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The sensing characteristics of periodic staggered surface plasmon gratings

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ABSTRACT

Bragg gratings, because of their favored surface plasmon coupling characteristic, are widely applied in nano-optics. We propose a periodic staggered Bragg gratings structure as a refractive index sensor by the finite element method. The optimized extraordinary optical transmission based on staggered gratings can excite surface plasmon resonance for much larger wavelength. The refractive index can be obtained by detecting the resonant wavelength shift of transmittance peak. This sensor exhibits high sensitivity and favorable linear characteristic in a wide variation interval of refractive index. The simulation results provide a further insight into nano optical sensors.

1. Introduction

The nano optical sensors with integrated small size, high sensitivity and broad bandwidth, are employed in the fields such as telecommunication, chemistry and biology [1,2]. The research of surface plasmon polaritons (SPPs), which are evanescent electromagnetic waves along the interface between metal and dielectric layer, has been a hot topic recently because it can overcome the diffraction limit of light. In practical application, SPPs are often considered as energy and signal carriers for their ability of propagation. Many correlational studies of SPPs in sensor have been done to explore SPPs' sensing performance over the last decades [3–7]. Generally, SPPs refractive index sensors work at near infrared wavelength range, and the sensitivity only reaches less than 2000–3000 nm/RIU, mostly around 1000 nm/RIU. The sensing structure is always designed with gratings, waveguides, nanoparticles etc. [8–14]. Such as plasmonic gold mushroom arrays with 1010 nm/RIU [9] and metal gratings coupled porous film with 700 nm/RIU [11]. Recently, some papers proposed sensing structures made with photonic crystal fiber (PCF) or special material, which can, under a given range of refractive index, reach sensitivity about 7000–8000 nm/RIU or even more than 10,000 nm/RIU [15–19]. Such as in-line microfluidic integration of PCF with 8699 nm/RIU [16] and D-shaped PCF biological sensors with 12,450 nm/RIU [19]. In spite of the high sensitivity, their linear characteristics of sensitivity are not so satisfying, i.e. the range of detection is within a very limited interval. Taking Refs. [16,17,19] for example, the working sensitivity is obtained only in the refractive index range from 1.3 to 1.4. Moreover, it can be seen in Ref. [19] that the peak maximum and full width at half maximum (FWHM) of the spectrum change distinctly with the variation of refractive index. Such general characteristics of PCF sensors ask for more stable spectrum and larger detecting interval for sensing.

Extraordinary optical transmission (EOT) is one of significant applications of surface plasmon [20–24], which can be obtained at a wavelength up to 10 times larger than the diameter of holes on the metal structure with subwavelength holes or narrow slits. The main acceptable origin of EOT is regarded as a hybrid resonance mechanism of SPPs and Fabry–Pérot (F–P) cavity [27,28]. When the depth of holes or slits is increasing, the micro cavity can contain more resonance modes and motivate not only one peak on spectrum. If the incident wave is p-polarized, the SPP mode has predominance at the wavelength close to the period of gratings, no matter how we changes the depth of holes or slits [27]. Since it is subwavelength slits to be studied, the zero order of diffraction is simply considered [28]. As a significant advantage of EOT, the position of its transmittance peak is sensitive to refractive index of cover material. That along with simple structure and high efficiency makes the refractive index sensor a favorable choice. However, the peak cannot maintain at a high value in a large interval of wavelength, as traditional EOT needs strong conditions.

In this paper, a periodic staggered gratings sensor simulation structure is proposed in the mid-infrared waveband. Such periodic

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structure with metallic and dielectric constituents can support SPPs along with waveguide modes. The staggered metal nanowires are utilized to introduce asymmetry to gratings. This structure brings different feature of transmission that can be used in sensor work [25,26]. In particular, we obtain a spectrum with higher sensitivity, better linear characteristic and wider interval of detection, which overcomes the problems of former structure mentioned above. The performance is simulated numerically by the finite element method (FEM) in frequency domain, and commercial software COMSOL Multiphysics is used.

2. Simulation structure

The design of sensing schematic and simulation structures in one period is shown in Fig. 1. Periodic staggered metal gratings are surrounded by the material to be detected, which refractive index is represented by n_a. The upper metal nanowires have half-period shift with the lower nanowires along x-axis (Both ‘asymmetry’ and ‘staggered’ are utilized to describe misalignment structure in former study, e.g. Ref. [25]. We think ‘staggered’ is a better choice to explain the half-period shift of nanowires). Between upper and lower metal nanowires there is one dielectric layer with refractive index n_b, while all nanowires are on the same side of dielectric layer in non-staggered gratings. The model extends infinitely on y-axis. We assume that a planar TM electromagnetic wave with wavelength λ incidents from top edge perpendicularly, and is absorbed by bottom edge. The direction of incident magnetic field is along y-axis. The width of a metal nanowire is w, and the width of slit is w', i.e. the horizontal distance between upper and next lower metal. The thicknesses of one layer metal and the dielectric layer are h and d, respectively. The simulation values of these parameters are shown in Table 1, and both staggered and non-staggered structure are employed in same size parameters.

