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Characteristics of surface plasmon resonances in thick metal film perforated with nanohole arrays

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ABSTRACT

The dependence of optical properties on the hole shape, period of nanohole arrays and metal film thickness, in thick silver film perforated with "high density nanohole arrays" is investigated using the finite difference time domain technique. The physical mechanism behind the light phenomena is discussed: the coupling between localized plasmon resonances and surface plasmon polaritons is found to play a crucial role on the optical properties, while the hole shape plays an important role on the coupling mechanism. Interesting light phenomena are observed in thick metal films perforated with rectangle nanohole arrays; the antisymmetric coupling between surface plasmon polaritons near the top and bottom film plane, and the antisymmetric coupling between localized surface plasmon resonances near the two long sides of the rectangular hole are excited in it.

1. Introduction

Optically thin metal films perforated with subwavelength hole arrays [1] have attracted a great deal of attention, due both to its fundamental characters and potential applications [2,3] since the discovery of the Extraordinary Optical Transmission (EOT) [1]. In its original form, the transmission resonances occur at wavelengths larger than the cutoff of the hole. On one hand the EOT was understood as the transmission mediated by the aid of electromagnetic surface modes supported by the holey metal surfaces [4–6]. On the other hand, experiments on the dependence of EOT with the hole shape revealed the existence of another type of transmission resonances which arise from electromagnetic modes localized close to the hole, both in hole arrays [7,8] and in isolated holes [9–11]. It is well established that metallic nanoholes support localized plasmon resonances (LSPRs) in much the same way as nanoparticles [12–16]. It is one of the research directions for metal hole arrays that do comprehensive researches to deepen our understanding of the mechanisms underlying the extraordinary optical transmission.

The optical properties of metal hole arrays are influenced by many factors, such as hole shape, period of nanohole arrays, thickness and material property of the metal film [6]. Previous researches were mainly focused on thin metal films perforated with subwavelength hole arrays, in the present work, we will investigate the optical property of thick metal films perforated with "high density nanohole arrays" (nanohole arrays with short period) using the finite difference time domain technique. In our considered structure system, localized surface plasmon resonances modes and surface plasmon polaritons will simultaneously play important roles on the optical properties of metal hole arrays: there is probably hybridization of localized surface plasmon resonances modes supported by metallic nanoholes when neighboring metallic nanoholes interact, and the hybridization is mediated by the nearby metallic surface plasmon polaritons which gives marked differences in optical response compare to metallic nanoparticles; while there are probably symmetric coupling mode and antisymmetric coupling mode between the top and down surface plasmon polaritons mediated by those localized surface plasmon resonances modes, so a much richer range of optical phenomena probably present, these will deepen our understanding of the mechanisms underlying the extraordinary optical transmission.

In detail, the dependence of optical properties on the hole shape, period of nanohole arrays and metal film thickness, in thick silver film perforated with nanohole arrays is investigated using the finite difference time domain technique in this paper. The physical mechanism behind the light phenomena is discussed. Interesting light phenomena are observed in thick metal films perforated with rectangle nanohole arrays, as the thickness of the metal films and

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the period of rectangular nanohole arrays vary respectively; the antisymmetric coupling between surface plasmon polaritons near the top and bottom film plane, and the antisymmetric coupling between localized surface plasmon resonances near the two long sides of the rectangular hole are excited in it. The research methods and results will be presented in detail below.

2. Numerical calculation

Our numerical calculations were performed using the finite difference time domain technique (FDTD) with a mesh size of 2.0 nm to solve the three-dimensional vector Maxwell equations in the optical structure of thick metal (silver) film perforated with nanohole arrays as showed in Fig. 1. We consider the exemplary system of silver nanohole arrays with different hole shape, four kinds of nanohole arrays with square lattice are rectangle nanohole arrays, isosceles triangular nanohole arrays, square nanohole arrays and circle nanohole arrays. The four kinds of nanoholes have almost the same area: the longer sides and short sides of the rectangular holes are 100 nm and 20 nm, respectively; the bottom sides and height of the isosceles triangular holes are 40 nm and 200 nm, respectively; the sides of square holes are 45 nm; the radius of circle holes are 25 nm. The period of nanoholes with the square lattice has a range of 150–400 nm. The thickness of metal film has a range of 60–2000 nm. The whole calculation region was set with a background index of 1 (air), the optical constants of the metal are based on experiment date [17]. The metal nanohole arrays were plane wave illuminated with the direction of the electric field E parallel to x-axis from the bottom of metal nanohole arrays. The perfectly matched layer technology and periodic boundary condition were used, while conformal meshing technology was adopted at the metal interfaces to decease numerical errors introduced by stair case approximation [18,19]. The transmission coefficient were calculated as the ratio of power transmitted through the structure to the incident power, and the reflection coefficient were calculated as the ratio of power reflected from the structure to the incident power.

