

Undulator-Like Radiation and N^2 Effects in Semiconductor Microstructures with Grating

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In the article the cooperative N^2 -effects are considered, that is the radiation whose power is $\sim N^2$, where N is the number of emitters which in this case is equal to the number of electrons in a bunch. The suggested effects are the result of combining two effects: the Gunn-effect in GaAs and undulator-like radiation, or “pumping wave” acting on the electrons and which is the result of undulator field, while the second is the backward effect of radiation which is produced by electrons moving within such microundulator. It is very probable that the effects can be used for the developing of a new semiconductor-based room temperature source of the THz-radiation.

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1. Introduction

Nowadays there is a growing interest in developing the new sources of THz-radiation because of variety of its possible applications ranging from security service [1] to biochemistry and medicine [2]. There are many propositions concerning possible schemes of THz generation/detection, broad-band as well as narrow-band, based on optical rectification, photoconductive effect, parametric conversion etc. (for the review see [2, 3]). It seems that the existing modern fabrication techniques enable to develop the room temperature sources of THz radiation, based on the “microundulator” which would be able to generate in this spectral region.

In this work the cooperative N^2 -effect is considered, that is the radiation, whose power is $\sim N^2$, where N is the number of emitters which in this case is equal to the number of nonlinear coupled oscillators which model the electrons in a bunch. We deal with two different models: in the first case the considered effect is the result of combining two others, namely the Gunn-effect in GaAs and undulator-like radiation which can be produced by means of microstructure with grating (microundulator). In the second case, suggested effect is in a sense similar to the Dicke superradiance, however it is not the spontaneous phase coherence arising in the ensemble of two-level atoms interacting via the emitted electromagnetic field, but rather, the result of interplay of another two effects. The first one is the “pumping wave” acting on the electrons and which is the result of undulator field, while the second is the backward effect of radiation which is produced by electrons moving within such microundulator. As a result, the specific phase coherence (“synchronization”) develops in the ensemble of emitters and they start to generate as a single oscillating charge Ne , while the power of emitted radiation becomes proportional to N^2 . It is very probable that the effect can be used for the

developing of a new semiconductor-based room temperature sources of the GHz and THz-radiation.

Suppose we have a microstructure shown in Fig. 1, which could be grown on a semi-insulating GaAs substrate, with the multiple electrodes on both sides of it, top and bottom (see Fig. 1), which create gratings. If the electric bias is applied to the electrodes, then a weak periodic potential modulation arises within the GaAs-sample and this periodic electric field becomes very similar to the periodic electric field used in some types of undulators.

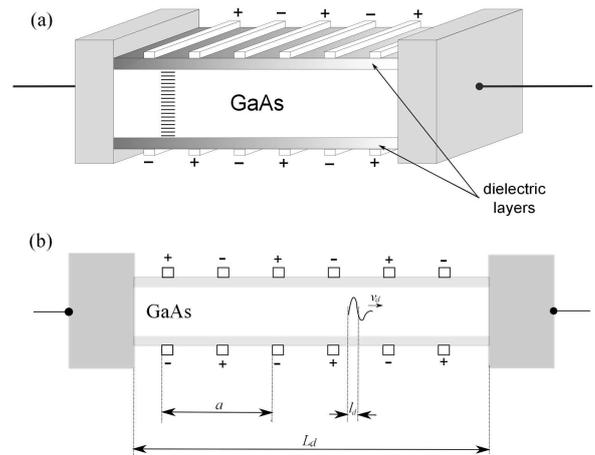


Fig. 1. Sketch of microstructure with grating.

The radiation field produced by the charged particles moving in such structure should consist of narrow spectral lines whose frequencies are $\omega = 2\pi mT^{-1}/(1 - \frac{L}{cT} \cos \vartheta)$, where c is light velocity, m is an integer and ϑ is the observation (excursion) angle. This is exactly the radiation spectrum emitted by the particles in an undulator. Suppose we have GaAs-sample normally used for the fabrication of the Gunn-effect diodes and assume that this Gunn-effect diode structure is equipped with the gratings similar to that presented in Fig. 1. Then, due to the gratings on the top of the structure there will be a weak periodic potential modulation within the semicon-

