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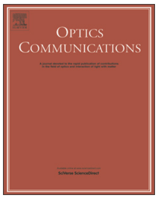

Optical refractive nanosensor with planar resonators metamaterial

Junqiao Wang [a,*], Kaijun Mu [a], Fengying Ma [a], Huaping Zang [a], Chunzhen Fan [a], Jinna He [a], Erjun Liang [a], Pei Ding [b]

[a] School of Physical Science and Engineering and Key Laboratory of Materials Physics of Ministry of Education of China, Zhengzhou University, Zhengzhou 450052, China
[b] Department of Mathematics and Physics, Zhengzhou Institute of Aeronautical Industry Management, Zhengzhou 450015, China

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ABSTRACT

We numerically investigated the optical properties of planar resonators metamaterial that exhibits two narrow transmitted dips with quality factors of 23 and 50 in the optical regions. The results show that, both of the two resonances reveal a distinct plasmon shift with respect to a small fluctuation in the refractive index of the surrounding medium, and calculated average refractive index sensitivities are 900 nm/RIU and 493 nm/RIU, and corresponding figure of merits of two modes are 16 and 32 in vacuum, respectively. The sensing performance can be improved by changing the geometric parameters of planar metamaterial due to the plasmon modes coupling effect, which offer an excellent potential for optical nanosensing applications.

Plasmonic nanostructures are of considerable current interest because of their unusual electromagnetic and optical characteristics and the prominent applications in surface enhanced Raman scattering (SERS) [1], biological and chemical sensing [2], perfect light absorption [3], optical antennas and switching [4], slow-light devices [5], and imaging and cloaking. [6,7] The unique ability of plasmon to focus incident light into subwavelength regions near metal nanostructure surfaces can lead to very large local field concentration. In addition to localized confinement of enhanced near-fields energy, plasmon resonances in nanostructures are sensitive to surrounding environments, and generally, the electromagnetic responses of plasmon resonances in metal nanostructures are commonly broad-band with large plasmon lifetime and low quality factor (Q factor) due to the significant radiation losses, which is unexpected in chemical/biological nanosensors. However, the resonant characteristics of metal nanostructures can be controlled by adjusting the shape, size and composition of nanostructure. As for sensing application, we appreciate the plasmon resonances with the both narrow optical spectra and large figure of merit (FOM), which indicate that the weak changes in surrounding environments can be perceived through direct observation of spectral shift of plasmon resonances.

In the past few decades, conventional plasmon resonance sensors based on surface plasmon resonance for a thin metal film and the localized surface plasmon resonance(LSPR) supported on isolated nanoparticles have been of great attention and widely studied [8,9]. Anker et al. reviewed developments on improving the sensitivity of optical sensors based on metal nanoparticle arrays and single nanoparticles [10]. Furthermore, recently, a lot of efforts have been applied to identify the high sensitive nanosensors based on plasmonic metamaterial. Liu group and Li group introduced a novel plasmonic sensor which combined the concepts of a perfect metamaterial absorber and an LSPR sensor in near-infrared region [11,12]. Pryce et al. investigated how the mechanical deformation of compliant metamaterials can be used to create new types of tunable sensing surfaces, they used split ring resonator (SRR) metamaterial on polydimethylsiloxane to demonstrate refractive index sensing with FOM of up to 10.1 [13]. Ren et al. proposed a plasmonic sensor based on a spiral G-shaped metamaterial, they achieved a spectral shift sensitivity of 410 nm/RIU and a FOM of 17 in the near-infrared region [14]. Mock et al. utilized the coupling between LSPR and propagating surface plasmon to probe the highly sensitive distance-dependent LSPR of the gaps [15]. In addition, Prodan et al. presented the plasmon hybridization concept in 2003, which can be used to describe the plasmon response of complex nanostructures of arbitrary shape [16]. Using the plasmon hybridization concept, the plasmon modes can be classified according to their irreducible representations, and a variety of nanostructures have been experimentally and theoretically exploited to improve performance of plasmonic nanosensors recognizing the variation of local refractive index [17–19]. Furthermore, due to hybridization between broad superradiant modes (bright modes) and narrow subradiant modes (dark modes) can induce Fano resonance exhibiting an asymmetric

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[*] Corresponding author.
E-mail address: junqiaowang@zzu.edu.cn (J. Wang).

