 1–11 μm (Adachi 1989). The concentration of free carriers in the n-GaAs film is $n_0 = 10^{13}$ cm^{-3}, length $L = 0.1$ cm, i.e. product $n_0L = 10^{12}$ cm^{-2} gives a threshold value at which the domain-type instabilities does not yet develop in the waveguide. Mobility of "unheated" electrons $\mu_0 = 10^4$ $cm^2/(V\ s)$, electron drift velocity $v_l = 2 \cdot 10^7$ cm/s, diffusion coefficient $D = 207$ cm^2/s (Blakemore 1982); static electric field $E_0 = 4.9$ kV/cm, perturbing field $E_1 \approx 490$ V/cm. An approximate formula from the monograph (Shur 1987), describing the experimental dependence for GaAs in the framework of the two-valley Ridley–Watkins–Hilsum model (Ridley and Watkins 1961), was used to obtain the differential mobility $\mu_d \approx -0.324$.

Figure 2 shows the dependences of the effective refractive indices $n_m^* = \beta_m/k_0$ (Fig. a) and coupling coefficients (Fig. b) on the waveguide film thickness for pairs of the same indexed (for the forward and backward waves) TE modes of the first three orders

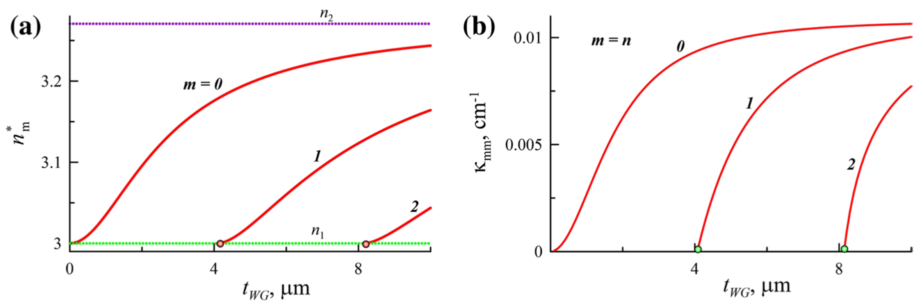

Fig. 2 Dependences of the effective refractive indices of TE modes (**a**) and coupling coefficients (**b**) for TE modes of the same order ($m = n$) on the thickness of the waveguide layer of an n-GaAs waveguide ($\lambda = 10.6$ μm)

($m = n =$ 0, 1 and 2). Due to the symmetry of the waveguide, the zero-order mode has no cutoff (Adams 1981; Hunsperger 2009), the region of existence of effective refractive indices is determined by the difference in the values of asymptotes $n_1 = 3$ and $n_2(\lambda)$. A sufficiently large thickness of the guide film $t_{WG} = 10$ μm allows one to use the coupling of the forward and backward modes of the order of $m = 0$ at a wavelength of 10.6 μm on one hand, and to stabilize the SCW distribution along the film, avoiding the formation of a strong field domain on the other hand (Barybin et al. 1979). Note that to maintain the stability of the SCW, additional measures may be required such as, for example, matching of load resistance (Shur 1987).

It can be seen from Fig. 2b that near the cutoff, the mode coupling coefficients increase rapidly, and when shifted to the large film thicknesses region, growth of κ_{mm} slows down. For any given thickness, the modes with the index $m = n = 0$ have the highest coupling coefficient, and for a guide film of maximum thickness, the value of κ_{00} is 0.01 cm^{-1}.

Further, to analyze the amplification and generation regimes, isolines or contours of equal gain factors were constructed for the backward TE_0 mode $R = |E_r(0)/E_i(0)|^2$ (coupled with the incident TE_0 mode) (Fig. 3a) and for the forward TE_0 mode $T = |E_i(L)/E_i(0)|^2$ (Fig. 3b) depending on the interaction length L and the level of the external optical pumping γ. The electric fields amplitudes $E_r(0)$, $E_i(0)$ and $E_i(L)$ correspond to the backward

