Superlattices and Microstructures 70 (2014) 70–81

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices

Solitary electromagnetic waves in a graphene superlattice under influence of high-frequency electric field

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ARTICLE INFO

Article history:
Received 14 November 2013
Received in revised form 23 February 2014
Accepted 3 March 2014
Available online 18 March 2014

Keywords:
Graphene
Superlattice
High-frequency electric field
Nonlinear electromagnetic wave
Electromagnetic soliton

ABSTRACT

The electron spectrum of graphene superlattice is shown to be modified under the high-frequency electric field. Using this modified electron spectrum d'Alembert equation is written for the electromagnetic waves propagating in the graphene superlattice. Under certain conditions the d'Alembert equation is shown to take the form of double sine-Gordon equation. The solutions corresponding to the solitary electromagnetic waves are obtained. The shapes of these waves are shown to depend on the amplitude of the high-frequency electric field.

1. Introduction

Currently the investigations of strong electromagnetic (EM) fields influence on the optical and electric properties of graphene structures are of heightened interest among researchers [1–12]. Due to graphene unique properties, this material can be used in a large number of technological applications of micro- and nanoelectronics [2,10]. Graphene is also a perspective material for optical applications [13–16]. Optical properties of graphene and of its structures are studied theoretically and experimentally in [17–24]. The quasi-classical theory of nonlinear EM response of graphene was developed in

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http://dx.doi.org/10.1016/j.spmi.2014.03.008

[21,22]. In [20,22] the possible applications of graphene structures for generation of terahertz (THz) radiation were discussed.

The relativistic character of graphene electron spectrum leads to unusual electrodynamic properties of graphene-based structures in the conditions of intensive external EM fields [25–30]. The effect of a high-frequency (HF) EM radiation on the electron dynamics in graphene structures was studied in [31–41], where the gap opening in the energy spectrum of originally gapless graphene was predicted.

New opportunities for building of the optoelectronic devices can be opened by predicted nonlinear optical properties of the graphene-based structures [14–16]. The possibility of using of superlattices (SL) as a working medium of generators and amplifiers of THz EM radiation [42–44] induces the interest to the electron transport properties of graphene SL (GSL) [20,24,45–51]. Besides, THz radiation can have a significant effect on the electron transport in low-dimensional systems [52]. Influence of HF electric field on the electron transport in GSL was investigated in [40,48,53] with quasi-classical methods. Band gap opening effect on the bilayer GSL conductivity was studied in [51].

The SL is also the suitable medium for nonlinear and solitary EM waves generation [50,54–58]. For instance, to form the cnoidal waves and solitons in semiconductor SL a relatively small electric fields ($\sim 10^3$ V/cm) in compared with bulk semiconductors are required [54,55]. Therefore structures with SL are of fundamental and practical significance [42–44,59,60]. The work of so-called soliton memory register based on the possibility of solitons propagation in the SL was described in [59].

However low value of EM pulse duration in comparison with the relaxation time is known to be one of conditions for solitary wave observing [54,55,58,60–63]. The strong damping of solitary waves in SL leads to the EM pulse transit time does not exceed 0.1–1 ps. This fact is an obstacle to the possibility of their practical application for the information transferring over long distances. It explains the search of ways to amplify and stabilize the solitary EM waves [64]. In particular, such problem also arises in connection with the possibility of GSL using in laser physics for generating of ultrashort EM pulses.

In the generation of EM pulses and solitons the use of graphene-based structures is more preferable than the use of ordinary semiconductors due to the following reasons. Firstly, at present time scientists have found that graphene is an ideal material for the construction of lasers of ultrashort pulses. This fact is due to the graphene property of absorbing light in a wide wavelength range [14–16]. It is already being used at present. In [14–16] the possibility of using of graphene-based absorber to produce laser pulses with duration of less than 200 fs was demonstrated.

Secondly, the duration of the EM pulse in semiconductor SL is comparable with the relaxation time [20,55]. This fact leads to the strong damping of solitons in SL and is one of the reasons that EM solitons are not yet observed in ordinary semiconductor SL. To observe the solitons the production of semiconductor SL of high purity is required. The relaxation time in graphene is much more than that of semiconductor SL. Therefore instead of production of pure semiconductor SL the GSL can be used. The high mobility of charge carriers of graphene allows hoping that the EM solitons will be observed in GSL. In [58] propagation of 2π-pulses in ideal GSL was studied theoretically.

The stabilization of the solitary wave shape in SL can be obtained by HF EM radiation [40,61–63]. The presence of HF field leads to the dynamical modification of the SL electron spectrum so SL becomes to the medium with the population inversion under the certain values of HF field amplitude [61]. A similar situation was considered in [62,63], where taking the SL electron energy spectrum second harmonic into account was shown to lead to fundamentally new results. The effect of the HF electric field of the sinusoidal and cnoidal EM waves on the shape of the solitary EM wave in such SL was studied in [62,63] correspondingly. It should be noted that in [62,63] the propagation of nonlinear EM waves was described by the modified double sine-Gordon equation. The dynamical modification of the electron spectrum of graphene structures exposed to the HF EM radiation was investigated in [31–41]. The stabilization of the solitary wave by HF electric field and formation of so-called dissipative pulses in GSL were studied numerically in [40] where the quasiclassical approach was used.

Below we consider the effect of HF electric field on the electron spectrum of the GSL. The modified energy spectrum of GSL was obtained analytically by Kapitza method. This result is new and is different from the spectrum of semiconductor SL in the conditions of HF electric field [61]. The influence of HF field on the shape of the solitary EM waves propagating in GSL is studied. In particular, the EM pulse area is shown to depend on the HF field amplitude. The type of the solitons (2π-pulses, π-pulses, 0π-pulses) propagating in the GSL is shown to be regulated by HF field amplitude. Such situation is