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Fano resonance in a U-shaped tunnel assisted graphene-based nanoring resonator waveguide system

Buzheng Wei *, Shuisheng Jian

Key Lab of All Optical Network & Advanced Telecommunication Network of EMC, School of Electronic Information and Engineering, Beijing Jiaotong University, Beijing 100044, China

Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

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ABSTRACT

A U-shaped tunnel connected side coupled nanoring resonator waveguide system is proposed to generate Fano interference in a novel mechanism. By mutually coupling the infrared light through the artificially introduced U-tunnel to the two nanorings with the same resonant wavelength, single symmetric Lorentzian resonance transforms to asymmetric Fano resonance within the original resonant spectral range. The transparency window bridges the distinct constructive interferences in either rings instead of the canceling the bright mode resonance compared to former conceptions. The sensitivity of the system reaches 167 $\mu m/RIU$ far higher than the level of hundreds nanometers and is highly tunable. The light at resonance is successfully trapped and slowed down to 1/144 times the speed in vacuum, which is also flexible to release by tuning the Fermi energy of graphene rings. Overall, our ideas may pave new avenues to the design of classical analogy of Fano resonance metastructures, sensors or light storage devices.

1. Introduction

Fano resonance stands for a process when an autoionized discrete state interferes with a continuum one characteristically giving asymmetric rise within the low absorption profile [1]. The findings of Fano resonance concentrate on the atomic use in early days, which hinders the application to a great extend due to its extreme experimental conditions and the difficulty to find proper nonlinear materials [2]. Recently, scientists and researchers focus on the classical manipulation of Fano line shaped resonance intensively in plasmonic nanostructures [3] or metamaterials [4] and earn remarkable achievements both theoretically [5] and experimentally [6]. Most previous studies exhibit the analogy of quantum state interference in metastructures consisting of a bright mode and a dark mode [7]. When destructive interference cancels the initial resonance in the bright mode, the dark mode becomes populated [8] resulting in an asymmetric transparency peak in the broad absorption spectral range. To achieve the direct interference between these two states, the mode resonators need to be well designed so that energy exchange happens in a specific way. Alternatively, if the resonance in two mode resonators is factitiously led to interfere with one another [9], similar results can be observed but not following the analogue method mentioned above. It is more likely to be treated as the superposition of different resonances.

In our former researches [10–14], we have utilized graphene as a highly tunable material to build metastructures and achieved electromagnetically induced transparency (EIT) in several samples. As a famous candidate for newly emerged family of integrated metamaterials, graphene occupies an outstanding performance status embodying in its surface gate controlled conductivity [15], low dissipation loss [16], tighter interface localization [17] and ultra fast carrier mobilities at room temperature [18], only to name a few. Moreover, graphene possesses a 2-D electronic system composed of a single atomic layer of carbon atoms arranged in a hexagonal crystal lattice, which enables a gapless semiconducting property and a massless linear electron–hole dispersion [19]. Most inspiringly, different from electric or magnetic independent material that needs heating or pressure to change refractive index, permittivity or permeability, graphene's conductivity largely depends on passive chemical doping [20], active external static bias voltage or external static magnetic field [21]. This property ensures a wind tunable band from mid-infrared to terahertz regime without breaking or refabricating the device. Here, we list a few contributions related to graphene-based Fano resonance in recent years. Chae investigated the

* Corresponding author at: Key Lab of All Optical Network & Advanced Telecommunication Network of EMC, School of Electronic Information and Engineering, Beijing Jiaotong University, Beijing 100044, China.
E-mail address: 14111010@bjtu.edu.cn (B. Wei).

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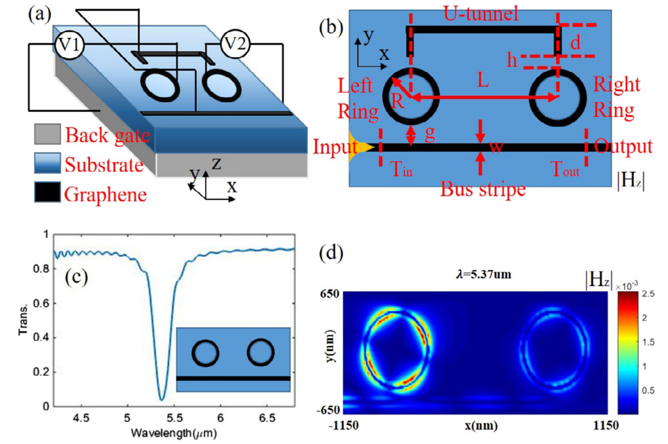

Fig. 1. (a) 3D model of the proposed structure. The gate voltage source is applied linking the graphene layer and the back silicon gate. (b) Top view of (a). The outer radii of the two rings are all R while the width of the graphene ribbon is uniformly w. The separation between the two rings from the circle center is L and center aligned with the x-direction component of the U-shaped strip. The length of y-direction part is d. The distance from the bottom of this strip to the top of each circle is all h and the gap between the bus waveguide and the bottom of each circle is g. $T_{in/out}$ stands for the two monitors inspecting the input/output power. (c) The transmission spectrum without the U-shaped tunnel shown in (b) and the parameters are $g = 50$ nm, $w = 50$ nm, $R = 300$ nm, respectively. The inset shows a simplified model of (b) without the tunnel. The Fermi energy of graphene ribbon is all 0.6 eV. (d) The z component magnetic field amplitude distributions at resonant wavelength 5.37 μm.

absorption of free-standing monolayer and bilayer graphene in ultraviolet region and the line shape was dominated by an asymmetric Fano resonance [22]. The excitonic resonance was attributed to couple to the Dirac continuum and the experimental data was quantitatively traced all way down to the infrared. Naresh.K fabricated a graphene-nanoantenna hybrid device which enabled efficient electrical modulation of Fano resonance at approximately 2 μm and was numerically verified by full-wave 3D finite-element simulations [23]. Zheng proposed a new configuration of graphene-MoS_2 hybrid structure for ultrasensitive detection of molecules which displayed an enhancement factor of sensitivity by intensity more than 2×10^{3}-fold when compared to the surface plasmon resonance sensing scheme [24]. These researches pave ways in many application areas such as sensing [25], optical storage [26], switching [27] and invisible cloaks [28].

