

Modulation and detection of the THz range signals using the highest harmonics of the fundamental frequency of the superlattice-based generator for biomedical applications

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ABSTRACT

The data transmission method using the highest harmonics of semiconductor superlattice-based microwave generator has been proposed for biomedical applications. Semiconductor superlattice operated in charge domain formation regime is characterized by the rich high-harmonics power spectrum. The numerical modeling of modulation and detection of the THz range signals using the highest harmonics of the fundamental frequency of the superlattice-based generator was carried out. We have shown effectiveness of the proposed method and discussed the possible applications.

Keywords: semiconductor, superlattice, high harmonics, THz, magnetic field, space charge domains, current oscillations

1. INTRODUCTION

The THz-data transmission plays an important role in many medical systems and biomedical scientific investigations.^{1,2} The main interest here is connected with the wireless data transmission from health implants, that will enable to monitor the condition of patients with unstable body and organ functions.^{3,4} Besides, the investigation of the chemical processes, that are taking part in different biological systems with high time resolution is the challenging task, that can be resolved by THz-spectroscopy.⁵

Development of semiconductor devices working in sub-THz and THz range is now of the great interest. Such technologies are critically important for a wide range of applications⁶ as astrophysics, medicine and security.^{7,8} Consequently, one of the most challenging tasks of modern electronics is the elaboration of the technically available sub-millimeter wavelength devices operating at room temperature.⁹ Typically, the using of nano- and microstructure-based setups as quantum-cascade lasers (QCLs), transferred electron devices (TEDs) and other devices that exhibit negative differential conductance is the well-known approach in studies considering this issue.^{10–12} Nevertheless, characteristics of such devices are strongly limited by it’s physical dimensions such as minimal length of active media in TEDs, from which the frequency of oscillations is strongly depends. One of the prominent methods to increase the frequency of generation is working with the highest harmonics of the

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main frequency.^{13–16} Note also that oscillation spectrum of nanoscale active media in most cases exhibit large number of highest harmonics, that can be used for generation or amplification of high-frequency carriers.

One of the promising devices demonstrating spectrum containing powerful harmonics and working in sub-THz range is the semiconductor superlattice. Semiconductor superlattices are composed from alternating layers of different semiconductor materials (two or more) with different band width. Such periodic structure promotes the formation of minibands in which electrons can travel along the semiconductor superlattice. If the product of the carrier concentration within the device and the sample length exceeds a critical value, the NDC triggers the formation of propagating charge domains, which could be utilized both for generation and amplification of sub-THz/THz radiation.^{17–19}

Recently, we have shown the possibility to obtain the amplification of the external signal by means of its synchronization with the main frequency and highest harmonics of current oscillations in superlattice.^{20–22} In this report we study numerically the THz signals modulation and detection approach using the highest harmonics of charge transport in semiconductor superlattice. We show the possibility to transmit the informational signal on the one of the highest harmonics of generation using the amplitude modulation of the main frequency, that will provide increase of the frequency of the transmission channel. We also simulate the process of data transmission by means of highest harmonics of carrier using the low-frequency experimental setup. The experimental application of the developed method shows good perspectives of using the semiconductor superlattice as the carrier generator in this case.

2. NUMERICAL MODEL

To investigate the collective electron transport in superlattice we use the model described in,^{22–24} with the semiconductor superlattice parameters taken from recent experiments.²¹ The miniband transport region is discretized into $N = 480$ layers, each of width $\delta x = 0.24$ nm, small enough to approximate a continuum and ensure convergence of the numerical scheme. The discretized current continuity equation is

$$e\delta x \frac{dn_m}{dt} = J_{m-1} - J_m, \quad m = 1 \dots N, \quad (1)$$

where $e > 0$ is the electron charge, n_m is the charge density at the right-hand edge of m^{th} layer, at position $x = m\delta x$, and J_{m-1} and J_m are the areal current densities at the left and right hand boundaries of the m^{th} layer model

$$J_m = en_m v_d(\bar{F}_m), \quad (2)$$

where \bar{F}_m is the mean field in the m^{th} layer.²³ The drift velocity, $v_d(\bar{F})$, corresponding to electric field, \bar{F} , can be calculated as in:²⁵

$$v_d = \frac{\Delta d I_1(\Delta/2k_B T)}{2\hbar I_0(\Delta/2k_B T)} \frac{e\bar{F}d\tau/\hbar}{1 + (e\bar{F}d\tau/\hbar)^2}, \quad (3)$$

where $d = 8.3$ nm is the period of the SL, $\Delta = 19.1$ meV is the miniband width, $T = 4.2$ K is the temperature, k_B is the Boltzmann constant and $I_n(x)$, where $n = 0, 1$, is a modified Bessel function of the first kind.

