Research on the Physical Mechanism of Extraordinary Optical Transmission

Hongzhi Wang

Hengshui University, Hengshui, China

Abstract: In recent years, the discovery of Extraordinary Optical Transmission (EOT) has greatly promoted the progress of surface plasmonic, which provided new ideas for regulating light waves at subwavelength scale, triggered an upsurge in explaining the mechanism of this physical phenomenon, and derived a series of related applications based on this phenomenon, such as sensing aspects, nano polarizers, filtering, light switching and scattering enhancement. This paper analyzes the mechanism and argument of abnormal transmission by SPP (surface plasmon polariton) model and CDEW (composite diffracted evanescent wave) model. The results show that the plasma excitation has strong localization, and it can break through the diffraction limit, and realize the manipulation and constraint of light wave at subwavelength scale.

Keywords: EOT; SPP; CDEW; surface plasmon polariton

1. Introduction

In 1998, Ebbesen [1] and others first discovered the optical abnormal transmission phenomenon in the sub wavelength microporous array structure of metal film, which led to the research upsurge of explaining the physical mechanism of the phenomenon, including: small hole, one-dimensional sub wavelength slits, two-dimensional sub wavelength hole arrays of different shapes and periodic structures around a single hole (bull's eye structure).the researchers fully analyzed the influence of various factors on the transmission characteristics [2-4]: size, shape, array period, ratio of substrate to lattice, array material, incident angle, frequency and array thickness, etc. There are scholars who propose interpretation models from the angle of phase, amplitude or combination of the two, such as surface plasma model theory (SPP model), composite attenuation wave model theory (CDEW model) and so on.

To date, there is no clear explanation for the EOT phenomenon, but it is generally believed that SPP plays an important role in it. the exact nature of light transmission through arrays has led to a heated debate, and some scholars even believe that SPP has no relationship: MJ.Treacy[5] believe that the abnormal transmission observed in metal gratings can be fully explained by dynamic diffraction theory. surface plasma is an intrinsic part of the diffraction field and does not play an independent causal role; J.M.Vigoureux [6] the near-field theoretical analysis of the Ebbesen experiment shows that the number of holes has little effect on the transmission field; But international scholars generally believe that the effective excitation of SPP leads to abnormal transmission phenomenon, which has strong localization, can break through the diffraction limit, and realize the manipulation and constraint of light wave at subwavelength scale..

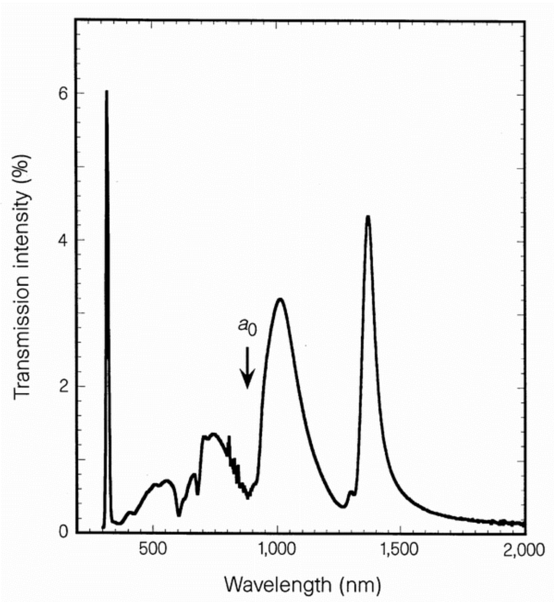
2. Theoretical model

Abnormal transmission of light through various subwavelength metal structures, including single slit, groove and one-dimensional grating for the mechanism of abnormal transmission phenomenon, it is generally considered to be an effective excitation of surface plasmon. it has strong localization and can break through the diffraction limit and realize the manipulation and constraint of light waves at subwavelength scale. Ebbsen et al first reported the abnormal transmission phenomenon on the Nature. When studying the silver film submicron hole array, we found the abnormal zero-level transmission spectrum phenomenon. the maximum transmission efficiency is several orders of magnitude higher than the traditional small hole theory. when the incident wavelength is about 10 times the aperture, the transmission rate of vertical incident reaches 200%, while the transmission efficiency of traditional theory should be only zero-point one order of magnitude. Formula (1) is the traditional formula of small hole transmission theory proposed by Bethe.

$$T = \frac{64}{27\pi^2}\left(\frac{D}{\lambda}\right)^4 \quad (1)$$

Where T is the transmittance, D is the diameter of the small hole, and is the wavelength of the incident light wave. in the classical theory, the transmittance is inversely proportional to the fourth power of the incident wavelength. However, Ebssen a transmission peak is observed at a specific incident wavelength and the transmittance increases dramatically, as shown in Figure 1.