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sharp line shape and generating a large electromagnetic field congregation, many researchers have paid attention to plasmonic metamaterial that induces Fano resonances in their optical spectra as a sensing platform [20–27]. For example, Zhang et al. analyzed the plasmon mode interactions of a metallic nanocube on a dielectric substrate, and symmetry-breaking introduced by an adjacent semi-infinite dielectric can introduce coupling and hybridization of the plasmon modes of a metallic nanostructure, which provided a new insight for achieving plasmonic Fano-resonant LSPR sensors with FOM of 20 [23]. Furthermore, electromagnetically induced transparency (EIT) phenomenon with narrow transparency band can be manipulated by Fano resonances through symmetry breaking, which is desirable for sensing applications due to narrow spectral width. Liu et al. demonstrated that a plasmonic EIT analog could be achieved using a planar complementary metamaterial which consists of cut-out structures in a homogeneous gold film, however, this metamaterial sensor only has a small FOM of 3.8 in the near-infrared regions [28]. Dong et al. designed a planar metamaetial composed of three metal bars, which revealed the gain-assisted plasmonic analog of EIT for the purpose to enhance the sensing [29].

In this paper, we theoretically discussed the optical properties of a designed planar metamaterial with two sharp transmitted dips. The designed planar metamaterial is the recombination of paired SRRs and metallic cavity, and the hybridization of LC resonance and cavity plasmon leads to two distinct dips in transmitted spectrum. By adjusting the geometric parameters of designed metamaterial, the plasmon resonance modes reveal narrow line width and large FOM, which offer a potential for biosensing in the optical and near-infrared regions. In comparison to other plasmonic systems, the high sensing performance with large FOM can be achieved in this planar metamaterial by strong plasmon modes coupling effect, which provide further insight into designing the excellent plasmonic nanosensors.

Fig. 1(a) and (b) shows a typically periodical array of the designed silver planar metamaterial and a sketch of a unit cell with relevant geometric parameters, respectively. The geometrical parameters are chosen as follows: $P=540$ nm, $s=120$ nm, $a=420$ nm, $w=40$ nm, $l=110$ nm and $g=20$ nm. The dielectric constants of silver measured by Palik are used to model the planar metamaterial, and the thickness is fixed as 60 nm [30]. The planar metamaterial is located on the SiO_2 substrate of thickness 100 nm and dielectric constants $\varepsilon=1.96$. The metamaterial is illuminated by a normal incident plane wave with an electric field polarization parallel to the y-axis. The simulation is carried out by the time domain solver of 3-D electromagnetic package (CST Microwave Studio), where the computational domain is truncated by Perfectly Matched Layers in the z-direction and the periodic boundary conditions are used to truncate the unit cell in the x–y plane. During simulating, the good convergence for calculated result can be obtained by utilizing adaptive meshing technique to handle the structure boundaries and geometries that need large aspect ratios of meshes.

Fig. 1(c) shows the simulated transmitted spectrum of the planar metamaterial as designated in Fig. 1(a) and (b). By using the structural parameters as described above, we obtained two narrow plasmon resonances around $P_1=224$ THz and $P_2=385$ THz, respectively, where the fitted full width at half maximum (FWHM) are about 9.9 THz and 7.7 THz, respectively. The calculated Q factor ($Q=\omega_0$/FWHM) of P_1 and P_2 modes are $Q_1=23$ and $Q_2=50$, respectively. In addition, due to the structure asymmetry of the metamaterial in x and y directions, the responses of x and y polarized light are different, and only one broadened resonance dip appears in spectrum with x polarized light.

