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Analysis of asymmetry of Fano resonance in plasmonic metal-insulator-metal waveguide

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ABSTRACT

A Fano resonance has stimulated interests due to its asymmetrical resonance profile. Fano resonance generally emerges due to coupling and destructive interference between two resonating modes having disparate quality factors. This coupling between modes leads to an asymmetrical resonance profile which makes Fano resonance quite distinct from the traditional Lorentzian profile. Asymmetry is a key feature of Fano resonance. It is examined using Complex plane analysis and redefined using Reflection Argand diagram. The newly defined parameter named as Argand Asymmetric ratio (ρ) is in line with the previously defined asymmetrical factor of Fano resonance. This newly defined parameter (ρ) is also studied against coupling and frequency detuning between resonating modes. The parameter is also numerically investigated by exciting Fano resonance in a pair of resonators coupled MIM (Metal-Insulator-Metal) waveguide using the OptiFDTD tool. The newly defined parameter can find its way in analyzing different Fano resonance based applications like as optical buffers, sign reversal Fano tuning, switches, modulators, etc.
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1. Introduction

The Fano resonance effect has attracted the attention of researchers due to its promising applications including biological and chemical sensing [1], Electromagnetically Induced transparency [2], slow light control [3]. Fano resonance is a unique phenomenon which is based on quantum interference effect [4]. It occurs due to interference between a discrete energy state and continuum spectrum of elementary excitation. The effect was firstly explained by Ugo Fano in 1961 [4]. In classical analogy, Fano effect can be modeled using two weakly coupled harmonic oscillators, in which one of the oscillators is driven by a periodic force while another is driven by first oscillator [5]. The eigen frequency of both the resonating structures is so close to each other so that they interfere with each other to give an asymmetrically shaped resonance [5]. This asymmetrically shaped resonance is completely different from traditional Lorentzian resonance profile. In the last decades, researchers have proposed that Fano resonance can also be excited in Terahertz regime using photonic crystal [6], plasmonics [7], and Metamaterials [8,9]. The Fano resonance has stimulated a huge interest in surface plasmon polaritons (SPPs) based nanoplasmonic structure because of its ability to overcome the diffraction limit and confine light in sub-wavelength dimensions [10,11]. Many structures based on plasmonic waveguides have been designed previously to achieve the Fano resonance [2,3,7–12]. Fano resonance can be excited in plasmonic structures mainly by two major effects: Firstly, by breaking the symmetry in the perfect structure such as the asymmetric stub pair in Metal-insulator-metal (MIM) waveguide [2], asymmetric plasmonic nanoclusters [12], broken symmetry in ring or disk cavities [13], and the asymmetric T-shape single slit [14], and secondly, by using the coupled-resonator system like cavity–cavity interference [15], the coupling of plasmonic nanoclusters [16] etc. Fano resonance is excited in coupled plasmonic system due to hybridization of different plasmon modes supported by two or more resonating structures and this hybridization leads to an asymmetrical resonance profile [17,18]. Asymmetry is a key parameter of Fano resonance and it can be used to model the resonance profile [2,7]. Kumar demonstrated the transition of Fano line from symmetry to asymmetry using a single factor (q) which characterizes Raman line [19]. Recently a tunable nanoplasmonic sensor based on the asymmetric degree of Fano resonance in MDM waveguide is proposed by Zhan et al. [20]. The Fano resonance excited in a coupled resonator systems, mainly depends on the coupling and frequency detuning between resonating ρ modes [21]. The asymmetry of the resonance can be tuned by changing either of the parameters.

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Here, we have analyzed asymmetrical nature of Fano resonance using complex plane analysis. A new parameter named as asymmetric Argand ratio (ρ) is defined to measure the degree of asymmetry in Fano resonance. The ratio ρ is in line with the asymmetric parameter of Fano resonance reported previously [19,20]. ρ is also studied against changing coupling and frequency detuning parameter. The uniqueness of the factor lies in the fact that the parameter ρ not only measures the amount of asymmetrical nature of Fano resonance effect but also provides information regarding sign of the interference. The parameter is also validated by exciting Fano effect in a pair of resonators coupled MIM-based Plasmonic waveguide. The resonances can be swept each other during the tuning process by tailoring the physical separation between resonating stubs. The asymmetric Argand ratio also varies by changing separation between resonators. Therefore, the defined ratio is apposite for applications in sign reversal Fano tuning, optical buffers, switches or slow light based applications.

2. Theoretical formulation of Fano-resonance based reflection spectrum

A theoretical formulation based on temporal coupled mode theory (CMT) is presented to study the effect of coupling and interference between two resonating modes [22,23]. Let the two resonating modes resonating at frequencies ω_1 and $\omega_2$have mode amplitude a_1 and a_2 respectively. The interaction between both the resonating modes can be governed using Eq. (1) [22].

$$\left.\begin{aligned}\frac{da_1}{dt} &= (i\omega_1+\gamma)a_1+\Omega a_2+ik_1s^+\\ \frac{da_2}{dt} &= (i\omega_2+\gamma)a_2+\Omega a_1+ik_2s^+\end{aligned}\right\} \quad (1)$$

