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Coupling and hybridization of surface plasmon polaritons (SPPs) in metal nanostructures

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Abstract. The surface plasmon polariton is generated by collective oscillation of electrons. It is mainly related to the resonance peak, intensity, nanostructure size and surrounding medium. This paper studies coupling and hybridization of the surface plasmon polariton (SPP) in metal nanostructures. First, optical characteristics of metal nanostructures are analyzed, including SPP characteristics and SPP system hybridization theories. On the basis, coupling and hybridization of the SPP, including diffraction coupling of the monolayer and double-layer nanoplate SPP resonance, bright-state and dark-state plasmon polariton, and the influence of the surrounding medium are examined.

1 Introduction

Optical properties of the metal nanostructure have been a focus of nanotechnology research. Under the effect of the external field force, the surface plasmon polariton (SPP) will be formed by the conduction band electronic collective oscillation. The resonant effect can absorb or scatter the incident light. All these properties of the metal nanostructure have found wide applications, including optical waveguide, chemical and biological sensors, image and information transmission, in the optical field.

2 Optical properties of metal nanostructures

A Plasmon polariton is a non-conduction band electron excited during the process of mutual coupling between the metal nanostructure and the incident electromagnetic field. The excitation model is usually reflected as absorption and scattering of the oscillating electromagnetic field by the sub-wavelength metal nanoparticle. The curved surface of the nanoparticle possesses the restoring force to drive electrons. The electrons thus undergo collective oscillation or resonance. The local electric field of the near field region both inside and outside the nanoparticle is augmented and strengthened to generate local SPPs. In terms of a metal nanostructure, resonance of SPPs usually happens in the visible light region. The visible light is selectively reflected or absorbed to demonstrate different colors. The application value of the nanoparticle color effect has been increasingly tapped. Window glass dyeing and tea cup decoration are two successful applications of the effect [1].

3 Surface Plasmon polariton system hybridization theories

A nanostructure system should be made up of two or more than two nanostructures. In a charge nanostructure, the near field electromagnetic effect is highly strong. Thus, a strong coupling effect happens among various structural components to endow its surface with more diverse SPP oscillation properties. This complex system cannot be described with the electric power theories alone. Nordlander et al. proposed an electromagnetic theory similar to the molecular orbital theory to describe the phenomenon of SPP resonance on a compound nanostructure system. The theory points

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out that SPPs on a compound nanostructure system should be divided into different energy levels and that, under the strong coupling effect, they will interact with each other to cause hybridization [2].

3.1 Monolayer and double-layer nanoplate SPP resonance

To start with, the extinction interface of the monolayer and double-layer nanoplate is calculated under the air environment. The key parameters are shown in Table 1.

Table. 1 Basic parameters of the monolayer and double-layer nanoplate

Nanoplate type	Diameter (nm)	Height (nm)	Inter-nanoplate distance (nm)	Alignment mode
Monolayer nanoplate	60	50	-	-
Double-layer nanoplate	60	50	10	Superposition

The incident beam comes through the axial direction. Calculation of the extinction interface shows that the nanoplate has a resonance model, which belongs to the dipole SPP resonance. The double-layer nanoplate has two resonance models. The bright-state SPP is located on the left wide slot; while the dark-state SPP is located on the right wide slot. The Distributed Fault Tolerance with Duplication (DFTD) is used to calculate the electric field and current distribution of the two resonance models, based on which the SPP resonance is further analyzed. Fig. 2 below present the analysis results.

Table 2. Analysis results of the SPP resonance

Excitation wavelength (nm)	Position with the maximum local electric field	Current characteristic	Charge characteristic	Resonance model
550	Quadrangle	Contrary to the current direction	The charge resonance phases are the same.	Bright-state SPP resonance
690	Between two nanoplates	Contrary to the current direction	The charge resonance phases are opposite to each other.	Dark-state SPP resonance

3.2 Bright-state and dark-state SPP diffraction coupling

Based on the above analysis results, the periodical diffraction coupling effect of the monolayer and double-layer nanoplate in a structure is studied. Key parameters influencing the bright-state SPP diffraction coupling effect are shown in Table 3.