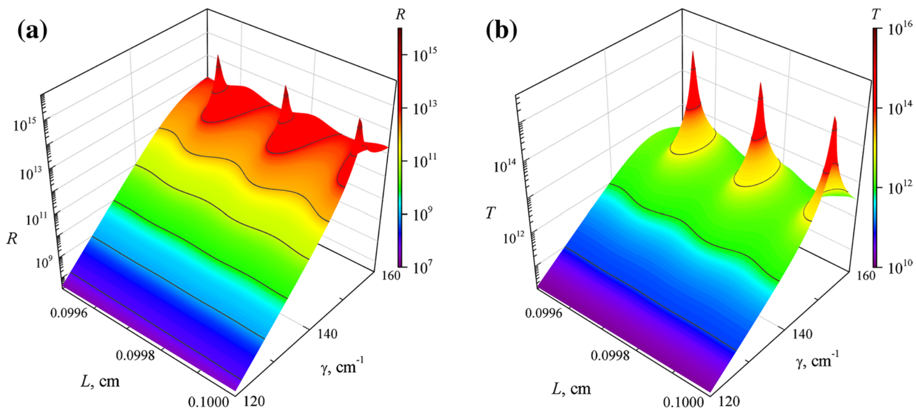

Fig. 3 Contours of equal gain of the backward (**a**) and forward (**b**) TE modes ($n = 0$) in the $L - \gamma$ plane; wavelength $\lambda = 10.6$ μm, film thickness $t_{WG} = 10$ μm, SCW perturbation field $E_1 = 490$ V/cm, detuning $\Delta\beta \approx 1.7$ cm^{-1}

Table 1 The values of the waveguide and radiation parameters, allowing the realization of SCW–optical coupling and laser generation of the forward and backward modes

Film doping level n-GaAs n_0 (cm^{-3})	Film thikness t_{WG} (μm)	Interaction length L (μm)	Pump level γ (cm^{-1})	Propagation constants detuning $\Delta\beta$ (μm^{-1})	Intermode coupling coefficient κ_{00} (cm^{-1})
10^{13}	10	1000	150	1.7	0.01

wave at the beginning of the perturbed region, the forward wave at the beginning and at the end of the interaction region, respectively.

It follows from Fig. 3 that the singularity points at which the values of the coefficients R and T exceed 10^{14} correspond to the three generated modes. Each subsequent laser mode emerges with an increase in the length of the region L by approximately 1 nm. In this case, the required level of optical pumping is about 150 cm^{-1}. Thus, laser modes in the structure under consideration can be generated by SCW-optical interaction without the participation of end reflectors.

The characteristics of the prototype waveguide resonator, in which generation at a wavelength of 10.6 μm can be achieved, are given in Table 1.

Note that a sufficiently high level of pumping is required, because of the small depth of permittivity modulation (in this case, $\Delta\varepsilon \approx 2.4 \cdot 10^{-5}$) on the one hand, and because of the noticeable mismatch of the propagation constants $2\Delta\beta = 2\beta_m - Q$ on the other hand. Nevertheless, the obtained value of γ is comparable with the value of the threshold amplification level ($\gamma \approx 100$ cm^{-1}) in corrugated waveguide lasers (Yariv 1989; Yariv and Yeh 2007), and the advantage of the considered waveguide structure is the ability to control the parameters of the SCW-grating.

4 Conclusions

During the analysis, the conditions for amplification and generation of difference synchronized optical radiation in a semiconductor waveguide based on n-GaAs were found. The reflectance and transmittance (gain coefficients) for pairs of counterpropagating TE modes with the same indices ($m = n = 0$), which have the highest coupling coefficient at the selected wavelength ($\lambda = 10.6$ μm), are studied. The advantage of the proposed scheme compared to a corrugated waveguide laser is the presence of a controlled SCW-grating. Tuning of the difference frequency of the SCW can be done by choosing the degree of doping of the semiconductor, changing the amplitude and polarity of the external electric field E_0, as well as the temperature regime. The results can be used to create tunable semiconductor laser emitters based on SCW-optical interaction.

Acknowledgements This work was supported by the Ministry of Education and Science of the Russian Federation [Grant No. 3.8154.2017/BP (I.P., D.S),] and Russian Fund of Fundamental Research No. 18-29-19101 (I.P., I.Z).

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