3. Results and discussion

Fig. 2 shows the light transmission coefficient spectrum for metal nanohole arrays with different hole shape in the wavelength range of 350–800 nm, the metal nanohole arrays have the same thickness of 60 nm, the hole arrays have the same period of 200 nm. Although different kinds of holes have the same area, it can be seen from the figure that metal nanohole arrays with different hole shape have very different optical behaviors, the metal films perforated with rectangle nanohole arrays and isosceles triangular nanohole arrays have extraordinary optical transmission coefficient peaks with more longer wavelengths and stronger strength than the metal films perforated with square nanohole arrays and circle nanohole arrays; the metal film perforated with circle nanohole arrays have almost the same optical behaviors as the metal film perforated with square nanohole arrays, but the strength of light transmission coefficient peak of metal film perforated with circle nanohole arrays is weakest and the wavelength is shortest. From Fig. 2, we can see that the hole shape would play an important role on the optical property of the metal film perforated with nanohole arrays. The above observed optical behaviors cannot be understood by the electromagnetic surface modes [4–6]. The dependence of EOT with hole shape revealed the existence of another type of transmission resonances which arise from electromagnetic modes localized close to the hole, as consist with previous experiments [7,8]. In the followings, we will take our focus on presenting the research results of the metal film perforated with rectangle nanohole arrays and isosceles triangular nanohole arrays, because they present more manifest characters which will be helpful for the investigation of the physical mechanism and at the same time they have more potential applications.

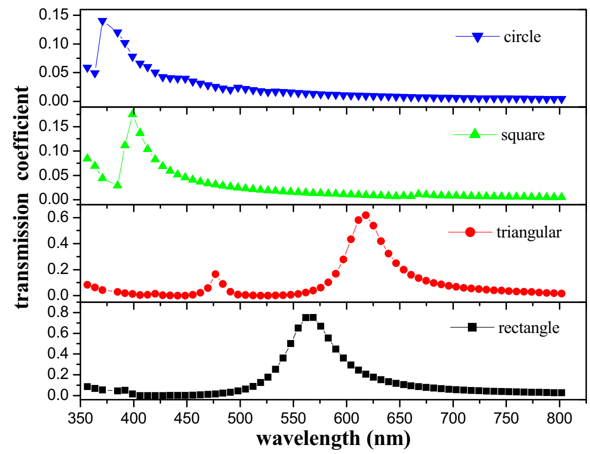

Fig. 2. The light transmission coefficient spectra in the wavelength range of 350–800 nm for metal nanohole arrays with different hole shape. The thickness of the metal nanohole arrays is 60 nm, the period of the hole arrays is 200 nm.

Fig. 3 shows the light transmission coefficient spectra in the wavelength range of 450–800 nm for the metal nanohole arrays with different periods [Fig. 3(a) for the metal films perforated with rectangle nanohole arrays and Fig. 3(b) for the metal films perforated with isosceles triangular nanohole arrays], the metal films have the same thickness of 60 nm, the nanohole arrays have the period in a range of 150–400 nm. It can be seen from Fig. 3(a) that the linewidth of light transmission coefficient peak becomes wide, the strength of light transmission coefficient peak becomes strong, and the transmission coefficient peak blueshift as the period of hole arrays decrease for the metal film perforated with rectangle nanohole arrays. From Fig. 3(b) we can see that the two light transmission coefficient peaks for the metal films perforated with isosceles triangular nanohole arrays present almost the same optical behaviors as those for the metal films perforated with rectangle nanohole arrays: the linewidth becomes wide, the strength becomes strong and the transmission coefficient peaks blueshift as the period of the hole arrays decrease. The increasing strength, widening linewidth and blueshifting of light transmission coefficient peak originate from the increasing coupling between the localized plasmon resonances mediated by the nearby surface plasmon polaritons as the period of the hole arrays decreases, those will be revealed by the following investigation on the electric-field distribution in metal nanohole arrays.

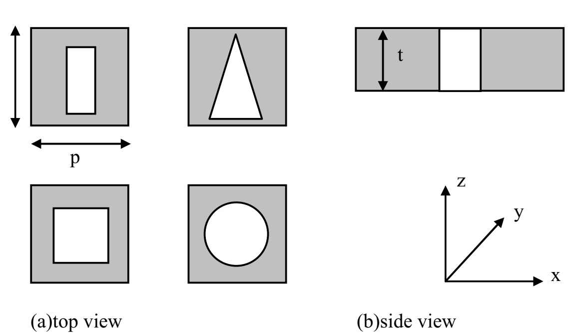

Fig. 1. The schematic diagram of metal film perforated with nanohole arrays. The thickness (t) of metal film has a range of 60–2000 nm. The period (p) of nanohole arrays with square lattice has a range of 150–400 nm, four kinds of nanoholes have almost the same area. The metal nanohole arrays was perpendicularly illuminated by a plane wave with the direction of the electric field E parallel to x-axis.