Physica B 473 (2015) 7–10

Contents lists available at ScienceDirect

Physica B

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

Dynamically tunable Fano resonance in planar structures based on periodically asymmetric graphene nanodisk pair

Zhengren Zhang [a], Xiaopeng Su [b], Yuancheng Fan [c], Pengfei Yin [a], Liwei Zhang [d], Xi Shi [b,*]

[a] School of Science, Chongqing Jiaotong University, Chongqing 400074, China
[b] Department of Physics, Tongji University, Shanghai 200092, China
[c] Key Laboratory of Space Applied Physics and Chemistry, Ministry of Education and Department of Applied Physics, School of Science, Northwestern Polytechnical University, Xi'an 710129, China
[d] School of Physics and Chemistry, Henan Polytechnic University, Jiaozuo 454000, China

ARTICLE INFO

Article history:
Received 8 March 2015
Received in revised form
20 April 2015
Accepted 23 May 2015
Available online 3 June 2015

Keywords:
Graphene
Fano resonance
Surface plasmons

ABSTRACT

We present a dynamically frequency tunable Fano resonance planar device composed of periodically asymmetric graphene nanodisk pair for the mid-infrared region. The two asymmetric graphene nanodisks can be directly excited by the light simultaneously and produce two kinds of reflected light with almost the same spectrum linewidth. By studying the local field distributions of our structure, we find that there are two kinds of modes for the two asymmetric graphene nanodisks, i.e., the symmetric mode and antisymmetric mode. Resonance coupling between the symmetric and antisymmetric modes generates the Fano resonance in our structure. This Fano resonance generation mechanism is different from it in traditional Fano resonance structure. In the traditional Fano resonance structure, the Fano resonance comes from the coupling effect between continuum and discrete structure. Moreover, we find that both of the Fano resonance amplitude and frequency of the structure can be dynamically controlled by varying the Fermi energy of graphene. Resonance transition in the structure is studied to reveal the physical mechanism behind it.

1. Introduction

Quantum interference in atomic system has led to several fascinating and extraordinary effects [1,2]. One of the most interesting phenomena is Fano resonance, which originates from the quantum-mechanical interference between a discrete excited state of an atom and a continuum sharing the same energy level [3,4]. Other than the Lorentzian resonance, the Fano resonance possesses a distinctly asymmetric line profile, and it has been found in classical optical systems [5]. Recently, the Fano resonances have also been observed in several plasmonic nanocomplex, and have found its application in switching [6], slow light [7], sensing [8], etc. Due to the interesting physics and abundant applications, generation of physical phenomena equivalent to Fano resonance at terahertz (THz) frequencies is currently one of the most exciting topics of plasmonics research [9,10]. It is known that the noble metal can support surface plasmons (SPs) in THz frequencies [11]. Thus, it is widely used to construct plasmonic nanocomplex to realize the Fano resonance. Nevertheless, metallic plasmonic nanocomplexes at infrared and visible wavelengths present significant challenges due to bulk plasmon losses. Bulk losses may be mitigated through the use of very thin noble metal films; however, fabrication of uniform thin metal films is experimentally challenging [12]. Additionally, the tunability of metal is difficult to achieve. In the normal case, to achieve the dynamically tunable Fano resonance, we need in carefully reoptimizing and amplifying or reducing the geometric parameters of the metal structures. This method is troublesome and is not the dynamic control in the true sense. These factors of the noble metal limit the practicality of the Fano resonance for a wide variety of applications.

Graphene, a two dimensional material with only one carbon atom thick, since its exfoliation from graphite [13], has become a well-known material with unique optical and electrical properties [12,14,15]. As it supports SPs with both high confinement and relatively low loss [13,16–19], graphene shows some advantages over metals for plasmonic devices, especially in THz spectral range. Moreover, the dielectric properties of graphene can be dynamically tuned by electrochemical potential via a chemical or electrostatic gating, magnetic field, or optical excitation [20–22]. This allows for the creation of surface plasmon based devices that can be effectively turned on and off or tuned to be active at different

* Corresponding author.
E-mail address: xishi@tongji.edu.cn (X. Shi).

http://dx.doi.org/10.1016/j.physb.2015.05.030
0921-4526/

frequencies. Therefore, it would be a meaningful work to construct a graphene nanocomplex to achieve the dynamically tunable Fano resonance.

In this paper, we present a controllable periodic structure with its unit cell composed of two asymmetric graphene nanodisks (the size of them is almost the same) for the excitation of Fano resonance. The two asymmetric graphene nanodisks are excited directly by the light at the same time and produce two kinds of reflected light with almost the same spectrum linewidth. By studying the local field distributions of our structure, we find that there are two kinds of modes for the two asymmetric graphene nanodisks, that is, the symmetric mode and antisymmetric mode. In the case of symmetric mode, the two disks support in-phase oscillations and provide a much broader superradiant dipole mode (strongly coupled to free space). In the case of antisymmetric mode, the two disks support out of phase oscillations and provide a subradiant mode (weekly coupled to free space). The coupling between the two modes generates the Fano resonance. This kind of Fano resonance generation mechanism in our structure is different from it in the traditional Fano resonance structure. In the traditional Fano resonance structure, the Fano resonance comes from the coupling effect between continuum and discrete structure, i.e., one structure provides a broad spectrum and the other structure provides a narrow spectrum, the destructive interference between the two structures leads to Fano resonance. Moreover, we find that the frequency-shift active control of Fano resonance can be realized by varying the Fermi energy of the graphene without reoptimizing and refabricating the nanostructures. The resonance transition in the structure is demonstrated to well explain the physical mechanism of it.