The electric fields F_m and F_{m+1} at the left- and right-hand edges of the m^{th} layer respectively, are related by the discretized Poisson equation

$$F_{m+1} = \frac{e\delta x}{\epsilon_0 \epsilon_r} (n_m - n_D) + F_m, \quad m = 1 \dots N, \quad (4)$$

where ϵ_0 and $\epsilon_r = 12.5$ are, respectively, the absolute and relative permittivities and $n_D = 3 \times 10^{22}$ m⁻³ is the n-type doping density in the semiconductor superlattice layers. The current density injected into the contact layers of the semiconductor superlattice subjected to the field F_0 is $J_0 = \sigma F_0$, where $\sigma = 3788$ Sm⁻¹ is the conductivity of the heavily-doped emitter.²³ The voltage, V_{sl} , dropped across the semiconductor superlattice defines a global constraint:

$$V_{sl} = U + \frac{\delta x}{2} \sum_{m=1}^N (F_m + F_{m+1}), \quad (5)$$

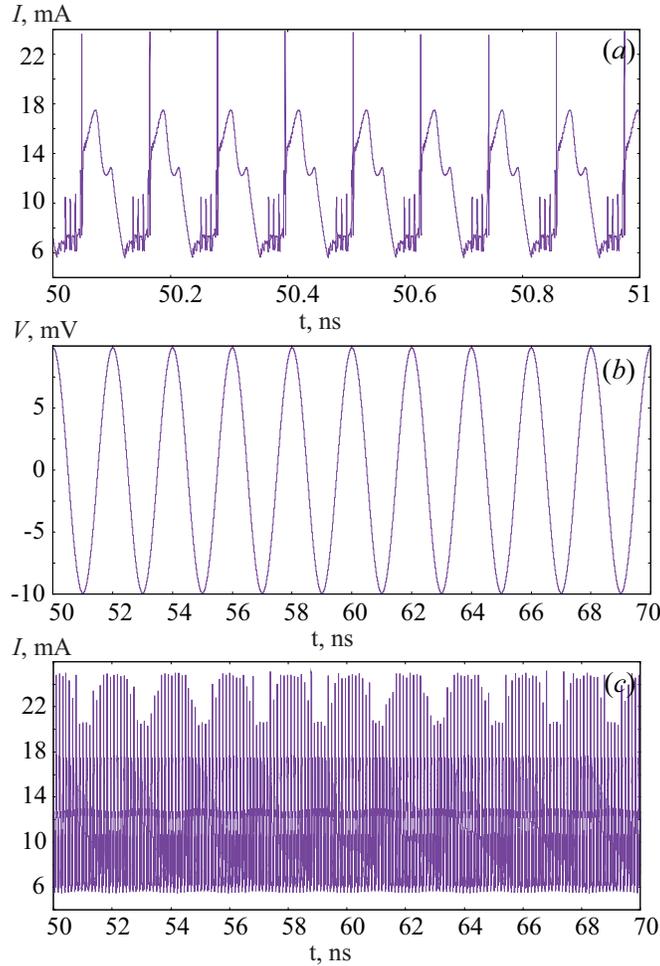


Figure 1. Time realizations of autonomous current oscillations of superlattice coupled to external resonant circuit (a), the external modulating signal (b), and the current on superlattice in resonator to which the external signal is applied (c). Supply voltage of superlattice $V_0 = 510$ mV, eigenfrequency of external resonator $f_Q = 41$ GHz.

where the voltage, U , dropped across the contacts includes the effect of charge accumulation and depletion in the emitter and collector regions, and the voltage across the contact resistance,²⁶ $R = 17 \Omega$. The current through the device is

$$I(t) = \frac{A}{N+1} \sum_{m=0}^N J_m, \quad (6)$$

where $A = 5 \times 10^{-10} \text{ m}^2$ is the cross-sectional area of the semiconductor superlattice.^{23,26}