Once the phenomenon of abnormal transmission is proposed, it attracts great interest of researchers. The research field has gradually expanded to single hole, one-dimensional subwavelength slit, two-dimensional hole arrays with different shapes and bull eye structures. Light can generate abnormal transmission through these structures. Later, it was found that the transmission characteristics are also affected by many factors, such as hole size, shape, array period, array material, substrate material, incidence angle, incidence frequency and array thickness. Many scholars explain the physical mechanism behind the abnormal transmission theoretically. At present, the theoretical explanation of the phenomenon can be divided into two categories: macro Bloch mode and micro surface wave interpretation. For micro surface wave interpretation, there are two kinds of models, one is SPP Model, the other is CDEW Model. However, there is still a great debate on the physical mechanism of EOT.



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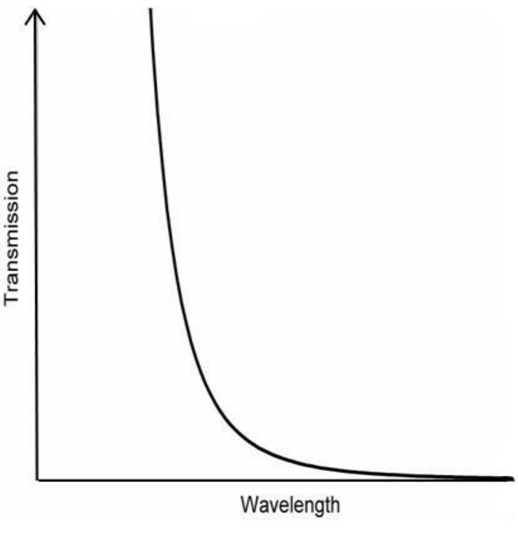


(b)

Figure 1. The variation curve of transmittance with incident wave under traditional theory and abnormal transmission.

(a) Zero-order transmission spectrum of silver thin film hole array in Ebssen literature, period a0=0.9 um, hole diameter 150 nm. the film thickness t=200 nm;(b) the relationship between the transmission coefficient and incident wavelength of the classical small hole transmission theory light through an infinite thin metal small hole.

2.1. SPP Model

Ebssen believes that when light is incident on the periodic array of two-dimensional metal subwavelength holes, each edge part of the hole is a diffraction point, and the TM wave of this point can be coupled to SPP, so as to enhance the abnormal transmission. The two-dimensional grid structure produces the coplanar momentum of Gx and Gy in the horizontal x and y directions, so when the SPP wave vector meets the following conditions, the position of the optical abnormal transmission peak of the small hole can be roughly calculated:

$$k_{sp} = k_x \pm n\mathrm{G}_x \pm m\mathrm{G}_y \tag{2}$$

Where k_{sp} is the surface plasmon wave vector, k_x is the component of the incident wave vector on the metal surface, n, m is the constant; $G_x = G_y = 2\pi / a_0$ (a_0 is the period of array) is the inverse lattice vector of x, y direction respectively. For a square metal, the resulting SPP propagates along the metal surface and then radiates to the free space light to another diffraction point. arrays distributed in the space period cause the wave vector of the SPP mode to exist periodically. for the positive incident transmission peak resonance approximately the following relationships (3):

$$\lambda_{peak} = \frac{a_0}{\sqrt{m^2 + n^2}}\sqrt{\varepsilon_D} \tag{3}$$

ε_D is the relative dielectric constant of the filled medium in the pore structure. Among them, the structure, shape, filling material, hole length and metal medium of the hole will have an impact. Many scholars at home and abroad have carried out in-depth experiments and theoretical analysis.

2.2. CDEW Model

The composite attenuation wave theory divides the electromagnetic waves scattered by the incident light in subwavelength defects such as slits, grooves and holes into radiation waves and surface waves. where the part of the wave vector less than the free space wave vector is the radiation mode out of the radiation; the part of the wave vector larger than the free space wave vector indicates that the wave vector is larger than the surface decay mode of the incident light. All decay waves propagating along the surface (SPPs is also one of the surface decay waves) are treated as a composite envelope wave. The composite attenuation wave is actually a collection of diffraction waves produced by the incident light source at subwavelength defects such as slits, grooves and holes, the nature of the whole reflected wave, as shown in Figure 2. CDEW model predicts three kinds of specific surface wave characteristics: First of all, this kind of surface wave is a combination of modes or a wave packet of a mode. The direction of each evanescent wave is perpendicular to the surface, the whole presents the characteristics of a wave, and its characteristic wavelength is; second, the first node appears at distance of half the characteristic wavelength at the center of the seam (It's basically the phase delay of π/2).Third, the amplitude of the composite attenuation wave is inversely proportional to the distance from the excitation point. The interference between the complex wave and the incident light wave in the gap or hole results in the periodic change of transmission.

