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Polarization insensitive transmission enhanced by staggered metal disk array

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The current consensus is exploring and optimizing the sensing performance of plasmonic transmission structure. The theory used is always trying to reduce the size of the structure, enhance the transmission efficiency, and improve the sensitivity. Here the polarization insensitive transmission and refractive index sensing performance enhanced by staggered metal disk array are investigated at infrared regime. With the metal disks being periodically staggered on both sides of a dielectric layer, there is a great improvement of the transmission efficiency at a specific operating wavelength. Compared with the extraordinary optical transmission on one-dimensional gratings, it is found that the transmission phenomenon is insensitive to the polarization of the incident light. Moreover, the sensing performances at each mode peak are enhanced by the staggered design, and the highest sensitivity reaches more than 5000 nm per refractive index unit (RIU). This work is beneficial for biosensing and extraordinary optical transmission research.

1. Introduction

Surface Plasmonics, as a method of local electromagnetic field enhancement, has been studied and applied for many decades [1,2]. Because the surface plasmon (SP) can bind the incident energy to the surface of nano-structure, it always gives rise to high absorption or low reflection. The extraordinary optical transmission (EOT), which was first proposed in 1999 [3], is an important application of SP. Its spectrum usually exhibits transmittance peaks where the transmission efficiency is much greater than expected by the standard aperture theory [4]. Different from some conventional situations, the EOT first introduced SP to the study of transmission system. In other words, the structure of EOT, such as one-dimensional (1D) periodic gratings with nano-slits and two-dimensional (2D) periodic subwavelength apertures arrays, usually does not include an opaque substrate. The position of the transmittance peaks, which is highly correlated with structural period, changes in permittivity and the order of diffraction, can be predicted by the conservation of momentum [24]. The related research contributes to biosensing, optical devices and telecommunications [5–10].

As a special electromagnetic evanescent wave, the SP is highly sensitive to the change of local refractive index (RI), which can be influenced by adsorbing biomolecules [11–13]. In other words, the spectra of transmittance, reflectance, and absorbance will be dramatically shifted with the change of RI. Therefore, many structures of SP excitation, such as the 1D periodic metal gratings or the 2D periodic metamaterials, are used for biosensing in a label-free method [14–18]. The latest studies based on surface plasmon polaritons (SPPs) reach the sensitivities as high as 3000nm/RIU, while for some small molecule analytes, the overall sensitivity provided by local surface plasmon (LSP) is typically at the orders of hundreds nanometers per RIU [19–21]. It is worth noticing that their sensitivities are always at the same order of magnitude as the period of structure [8,15]. Recently, the sensitivity based on waveguide or photonic crystal fiber reaches more than several tens of thousands per RIU [22], nevertheless, their large size brings much loss. The EOT-based biosensors develop rapidly, however, the method of biosensing still encounters some obstacles in many existing studies. For instance, simply increasing the period does not necessarily bring greater sensitivity because the structural change may destroy the original resonant modes, and cause the absence of EOT. Another common limit is that the excitation of SP asks for TM-polarized incident wave and noble metal, which results in a high demand for incident light polarization conditions and high production costs, respectively.

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In this paper, we propose a structure of staggered metal disk array with a layer of dielectric interposed. Although the structure is fundamentally different from the common EOT gratings or hole array, the peak positions are in good agreement with the EOT prediction of the conservation of momentum. This could be explained by the fact that the Mie resonance in the gaps between the disks reaches a similar effect of the hole array. As the period is doubled, it is found that the asymmetry greatly increases the resonant wavelength and sensitivity, while at the same resonant wavelength, the transmission efficiency of the symmetrical structure with same period is much lower. This result dramatically improves the sensitivity that EOT-like structure can achieve in biosensing application [more than 5000 nm per refractive index unit (RIU)]. Furthermore, regardless of the polarization angle, the total contribution of SPPs to transmittance in each direction is constant, which means the polarization does not affect the transmission performance. Overall, this work aims to provide a useful thought to improve the transmission and sensing performance of EOT-like structure from efficiency, practicality and sensitivity. The finite-difference time-domain (FDTD) method is used to proceed simulation in three-dimensional, and the simulation software Lumerical FDTD Solutions is utilized.

