Generation of optical pulses due to phase modulation of surface electromagnetic wave in a cylindrical semiconductor waveguide with a space charge wave

Aleksei Abramov[a*], Aleksei Kadochkin[a], Sergey Moiseev[a,b], D. Sannikov[a], A. Fotiadi[a,c]

[a]Ulyanovsk State University, 42 Leo Tolstoy str., Ulyanovsk, Russia
[b]Kotelnikov Institute of Radioengineering and Electronics of the Russian Academy of Sciences, Ulyanovsk Branch, 48/2 Goncharov Str., Ulyanovsk, Russia
[c]Electromagnetism and Telecommunication Department, University of Mons, Mons, B-7000, Belgium

* e-mail: aleksei__abramov@mail.ru

ABSTRACT

The amplification and phase modulation of a surface electromagnetic wave propagating along a helical trajectory in a cylindrical semiconductor waveguide under the condition of phase matching with a longitudinal space-charge wave are considered. The evolution of a phase-modulated electromagnetic wave after passing through a semiconductor waveguide is studied and the conditions leading to the transformation of an initially stationary wave into a sequence of optical pulses with a terahertz repetition rate are determined.

Keywords: semiconductor cylindrical waveguide, space-charge wave (SCW), modulation instability, generation of frequency-modulated pulses

1. INTRODUCTION

Generators of a broadband optical combs are of great interest for many technical applications as a high-frequency laser system that make it possible to obtain sequences of ultrashort pulses. A standard frequency comb is a set of coherent narrow laser lines. Spectrum lines are equidistant from each other, and the central spectral line characterized by maximum brightness. The field of practical application of comb spectrum generators is wide. It includes an optical communication, spectroscopy, metrology, microwave photonics, etc. [1,2]. The sources for generating the frequency comb are fiber soliton lasers with harmonic mode locking [3,4]. In this work, to obtain an optical frequency comb, it is proposed to use a semiconductor cylindrical waveguide based on n-GaAs with a space charge wave (SCW) propagating in its bulk. We consider the conditions under which the input radiation is converted into modes of whispering gallery. Such modes propagate along a cylindrical helical line with a small step, and the speed of their movement along the axis of the waveguide can be close to the value of the drift velocity of the current created by the electrical potential difference applied to the ends of the waveguide. The gain achieved in this waveguide is determined by the efficiency of energy transfer from the electric current wave the electromagnetic (EM) wave in the waveguide [5,6]. The interaction of an initial continuous EM wave and SCW leads to the formation of an EM pulse sequence. This transformation can be used to develop pulse generators based on the physical principles different from the known methods of nonlinear optics [7-10].

2. MAIN EQUATIONS

We consider the interaction of a spirally propagating surface EM wave and an alternating drift current in a cylindrical GaAs-waveguide (see Figure 1). The EM wave (laser beam) is introduced through a prism into a cylindrical waveguide at a small angle. The EM wave is output through a second prism located at some distance from the first prism. Small input angles provide a significant reduction in the speed of the EM wave transfer along the waveguide axis. The drift velocity of charge carriers in a semiconductor sample based on n-GaAs depends on the external electric field strength

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and is well described within the Ridley-Watkins-Hilsum model [11]. The SCW occurs in the bulk of the semiconductor at high applied electric field strengths [12,13].

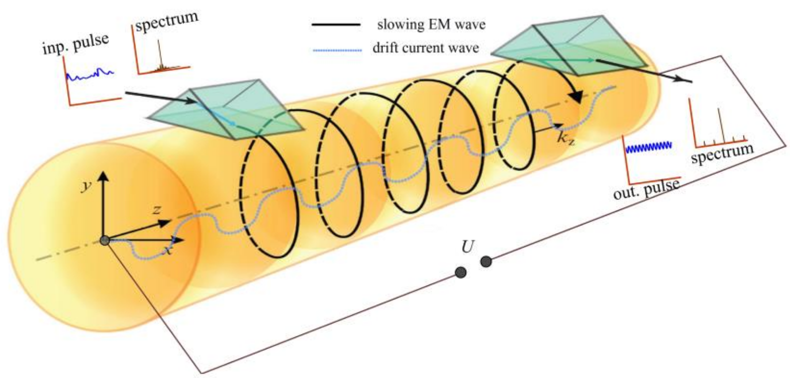

Figure 1. The cylindrical waveguide for comb spectrum generation.

