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On generation of electromagnetic waves in the terahertz frequency range in a multilayered open dielectric waveguide

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ABSTRACT

We show that it is possible to produce terahertz wave generation in an open waveguide, which includes a multilayer dielectric plate. The plate consists of two dielectric layers with a corrugated interface. Electrons, drifting in the potential well, interact with the non-uniform electric field which is induced near the dielectric interface by the natural wave of the waveguide. The corrugated period and parameters of the electronic system are chosen in order to ensure the most effective interaction of electrons with a wave. Generation of electromagnetic waves is achieved by converting the electrons' energy into the electromagnetic wave energy.

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1. Introduction. Scheme of the device

Possibilities of terahertz wave generation have received a great deal of attention. Devices exploiting this waveband are set to become increasingly important in a very diverse range of applications, including medicine and biology. Nevertheless, the terahertz range, characterized by a frequency from a few tenths of terahertz to several terahertz, is studied much less in comparison with its neighbors: the optical range (at the higher frequency border) and the microwave range (at the lower frequency border) [1,2]. Electro-vacuum devices (such as backward-wave tubes and traveling-wave tubes and also crossed-field oscillators) are used extensively for microwave generation. However, a straight-forward adaptation of microwave generator circuit for generators of terahertz radiation (in current electric vacuum devices) causes serious difficulties. Possible solutions to the problem of generating terahertz waves have been proposed in our recent Letter [3]. In a scheme described in [3], terahertz waves are excited by electrons which move in vacuum at a small distance from a corrugated surface of a dielectric and interact with the non-uniform electric field induced near the corrugated surface. Parameters of discussed in [3] electro-vacuum terahertz generators could be significantly better than the existing ones. The power of such devices could reach the level of watts, and efficiency may exceed 50–80%.

In this Letter we propose a solid-state terahertz generator concept. In the proposed scheme, generation of terahertz waves is achieved, as in the electro-vacuum microwave generators, by converting electrons' energy into electromagnetic energy due to deceleration of electrons in the electric field of the wave. The most efficient energy transfer between electrons and the wave field occurs when the electron velocity is close to the phase velocity of the wave. However, the phase velocity of electromagnetic waves is much greater than the electrons' velocity in dielectric waveguides with not very high values of permittivity ε ($\varepsilon \leqslant 10$). Traditionally, slow-wave systems are used to reduce the phase velocity in the electro-vacuum devices. These are waveguides with periodically varying parameters. The typical sizes of the slow-wave systems are of the order of the wavelength. However, there is a high absorption of electromagnetic radiation in such small slow-wave structures. It is extremely difficult to slow a wave and also to avoid wave energy losses in the terahertz frequency range.

The point of our work is to describe a scheme of a terahertz generator, in which the regime of efficient energy exchange between electrons and the electromagnetic wave is achieved without slowing-down of the electromagnetic wave propagating in the waveguide.

The generator circuit includes a thin dielectric plate, which can act as an open waveguide. In such waveguide the electromagnetic field partially penetrates from the plate into the surrounding space, decaying exponentially with distance from the plate. Thus the electromagnetic wave field is focused in the region which includes the plate itself and some region near the plate. Ohmic losses of electromagnetic waves are only into the dielectric plate, while wave energy is concentrated mainly outside the plate. The ohmic losses of electromagnetic waves are low in an open waveguide with a thin dielectric plate.

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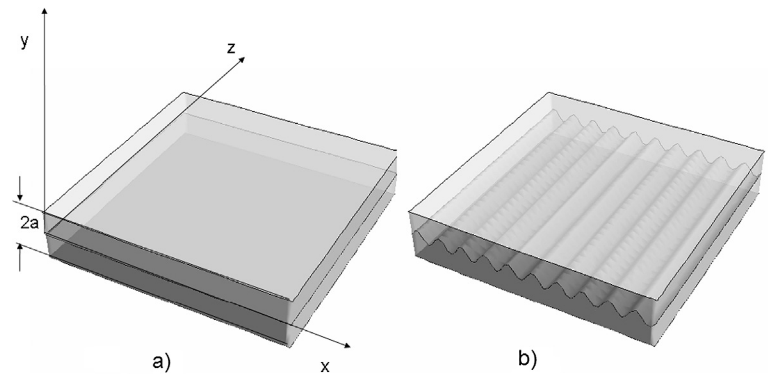

Fig. 1. Dielectric plate with a flat dielectric interface (a) and with a corrugated dielectric interface (b).

In the proposed scheme, the device plate consists of two dielectric layers with different values of permittivity. Near the dielectric interface there is a thin semiconductor layer, which is a conductance channel for charge carriers. The electrons move through the channel in the transverse direction of the waveguide and interact with the inhomogeneous electric field induced by the principal H-wave electric field near the dielectric interface.

