Enhanced Transmission through the Nanoparticle Coat

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Abstract. By using the full-vectorial three-dimensional finite-difference time-domain method and the perfect electronic conductor as the materials, we studied the enhanced transmission spectra through a substrate with the perfect electronic conductor nanoparticle coat. Single metal nanoparticle exhibited characteristic localized surface plasmon modes. By placing more plasmonic nanoparticles close to each other to make up of a plane, it was possible to observe the interaction between the modes of each individual nanostructure. The results showed that the enhanced transmission spectra through a substrate with different nanoparticle coats which were made by different numbers of the layers or by different metals exhibited different peaks whose values could reach 1. The number of the nanoparticle coat layers influenced the number and the positions of the enhanced transmission peaks.

1. Introduction
Since the phenomenon of the enhanced transmission through the subwavelength array holes is discovered by Ebessen and co-workers [1], it is focused by many scientists around the world. After that time, there are many researches on the enhanced transmission with both the experiments and theories. In the experiments, there are many researches on the enhanced transmission by using the noble metal materials such as the gold [2] and the silver [3] and the semiconductor for example the silicon [4]. Many kinds of subwavelength holes such as rectangular holes [5], cylinder holes [2] and ellipsoid holes [6] and nanoslits [7] were researched to investigate the enhanced transmission spectra. The nanoparticles also attract the scientists’ eyes. The metal nanoparticles mixed in the dielectric were deposited on the dielectric substrate or a multiple substrates such as metal-insulator-metal structure [8] in experiments. At the same time, there are many researches on theories about the interaction between particles with different shapes and materials and substrates with metal-insulator-metal or insulator-metal-insulator structures. The single nanoparticle coupled with a metal film was just given in [9]. The different shapes of the particles on the single substrate were studied for the scattering [10-12]. The nanoparticle coat
deposited on the substrate made by glass (SiO$_2$) has low reflection phenomena$^{[13]}$. They studied the collective resonances of the whole nanoparticle coat. Single metal nanoparticle exhibited characteristic localized surface plasmon (LSP) modes. It exhibits the feature of enhanced electronic field. When they get together, the resonance of the nanoparticles is formed to be a bridge to guide the electromagnetic field passing by. They show the phenomenon of enhanced transmission. In another word, the reflective wave is reduced and the transmission wave is enhanced.

In this Letter, we use the nanoparticles as the elements and study the transmission spectrum to find out the position of the enhanced frequency and the effective of enhancement. We research a new phenomenon of enhanced transmission through such a structure with the perfect electronic conductor (PEC) nanoparticle coats deposited on a substrate. The results showed that when nanoparticle coats were made by different numbers of the layers or by different noble metals deposited on a insulator substrate, the enhanced transmission spectra peaks’ positions and intensities were varied with the space between two nanoparticle lines, numbers of layers and the gold or silver nanoparticle coats. The PEC could be naturally extended to the real metal. In addition, we also take the gold and silver as real material not as PEC to discover the difference of the enhanced transmission. This kind of structure we researched might be as a new kind of filter in the future and also used in controlling light in nanosize.

2. Models and Results
We use the PEC as the material to make up of the nanoparticle. The radius of the nanoparticle is 105nm. The particles deposited on the SiO$_2$ substrate are arranged next to next in a line and the lines are made up of a plane which the area is about 1.995$\mu$m×1.995$\mu$m shown in Fig. 1. We use the FDTD method to get the transmission spectra.

![Figure 1. The schematic of the substrate with nanoparticle coat.](image)

Firstly, a single nanoparticle coat layer is discussed and the transmission spectrum is shown in Fig. 2. The space between two nanoparticle lines is varied from 0 to 120 nm. All the spectra make up of a map. From this map, we can know that the transmission is changed acutely and brightly near the space at 27nm. Whereas, the effective of transmission at the same frequency always reaches the maximum with the space of two lines about 88nm. Compared with other’s experiment work which the maximum transmission is 95% at about 600nm$^{[13]}$, it could be near 97% in the same wavelength in our simulation. Obviously they are in accordance with each other very well.

The value of transmission is all about $10^{-4}$ with the space at 0. The particles are so close to prevent the light. These electrons at the surface of the nanoparticles resonate to make up of the surface
The narrow space limits the resonance. With the space at about 27nm, the values of transmission change greatly. The space between two lines of the sample influences the collective resonance of the electrons at the surface. It also influences the scattering of the light. Single nanoparticle appears the LSP mode. When they are set in a line closed to each other and these lines are made up of a plane, the nanoparticle line exhibits a collective action. When the space becomes larger, the surface plasmon of the nanoparticles is enhanced. The surface plasmon course the enhanced transmission.

