Generation of frequency modulated laser pulses in a cylindrical semiconductor structure with a traveling space charge wave

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Abstract

The propagation of a slow surface electromagnetic wave of the whispering gallery mode type formed on the surface of a semiconductor cylindrical waveguide is considered. The dynamic of interaction of circularly propagating electromagnetic radiation at wavelength 1.55 µm with an alternating drift current wave in the bulk of a semiconductor is studied. It is assumed that the drift velocity of charge carriers coincides with the speed of circular surface wave which moves along the axis of a cylindrical waveguide. In this case, it is possible to achieve strong phase modulation of a slow surface wave over a wide range of wavelengths so as, the modulated radiation can be converted into a sequence of short pulses. The peak power of the generated pulses is shown to be orders of a magnitude higher than the average pump power. The length of the optical waveguide at which wave packets are formed is determined by the depth and frequency of light modulation in the semiconductor cylindrical waveguide.

Keywords: semiconductor waveguide, space charge wave, phase modulation, generation of ultrashort pulses.

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Introduction

It is known [1 – 5] that amplification of electromagnetic (EM) radiation in waveguide structures can be achieved through its interaction with drift current. To do this, it is necessary to perform phase matching, i.e. matching the phase velocity of the EM wave and the drift velocity of free charge carriers. A similar regime of EM wave amplification is implemented in a microwave backward wave oscillator [5, 6]. One of the ways to achieve phase matching of waves in a guiding structures is to reduce the phase velocity of the EM wave along the axis of the waveguide. Thus, the regarded regime in a cylindrical waveguide can be realized by introducing radiation at a small angle to the tangent plane of the cylinder. In this case, the surface EM wave can be considered as a whispering gallery mode (WGM) [7]. Note that there are also alternative schemes for introducing radiation into a cylindrical waveguide structure. These schemes assume the presence of a spiral phase plates or binary vortex axicons [8]. In this case the input radiation is a vortex surface plasmon polaritons with amplitude, which depends on radial coordinates of a cylindrical waveguide [9, 10]. Next we will consider the WGM modes.

WGMs propagate along a cylindrical spiral trajectory with a small pitch. The phase speed of WGM along the axis of the cylindrical waveguide can be close to the value of the drift speed of the current formed by the electrical potential difference applied to the ends of the structure. The amplification of WGM in the waveguide is determined by the efficiency of energy exchange between the EM wave and current wave.

In papers [11 – 14] the conditions for the fulfillment of phase matching between a surface EM wave propagating along a helical trajectory and a current wave flowing with the drift velocity of free charge carriers in a cylindrical waveguide were considered. The efficiency of energy transfer to the EM wave was also estimated. In paper [12] a mechanism for direct current amplification of a surface EM wave in a cylindrical waveguide made from doped silicon (indirect gap semiconductor) was proposed. It was noted that an indirect gap semiconductor is not the optimal material for amplification of surface EM wave. High amplification can be achieved by using cylindrical structures with high surface conductivity, such as waveguides coated with carbon nanotubes [15]. Light propagation in a cylindrical dielectric waveguide with a shell made of an anisotropic metamaterial was considered in paper [16]. In this case, the slowing down of the electromagnetic wave is realized by using the core geometry of a special profile. Also, slowing down and stopping the EM wave is possible in a spiral waveguide coated with a dispersive metamaterial [17].

In this paper, we analyze the conditions leading to amplification and phase modulation of the surface EM wave. It is shown that the depth of phase modulation of the surface wave can reach large values $\delta \gg \pi/2$ under the condition of synchronization with modulated current pumping. The synchronization of EM wave of near-infrared wavelength and current wave is realized automatically due to the formation of a space charge wave (SCW) in the bulk of the semiconductor waveguide.

1. SCW in a cylindrical GaAs waveguide

We consider the interaction of a spirally propagating surface EM wave and an alternating drift current (or SCW) in a cylindrical GaAs waveguide. Let an EM wave (laser beam) with the wavelength λ_0=1.55 µm be introduced through a prism into a cylindrical waveguide at a small angle θ (Fig. 1). In this case, the surface EM wave formed in the waveguide will propagate along a helical trajectory. The EM radiation 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: $v_z = v \sin\theta \ll v$, where $v = c/n_0$ is a wave speed in a waveguide material characterized by its refractive index $n_0 = n_0(\omega)$. A constant electrical potential difference is applied to the ends of the waveguide.