The plasmon resonances with the narrow line width and high Q factor are two appreciated characteristics for achieving high sensing performance in metamaterial sensor. In order to investigate the sensing performance of the designed planar metamaterial, we calculated the transmitted spectra in different dielectric environments (i.e. keep the substrate and change the permittivity of the upper space) as presented in Fig. 2(a). With the increasing of the refractive index of dielectric environments, both of the plasmon resonances P_1 and P_2 exhibit a red-shift in transmitted spectra. This can be understood by the fact that the resonance wavelength is proportional to the refractive index [31]. Two resonance dips reveal distinct plasmon resonance shifts with respect to a small fluctuation in the refractive index of the dielectric environments, even for $\Delta n=0.01$. The refractive index sensitivities are defined as the wavelength shift per refractive index unit (RIU). As shown in Fig. 2(b), the average refractive index sensitivities of P_1 and P_2 modes are 900 nm/RIU and 493 nm/RIU, respectively. For sensing application, a high FOM (refractive index sensitivity/FWHW) is desired, which is usually applied to further evaluate the sensing performance. The calculated FOM of P_1 and P_2 modes are 16 and 32, respectively. Therefore, the P_2 resonance has greater FOM than P_1 due to the narrower line width. Both P_1 and P_2 modes in designed planar metamaterial reveal high refractive-index sensing sensitivity and FOM, which offer an excellent potential for biosensing in the optical and near-infrared regions.

In order to insight the physical mechanism to induce the two plasmon resonances in the proposed planar metamaterial nanosensor, we plot the real part of electric field E_y [(a), (b)], magnetic field H_z [(c), (d)] and current C [(e), (f)] distributions in the x–y plane at resonance frequencies of $P_1=238$ THz and $P_2=350$ THz, respectively, as shown in Fig. 3. The electric field hot spots appear between the two gaps of U-shaped SRRs at two ends of designed structure at $P_1=238$ THz, and the negative charges locate at upper arm and positive charges at the lower one, as shown in Fig. 3(a). SRRs can be modeled as LC resonators in which the effective inductance arises from the loop formed by the U-shaped SRR and effective capacitance is due to the gap region between SRR arms. The LC resonances of SRRs can be excited with an E-field perpendicular to the SRR arms. The primary plasmon resonances of two U-shaped SRRs at two ends of the structure are in-phase and strongly confined, generating a huge net electric moment contributing to the resonance at $P_1=238$ THz. Moreover, the magnetic fields are mainly confined in the left and right regions of the structure, as shown in Fig. 3(c). Due to the out-of-phase current loops induced in the left and right ends of structure, shown in Fig. 3(e), the magnetic dipole moments induced in the two ends regions are opposite in the z-directions, as shown in Fig. 3(c). Therefore, the net magnetic moment of the whole structure is zero due to the cancellation effect in this structure. The mode at $P_1=238$ THz is therefore attributed to the LC resonance. On the other hand, as for the resonance at $P_2=350$ THz, the electric field hot spots appear at the middle square cavity region, and the negative and positive charges concentrate on top and down metal arms of metamaterial, as shown in Fig. 3(b). The concentrated charges locate around middle cavity, which can induce the cavity plasmon mode. One current node appeared at the middle arms refers to the excitation of the fundamental cavity plasmon mode. The high-order plasmon modes can be excited by extending of the length of the cavity, while the more current nodes appear. Due to the structure symmetry in y direction, the magnetic dipoles excited by out-of-phase current in the two parts of the middle regions have the opposite directions and same strength, which lead to cancellation effect. Therefore, the resonance at $P_2=350$ THz is a result of the fundamental cavity plasmon mode.

In fact, we can comprehend the interaction between the designed metamaterial and light wave by considering the whole structure unit cell as the combination of two separate elements: one is a paired SRR, and the other is a metallic cavity. We plot the