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Fano Resonance in Coupled Semicylindrical Microresonators

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H. Haroyan, T.Yezekyan, H. Parsamyan, A. Ninoyan

Yerevan State University, Alex Manoogian str. 1, 0025, Yerevan, Armenia

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Abstract: A system of two, coupled semicylindrical microresonator with relatively simple excitation by a plane wave is studied and Fano resonance was obtained there. The resonator is formed on the base of a dielectric/metal/dielectric structure, where the wave energy penetrates into the resonator through a thin metal layer and is stored in a semicylindrical dielectric with high permittivity. The proposed microresonator combines the steep dispersion of the Fano resonance profile and compactness of the semicylindrical system. The control of evanescence coupling between two resonators is realized by varying the distance between resonators. Numerical analysis is carried out to investigate the process of tuning the system under the conditions of Fano resonance and further control over the coupling.

Keywords: Fano resonance, semi-cylindrical, microresonators, evanescence coupling.

1. Introduction

Efficient and low-loss optical coupling to high quality (Q) factor Whispering Gallery Mode (WGM) microresonators [1] is important for a wide range of applications include frequency [2,3] and soliton mode-locked microcombs [4–8], bio and nano-particle sensors [9–11], cavity optomechanical oscillators [12], Raman lasers [13], and quantum optical devices [14,15]. Usually, to achieve phase-matched and mode-matched evanescent wave efficient coupling, it is necessary to use a host material of resonator with relatively low refractive index compared to those of standard waveguide coupling materials. In addition, fiber tapers as unclad waveguides are quite brittle and applicable only for resonators, refractive index of which is close to the refractive index of fiber. Hence, for waveguide coupling regime it requires tens or hundreds micrometer diameters of coupling region to achieve effective phase-matching. At the same time, for Biosensing purposes, binding of single virions is observed from discrete changes in the resonance frequency of a WGM excited in a microcavity. It is shown, that the magnitude of the discrete wavelength-shifted signal can be sufficiently enhanced by reducing the microsphere size [9,16]. On the other hand, the effective control of the light wave as a rule is realized using materials with a large refractive index.

Recent developments have greatly improved the sensitivity of optical sensors based on metal nanoparticle arrays and single nanoparticles. This kind of sensors is used for biosensing purposes that is to detect molecular binding events and changes in molecular conformation. The device is based on biological, or bioinspired receptor unit with unique specificities toward corresponding analytes. These analytes are often of biological origin like DNAs of bacteria or viruses, or proteins which are generated from the immune system (antibodies, antigens) of infected or contaminated living organisms. Still, one of many other challenges in biosensor development is the sensitivity.

Meanwhile, since its discovery, the asymmetric Fano resonance has been a characteristic feature of interacting quantum systems. Recently, the Fano resonance has been found in plasmonic nanoparticles, photonic crystals, and electromagnetic metamaterials and there are several papers on the use of that effect for biosensors.

In one of our previous works, we proposed a simple system consisting semicylindrical microresonator, which can be used as a biosensor [16]. In present paper, our aim is to combine the steep dispersion of the Fano resonance profile and compactness of the semicylindrical system to obtain more sensitive device due to high Q-factor.

Here we propose a structure, which consists of two coupled semicylinders with different radii (it is necessary for having different resonant conditions) placed on metal thin layer; an incident plane wave is used to excite resonators (see Fig.1). The main advantage of this structure is the easy coupling method with incident plane wave. Resonator system combines properties of Fabry-Perot resonator, where the input of wave energy is carried through mirrors, and cylindrical resonator, where Whispering-gallery modes with azimuthal m and radial l mode numbers are formed. Here, the possibility of simple input and output of radiation is combined with the possibility of using the unique properties of an evanescent wave on cylindrical surface of a dielectric. The control of evanescence coupling between two resonators is realized by varying the distance between resonators.

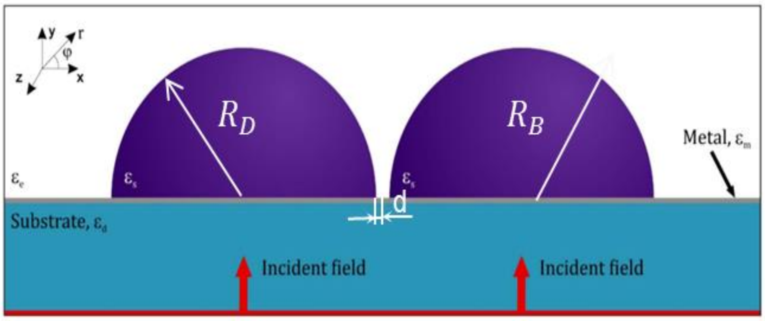


Fig. 1. The cross section of the structure of coupled semicylindrical microresonators with different radii. $\varepsilon_d = 2.25$, $\varepsilon_e = 1$ are dielectric permittivities of the substrate (SiO2 Silica) and the surrounding medium (Air), respectively. As a metal and semicylinder medium Ag and GaAs (ε_s) were used correspondingly.

