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Investigation of some electromagnetic modes in the metal-dielectric system by the absorption spectrum

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Abstract

The surface plasmon resonance and the spherical cavity resonance in the system of a layer of periodically arranged dielectric spheres laid on outside of a metal slab or embedded in the metal substrate are investigated by observing the absorption spectrum. The absorption spectra for these systems can be accurately calculated by multiple scattering approaches. The calculated results show that there are some absorption peaks, which can be identified to the resonances of surface plasmon or cavity modes. The surface plasmon resonance occurs when the metal-dielectric interface is periodically modulated, as in both of the systems we considered. The frequency of the surface plasmon resonance is mainly determined by the periodicity of the modulated surface, and can be obtained by an analytic theory. Our calculated results are consistent very well with the analytic ones for both thick and thin metal slab. The cavity resonances only occur for the system of dielectric spheres embedded in a metal substrate. In this system, the resonances of both of the cavity mode and the surface plasmon coexist. In general, the absorption peaks for both of them are relatively weak, because their resonance frequency is far from each other. However, we can design the system to be that the resonances of the cavity mode and the surface plasmon are in almost the same frequency. In this case, a sympathetic resonance will occur, where the absorbance will be dramatically enhanced at the frequency.

Keywords: Surface plasmon; Cavity mode; Absorption spectrum

1. Introduction

Recent experimental discovery of the enhanced optical transmission through metal films with periodic subwavelength holes has given rise to a considerable interest in the optical properties of such structures due to their possible numerous applications in optics and optoelectronics as well as rich physics behind the phenomenon of the transmission enhancement [1–4]. The different, sometimes contradictory mechanisms of the transmission enhancement have been proposed and are being debated invoking surface-plasmon polaritons, different types of waveguiding modes in holes or slits, localized plasmons, and various combinations of the above [4–12]. The aim of all these research focuses on the understanding of electromagnetic mode in a system composed of metal and dielectric material and controlling the useable properties of them in applications.

This paper will introduce our recent research on the system of a layer of dielectric (glass) micro-spheres laid on outside of a metal (Ag) slab (Fig. 1(a)) or embedded in the metal substrate (Fig. 1(b)). The glass micro-spheres are arranged in a periodic triangular lattice with lattice constant α, which is the nearest neighbor distance between the spheres. The thickness of the metal slab and the distance between the center of the glass sphere and the upper surface of the metal in Fig. 1(a) will be denoted as t and h, respectively. The thickness of the cover layer in Fig. 1(b) is denoted as d_c, which is chosen to be smaller than the skin depth so that external field can excite the electromagnetic modes in the cavity. In our calculation, the permittivity of the glass is set to be a constant with no absorption, $\varepsilon_{\mathrm{sph}} = 1.96$, and that of the silver $\varepsilon_{\mathrm{Ag}}$ is taken to be a Drude metal with plasma frequency $\omega_p \hbar = 9.2$ eV and $(\omega_p \tau)^{-1} = 0.02$, as generally used in the literature. In this paper, the radius of the glass sphere and the thickness of the cover layer are fixed at $S = 0.1$ μm and $d_c = 5$ nm, respectively.

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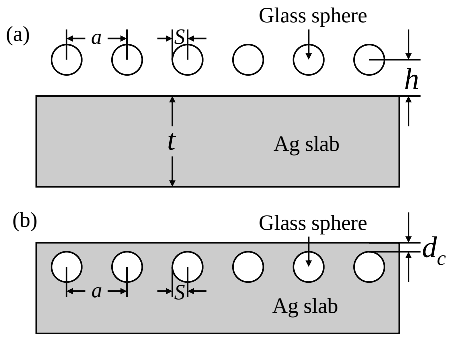

Fig. 1. A schematic sketch of the system we are investigating.

Other parameters, such as, α and h are variable for observing the trend.