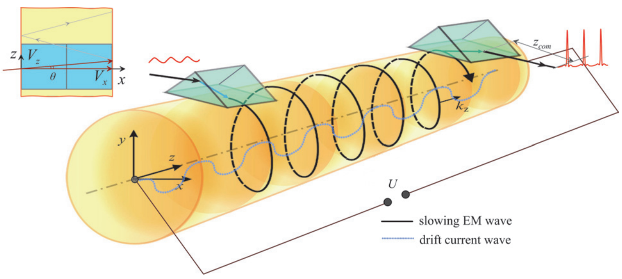

Fig. 1. Geometry of the cylinder GaAs-waveguide with a surface EM wave propagating along a spiral path. Here input and output radiation light waves are shown by red lines, surface EM wave is shown by black circular line, alternating drift current wave is shown by light blue dots, U is the electrical potential difference applied to the ends of the waveguide, z_{com} is the compression length of the EM wave. On inset: v_z and v_x are longitudinal and transverse components of the EM wave velocity, θ is the input angle of light

The drift velocity of charge carriers v_0 in n-GaAs semiconductor samples is determined by the strength of the acting electric field E and is well described within the framework of the Ridley-Watkins-Hilsum model [18]:

$$v_0(E) = v_s\left[1+\frac{E/E_s-1}{1+A(E/E_s)^t}\right], \qquad (1)$$

where $E_s = v_s/\mu$ and dependencies $t(\mu) = 4+1280/sh(40\mu)$, $v_s(\mu) = (0.6+0.6\mu-0.2\mu^2)\cdot 10^5$, $A(\mu)=0.6\cdot[\exp(10\mu-2)+ +\exp(-35\mu+7)]^{-1}+0.01$ determined by the mobility of charge carriers in the sample. At room temperatures, the calculation results obtained using Eq. (1) are in good agreement with the experimental results [19].

The inset to Fig. 2 shows the «velocity-field» dependences for four different values of free charge carrier mobility μ = 0.14, 0.42, 0.62, 0.85 m²/(V·s), calculated using Eq. (1). One can see that the drift velocity can vary over a wide range of values depending on the electric field strength E. The range $E<4$ kV/cm is characterized by a rapid increase in the drift velocity of free charge carriers with a relatively small change in the field strength. The maximum value of the drift velocity in the interval 3 kV/cm $< E <$ 6 kV/cm is achieved at the threshold field value $E = E_t$, which is depends on the concentration of carriers in the semiconductor. The condition of negative differential mobility $dv/dE < 0$ is satisfied for $E > E_t$.

At relatively high values of electric field strength E the drift velocity of the current weakly depends on E (see Fig. 2), and SCWs (caused by the instability of the uniform field distribution) are formed in the bulk of the semiconductor [19, 20].

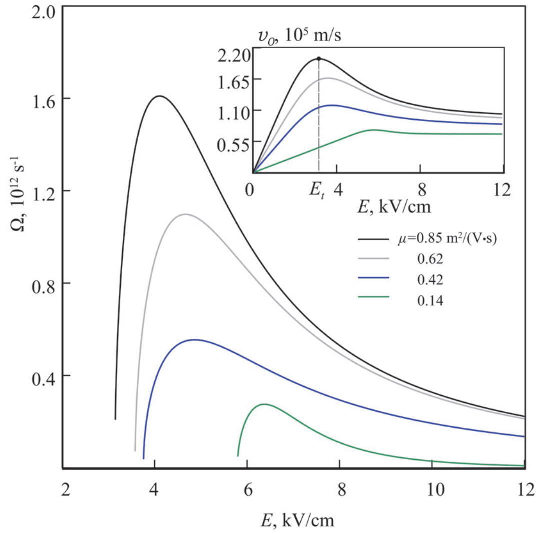

Fig. 2. Frequency Ω of modulation of the current wave in GaAs versus the applied external field E for the mobility values of free charge carriers μ = 0.14, 0.42, 0.62, 0.85 m²/(V·s). The inset shows the dependences of the drift velocity of free charge carriers v_0 on the electric field strength for the same mobility values

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 $N(\Omega,t) \approx N_0[1+\kappa\cos(\Omega t - qz)]$, 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 $\omega_p = \omega_{p0}[1+\kappa\cos(\Omega t - qz)]^{1/2}$, where $\omega_{p0} = (e^2 N_0/\varepsilon_\infty \varepsilon_0 m_{eff})$ 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 local refractive index wave of GaAs waveguide is determined by value [11]

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

where

$$n_0 \approx \sqrt{\varepsilon_\infty}\left(1-\frac{\omega_{po}^2}{2\omega^2}\right)$$

is refractive index of GaAs in the absence of SCW, $m \approx -\omega_{po}^2\kappa/2\omega^2$ is refractive index modulation depth, and ε_∞ is dielectric constant of GaAs at high frequencies. In the considered case the parameter $m < 0$, since the regions of electronic «antinodes» correspond to a minimum of the refractive index and the radiation is «pulled» into the region of lower values of space charge concentrations. Thus, a propagating SCW can be excited in the bulk of the semiconductor with the refractive index modulation amplitude $\Delta n = |m| n_0$, frequency Ω and phase velocity v_{scw}. Its refractive index changes according to Eq. (2). In this work, numerical calculations were carried out for the following values of GaAs parameters: $N_0 = 3.5 \cdot 10^{23} \mathrm{m}^{-3}$, $\varepsilon_\infty = 11$, $m_{eff} = 0.071 m_e$ [21].