In FEM, we mesh the solution domain into multiple units as fine as possible, and solve the basic equation of electromagnetic field in each unit. The electric field distribution in space is derived from the parameters of 2D TM mode port by introducing vertical propagation constant k_z, i.e. $\vec{E}(x, y, z) = \vec{E}(x, y)e^{-ik_z z}$. The coupling between incident wave and structure defines the electric field, which can be obtained by solving wave equation [3]:

Table 1
Simulation parameters of the structure.

Parameter	Value	Remarks
n_b	1.5	The refractive index of dielectric layer
w	3000 nm	The width of metal
w'	500 nm	The width of silt
h	250 nm	The height of metal
d	500 nm	The height of dielectric

$$\nabla \times \left(\nabla \times \vec{E}\right) - k_0^2\varepsilon_r\vec{E}=0 \tag{1}$$

$$\nabla\times\mu^{-1}\left(\nabla\times\vec{E}\right) - k_0^2\left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0}\right)\vec{E}=0 \tag{2}$$

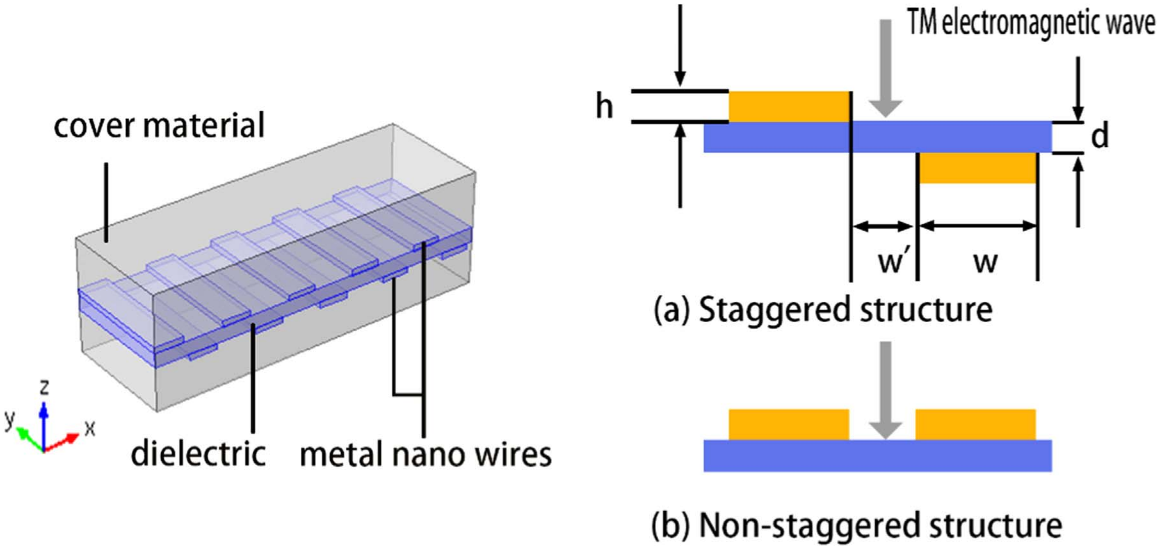
The solutions of Eqs. (1) and (2) are applicable in the situation of dielectric/air and metal, respectively. The relative dielectric constant ε_r is determined by corresponding position's material. The wave vector number in vacuum is k_0. The angular frequency of propagation wave mode is ω. The relative permeability μ and the relative conductivity σ are set to 1 and 0, respectively. The metal is gold, and the relationship between the dielectric constant ϵ of gold and ω is given by Drude–Sommerfeld theory. The expression of dielectric constant $\varepsilon_r=\epsilon(\omega)$ is:

$$\epsilon(\omega)=1-\frac{\omega_p^2}{\omega^2+i\Gamma\omega} \tag{3}$$

where ω_p is the plasma frequency, and Γ is the damping coefficient, which is the ratio of Fermi velocity and the electron mean free path between scattering events [3]. Using material parameters of gold: $\omega_p=1.\,37225\times10^{16}$ rad/s, $\Gamma=10^{14}$ rad/s to substitute the items of upper function, the dielectric constant spectrum of gold in mid-infrared range can be obtained. Here, we utilize the equation form with real and imaginary part of $\epsilon(\omega)$ in simulation, so Eq. (3) is divided into:

$$\epsilon(\omega)=1-\frac{\omega_p^2}{\omega^2+\Gamma^2}+i\frac{\Gamma\omega_p^2}{\omega(\omega^2+\Gamma^2)} \tag{4}$$

Floquet periodic boundary condition is defined at both horizontal ends in x-axis of simulation area. The Floquet periodic



(a) Staggered structure

(b) Non-staggered structure

Fig. 1. The sensing schematic diagram and two comparison simulation structures in one period: periodic staggered gratings covered by the material to be detected. (a) Staggered structure. (b) Non-staggered structure. The refractive index of dielectric layer is 1.5. A TM electromagnetic wave incidents along z-axis, and the direction of magnetic field is along y-axis.