One advantage of studying these systems is that they can be calculated accurately by a multiple scattering approach. The mathematical details of the method can be found in the literature [13–15]. This method expands the electromagnetic waves in terms of vector spherical harmonics centered on spherical scattering objects and is particularly suitable for the systems which have spherical scatterers and flat interfaces. Further, as a frequency-domain method, it can handle systems with dispersion and absorption as specified in frequency-dependent and complex dielectric functions of the components. In theoretical point of view, these systems are very close to some analytically soluble system. When h or d_c is large enough, the metal-dielectric interface is close to a perfect interface, which means the interface is flat and both media beside the interface are semi-infinitely uniform. For a perfect interface, there exists an analytically soluble surface electromagnetic mode, which is called surface plasmon. Another analytically soluble electromagnetic mode concerned with the system shown in Fig. 1(b) is the cavity mode of a dielectric sphere embedded in an infinite large metal. When d_c is not very small, there exist approximated cavity modes in the system, though there is a little of leakage of the mode into the vacuum. Further, these electromagnetic modes and the incident plane wave stay in different range, so their coupling is relatively weak. For this reason, each electromagnetic mode exists nearly independent and its basic properties are almost retained. All these characters are suitable for both the understanding of the fundamental physics and the controlling of the applicable properties of the system.

2. Surface plasmon and cavity modes

For a perfect interface composed of semi-infinite air and metal Ag, surface plasmon can exist and it has following dispersion relation [16,17],

$$k_{\mathrm{sp}}^2 = \frac{\omega^2}{c^2}\left(\frac{\varepsilon_{\mathrm{Ag}}}{1+\varepsilon_{\mathrm{Ag}}}\right), \tag{2}$$

where k_{sp} is the in-plan wave vector of the surface plasmon. The surface plasmon can not be excited directly by a plane incident wave if the interface is perfect, but can be excited by evanescent waves or by scattering centers near the surface, such as the dielectric spheres in our system. The scattered wave from each sphere is strongly coherent, because they come from a same incident plane wave. If the spheres are arranged periodically, according to Brag scattering principle, the scattered wave can only exist in some particular direction, in which the scattered wave from every spheres has the same phase, so they will form a strong scattered wave on the whole system, otherwise they will cancel each other because their phase is different. This criterion is also correct for the component of surface plasmon in the scattered wave. So for a plane incident wave with wave vector $\mathbf{k}_0$ in air, the surface plasmon on a periodically modulated surface can only occur at the frequencies that satisfy,

$$\mathbf{k}_{\mathrm{sp}} = \mathbf{k}_0 \sin\theta_0 \pm p\frac{2\pi}{\alpha}\mathbf{u}_1 \pm q\frac{2\pi}{\alpha}\mathbf{u}_2, \tag{3}$$

where θ_0 is the angle of incidence, $\mathbf{u}_1$ and $\mathbf{u}_2$ are the unit reciprocal lattice vectors of the periodic surface, and p and q are integer numbers. In another words, a periodically modulated surface has a surface plasmon resonance at the frequencies determined by Eq. (3), because the surface plasmon would be excited by the incident wave at these frequencies. For normal incident, the lowest resonance frequency corresponds to the in-plan wave vector being equal to one of the reciprocal vector in Eq. (3). It follows that,

$$\frac{2\pi}{\alpha} = \frac{\omega}{c}\frac{\sqrt{3}}{2}\sqrt{\frac{\varepsilon_{\mathrm{Ag}}}{1+\varepsilon_{\mathrm{Ag}}}}, \tag{4}$$

which is only a function of the periodicity of the metal surface.

When the metal is not semi-infinite but with a finite thickness, there are two air–metal interfaces. Surface plasmons can exist on both of them, and they will weakly couple each other through the field in the metal slab. As a result, they form two altered surface modes, correspond to symmetric and antisymmetric surface plasmons, if the absorption in the metal is negligible. These surface modes have following dispersion relations [18], if the metal slab is relatively thick ($\exp(-tk_{\mathrm{sp}}\sqrt{-\varepsilon_{\mathrm{Ag}}}) \ll 1$)),

$$\mathbf{k}_{1,2} = k_{\mathrm{sp}}\left[1 \pm \frac{2\varepsilon_{\mathrm{Ag}}}{1-\varepsilon_{\mathrm{Ag}}^2}\exp(-tk_{\mathrm{sp}}\sqrt{-\varepsilon_{\mathrm{Ag}}})\right], \tag{5}$$

where, the in-plan wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$ correspond to symmetric and antisymmetric surface plasmons, respectively. By the same reason that we mentioned previously for the case of semi-infinite metal system, the surface plasmon can only be excited by the incident plane wave with