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dutor. Suppose now that all other conditions necessary for the Gunn-effect to appear are fulfilled. Then, the strong electric field domain moving within the sample is accompanied by the electron “bunch”, whose electron concentration is greater than some threshold concentration and which can be estimated at about 10^{16} cm $^{-3}$. The thickness of the “bunch” l_d ranges from 1/10 to 1/30 of the sample length L_d . If we suppose the length of the Gunn-effect diode L_d to be equal to 10^{-3} cm, then the thickness of a bunch can be estimated to be $\approx 3 \times 10^{-5}$ cm. If we suppose the period of grating a on a top and bottom of the structure to be about 2×10^{-4} cm, the frequency of the undulator-like radiation produced by the structure, will be about $\omega_0 \approx \frac{2\pi v_d}{a}(1 - v_d/c) \approx 3.14 \times 10^{11}$ Hz. (Here we take into account that the speed of the strong field domain v_d is about 10^7 cm s $^{-1}$ and hence, $v_d/c \approx 10^{-3}$ and radiation frequency practically does not depend on the excursion angle ϑ). The corresponding wavelength is about $\lambda \approx 0.1816$ cm and obviously, $l_d \ll \lambda$. Since in our case the velocity of electrons is much smaller than c , to take into account that the size of the bunch has to be much smaller than the period of grating $l_d \ll a$ is even more important than to take into account the condition $l_d \ll \lambda$ [4]. The last one guaranties that electrons in the bunch will generate roughly with the same phase. Now we have all reasons to believe that the electron “bunch”, that is the domain of high electron concentration accompanying the strong field domain in the Gunn-effect diode, will generate as a point source. Then the structure in question will generate the pulses of radiation, whose intensity $\sim N^2$. Then the evolution of the ensemble of nonlinear oscillators is described by the system of equations

$$\ddot{x}_i + \omega^2 x_i = f(x_i, \dot{x}_1, \dots, \dot{x}_N, t), \quad (1)$$

for $i = 1, \dots, N$, where

$$f(x_i, \dot{x}_1, \dots, \dot{x}_N, t) = \frac{1}{6} \frac{\omega^2}{a^2} x_i^3 - \frac{2e^2 \omega^2}{3mc^3} \sum_{j=1}^N \dot{x}_j + \frac{eE}{m} \cos(\nu t).$$

The first term on the right-hand side is responsible for nonlinearity, since we do not assume the displacements to be small, they can be arbitrary. The second term represents radiation damping of electrons and the third one is nothing else but an external driving field associated with emitted undulator-like radiation whose amplitude is E . We seek a solution $x_i(t)$ to the system of Eqs. (1) in the form

$$x_i(t) = a A_i(t) \cos(\nu t + \theta_i(t)), \quad (2)$$

where by hypothesis $A_i(t)$ and $\theta_i(t)$ are the functions whose rate of variation is small compared with the angular frequency ν . Due to this assumption, one can derive the following set of equations:

$$\frac{dA_i}{d\tau} = H \left[\sum_{j=1}^N A_j(\tau) \cos(\theta_i(\tau) - \theta_j(\tau)) \right]$$

$$-G \sin \theta_i(\tau) \quad (3)$$

$$\frac{d\theta_i}{d\tau} = -\frac{1}{2} \frac{\nu^2 - \omega^2}{\nu^2} - \frac{1}{16} \frac{\omega^2}{\nu^2} A_i^2(\tau)$$

$$-\frac{G}{A_i(\tau)} \cos \theta_i(\tau) \quad (4)$$

where

$$\tau = \nu t, \quad H = \frac{e^2 \omega^2}{3\nu m c^3}, \quad G = \frac{eE}{2am\nu^2}.$$

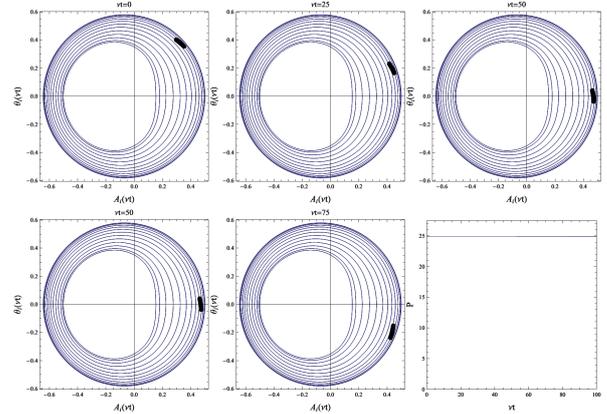


Fig. 2. Phase portrait in case of initial phases clustered around $\pi/4$ with the dispersion 0.15. Individual solid lines represents trajectories for different values of initial phase. Cluster of black dots indicates oscillators.

Equations (3), (4) can be solved numerically. In our calculations we set $c = 3 \times 10^{10}$ cm/s, $e = 4.0832 \times 10^{-10}$ cgs units, $m = 1.2 \times 0.91 \times 10^{-28}$ g (effective mass of an electron in the “heavy valley” of GaAs-conduction band), $\omega = \nu = 3.14 \times 10^{11}$ Hz, $E \approx 4$ V/cm = 0.0135 cgs units (assuming one hundredth of electron energy in a Gunn diode will be converted into generated radiation), $a = 2 \times 10^{-4}$ cm, $N = 10^4$, $G = 0.0015$ and $H = 8.18 \times 10^{-12}$.

