Reversed radiation pressure effect on electrons under plasmonic resonance in a magnetic metamaterial

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Abstract

We numerically studied optical radiation pressure effect on metallic thin film in a magnetic metamaterial under oblique incidence. The model system consists of an aluminum nanowire and a spatially separated homogeneous gold thin film. We found that for localized SPPs coupling electrons in the metallic film are pulled and pushed depending on the detuning of the resonance. Our numerical calculation and analysis revealed that for the pushing force anti-parallel plasmonic coupling is induced in the structure. On the other hand for the pulling force parallel plasmonic coupling are also induced in addition to the anti-parallel mode. We found that optical pulling force on electrons originates from the parallel plasmonic coupling.

1. Introduction

When a photon propagates in a material, radiation pressure is induced in the material to the propagation direction of the photon. Usually materials are never pulled to the light source but pushed to the propagation direction of light due to the momentum transfer. Radiation force of light is the essential tool in the area of optical manipulation, which enable us the non-contact manipulation of nanoparticles and biological objects. Recently plasmonic drag effect is one of the hot areas in the plasmonics. Surface plasmon polaritons (SPPs) are corrective oscillation of electrons coupled with photon which are strongly localized at the interface between a dielectric and a metal. Vengurlekar and Ishihara showed that with the Kretschmann geometry, SPPs induce a strongly enhanced voltage across metallic thin film [1]. When a photon propagates in a material with free carriers, the carriers are dragged by the photon due to the momentum transfer, which is called as photon drag effect. In analogy with the photon drag effect SPPs can also drags free carriers, which is called as the plasmonic drag effect. More recently, Kurosawa and Ishihara experimentally and numerically clarified the mechanism of generation of the enhanced SPP voltage in a dielectrically modulated metallic thin film [2]. Noginova *et al.* demonstrated that the plasmonic drag effect (PDE) can be controlled using an external current [3]. In Ref. [2] and Ref. [4], microscopic force acting directly on an electron was considered in PDE. In the context of metamaterials, Veselago predicted the radiation pressure can be directed to the light source when propagating medium with simultaneously negative permittivity and permeability [5]. In this abstract we numerically show for the first time plasmonic drag effect can be directed to the light source.

2. Structure and its fundamental optical responses

In Fig. 1(a) we show the schematic of metallic structure in consideration which consists of an aluminum nanowire and a spatially separated homogeneous gold thin film. The period of the structure is 300 nm.

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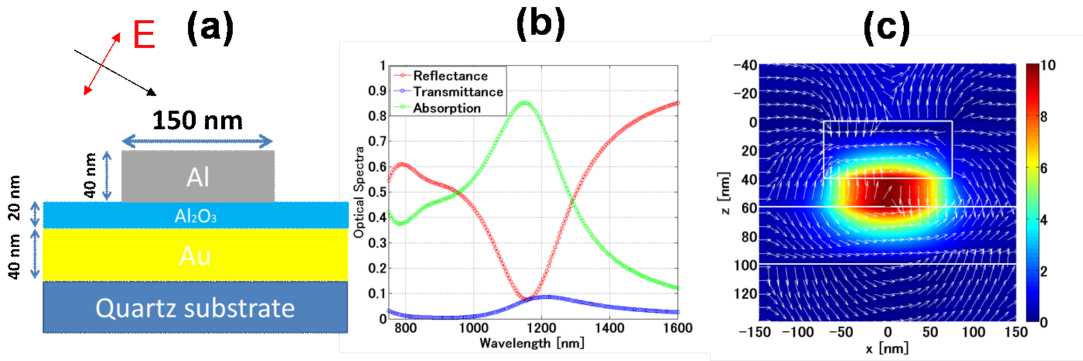

Fig. 1: (a):Schematic of unit cell of the structure. (b): Optical Spectra. (c): Pseudo color indicates the magnetic field intensity. The arrows whose length are normalized to unity indicate the vector flow of the electric field. In both cases snapshots are drawn.

In Fig. 1(b) we show transmittance, reflectance, and absorption spectra and we find that absorption is strongly increased around the wavelength 1150 nm. In order to reveal the origin of the resonance we performed near field calculation. Fig. 1(c) shows the pseudo color plot of the magnetic field and the arrows indicate the vector flow of the electric field. The magnetic field is strongly localized in the spacer between the nanowires and the metallic film and the electric field distribution pattern exhibits the anti-symmetric plasmonic coupling. Thus the metallic structure has magnetic resonance associated with anti-symmetric plasmon mode.