According to the principle of energy conservation

$$s^- = ks^+ + ik_1a_1 + ik_2a_2 \quad (2)$$

where s^+ and s^- are flux entering into the input waveguide and reflected from input waveguide respectively, k = direct scattering of the incident flux without exciting resonant mode, Ω is the coupling parameter that defines the degree of coupling between both the resonating modes, and $k_{1(2)}$ is coupling coefficient between external flux and different resonating modes. Combining Eqs. (1) and (2) gives complex reflection coefficient equal to:

$$r = \frac{s_-}{s+} = \frac{k_1^2(i\omega_2 - i\omega + \gamma)}{(i\omega_2 - i\omega + \gamma)(i\omega_1 - i\omega + \gamma) + \Omega^2} \quad (3)$$

Here, γ is the loss (radiative or non-radiative) in the circuit. The reflectance is defined as $R = |r|^2$. Equation $\omega_{2,3}$ represents completely asymmetrically shaped resonance with a sharp dip at frequency

When the system satisfies the condition of degeneracy ($\omega_1 \approx \omega_2$), coupling results in so-called Electromagnetically Induced transparency (EIT) and is characterized by a sharp transition in the middle of the resonant spectrum [12]. The reflection spectrum is studied for changing coupling and frequency detuning parameter in the next section.

3. Complex plane analysis of Fano resonance spectrum

The coupling parameter (Ω) plays an important role in shaping the Fano resonance. Fig. 1 shows the reflection spectrum for different values of Ω and constant frequency detuning parameter ($\Delta\omega = 0.07$). The resonance spectrum proves that initially when coupling parameter is low, resonance profile is highly symmetrical (shown in Fig. 1(a)) but with the increased value of coupling

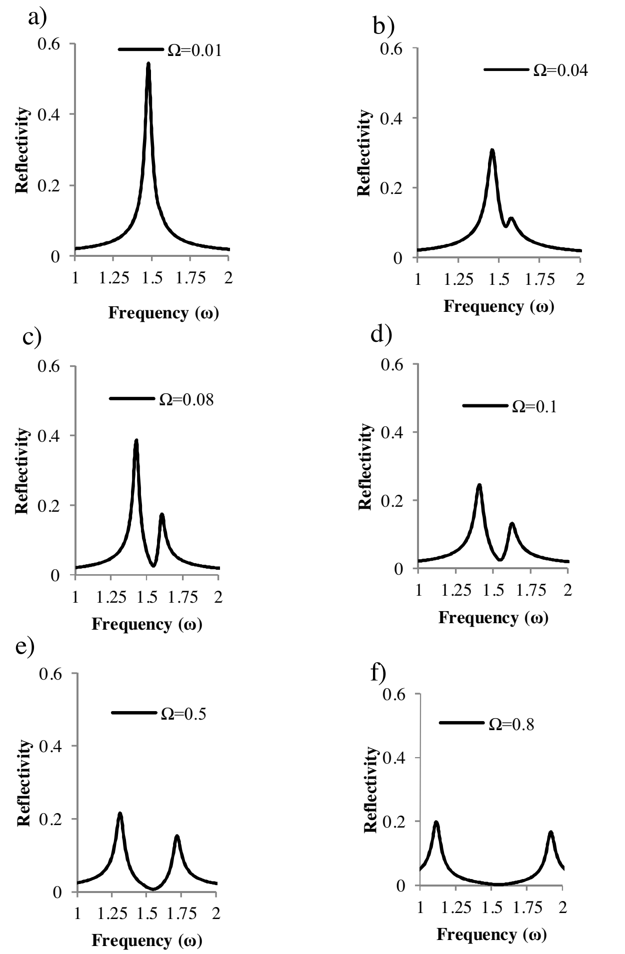

Fig. 1. Reflection spectrum (obtained by CMT) with following assumed parameters:$\omega_1 = 1.48ev$,$\omega_2 = 1.55ev$, $\gamma = 0.018ev$, and with different coupling parameters.

parameter symmetrical line turn into asymmetrically shaped profile. The resonant frequency of the narrow dark mode overlaps with the spectrum of broad bright mode and shows completely asymmetrically shaped resonance, which is known as Fano resonance. The reflection spectrum becomes more and more asymmetrical for increased value of coupling coefficient.

Thus, an asymmetrical parameter of Fano shaped resonance profile can be tailored by changing the coupling parameter. Asymmetry parameter is an important factor of Fano resonance that defines the shape of resonance. Fano resonance is excited in coupled plasmonic system due to hybridization or destructive interference between different plasmon modes supported by two or more resonating structures [17,24]. The hybridized modes can be categorized in bright and dark modes. Bright modes can easily couple to electromagnetic excitation and can radiate efficiently and thus, bright Plasmon modes are spectrally broad while dark modes are not radiative broad and exhibit weak radiative coupling to incident excitation [24]. Excitation of Fano resonance demands coupling and interference between both the dark and bright modes [17,18,24]. It can be seen from Fig. 1 that as the coupling is increased, the separation between the two resonant peaks also increases but the frequency of the dip remains constant. This resonance dip in the curve shows the frequency of dark mode. If the coupling is increased after a limit, both the modes do not couple to destructively interfere as the frequency of the dark mode does not lie within the broad spectrum of bright mode and it leads to two distinct resonant peaks.

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