2. Numerical model and theory

The schematic of the three-dimensional numerical simulation model with a 2D period is shown in Fig. 1(a), and the cross-section schematic in one period is shown in Fig, 1(b). Two layers of gold disks are staggered on both sides of the middle dielectric layer with refractive index $n = 1.5$, and the periodicity of metal disks on each side is along the x and y-axis simultaneously. The gold is characterized by the permittivity ε_1 with the Drude model $\varepsilon_1 = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\gamma\omega)$. For which $\varepsilon_\infty = 7.9$, $\omega_p = 8.77eV$, and $\gamma = 1.13 \times 10^{14}c^{-1}$ are set. These values work in the infrared regime without considering the response of bound electrons [1]. The diameter of the metal disk is represented by d, and the structural period is p ($p = 2d + 2w$), where w is the horizontal distance between two adjacent disks on different side. A planar electromagnetic wave incidents along z-axis with wave number being $k = 2\pi/\lambda$. The incident angle and polarization angle are θ and φ, respectively. In this paper we discuss the case of vertical incidence ($\theta = 0$) by default. In Fig, 1(b), the thickness values of the dielectric layer and metal disks are h_1 (set to 500 nm) and h_2 (set to 250 nm), respectively. In the study of sensing, the analyte solution is

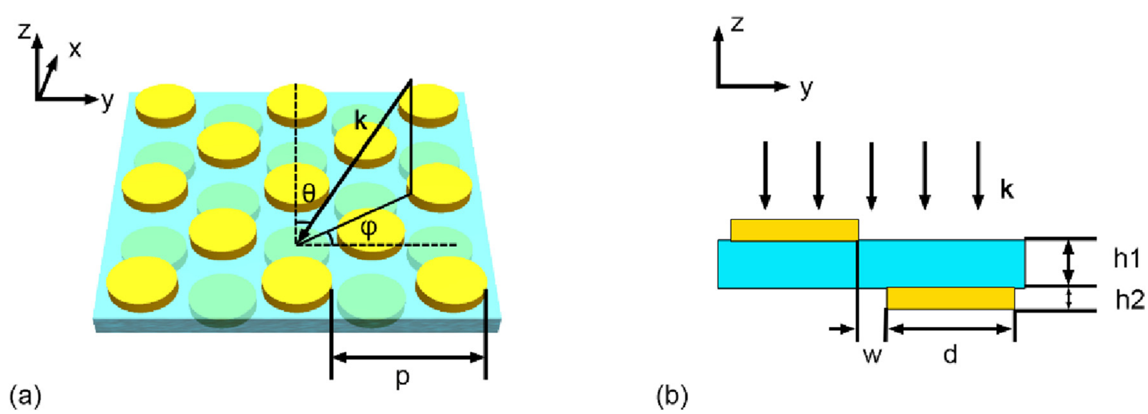

Fig. 1. The simulation schematic of the staggered metal disk array. The diameter of disk is 3.25 μm, and the period is 7 μm. (a) 3D structure, (b) 2D structure.

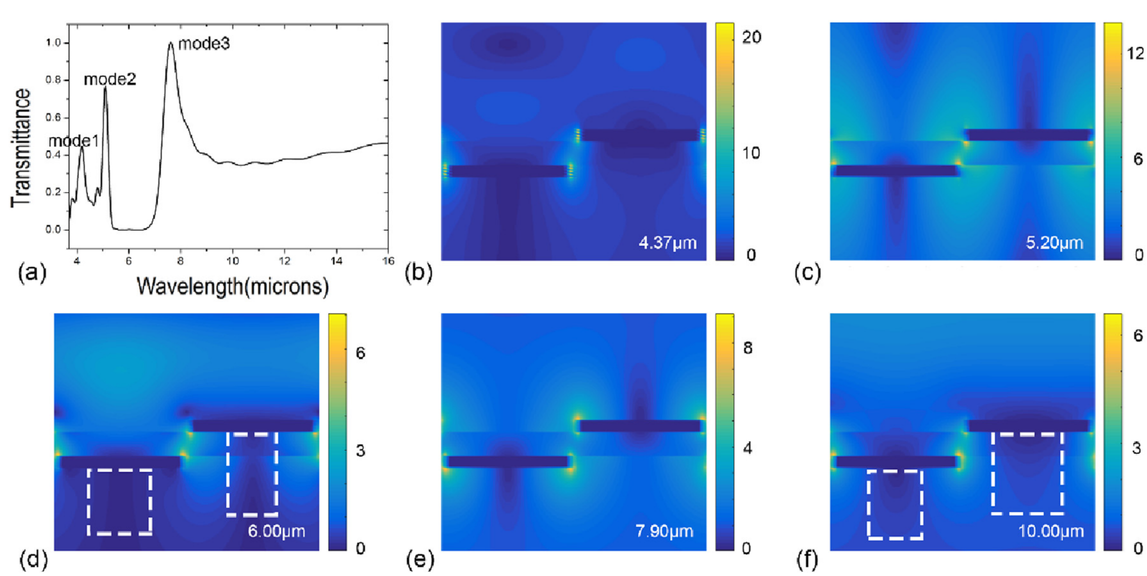

Fig. 2. (a) The transmittance spectrum of staggered disk array, and the wavelengths of the three modes are 4.37 μm, 5.2 μm and 7.9 μm. (b–f) The distribution of the normalized electric field in the cross section of the array. The shadows in the white dashed line boxes indicate the low transmission efficiency without transmission modes. The wavelength is marked in the lower right corner.