The SCWs are characterized by a frequency Ω and a wave number q which are related to its phase velocity as $v_{scw} = \Omega / q$. The concentration of nonequilibrium carriers in the SCW is described by expression

$$N(\Omega, t) \approx N_0 \left[1 + \kappa \cos(\Omega t - qz)\right], \tag{1}$$

where N_0 is the concentration of free charge carriers in the absence of modulation and $\kappa > 0$ is the depth of current modulation. As a consequence, for the local value of the semiconductor plasma frequency we can write the expression $\omega_p = \omega_{p0}\left[1 + \kappa \cos(\Omega t - qz)\right]^{1/2}$, where $\omega_{p0} = \left(e^2 N_0 / \varepsilon_\infty \varepsilon_0 m_{eff}\right)^{1/2}$ is the «unperturbed» plasma frequency (in the absence of SCW) with the effective mass m_{eff} and concentration of carriers N_0. In the approximation $\gamma_c \to 0$ (γ_c is a relaxation parameter) the refractive index wave of GaAs waveguide is determined by its effective value

$$n_{eff}(z,t) \approx \sqrt{\varepsilon_\infty}\left(1 - \frac{\omega_{p0}^2}{2\omega^2} - \frac{\omega_{p0}^2}{2\omega^2}\kappa \cos(\Omega t - qz)\right) \approx n_0\left[1 + m\cos(\Omega t - qz)\right], \tag{2}$$

where ε_∞ is the dielectric constant of GaAs at high frequencies, n_0 is the refractive index of GaAs in the absence of SCW, $m \approx -\omega_{p0}^2 \kappa \big/ 2\omega^2$ is the refractive index modulation depth. Thus, a propagating SCW can be excited in the bulk of the semiconductor with the refractive index modulation amplitude $\Delta n \approx m n_0$, frequency Ω and phase velocity v_{scw}.

There are various models based on the quasi-hydrodynamic approximation that are used to obtain the relationship between the wave number q and the SCW frequency in n-GaAs thin films [14]. In the one-dimensional case, the dispersion equation for the SCW has the form [13]:

$$i(\Omega - q v_{scw}) + \omega_m \mu_1 + D q^2 = 0, \tag{3}$$

where $\mu_1 = \mu^{-1}(dv/dE)$ is a reduced differential electron mobility, μ is the mobility of «unheated» electrons, ω_m is the Maxwell relaxation frequency, D is the diffusion coefficient. The frequency of the SCW propagating in the waveguide without amplification and losses with phase velocity can be found from Eq. (3):

$$\Omega = v_{scw}\sqrt{-\mu_1 \omega_m / D}. \tag{4}$$

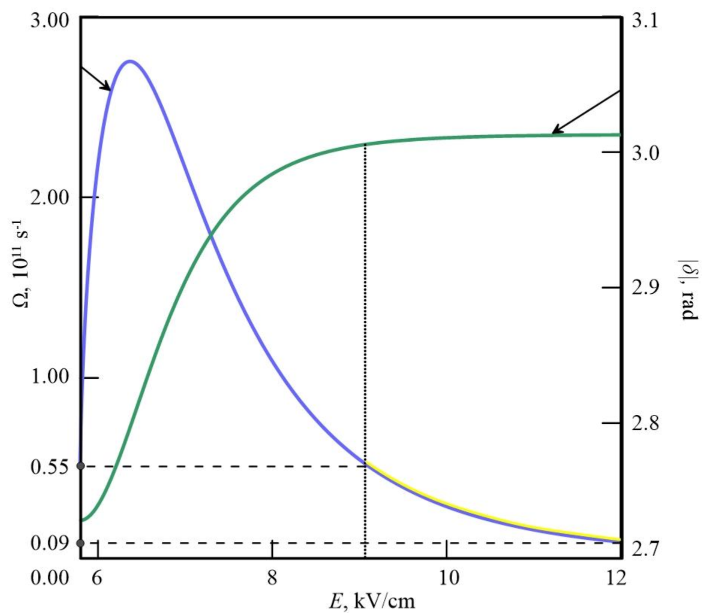

Figure 2. Frequency of modulation of the current wave (blue line) and the phase modulation deep (green line) as functions of the applied electrical field *E*.

In according to Eq. (4) the existence of SCW is limited to the region of negative differential mobility $\mu_1 < 0$, i.e. the region of negative values of the derivative dv / dE .

Figure 2 shows the dependence of the SCW frequency on the applied external field (blue line). Dependence are calculated for the mobility of free charge carriers $\mu = 0.14\ \mathrm{m}^2 / (\mathrm{V{\cdot}s})$. The experimental data for the diffusion coefficient and drift velocity at T = 300 K are taken from the papers [15, 16]. These parameters are functions of the external electric field strength *E*. The phase velocity of the SCW is comparable to the drift velocity of free charge carriers and amounts to $v_{SCW} = \Omega / q' \approx 2 \cdot 10^5$ m/s. The dependence $\Omega(E)$ has a pronounced maximum at field values near $6.4 \cdot 10^5$ V/m.