Figure 2 presents the solution of Eqs. (3), (4) in a series of phase diagrams where $A_i(\tau)$ is plotted as a function of $\theta_i(\tau)$ for the consecutive moments of dimensionless “time” $\tau = 0, 25, 50, 75, 100$ for the case when initial phases are clustered around $\pi/4$ with the dispersion 0.15. Obviously, the case corresponds to the situation when $l_d/a = 0.15$. Initial amplitudes $A_i(0)$ for all oscillators are taken to be equal 0.5. Phase diagrams are accompanied by the plot of a function $P(\tau)$, which is a measure of phasing of the electrons in a bunch, defined as:

$$P(\tau) = \frac{1}{N} \left| \sum_{j=1}^N \exp \theta_j(\tau) \right|^2.$$

It ranges from 0 when all oscillators have completely random phases, to N when all of them oscillate with roughly the same phase. We conclude that in the first case the driving field is too small to cause phasing of oscillators.

Analyzing the second case, we set the upper bound of the sequence of moments of “time” as to be 100; that corresponds to the time needed for an electron bunch to flight through a Gunn diode.

In Fig. 2 we have shown the results of calculations obtained by using the number of oscillators $N = 25$, because at the greater number of oscillators the trajectories become too dense for the phase portraits to be readable and clear. However, it should be noted that with a greater number of oscillators taken into consideration, the picture remains the same in its general features. This is because even if one assumes $N = 10^7$ the first term on the right side of Eq. (3) (the only term dependent on N) will be by far smaller as compared to other terms even in case of the most favorable conditions when all phases θ_i coincide.

Treating the second model, we use the following set of equations [5]:

$$\ddot{x}_i + \omega_i^2 x_i = f_i(x_i, \dot{x}_1, \dots, \dot{x}_N, t), \quad (5)$$

for $i = 1, \dots, N$, where

$$f_i(x_i, \dot{x}_1, \dots, \dot{x}_N, t) = \frac{1}{6} \frac{\omega_i^2}{a^2} x_i^3 - \frac{2e^2 \omega_i^2}{3mc^3} \sum_{j=1}^N \dot{x}_j + \frac{e}{m} (E_0 + E(t)) \cos(\nu t), \quad (6)$$

which differs from Eq. (1) in that respect that here the frequencies ω_i are all different and distributed at random. Above all, we also take into account the randomness of initial phases. The set of equations was solved numerically and the results of calculations are shown in Fig. 3.

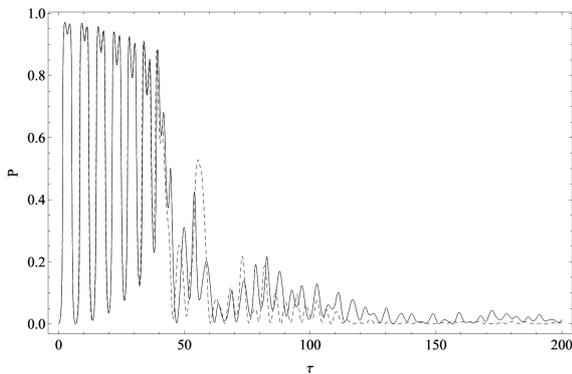


Fig. 3. The plot represent phasing versus dimensionless time τ : in the left frame two curves, solid and dashed correspond to two different distributions of the amplitudes, phases and frequencies of the oscillators (see text below), they correspond to the electron concentration 10^{17} cm^{-3} .

2. Conclusion

In this paper we have considered cooperative N^2 -effects which to our mind, can occur in the GaAs-structure with grating. In the first model studied by us the effect is due to combining two other effects, namely the Gunn-effect and the undulator-like radiation. The mechanism which leads to the proportionality of radiation power to N^2 is the initial phasing of electrons in a bunch due to the Gunn effect and the fact that linear size of a bunch l_d is much smaller than the period of grating a ($l_d \ll a$) as well as the radiation wavelength.

Treating the second model, we have considered the time evolution of a great number of coupled nonlinear charged oscillators which interact with the external driving electric field and with each other by means of radiation field. This model corresponds to the electrons moving in the periodic electric field of “microundulator” composed of the GaAs-semiconductor layer with the properly matched grating on the top but with the lack of initial phasing that is, in the absence of the Gunn effect. The external periodic driving field is nothing else but the undulator field and it is analogous for instance, to the “pumping wave” in maser or laser. In the frame of the model we also took into account the backward effect of the radiation field on the electrons moving within the microundulator. The effect resembles to some extent the Dicke superradiance, but differs from it in the respect that the oscillators not only interact with each other via the emitted radiation but rather, are under the influence of the undulator field. In the simulations we assumed the frequencies of the oscillators to be distributed at random around some definite frequency and the randomness of the initial phases of oscillators.

It seems very probable that the predicted effect can be used for the developing of generators which could produce radiation at the frequencies even up to a few THz at room temperature.

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