![Figure 2. The spectra of a single nanoparticle layer: the space between two nanoparticle lines is varied from 0nm to 120nm.](image)

The electrons at the surface of the nanoparticles resonate to form surface plasmons on metal nanoparticles (SPN). We take an area to investigate the electric field distributions of the samples and reflection spectrum. We choose two kinds of areas to keep the same numbers of particles: one is about 320nm×300nm for the space=0nm and the other is about 220nm×500nm for the space=110nm, 112nm and 114nm. The distributions of $|E|^2$ at middle of the coat layer are shown in Fig. 3. Considering the effect of the periodic boundary conditions in the simulation, we should observe the field distribution the area of the around centre. For the case of space=0nm, we find the distribution of the electric intensity is weak. The reason why electric intensity excited by surface plasmon so weak in this case is that nanoparticles set next to next shown in Fig. 1 lead to the electric field decreased as shown in Fig. 3 (e). The excited surface plasmon of the nanoparticles is coupled to each other along the direction of the polarization. The electric field of two half spheres in one nanoparticle is opposite seen in Fig. 3 (f). When the particles are set next to next, the fields are decreased at the contact surface shown in Fig. 3 (g). The field near the surface of the particles is weak and the transmission is prevented. When the space of two nanoparticle lines increases linearly, the value of the transmission presents changing with periodic and increasing. From (b), (c) and (d), we can see that the average amplitude in (c) is more than the others and the value of the transmission is also larger than the others. Obviously, the surface plasmon excited lead to the strong intensity distribution. The coupled SPN helps to enhance the transmission light.
When we put the nanoparticle lines in a plane perpendicular to the direction of the incident light, the nanoparticle coat exhibits the character of the enhanced transmission. If we put the nanoparticle lines in a plane parallel to the incident light, there is a new phenomenon. Then, we change the number of the nanoparticle layers. Comparing with one layer, the number of the layers which we considered is two, three, four and five, respectively. We choose the space of two nanoparticle lines is 28nm and get the transmission spectrum and show in Fig. 4.

From Fig. 4, we can see that there is more than one peak in each spectrum except (b) in Fig. 4. Except the first peak in the spectra, the other peak frequencies are all among the $1 \times 10^{14}$Hz~$7.6 \times 10^{14}$Hz. In the spectrum of two, three, four and five coat layers, the peak number is incidently equal to the number of the layers. The reflection light and the transmission light couples and then the mixed light goes from one layer to another. The final result is that there are several peaks in the spectra. Comparing with the lattice of 28nm, we also choose the lattice of 88nm and get the same phenomenon. The difference between the two kinds of lattice is the values of the transmission. The values of the transmission are all over 0.8 with the lattice of 88nm. If we use this structure as a filter, the space of 88nm could not prevent the light which we do not need. If the space we used is too small, the transmission coefficients are too small. So we must choose the space of about 28nm. When the nanoparticle lines are set in a plane along the incident light, the plane is formed as a channel to guided the light. The incident light is $p$-polariton and the polariton is perpendicular to the coat and parallel to the direction of the layer. The space influences the width of the spectrum. The larger the
space is, the wider the width is. When the particles were set in a line and parallel to the polariton of the incident light, the surface plasmon of nanoparticles strengthens the exciting field at the position of the other particle\textsuperscript{[14]}. Influenced by the space and the polariton, the spectra exhibit several sharp peaks.

Figure 4. The transmission spectrum with the one (b), two (c), three (d), four (e) and five (f) coat layers.

3. Discussion
Similar behavior can also be expected in the optical regime for a real metal. Here we also calculate the transmission spectra through Ag and Au nanoparticle coat layers by the 3D FDTD method. The radius of the nanoparticles is 105nm. The space is 28nm. The frequency-dependent permittivity of Ag and the permittivity of Au are referred to the literature\textsuperscript{[15]}. The incident light is $p$-polarization. We just use five different kinds of layers and get the transmission spectra shown in Fig. 4. The spectra of one layer, two layers, three layers and five layers in Fig. 5 are similar with Fig. 4. The intensities of some peaks in Fig. 5 are less than the ones in Fig. 4. The positions of the peaks in Fig. 5 have red-shifts. The electromagnetic field exists in the real metal nanoparticles. It influences the collective resonance of all the nanoparticles. The dielectric functions of metals also influence the surface plasmon of particles. Both the two reasons change the frequency of the enhanced transmission peak.

Figure 5. The transmission spectra of the Ag and Au nanoparticle coat layers with one, two, three, four and five layers: (a) is all the spectra of Ag nanoparticle coat layers; (b) is all the spectra of Au nanoparticle coat layers.
4. Conclusion

In conclusion, we discuss the enhanced transmission spectra through the substrate with nanoparticle coat layers. We change the number of the layer and get different transmission spectra. The single nanoparticle coat layer is perpendicular to the polariton of incident light to exhibit the enhancement. By changing the space of the samples, we know that the space constant influences the amplitude of the enhanced transmission spectra. The more the space is, the higher the amplitude is. By changing the number of the layers, we know that the direction of the nanoparticle layers which is parallel to the polarization of incident light exhibits the electromagnetic field and the energy propagating and the number of the layers influences the number of the enhanced transmission peaks. The more layers the more peaks. All of these, we know that the space between two lines, the number of the layers and the materials decide the frequency and the amplitude of the enhanced transmission peaks together.

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