The dielectric interface has a periodic structure: the coordinate of the dielectric boundary changes on a periodic law in the waveguide cross-section. The H-wave will change in this case, compared with the unperturbed wave propagating in a plate with a smooth dielectric interface. Indeed, the unperturbed wave causes the polarization of the dielectric in the zone of the corrugation, and this polarization, in turn, induces a secondary field which is superimposed on the unperturbed. The induced electric field is comparable with the electric field of the principal waveguide wave only in a very narrow region near to corrugation. But the induced electric field decays exponentially with distance from the corrugation. (The characteristic scale, which changes the secondary field, is determined by the amplitude and period of the corrugation.) The semiconductor layer, including inside the two-dimensional conductance channel for electrons, is located in a region near the boundary of dielectrics, where a non-uniform electric field is strong enough.

Since the dielectric interface is a periodic texture, the induced electric field consists of infinite number of spatial harmonics. The corrugated period and parameters of the electronic system are chosen in order to ensure the most effective interaction of the electrons with one of a number of harmonics of the inhomogeneous electric field near to corrugation. The most efficient energy transfer between electrons and the electromagnetic wave takes place under the synchronism condition, when phase velocity of the wave, which interacts with electrons, is close to the drift electron velocity. In this case, part of the electrons with a velocity greater than the phase velocity of the wave are decelerated in the electric field wave and give a fraction of its energy to the wave, thus amplifying the wave.

In our recent Letters [3,4] we considered interactions of electromagnetic waves with electrons moving in a vacuum above a corrugated surface, that is a case of ballistic electron transport. In this Letter, we describe the interaction of electromagnetic waves with the electrons drifting in a semiconductor quantum well. In this case, it is necessary to take into account collisions and diffusion of electrons interacting with the wave field.

To date, there are many papers (for example, the review [5]) devoted to theoretical studies of interactions of drifting electrons with the fields of E-wave propagating through a slow-wave structure.

In this Letter, we propose and investigate a scheme in which electrons drift in the transverse direction of the open multilayer waveguide and interact with the H-wave induced field near a corrugated dielectric interface. However, the electromagnetic wave, propagating along the waveguide, is not slowed down.

In the second section of this Letter, we formulate a model and carry out calculations of local inhomogeneous electric field induced near the corrugated dielectric interface in an electric field of H-wave in the waveguide. In the third section we describe the electronic system, which interacts with an inhomogeneous electric field of the wave. We define the parameters of the system under which the amplification of the electromagnetic field is most effective. In the fourth section we give a brief conclusion.

2. Wave electric field in open waveguide of two dielectric layers with a corrugated interface

The proposed scheme of the generator is an open waveguide based on a thin dielectric plate with thickness $2a$. The plate consists of two dielectric layers with different permittivity ε_1 and ε_2 (Fig. 1). Electromagnetic waves, including waves in the terahertz frequency range ω, can propagate in the waveguide. For sufficiently thin plate $a \ll c/\omega$ (where c is the speed of light) and for not too large values of ε_1 and ε_2, the electromagnetic wave energy is mostly concentrated in the region outside the plate. In such open waveguide, the electromagnetic wave propagates with the velocity, which is close to the speed of light, and has a propagation constant $k = \omega/c$ in z-direction.

We will consider the special case of a magnetic wave (H-wave), propagating in the z-direction. H-wave has only the x-component of the electric field, and is described by $\vec{e}_x E_x \exp(ikz - \omega t)$, where $\vec{e}_x$ is unit vector along x-direction. H-wave electric field, in principle, can couple with drifting carries, which move also in the x-direction of the waveguide. It is the H-wave is of interest to us because an antinode of the H-wave electric field is located in the center of the cross-section of the plate, that is the region, where the dielectric plate with a conductance channel are (Fig. 2).

For a plate with a flat dielectric interface (Fig. 1a), E_x can be written as

$$E_x = \begin{cases} \frac{i\omega}{c\cdot\chi} \cdot A_{in} \cdot \cos(\chi y), & |y| \leqslant a, \\ -\frac{i\omega}{c\cdot s} \cdot A_{out} \cdot \exp(-sy), & |y| \geqslant a. \end{cases} \tag{1}$$

Here $|y| \leqslant a$ is the region inside of the plate, $|y| \geqslant a$ is the region outside of the plate, $\frac{i\omega}{c\cdot\chi} \cdot A_{in} \approx -\frac{i\omega}{c\cdot s} \cdot A_{out}$, χ and s are related by $sa\cdot = \frac{1}{\varepsilon} \cdot \chi a \cdot \mathrm{tg}(\chi a)$ and $(\chi a)^2 + (sa)^2 = \frac{\omega^2 \cdot a^2}{c^2}(\varepsilon - 1)$, $\varepsilon \approx \sqrt{\varepsilon_1 \cdot \varepsilon_2}$ is the average value of permittivity of dielectric plate.

The magnetic field components of the H-wave are described by functions $\vec{e}_z H_z \exp(ikz - \omega t)$ and $\vec{e}_y H_y \exp(ikz - \omega t)$, where $\vec{e}_z$ and $\vec{e}_y$ are unit vectors along the z- and y-directions. In the case of a plate with a flat dielectric interface, $H_z(x, y)$ and $H_y(x, y)$ inside the plate and outside the plate are

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