The interaction between the EM wave propagating along the surface of the cylinder and the SCW in the bulk of the semiconductor waveguide leads to the deep phase modulation of the introduced EM radiation. The amplitude of the modulated radiation at the output of the waveguide is determined by the relation

$$A_s(z = l, t) \approx \sqrt{P_n}\left[1 + \delta_a \cos(\Omega_a t)\right] \exp\left[-i\delta \cos(\Omega t)\right], \tag{5}$$

where $\delta_a << 1$ and Ω_a are the depth and the frequency of amplitude modulation respectively, P_n is the saturation power. The depth of phase modulation at the output of a cylindrical waveguide can be estimated from the relation [17]

$$\delta \approx m n_0 \omega l / 2v_0 \approx -\omega_{p0}^2 l \kappa / 4\omega v_0 \,. \tag{6}$$

Figure 2 also shows the dependence of the absolute value of the phase modulation depth $|\delta|$ (green line) for $n_0 = 3.37$, modulation depth $|m| = 10^{-5}$, carrier frequency $\omega = 2\pi c / \lambda_0 \approx 10^{15}$ s^{-1} and plasma frequency $\omega_{p0} \approx 10^{13}$ s^{-1} . Numerical analysis gives that for the selected parameter values the phase modulation depth takes values in the range from 2.7 to 3.1 radians. This dependence is monotonic, and at large field values it weakly depends on the external field since the drift velocity reaches saturation. Thus, the deep of phase modulation acquired by an EM wave in the field range from 9 to 12 kV/cm can be considered almost constant ($\delta \approx 3$), while the modulation frequency varies in the range from $0.09 \cdot 10^{11}$ to $0.55 \cdot 10^{11}$ s^{-1} (marked yellow color in Figure 2).

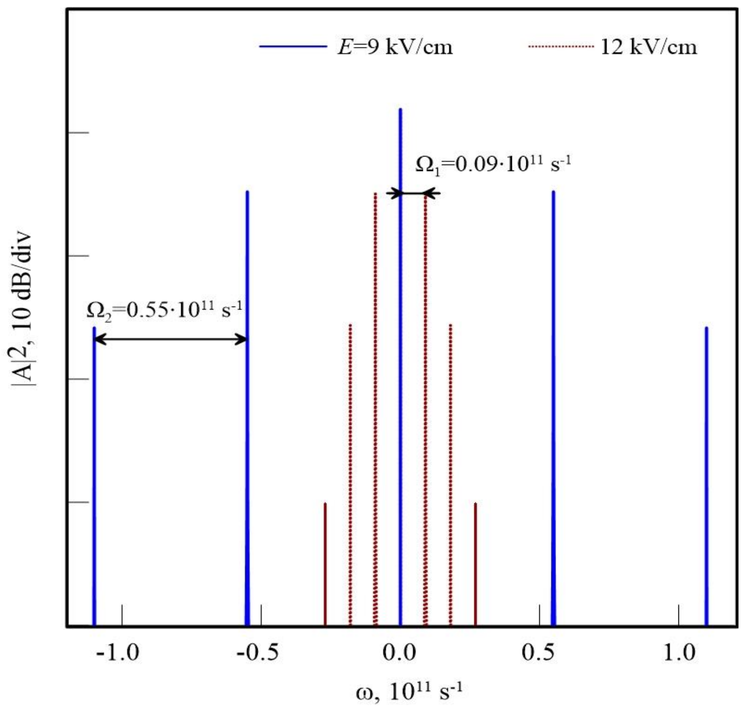

Figure 3. Spectra of output radiation for different value of applied electrical field.

So, the cylindrical semiconductor waveguide ensures the formation of wave packets with deep phase modulation and relatively low amplitude modulation. The spectrum of such radiation has a comb shape (see Figure 3). Its central line is characterized by maximum intensity. Moreover, the phase of the modulated radiation at the output from the resonator is determined by the initial values of both the deep of the current modulation and the modulation frequency. The frequency interval between the generated lines exactly matches the modulation frequency Ω . The width of the line spectrum $\Delta\omega$ is related to the modulation depth and the modulation frequency through the relationship $\Delta\omega \approx |\delta|\Omega$. The spectral lines can be rearranged when the applied external electric field changes. When the applied electric field increases from 9 kV/cm to 12 kV/cm, the frequency interval decreases from $\Omega_2 = 0.55 \cdot 10^{11}$ s^{-1} to $\Omega_1 = 0.09 \cdot 10^{11}$ s^{-1}.

CONCLUSION

We have considered a model of a semiconductor frequency comb generator, which expands the known approach to developing harmonic mode-locked lasers. The key element of the model is a cylindrical GaAs-waveguide, which combines the functions of modulator and power amplifier. The spectrum of the generated pulses consists of spectral lines forming an optical frequency comb. The comb spectrum can be modified by changing the voltage applied to the ends of the waveguide. The obtained results can be used in various fields of spectroscopy, radiophotonics and quantum electronics.

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