Terahertz Parametric Gain in Semiconductor Superlattices

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Abstract—We consider a high-frequency response of electrons in a single miniband of superlattice subject to dc and ac electric fields. Action of ac electric field causes oscillations of electron’s effective mass in miniband, which result in a parametric resonance. We have established a theoretical feasibility of phase-sensitive parametric amplification at the resonance. The parametric amplification does not require operation in conditions of negative differential conductance. Therefore a formation of destructive domains of high electric field inside the superlattice can be prevented. Here we concentrate on the parametric up- and down-conversion of electromagnetic radiation from available frequencies to desirable THz frequency range.

I. INTRODUCTION

Terahertz spectral range of electromagnetic radiation is located between optical and microwave frequencies. It is the borderline of optics and electronics, and there still exists a technological gap in construction of compact and reliable sources, amplifiers and detectors. Semiconductor superlattices have been proposed as a candidate for active material in such kind of devices [1]. Realization of a regenerative superlattice THz amplifier/oscillator is complicated by an existence of electric instability, which leads to a formation of destructive high-field domains inside the nanostructure.

Recently we theoretically established the feasibility of regenerative parametric amplification in superlattices due to the parametric resonance caused by the oscillations of electron’s effective mass in miniband [2]. We showed that the parametric amplification does not require operation in conditions of negative differential conductance [3] and thus, at least for a moderate doping, the formation of destructive high-field domains inside the superlattice can be prevented [4]. The superlattice parametric amplifier does require a relatively strong ac pump. Currently, suitable powerful sources of coherent radiation exist at the low frequencies of about 100 GHz and at some particular high frequencies of several THz [5].

After a short description of the amplification schemes, we study the parametric amplification and generation at even harmonics and high-order half-harmonics of the pump frequency, as well as amplification and generation with frequency halving. We focus on the parametric amplification and generation of desirable THz radiation (200 GHz - 1 THz) with the use of available sources of low- and high-frequency radiation.

II. AMPLIFICATION SCHEMES

We employ the semiclassical approach based on a solution of Boltzmann transport equation [2]. We consider electron dynamics in a single superlattice miniband subject to the pump field consisting of dc bias and strong ac field

\[ E_p = E_{dc} + E_0 \cos \omega t \] (1)

and a weak, phase-shifted probe field

\[ E_{pr} = E_1 \cos(\omega_1 t + \phi) \] (2)

There naturally arises two distinct schemes of parametric amplification of the probe field without corruption from generated harmonics: Parametric amplification at even harmonics \( \omega_1 = 2\omega, 4\omega, \ldots \) in the unbiased superlattice \( (E_{dc} = 0) \) and amplification at half-harmonics \( \omega_1 = \omega/2, 3\omega/2, \ldots \) in the biased superlattice.

For both these schemes absorption of the probe field can be represented as a sum of phase-dependent coherent and phase-independent incoherent components. The incoherent component of absorption can be interpreted as a free-carrier absorption modified by the pump field, while the coherent contribution is caused by the periodic variation of effective mass and a specific quantum inductance. The parametric gain has a maximum for some optimal value of the relative phase \( \phi = \phi_{opt} \) [2].

In our calculations of magnitude of parametric gain we used the following parameters of typical GaAs/AlAs superlattice: superlattice period \( d = 6 \) nm, miniband width \( \Delta = 60 \) meV, scattering time \( \tau = 200 \) fs, density of electrons \( N = 10^{16} \text{ cm}^{-3} \) and temperature 300 K. For such superlattice the Esaki-Tsu critical field \( E_c \) [1] is approximately 5.5 kV/cm.

III. PARAMETRIC UP-CONVERSION

Both schemes, parametric amplification at even harmonics and half-harmonics, can be used for up-conversion of electromagnetic radiation from microwave frequencies to the THz frequency range [6].

As can be seen from Fig. 1 the magnitude of the gain is still significant even for \( \omega_1 = 6\omega \) with \( \omega/2\pi \) being around 100 GHz. In particular, this enables amplification of probe field with the frequency of about 1 THz by using a pump field of frequency 170 GHz. By using the pump field of a
As can be seen from Fig. 2, the magnitude of the gain at high-order half-harmonics in biased superlattices is no less than the gain at high-order even harmonics in unbiased superlattices. Thus, amplification of probe field of 1 THz can be achieved also in the case, where the probe frequency is a half-harmonic of the pump frequency.

**IV. PARAMETRIC DOWN-CONVERSION**

The parametric amplification at half-harmonics, can be also used for the parametric down-conversion. Fig. 3 shows that large gain at $\omega_1 = \omega/2$ can be achieved with the pump field of modest amplitudes. Therefore, employing a suitable pump field with frequency 1-2 THz – that can be generated with the help of modern quantum cascade lasers or devices based on difference-frequency optical mixing [5] – a probe field with frequency 0.5-1 THz can be amplified in superlattice.

**V. CONCLUSION**

Our theory showed that the parametric resonance in superlattice miniband can be used for the phase-sensitive parametric amplification at THz frequencies. Moreover, all the requirements for frequencies and strengths of the pump fields can be already fulfilled at the present state of microwave and terahertz technologies. Therefore, superlattice parametric devices can potentially form a basis for future amplifiers operating in THz frequency domain.

In conclusion, we would like to note that it is also possible to achieve phase-insensitive amplification in conditions of suppressed electric domains for incommensurate pump and probe frequencies [7]. In this case, high-frequency gain in superlattice resembles Bloch gain, i.e. it occurs due to scattering-assisted quantum transitions.

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