Sub-THz/THz amplification in a semiconductor superlattice

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***Abstract*—We examine the feasibility of amplification of the electromagnetic signal in semiconductor superlattice by moving charge domains, which are generated in superlattice by applied DC bias. We show that an external resonator connected to the semiconductor superlattice significantly broadens the frequency range of amplified signals to the higher harmonics of domain transient frequency. These promising results open the way to use semiconductor superlattices as the efficient sub-THz/THz amplifiers.**

I. Introduction

THE progress in many key areas of science and technology such as astrophysics, broadband communications, and security[1-3] is closely connected with the development of new devices that operable in the sub-terahertz and terahertz range (0.1–10 THz) of the electromagnetic spectrum. Nevertheless, the strong limitation of THz technologies holds by now. The principle reason for this is the lack of reliable compact sources able to work in the THz range. Sufficient progress has been recently achieved in the build out of sub-THz/THz sources, however the development of amplifiers of sub-THz/THz signals still remains an important challenge[4,5].

Here, we discover the feasibility of using semiconductor superlattices for the amplification of electromagnetic waves in the THz range using the main obstacle for realization of Bloch gain - the moving charge domains. SLs comprise multiple alternating layers of different semiconductor materials, which form a periodic modulation of the conduction band[6]. This creates a tunable active media, regularly implied as suitable for the realization of Bloch gain. However, the same quantum mechanisms that give rise to Bloch gain result in electric instability, which leads to the formation of moving high-field charge domains, that could be utilized for amplification of the applied signal[6].

II. Results

The system under study is presented as the device consisting of a superlattice placed into a coaxial resonator and ferrite circulator that separates the input and output signals (see Fig. 1(*a*)). Here, the active media presents itself a strongly coupled SL, where electron transport occurs within a single miniband. The time-dependent mathematical model described in Refs. [7,8] is used to describe the charge dynamics in the superlattice coupled to external resonator. In our calculations, we take parameters corresponding to semiconductor superlattice used in recent experiment[9,10].

Fig. 1(*b*) illustrates the calculated I(V)–characteristics of a superlattice coupled to the external resonator at different resonant frequencies f_Q. The dependencies are typical for superlattice with an Esake-Tsu peak and specific segment with negative difference conductivity [2]

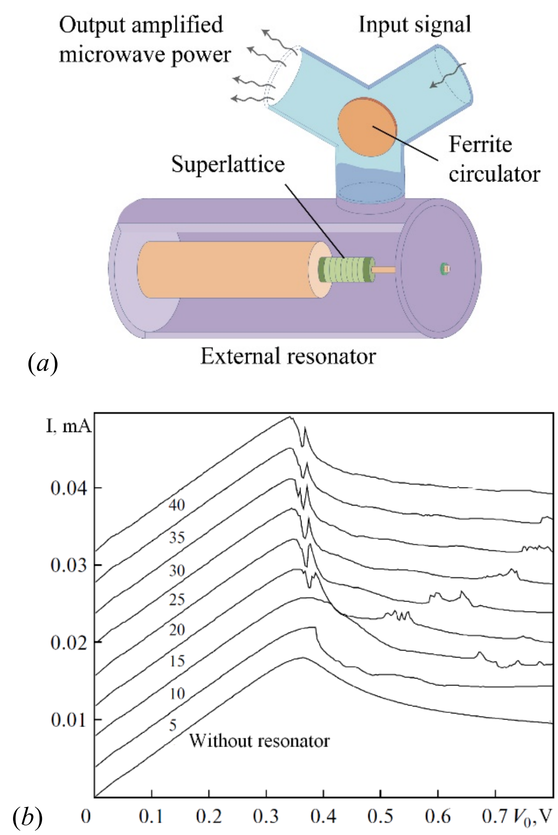

Fig. 1: (a) Schematic diagram of a semiconductor superlattice coupled to an external electromagnetic resonator driven by external field. (b) $I(V)$-curves of a superlattice coupled to the external resonator at different resonant frequencies f_Q [GHz]

Fig. 2 shown power spectrum of current oscillations in autonomous superlattice. Easy to see, that it is rich in harmonics, and generation obtains at sub-THz frequencies (0.2-1 THz).