Fano resonance is a type of resonant scattering phenomenon that gives rise to an asymmetric line-shape and it occurs when a discrete quantum state interferes with a continuum band of states. The nature of the asymmetry was established with the theory of configuration by Fano in 1961 [17].

The microscopic origin of the Fano resonance arises from the constructive and destructive interference of a narrow discrete resonance with a broad spectral line or continuum.

Classical analogy of Fano resonance has been also investigated in the case of two coupled damped oscillators with a driving force applied to one of them [18]. The characteristic equations of motion for this system have following forms:

$$\begin{aligned} &\ddot{x}_1 + \gamma_1 \dot{x}_1 + \omega_1^2 x_1 + \upsilon_{12} x_2 = a \cdot e^{i\omega t} \\ &\ddot{x}_2 + \gamma_2 \dot{x}_2 + \omega_2^2 x_2 + \upsilon_{12} x_1 = 0 \end{aligned} \tag{1}$$

where ω_1 and ω_2 are natural frequencies (eigenmodes) of the oscillators in the absence of damping (defined by the mass and the spring constant), γ is a frictional parameter, υ_{12} is a coupling coefficient, and ω is a frequency of the external force. If coupling parameter is weak $(\omega_1^2 - \omega_1^2 \gg \upsilon_{12})$, then the eigenmodes of coupled system can be written as

$$\tilde{\omega}_1^2 \approx \omega_1^2 - \frac{\upsilon_{12}}{\omega_2^2 - \omega_1^2}, \qquad \tilde{\omega}_2^2 \approx \omega_2^2 + \frac{\upsilon_{12}}{\omega_2^2 - \omega_1^2}, \tag{2}$$

Similarly with mechanical oscillator the equation can be applied also for electromagnetic oscillators or resonators, where ω_1 and ω_2 are resonant frequencies, γ is a losses parameter and ω is a frequency of the external field. Let's for clarity to name the resonator which excites by external field as "Bright", and the second one "Dark".

2. Results and discussion

Numerical analysis based on finite element method is carried out for demonstrating Fano resonance for two coupled semicylindrical resonators. Since we are consider Fano resonance as a way for improving sensing features of system our investigations are focused on achieving of higher quality Q factor due to sharpness of resonant curve and demonstration non-symmetrical behavior of resonant curves owing to Fano effect in coupled system. First of all to achieve our goal we are studied distributions of the electric filed E_z component amplitudes in single resonator for particular mode to have a reference point (see Fig.1). The values of the parameters are chosen as: $\varepsilon_d = 2.25; \varepsilon_e = 1; R = 1.5\mu m$ and $h = 80nm$; the values of εm (as a metal we use silver) and εs (as a semiconductor we use $GaAs$) have been chosen according to Ref. [19] and [20], respectively. The Q-factor of the resonator was determined by the equation $Q \approx \lambda p / \Delta\lambda$, where λp and $\Delta\lambda$ are the peak wavelength and the full width at half-maximum, respectively, for considered parameters $Q \approx 7600$. In our previous work we determine conditions when radiation from the curved boundary is negligible, and the Q-factor of resonator is mainly determined by the radiation from metal layer and Joule's losses. For chosen parameters the curve radius that is the radius of semicylinder can be take started from $R \approx 1\mu m$ where radiation from the curved boundary can be neglected.

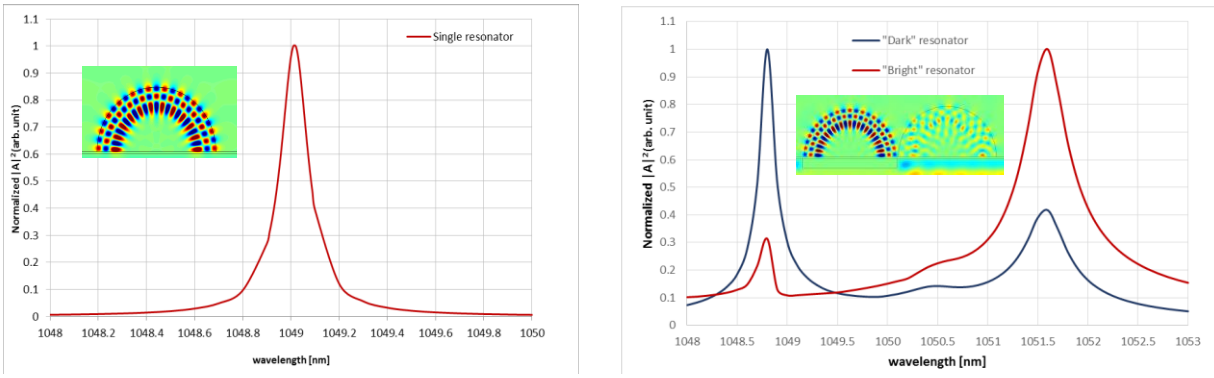
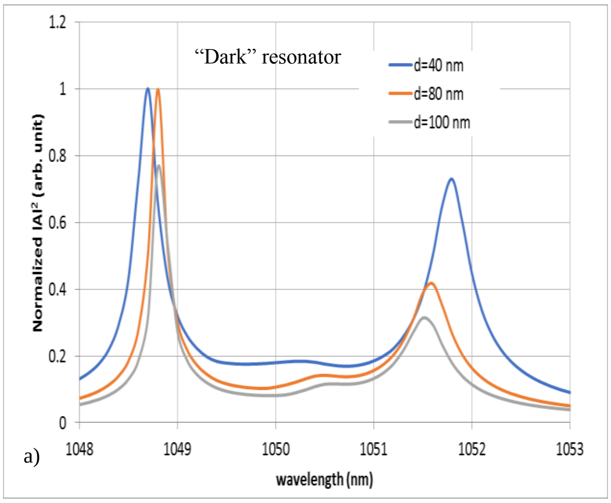