Next, we consider the frequencies of a SCW propagating in the semiconductor waveguide. In the one-dimensional case, the dispersion equation for the SCW has the form [20]:

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

where $\mu_1 = \mu_0^{-1}\left(dv / dE\right)$ is the reduced differential electron mobility, μ_0 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 v_{scw} can be found from Eq. (3): $\Omega = v_{scw}\sqrt{-\mu_1 \omega_m / D}$. The existence of the SCW is limited by the region of negative values of differential mobility μ_1. Fig. 2 shows the dependences of the SCW frequency on the electric field in a GaAs waveguide for carrier mobility values $\mu = 0.14$, 0.42, 0.62, 0.85 m^2/(V·s). Here the experimental data for the diffusion coefficient and drift velocity at $T = 300$ K [19, 22] were taken as the calculated parameters of GaAs. These parameters are the functions of the external electric field strength. The region of existence of the SCW at high mobility values the dependence $\Omega(E)$ is seen to have a pronounced maximum at a field value of about $E_0 = 4.5 \cdot 10^5$ V/m. The maximum becomes smaller and shifts to the high field region with decreasing the carrier mobility. The SCW frequency changes most strongly with a small change in voltage near the maxima of function $\Omega(E)$. Terahertz modulation frequencies are achieved at higher mobility values $\mu = 0.62$ and 0.85 m^2/(V·s) for electric field strength in the range (4.0–5.0)·10^5 V/m.

2. Modulation of SCW in waveguide

Deep phase modulation of the introduced EM radiation is achieved during the self-synchronized interaction of surface EM wave with the SCW. In this case, the interaction between SCW and spirally propagating surface EM is described as [23]:

$$\frac{\partial A}{\partial \xi} = -i\frac{m n_0 \omega}{c}\cos\left(\Omega\tau\right) A + GA, \qquad (4)$$

where $\tau = t - \xi / v_g$ is time in a running coordinate system associated with the "spiral" coordinate ξ (coordinate along the trajectory of the EM wave) and G is the resulting wave amplification. The power of quasi-continuous EM radiation introduced into the system should be relatively low (less than 10 mW) to minimize nonlinear effects. So, we can assume with good accuracy that the amplitude of the modulated radiation at the output of the cylinder waveguide is determined as

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

where P_n is the power saturation, δ_a and Ω_a are the amplitude modulation depth and frequency modulation depth, respectively. The initial amplitude modulation is assumed to be weak $\delta_a \ll 1$. The depth of phase modulation at the output of a cylindrical waveguide can be estimated as

$$\delta \approx m n_0 \omega l / 2 v_0 \approx -\omega_{po}^2 l \kappa / 4 \omega v_0. \qquad (5)$$

Fig. 3 shows the dependences of the acquired modulation depth δ on the external field $E > E_t$ for four selected values of carrier mobility. Here, numerical analysis is carried out for modulation parameter $m = -10^{-5}$. Numerical analysis of Eq. (5) shows that for the selected parameter values the depth of phase modulation is very large. First of all, this is achieved due to the large effective interaction length, equal to the length of the modulator fiber $l = 0.1$ mm. All dependencies are monotonous. At large field values, they weakly depend on the external field, since the drift velocity in these regions reaches saturation.

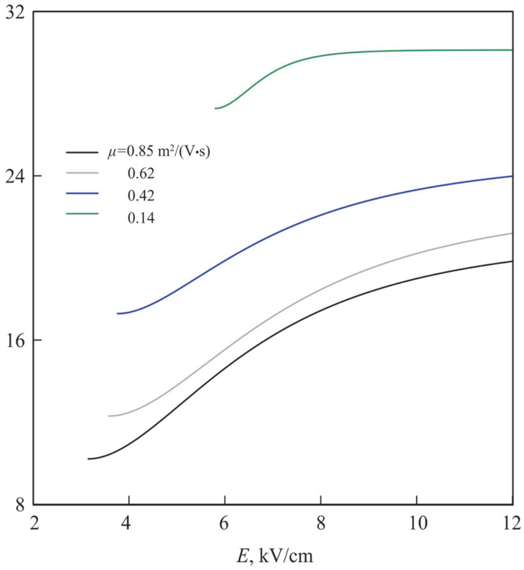

Fig. 3. The phase modulation depth versus on the applied external field E for carrier mobility values μ = 0.14, 0.42, 0.62, 0.85 m²/(V·s)

For the large values $\mu = 0.85$ m^2/(V·s) the depth of phase modulation $\delta \approx 15$ while for $\mu = 0.14$ m^2/(V·s) it becomes almost twice as big ($\delta \approx 30$). Note that at large values of mobility, the greater controllability of the modulation parameter is achieved by changing the magnitude of the applied field. Thus, the phase shift acquired by an EM wave is determined mainly by the mobility of carriers μ in the semiconductor.

Conclusion

In this paper we consider the interaction of a surface electromagnetic wave of the whispering gallery mode type and a space charge wave in the semiconductor cylindrical waveguide. It is shown that deep phase modulation of electromagnetic radiation can be carried out in a waveguide in a wide range of wavelengths. It is important to note that with further propagation, such a phase-modulated electromagnetic wave can transform into a sequence of ultrashort pulses with high peak amplitude values.

Acknowledgements

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