To determine areas of gain we define the absorption[5] (α) of external signal with frequency f_{ext}

$$\alpha(f_{ext}) = \frac{\mathrm{Re}[\sigma(f_{ext})]}{n_r \varepsilon_0 c_0},$$

where $\sigma(f_{ext})$ is the high-frequency conductivity, n_r is the refractive index of the space charge material and $g = 1/(\varepsilon_0 c_0)$ is the impedance of free space, where ε_0 is the electric constant and c_0 is the speed of light in vacuum.

Value of $\alpha > 0$ means the absorption on the given frequency whereas $\alpha < 0$ corresponds to the induced (stimulated) radiation on the frequency f_{ext} in the perpendicular to the superlattice longitudinal direction.

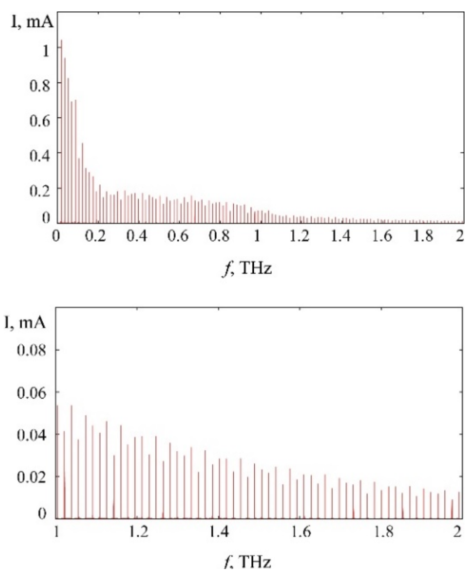

Fig. 2: Amplitude spectra of current oscillations in the semiconductor superlattice. Frequency range 1–2 THz is shown in the bottom panel. Supply voltage applied to the semiconductor superlattice is $V_0 = 610$ mV

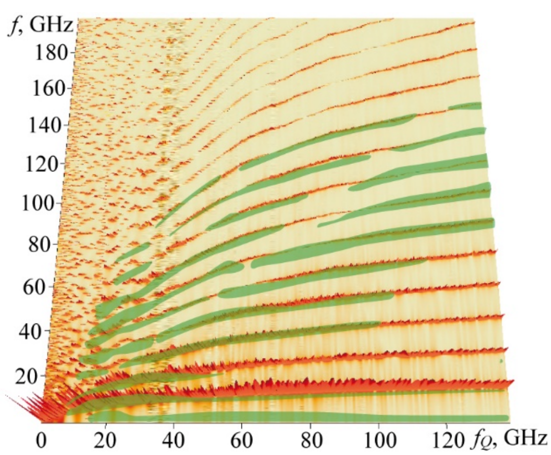

Fig. 3: Power spectrum of the current oscillations, $S(f)$, vs resonant frequency, f_Q. The amplification regions where $\alpha < 0$ is shown as light green area. Supply voltage equal to 510 mV and external signal amplitude $V_{ext} = 20$ mV. Red denotes high power density of the current oscillations

We show that tuning the resonator to the first harmonic, f_0, of the superlattice current oscillations leads to amplification at the frequencies close to f_0, and also creates the possibility for amplification near higher harmonics of the current oscillations. For resonant frequency f_Q close to the higher harmonics of f_0, we find that there is an increase in the frequency of the amplified signal. The superimposition of the areas of the amplification in the (f_Q, f_{ext}) parameter plane (where f_{ext} is the frequency of the external signal) in given on a color map, showing the spectrum, $S(f)$, of the current oscillations (see Fig. 3) calculated for a range of f_Q. Red/yellow corresponds to high/low power density. The regions of amplification are shown by light green. Fig. 3 reveals amplification when f_Q is close to the harmonics in the current oscillation spectrum. Increasing f_Q enables gain for signals whose frequency is much higher than the fundamental frequency of the current oscillations in the superlattice.

Within the semiclassical picture, the physical mechanism of such high-frequency gain can be understood in terms of ballistic trajectories of electrons in the quasi-momentum space. The miniband electrons are gathered into certain favorable trajectories forming electron bunches, which are eventually responsible for the negative absorption[11].

III. Summary

We have shown that propagating charge domains in semiconductor superlattices can be used for the amplification of microwave signals. Our findings open new prospects for using semiconductor superlattices for amplification in sub-THz/THz range.

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