In this paper, we introduce a U-shaped tunnel to guide the incident wave from a side coupled ring resonator to the other and artificially build two resonant dips on the shoulder of a transparency window. Differently, there exists no excitation pathway destructive interference which is usually utilized in the classical optics analogy of Fano resonance based metastructures. The tunability is systematically investigated in the numerical simulation section which is verified using the Finite difference time domain method. By properly designing the tunnel length, different order of modes share Fano line in the resonant spectrum. Finally, the slow light effect in this system is studied.

2. Analytical analysis

As cognitive universality, the transmittance of a side ring-resonator-coupled stripe waveguide presents a trough at oscillation frequency within the high transmission profile. The oscillation valley depth and width announce a relationship with Lorentzian line defined damping factor, oscillation frequency and other fitting constant parameters [6]. Still, if two ring resonators with the same resonant frequency do not couple with each other directly and are placed at the same side of the stripe waveguide, only one oscillation trough remains to be observed. This phenomenon is proved in Fig. 1(c). The inset of Fig. 1(c) indicates the top view of Fig. 1(a) without the U-tunnel. The magnetic field in Fig. 1(d) explains that at resonant frequency, the light energy firstly traps in the left ring resonator forming a steady standing wave and the bypassed light coupling to the right resonator forms extremely weak resonance. Without the direct coupling between the two resonators, Fano resonance cannot be generated accordingly. Therefore, we introduce a connection to guide the wave from the left resonator to the right one to construct interference and generate Fano resonance. As shown in Fig. 1(b), the U-shaped tunnel waveguide is responsible for forming the interference process.

Here, by adding a guided wave tunnel, five energy traveling pathways are therefore constructed. The first is that the light directly travels from input port to the receiving port without coupling to any resonators. Second, the light only couples to the left one and then goes to the receiving port. Third, in contrast, the light only couples to the right. Fourth, the light couples with both resonators by not going through the tunnel but the bus stripe waveguide. Final one, the light firstly couples to the left ring and then goes through the U-tunnel to generate resonance in the right ring and then leaves through the receiving port. The light traveling in this way can generate interference with that from other ways. The diagram representations of these five pathways are highlighted with different colors in Fig. 2(b–f). Actually, a transfer matrix method [29,30] can be applied to elucidate the whole process in this waveguide system. For the sake of simplicity in the theoretical analysis, the first four ways are concluded as the one discrete state and the fifth is the other. The five pathways electric field amplitude spectra according to [30] are correspondingly plotted in Fig. 3(d) and (e). The first four ways are separate parts of the first discrete state so the combination transmission is plotted in Fig. 3(b), as well as the fifth way in Fig. 3(c). According to the transfer matrix, the fitting curve of the whole transmission is plotted in Fig. 3(a). Around the coincident resonance wavelength, the two discrete states mutually couple together, and asymmetrical Fano resonance appears [30]. However, one must notice that the fifth ways intensity is much weaker than the others which makes the interference almost invisible. Therefore, the Fano interference from the mutually coupled resonators seems unpersuasive. Actually, the fitting parameters change may bring significant influences to the spectral responses. Hence, we should point out here that by altering the gap distance, h or the tunnel length in either side ring resonator in the simulation setup, each way's transmission can be accordingly modified to seek a better Fano performance with balanced impact from each state, i.e., the fifth way influence can be enlarged intensively when a proper geometry is designed. Since this process can be time and memory consuming but under the same mechanism, we use this dimensional design here expecting future optimizations. An important parameter of the Fano system is the dephasing time calculated by $T_d = 2\hbar/FWHM$ [31,32]. $FWHM$ corresponds to the frequency domain full width half maximum and $\hbar$ is the reduced Planck's constant. For the main dip in Fig. 2(a), the dephasing time is 2.23 ps.

However, according to our former study [11,12], Fano resonance formed in such systems is attributed mainly to two mechanisms. One is by mimicking different excitation pathways in atomic systems that the transparency state cancels the resonance in the bright mode [11] and the other way is to split resonance level [12]. Apparently, in this paper, the design cannot be classified into these two items. The magnetic field distributions of the two dips and the transparency peak in Fig. 2(a) are plotted in Fig. 4. First, from Fig. 4(b) we can see that the transparency state at 5.32 μm does not cancel any oscillations in either rings. On the contrary, both rings and the U-tunnel are enhanced in resonance. The light coming from different pathways constructively interferes with each other in both rings. Second, at 5.26 μm, the left ring is originally supposed not to be excited without the U-shaped tunnel but presents a stronger resonance when the bridge is built, similar to the initial single resonance at 5.43 μm in Fig. 2(a) and at 5.37 μm in Fig. 1(c). Because the two resonators share the same resonant frequency, energy level splitting