3. Results and discussion

In this section we present the method for the evaluation of the radiation pressure and the results. In the dipole approximation model, materials are regarded as the mass of a dipole and electromagnetic DC force acting on the dipole is generally given as [6, 7]

$$\mathbf{F}_{DC} = \frac{\alpha_R(\omega)}{4}\nabla|\tilde{\mathbf{E}}|^2 + \frac{\alpha_I(\omega)}{2}\mathrm{Im}\left\{\sum \tilde{E}_j^* \nabla \tilde{E}_j\right\}, \tag{1}$$

where $\alpha(\omega) = \alpha_R(\omega) + i\alpha_I(\omega)$ is a complex polarizability of the material, $\tilde{\mathbf{E}}$ is a complex amplitude of electric field:$\mathbf{E}(t) = \mathrm{Re}\{\tilde{\mathbf{E}}e^{-i\omega t}\}$ and $j = x, y, z$. The first term in Eq. (1) is called as gradient force, while the 2nd term is called as scattering force. As is shown in Ref. [2], the first term in Eq. (1) vanishes due to the periodic boundary conditions when the structure in consideration is plane film shaped. So we focus on the scattering force for the evaluation of radiation pressure on the metallic film. On the other hand the nanowires play the role of dipole moments of the system and the gradient force is dominant in case of metallic structure. In Fig. 2 we show the calculation results of the scattering force spectrum for the metallic film and the gradient force spectrum for the nanowire, respectively. In Fig. 2 the scattering force exhibits dispersive structure around the magnetic resonance. Below and above the resonance radiation pressure is negative and positive, respectively. Below the resonance electrons in the metallic film are pulled to the incident direction. Thus optical pulling force on electrons was predicted in the plasmonic systems. The gradient force on the nanowire is negative in the wavelength in interest. In order to clarify the physical picture of the optical pulling force, we show the field distribution pattern for the below and above the resonance in Fig. 2, where the schematics of the distribution are also shown.

Above the resonance anti-parallel plasmonic modes are clearly shown, whereas below the resonance parallel plasmon modes are excited in addition to the anti-symmetric modes. Image dipoles of the nanowires are induced in the metallic film. As is shown in Fig. 2 the gradient force on the nanowires are negative. Therefore radiation force on the image dipoles are positive, which results in the positive force above

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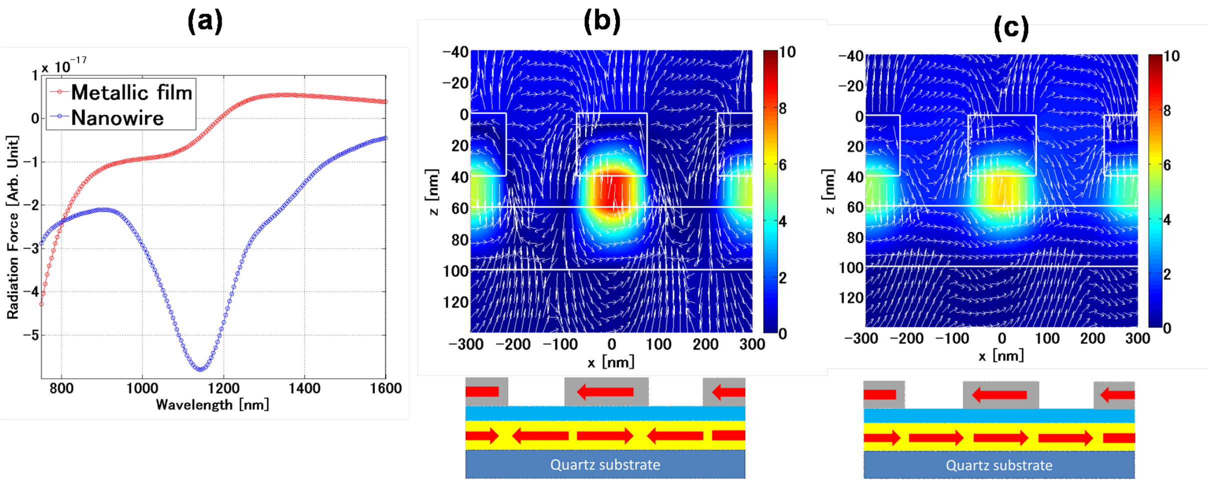

Fig. 2: (a): Scattering force spectrum (red) on the metallic film. Gradient force spectrum (blue) on the nanowire. (b) Wavelength is 1100 nm. (c): Wavelength is 1300 nm. In (b) and (c), field distributions are at the incident angle 30°. Pseudo color indicates the magnetic field intensity. The arrows whose length are normalized to unity indicate the vector flow of the electric field. In both cases snapshots are drawn.

the resonance. On the other hand, below the resonance image dipoles whose direction is in the same direction as that of the nanowires are induced in addition to the oppositely directed image dipole, which give rise to negative radiation force on the metallic film. Given that space inversion symmetry is broken by the oblique incidence and radiation pressure is negative below the resonance, radiation force due to the parallel plasmonic mode coupling is considered to be dominant compared to that of anti-parallel plasmonic mode coupling. We can verify our prediction experimentally by measuring a voltage across the metallic film as is presented in Ref. [2].

4. Conclusion

We numerically studied radiation pressure effect on a magnetic metamaterial which consists of a aluminum nanowire and a homogeneous film separated by a spacer and found that electrons in the metallic film are driven to the incident direction. We numerically and analytically revealed that dipoles induced in the metallic film play the essential role in the direction of radiation pressure on electrons.

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