Fig.2. Electrical field Ez component normalized amplitude vs. wavelength for coupled resonators.

After the second "Bright" resonator with different radius $R = 1.6\ \mu\text{m}$ is placed near the existing resonator, the distance between resonators $d = 80nm$. To prevent the penetration of external field into resonator and therefore excitation of "Dark" resonator the metal layer thickness is widened (see Fig.2). As it can see from Fig.2 the resonant wavelength of resonator with $R = 1.5\ \mu\text{m}$ is shifted from $\lambda_0 = 1049.01\ \text{nm}$ to $\lambda_0 = 1048.8\ \text{nm}$ and resonant curve became more sharper hence the Q factor higher $Q = 12000$, which is 1.58 times bigger. It is noticeable that asymmetrical resonant behavior of electric field vs. excitation wavelength is also seen, which is another proof of Fano resonance existence. It's useful to note that obtained results are expectable within classical interpretation of Fano resonance presented in [18]. However it should be mentioned that at the same time the square of electric field amplitude of single resonator is about 4 times higher.



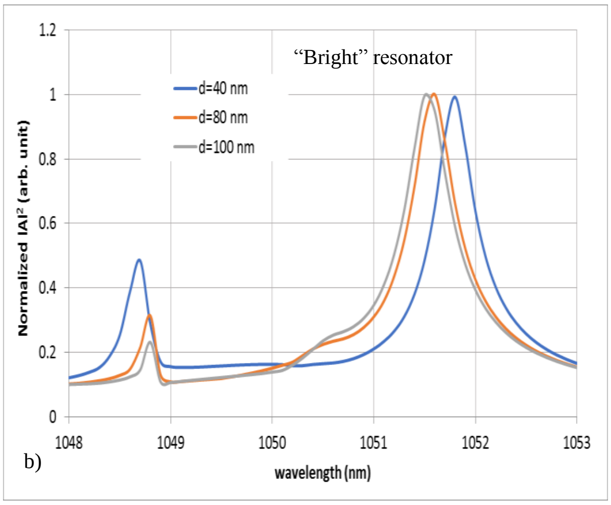


Fig.3. Elctrical field Ez component normalized amplitude vs. wavelength a) in "Dark" and b) in "Bright" resonators, for different d distances between resonators.

To control the coupling coefficient the distance d between resonators is varied and resonant curves are obtained (see Fig.3). As seen from Fig.3 a) within investigated wavelength range there are two resonant peaks instead of one as for single resonator. Moreover, the main resonant curve near the $1049nm$ is shifted and sharpened, the second resonant peak arisen due to field penetration from "Bright" resonator which resonant wavelength is near to $1051nm$. It is clear, as closer resonators as higher coupling and influences of "Bright" resonator onto "Dark" one, hence higher the second peak value, which brings to the widening of main resonant curve. On the other hand, the bigger distance between resonators the lower main resonant peak since the "Dark" resonator excites from "Bright" one. Therefore there is an optimal distance to obtain sharper resonant curve with reasonable strength of field inside the resonator, for chosen parameters this distance is about $d \approx 80nm$.

From Fig.3 b) follows the existence of second asymmetrical resonant curve of "Bright" resonator at the resonant wavelengths as for "Dark" one, the bigger distance the smaller second asymmetric peak due to weak coupling. It is also worth to mention that with increasing d distance the resonant peaks getting closer together.

3. Conclusion

In summary, a system of two, coupled semicylindrical microresonator with relatively simple excitation by a plane wave is studied and Fano resonance is demonstrated. The resonator is formed on the base of a dielectric/metal/dielectric structure, where the wave energy penetrates into the resonator through a thin metal layer and is stored in a semicylindrical dielectric with high permittivity. Resonators system combines properties of Fabry-Perot resonator, where the input of wave energy is carried through mirrors, and cylindrical resonator, where Whispering-gallery modes with azimuthal and radial modes are formed. The control of evanescence coupling between two resonators is realized by varying the distance between resonators. Due to the coupling the resonant curve became more sharper hence the Q factor is 1.58 times bigger in comparison with single resonator with same parameters. The obtained results substantiate the practical value of the proposed system as an acceptable way to improve the sensing characteristics of this type of microresonator.

Acknowledgments

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