We considering the superlattice interacting with the external resonant circuit (as described in^{27,28}) and apply the Kirchoff's equations to simulate it's dynamics in the single-mode assumption:

$$\frac{dV_1}{dt} = \frac{I(V_{sl}) - I_1}{C}, \quad \frac{dI_1}{dt} = \frac{V_0 - V_{sl} + RI_1 + R_t I(V_{sl})}{L}, \quad (7)$$

where $V_1(t)$ and $I_1(t)$ are, respectively, the voltage across the capacitor and the current through the inductor. Thus, the voltage dropped across the SL is $V_{sl} = V_0 - V_1 + V_{ext} \cos(\omega_{ext} t)$, where V_{ext} and ω_{ext} is the amplitude and frequency of external informational signal respectively. The eigenfrequency of the resonator is $f_Q = 1/(2\pi\sqrt{LC})$ and the quality factor is $Q = (1/R)\sqrt{L/C}$.

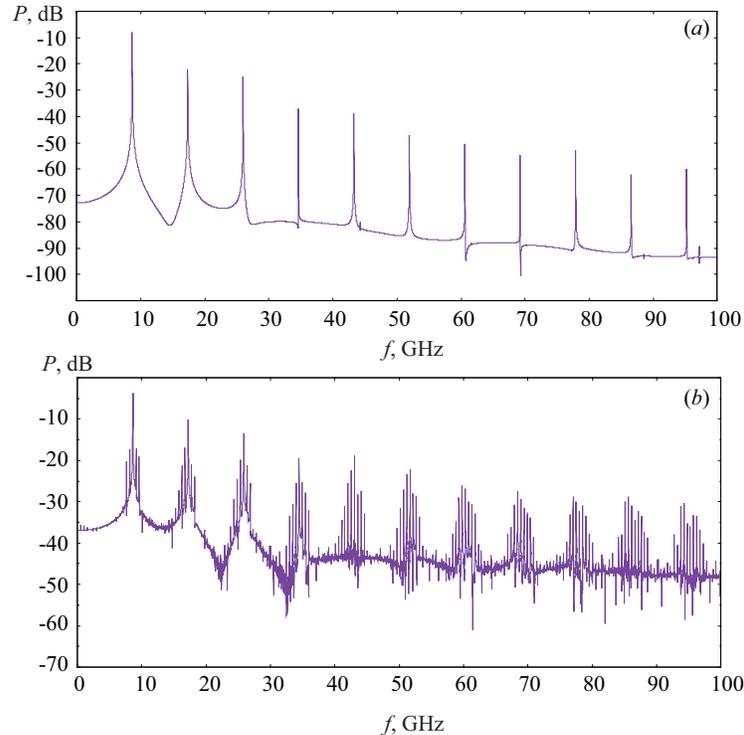


Figure 2. Power spectrum of autonomous (a) and modulated (b) current oscillations in the semiconductor superlattice. Supply voltage of superlattice $V_0 = 510$ mV, eigenfrequency of external resonator $f_Q = 41$ GHz.

3. RESULTS

Figure 1 (a) shows the time realizations of the current oscillations in the superlattice placed in external resonant circuit. One can see the sharp spike accompanying the arrival of charge domain on collector. This spike determines the highest harmonics in the spectrum of oscillations and can be amplitude modulated using the external signal. The latter gives us opportunity to transmit the informational signal by means of highest harmonics of generation.

To model the data transmission using the semiconductor superlattice we considering the method of the amplitude modulation. We input the informational signal with frequency 500 MHz, which realization is shown in Fig. 1 (b), to the system under study, and the amplitude of external signal is adequate to effect the current oscillations in the superlattice. By the way, the applied voltage strongly effects the frequency of charge transport in the superlattice, that could make the amplitude modulation inapplicable for using the superlattice as a carrier of external signal. But using the external resonator, tuned to the high frequencies stabilizes the fundamental frequency of generation in superlattice.

Figure 1 (c) shows the time realizations of modulated signal, obtained by application of informational signal to the superlattice in external resonator. One can see, that external signal strongly effects the amplitude of local maxima of current oscillations, i.e. on the charge concentration in the domain propagating through superlattice. The large maxima, that determines the exit of charge domain from nanostructure in well-modulated as well.

