Superlattices and Microstructures 75 (2014) 692–700

Contents lists available at ScienceDirect

Superlattices and Microstructures

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

Surface polaritons of one-dimensional photonic crystals containing graphene monolayers

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ARTICLE INFO

Article history:
Received 15 June 2014
Received in revised form 20 August 2014
Accepted 23 August 2014
Available online 18 September 2014

Keywords:
Photonic crystal
Graphene
Surface polariton
Tunability

ABSTRACT

We investigated theoretically the existence of surface polaritons (SPs) at the interface of a one-dimensional photonic crystal containing graphene monolayers. It is shown that the structure has a new type of the photonic band gap in the THz region which is strictly omnidirectional for the TM-polarization and can support the SPs for both TM-polarization and TE-polarization. The results show that the characteristics of the SPs depends on the optical properties of the graphene sheets which can be controlled by a gate voltage. We plotted the electromagnetic field profiles of the SPs at the frequency range of the graphene induced band gap and a conventional Bragg gap of the structure. It is found that the SPs at the graphene induced band gap are more localized than the SPs at the Bragg gaps.

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1. Introduction

Surface polaritons (SPs) are a kind of electromagnetic normal modes, which propagate along the interface and have an evanescent behavior both sides of the interface with their electric and magnetic fields localized near the interface. The physical origin of the SPs are similar to that of the surface plasmon polaritons (SPPs) which exist at the interfaces of metal films. So, these modes can be considered to be an optical analog of the SPPs [1]. From this point of view, the SPs are very sensitive and convenient tools for studying the physical properties of the surfaces. Therefore, the investigations of SPs are

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http://dx.doi.org/10.1016/j.spmi.2014.08.025
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important from the scientific point of view and the practical applications [2]. During the past decade, SPs supported by semi-infinite one dimensional photonic crystals (1D PCs) have gained much attention due to their potential capability for many applications such as sensors, fluorescence emission enhancement, enhancement of the Goos-Hanchen shift [3–7]. This kind of SPs can be excited in a broad range of frequency by properly choosing the optical and geometrical parameters of the PC and modifying its photonic band gaps (PBGs). This capability can be considered as an advantage of the SPs comparing with the SPPs.

Until now, the optical properties of the PCs containing various kinds of materials including dielectrics, metals, semiconductors and metamaterials have been investigated [8–11]. Besides, the excitation of the SPs at the interfaces of the 1D PCs containing metallic layers, single-negative or double-negative metamaterials have been studied extensively [11–16]. Meanwhile, it is important to control the dispersion properties of the SPs by tuning the PBG of the PCs. This can be possible by controlling the optical properties of the constituent materials. So, it is highly appropriate to use the materials with externally controllable optical properties. In this regard, graphene monolayers can be a suitable option for using in the 1D PC structures.

Graphene, a single two-dimensional plane of carbon atoms forming a honey-comb lattice, is a gapless semiconductor with controllable electronic and optical properties [17]. High mobility of carriers, flexibility, robustness and environmental stability are the general features of the graphene [18,19]. At the THz and far-IR frequencies, the dissipative losses of the graphene is less than the usual metals and its electronic and also optical response is described by the surface conductivity which is related to its chemical potential and can be controlled and tuned by the external electric fields [20,21]. Due to these unique characteristics, people have been motivated to study the multilayer structures containing graphene sheets. For example, THz hyperbolic metamaterials and hyperlenses made of graphene multilayers [22–24] have been investigated, recently. Also, the excitation of the SPs in some kinds of graphene-based layered structures have been studied and experimentally realized by different research groups. As examples, Liu et al. showed that the absorption of the graphene on the top of a 1D PC is enhanced greatly due to photon localization [25]. Sreekanth et al., experimentally demonstrated the excitation of the surface waves in a graphene-based Bragg grating using prism coupling technique [26]. In another research, Sreekanth et al. investigated the propagation length of the plasmon waves in a graphene monolayer sandwiched by two identical anisotropic dielectrics [27]. Wang et al. theoretically studied the coupling between SPPs in monolayer graphene sheet arrays [28].

In Ref. [29], the authors investigated the PBGs of a 1D PC in which the graphene sheets were embedded between adjacent dielectric layers. They revealed that the structure has a new type of the band gap (the so-called graphene induced photonic band gap (GIPBG) in the THz region which is omnidirectional only for the TM-polarization; and its characteristic properties is different from the conventional Bragg gaps. In the present paper, we are interested to study the dispersion properties of the SPs at the interface of a semi-infinite uniform dielectric medium and a 1D PC containing graphene monolayers in the GIPBG. In our numerical analysis, we use the well known transfer matrix method [1] to calculate the PBGs of the 1D PC and the dispersion curves of the SPs. We show that the dispersion properties of the SPs can be controlled by tuning the chemical potential of the graphene sheets. Moreover, it is shown that the SPs at the GIPBG are more localized than the SPs at the Bragg band gaps.

2. Theoretical model

In this section we obtain the dispersion relation of the SPs propagating along the x axis situated at the interface between a dielectric uniform medium with the permittivity of ε_v and a semi-infinite 1D PC. The 1D PC consists of alternate layers A and B with the graphene monolayers between the adjacent layers. Here, A and B represent two isotropic dielectric materials with the permittivity of ε_A and ε_B, and thicknesses of d_A and d_B, respectively (Fig. 1). We assume that the PC is capped by a layer of the same material A but different width, d_c. We choose the layers to be parallel to the $x - y$ plane with the z axis normal to the interfaces of the layers. The general expression for the surface conductivity of the graphene monolayers can be written as [30]

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