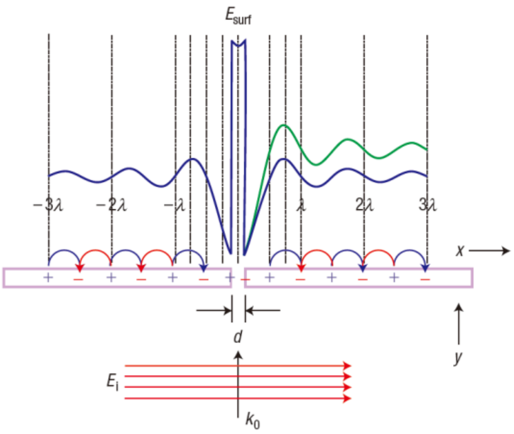


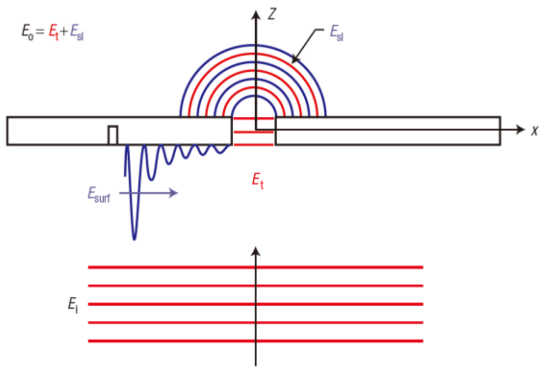
Figure 2. A plane wave is perpendicular to the subwavelength gap,a part of the incident wave constitutes a composite attenuation wave in the ±x direction.

Gay studies a beam of plane wave E_i from perpendicular incidence to subwavelength slots and grooves, so as to verify the correctness of the theory of composite attenuation wave model. Due to the existence of groove structure, metal produces attenuation wave Esurf on the side of the incident light, and propagates along the gap. When it reaches the gap, it turns into free propagation field Esl, and the interference between the incident field and the gap or small hole results in Et, the interference between the two results in the opposite space propagation field $E_0 = E_t + E_{surf}$, and the actual size can be measured in the far field. A composite attenuation wave Esurf can be expressed as:

$$E_{surf} = \frac{E_i}{\pi} \int_{\pm k_0}^{\pm\infty} dk_x \frac{\sin(k_x d/2)}{k_x} \exp(ik_x x)\exp(-k_z z) \quad (4)$$

Where Ei is the incident wave intensity, kx and kz are the components of the free space wave vector in the xz direction, and d is the gap width. Formula (4) can be approximately:

$$E_{surf} = \frac{E_i}{\pi}\frac{d}{x}\cos(k_{surf}x + \pi/2) \quad (5)$$



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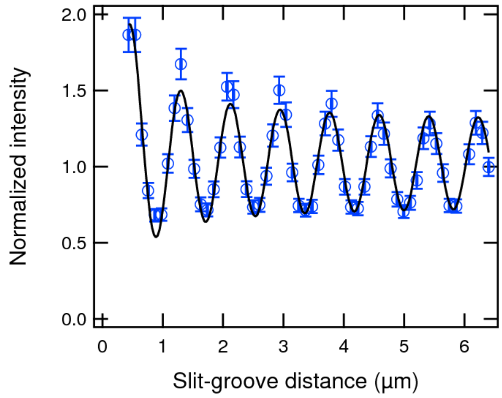

(b)

Figure 3. (a) theoretical model diagram of gay research CDEW, plane wave incident vertically to the gap-groove structure; (b) normalized far-field strength and gap-groove distance relationship diagram, good consistency between experimental and calculation models after fitting.

3. Helpful Hints Conclusion

About CDEW model theory, some scholars also put forward the oppugn. According to the CDEW model theory, for any polarized light, whether TM wave or TE wave, the transmission field intensity will oscillate periodically with the increase of slot spacing. However, the rigorous numerical solution of Maxwell equations shows that the transmission field intensity will oscillate only when TM wave is incident, while the transmission field intensity will oscillate between the slot and TE wave when TE wave is incident In view of the above disputes, at TE wave incidence, the intensity of TE wave is independent of the distance between slot and slot, some scholars put forward the SPP-CDEW combination model, which accounts for different proportion in the abnormal transmission intensity at different wavelengths. In a word, since the EOT phenomenon was proposed, there has been controversy about the underlying physical mechanism.

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