To define the possibility to transmit the information on highest harmonics we compare the spectrums of autonomous and modulated current oscillations in superlattice coupled to external resonator. The spectrum, corresponding to the autonomous case is shown in Fig. 2 (a). One can see, that spectrum presents itself a composition of equidistant sharp spikes corresponding to the fundamental frequency of charge transport in superlattice and it's harmonics. The application of the external signal causes the appearance of satellites near the main frequency and highest harmonics, that is reflected in Fig. 2 (b). The appearance of satellites on high frequencies evidences, that we can use one of the highest harmonics of current oscillations in superlattice to transmit the informational signal via amplitude modulation.

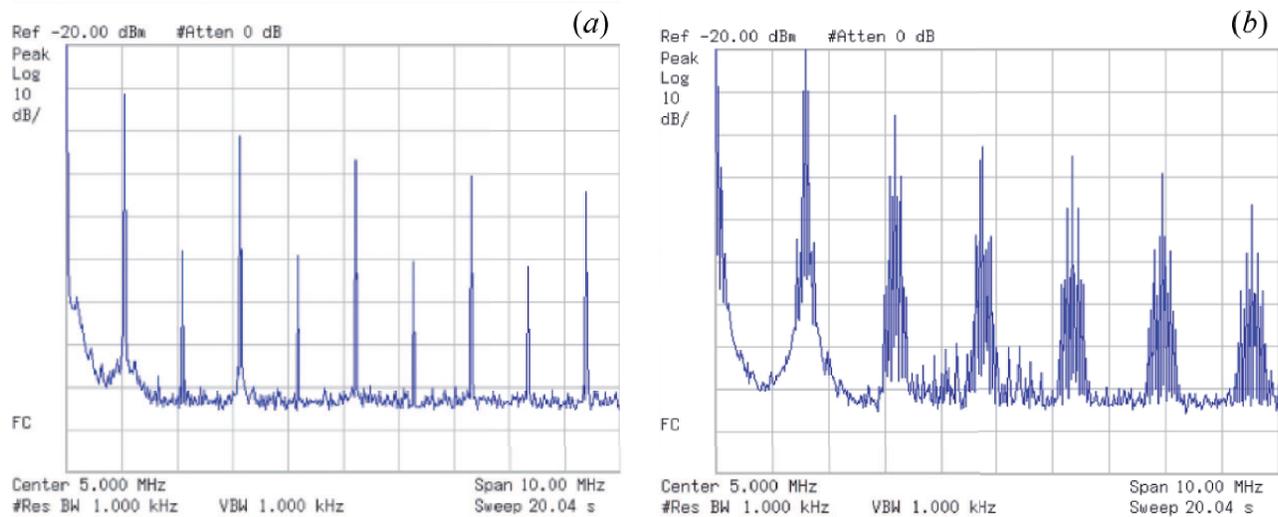


Figure 3. The power spectra of the carrier signal (a) and the modulated signal (b), obtained in experimental low-frequency setup.

In our experimental study a standard square wave generator with a frequency $f_n = 1 - 2.5$ MHz was used as a carrier generator. As an information signal generator we used the standard generator of harmonic oscillations with frequency $f_i = 10 - 50$ kHz. This signals enter the inputs of the amplitude modulator. The high-pass filter with a cutoff frequency $f_1 = 100$ kHz isolates the modulated signal from the modulating one. After the amplifier output signal goes to the receiver input. The receiver high-pass filter with a cutoff frequency $f_2 = 5$ MHz selects the highest harmonics of the modulated signal, providing the receiving of signal at 3-7 harmonics of carrier frequency. The filtered signal is amplified and goes to the amplitude detector.

The data transmission was successfully performed using the defined setup. The Fig. 3 (a) shows the power spectra of carrier signal. One can see, that spectrum exhibit multiple highest harmonics, that is determined by the square form of the impulse signal. The modulated signal, which is presented in Fig. 3 (b), shows the appearance of satellites near the main frequency of carrier and its highest harmonics. The good correspondence between the numerical simulations and the experimental study can be concluded.

4. CONCLUSIONS

In this paper we report the results of the study of data transmission using the semiconductor superlattice coupled to external resonant system. We show, that highest harmonics of current oscillations in superlattice can be used to transmit the informational signal, which frequency is much lower than the frequency of the transmission channel. We believe, that this study will be interesting for development of new sub-THz and THz devices for perspective biomedical applications.⁵

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