2. Proposed designs

The schematic of the asymmetric graphene disk nanostructure is presented in Fig. 1 (the graphene sheet has the thickness of $d=1$ nm). The radii of the two graphene nanodisks in the unit cell are R_1 and R_2, respectively. The two asymmetry graphene nanodisks are on the same plane, and the distance between them is denoted by g ($g=68$ nm). We suppose that the structure is surrounded by air for simplicity and illuminated along the z direction. The designed structures are investigated in the mid-infrared frequency range at around 25–40 THz.

All the designed graphene-based planar structures in this paper are numerically studied by utilizing the commercial package CST Microwave Studio. The conductivity of graphene σ is computed within the local random phase approximation limit at the zero temperature [23], which can be written as

$$\sigma(\omega)=\frac{ie^2E_F}{\pi\hbar^2(\omega+i\tau^{-1})}+\frac{e^2}{4\hbar}\left[\theta(\hbar\omega-2E_F)+\frac{i}{\pi}\left|\frac{\hbar\omega-2E_F}{\hbar\omega+2E_F}\right|\right]$$

$\tau=\mu E_F/ev_F^2$ is the relaxation rate with $\mu=10^4\ \mathrm{cm^2/V\,s}$ and $v_F\approx 10^6$ m/s, the mobility and Fermi velocity, respectively. $E_F=\hbar v_F\sqrt{\pi|n|}$ can be easily controlled by electrostatic doping via tuning charge-carrier density n. In the mid-IR frequency range, such a conductivity form indicates strong plasmonic response. As can be seen from the equation, changing the Fermi energy enables the control of the propagation characteristics of the graphene plasmons.

3. Results and discussion

To begin with, the reflectance spectra of graphene nanostructures with only one nanodisk (81 nm or 84 nm in radius, the Fermi energy is set to be $E_F=0.5$ eV) in the unit cell are presented in Fig. 2. For the small graphene disk periodic nanostructure, there is a reflected peak in its reflection spectrum at $f=30.72$ THz. For the big graphene disk periodic nanostructure, the reflected peak appears at $f=30.18$ THz. The reflected peaks for the two kinds of structures in the reflection spectrum are caused by the exciting of SPs resonance in graphene nanodisks. It is known that the phase-advance oscillation appears below the resonant frequency and delayed phase oscillation occurs above the resonant frequency in a resonance system. From Fig. 2 we can find that the small and big graphene disk periodic nanostructure exhibit different behavior for the external field response at the range of 30.18–30.72 THz and the same behavior at other frequency range. Thus, a combination of the two structures will lead to the occurrence of constructive and destructive interference, which can produce Fano resonance.

Subsequently, we investigate the periodically asymmetric graphene nanodisk pair structure which has two graphene nanodisks in the unit cell (see Fig. 1(a)). As we expected, there is an asymmetric Fano line-shape appears in the reflectance spectrum, as shown in Fig. 3(a). How do we understand the origin of the Fano resonance nature on this system? In order to reveal the mechanism behind the Fano resonance of this structure, Fig. 3(b)–(d) shows the field distributions in the disks' cross section at certain frequencies. The corresponding frequencies are also marked in Fig. 3(a). From Fig. 3(b)–(d) we can find that the field distributions exhibit a symmetric mode at $f=29.74$ THz, 31.12 THz (we find that the field distribution in I and III are also symmetric mode), and exhibit an antisymmetric mode at $f=30.18$ THz (we find that the field distribution in II is also antisymmetric mode). In

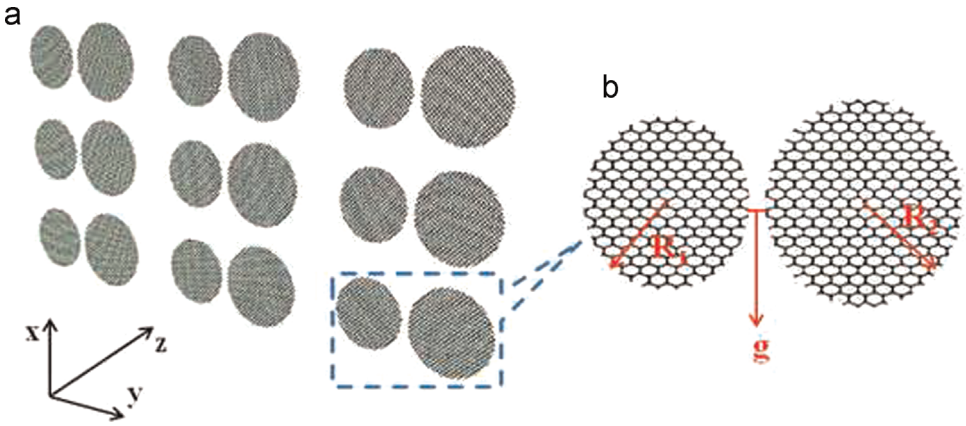

Fig. 1. (a) Schematic model of graphene disk nanostructures. (b) A unit cell of structure of our design. Geometric parameters are denoted by red letters. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)