Table 3. Key parameters of the bright-state SPP diffraction coupling

Structure periodical transmissivity	Calculation formula	Extinction cross-section	Nanostructure period d（nm）	Nanostructure array	Ambient medium	Incident beam direction
T	T=1-Cext /d2	Cext	600	Periodical array in four directions	Air	Come in through the axial direction of the nanoplate

After the structure periodical transmissivity, T, is calculated, the calculation formula in Table 3 is used to work out the extinction cross-section, Cext. The extinction cross-section period of the nanoplate, either monolayer or double-layer, is both 600nm. In the monolayer nanoplate array, plasmon polaritons exist on a dipole surface. Besides, on the extinction spectrum, there is a high-intensity, narrow resonance peak located near 615nm, and nearby 600nm there is a sharp and deep sinking, corresponding to the array period. The phenomenon indicates coupling between the array dipole plasmon polaritons on the monolayer nanoplate and its diffraction model. Therefore, a new SPP resonance appears. In a double-layer nanoplate array extinction spectrum, there is also a high-intensity, narrow resonance peak located near 617nm, and nearby 600nm a sharp and deep sinking is also observed. This proves that the diffraction coupling of the bright-state SPPs on a double-layer nanoplate coincides with that observed in the monolayer nanoplate.

The following part studies the dark-state SPP diffraction coupling and its key parameters are shown in Table 4.

Table 4. Key parameters of the dark-state SPP diffraction coupling

Structure periodical transmissivity	Calculation formula	Extinction cross-section	Nanostructure period d (nm)	Nanostructure array	Surrounding medium	Incident beam direction
T	T=1-Cext /d2	Cext	690	Periodical array in four directions	Air	Come in through the axial direction of the nanoplate

The period, d=600nm, is changed to d=690nm. Other parameters of the dark-state SPP are identical to those of the bright-state SPP. In a monolayer nanoplate array, plasmon polaritons exist nearby the dipole. Besides, the SPP generated by the diffraction coupling appears around 698nm of the extinction spectrum. Besides, the resonance intensity obviously descends. On the double-layer nanoplate array, there is a narrow resonance peak and a sharp sinking, located nearby 695nm and 690nm, respectively. The resonance intensity increase of the double-layer nanoplate is obviously higher than that of the monolayer nanoplate. The phenomenon suggests that the dark-state SPP on the double-layer nanoplate undergoes coupling with its diffraction. According to the dipole approximation, a single nanoparticle of a structure undergoes mutual coupling through diffraction in a period, but a large part of the dark-state SPP diffraction is inhibited. This justifies existence of the delay effect.

3.3 Influence of the surrounding medium on SPP coupling

In order to study the SPP diffraction coupling effect and analyze influence of the surrounding medium, the array period and the surrounding medium refractive index should be changed. The diffraction coupling peak position of the plasmon polariton in a periodical nanostructure can be written as $\lambda=d\times n$, where d is the array period and n is the surrounding medium refractive index. In the air, n=1.00, and the period is set to be 670nm, 680nm, 690nm, 700nm, and 710nm, respectively. Along with increase of the period, SPPs are changed. When the maximal resonance appears at d=690nm, the period will continue to increase, thus resulting in a decline of the resonance intensity. In the water, n=1.33, and the dark-state SPP is transferred to 860nm. Then, the period is set to be 630nm, 640nm, 650nm, 660nm, and 670nm, respectively. Along with increase of the period, the change trend of the resonance peak is almost the same to that when the medium is the air. When the maximal resonance intensity is located at 670nm, the corresponding wavelength is 860nm. The comparison results between the two are presented in Table 5.

Table 5. Comparison of changes with the surrounding medium

Surrounding medium	Refractive index	Resonance peak	Comparison results
Air	1.00	Close to the period	Changes of the refractive index of the surrounding medium does not influence the coupling effect.
Water	1.33	Close to the period	

4 Conclusions

To sum up, the above analysis of the SPP coupling and hybridization effect on metal nanostructures can contribute to a better understanding of optical properties of metal nanostructures. Research findings of this paper can be boiled down into four points. First, SPPs can be divided into different energy levels, and will interact with each other under a strong coupling effect, and the interaction process is known as hybridization. Second, the bright-state SPP diffraction coupling in a double-layer nanoplate array coincides with that in a monolayer nanoplate. Third, a large part of the black-state SPP diffraction is inhibited, thus resulting in the delay effect. Fourth, changes of the reflective index with different surrounding mediums adopted will not influence the coupling effect.

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