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ORIGINAL RESEARCH ARTICLE

Study on the absorption characteristics and refractive index sensitivity characteristics of the periodic structure of double nanorods

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ABSTRACT

Metamaterial perfect absorber is very important in the study of refractive index sensor. The time domain finite difference method is used to simulate the surface plasmon structure. The double nanorod periodic structure is designed, and the parameters of the top layer structure are optimized according to the impedance matching principle, and the absorption rate of the structure to the light wave reaches 99.6% when the wavelength is about 12 mm. The absorption spectroscopy of the structure is studied with the change of the refractive index of the spatial medium around the structure, and the sensitivity of the double nanorod structure is 4,008 nm/RIU, which can be used to measure the refractive index of the gas.

Keywords: Surface Plasmon; Sensor; Nanorod; Absorption Spectrum; Sensitivity

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1. Introduction

Electromagnetic metamaterials are light-manipulated artificial composites. By changing the parameters of the surface nanostructure units or the arrangement of the structural units, the effective dielectric constant and effective permeability of the metamaterial can be adjusted, so that electromagnetic devices with extraordinary properties can be obtained, such as polarization converters, stealth cloaks, superlenses and absorbers[1–4]. In 2008, Landy *et al.* designed the first metamaterial perfect absorber, and researchers began a research boom on metamaterial absorbers.

According to the bandwidth of the absorption band, the absorber is mainly divided into two types of absorbers. One is the broadband absorber, which is mainly used in solar cells[6,7]; the other is the narrowband absorber, which is mainly used in the field of photoelectric detection and sensors. High-sensitivity sensors have broad application prospects in chemical, biological, and medical fields[8].

Metamaterial structures based on narrow bandwidth, high absorption and high-quality factors have received great attention for the study of highly sensitive refractive index sensors, and scholars have proposed nanostructures of various shapes, such as nano-rings, nano-disks, nano-rectangles, butterfly-shaped and other mixed arrangement structures[9–13]. In 2013, Tuongs designed a concentric double-ring structure to implement a dual-band absorber. In 2015, Lu *et al.* proposed a nanorod absorber with an absorption rate of more than 95%[15]. Although the absorption coefficient of these study structures is high, the morphology and structure of the surface plasmon nanostructures are more complex.

At present, the research of metamaterials is mainly in the theoretical and experimental stages, and the production cost and efficiency of metamaterials with complex structures are high and inefficient, which is not conducive to the future large-scale production of metamaterials.

In this paper, a metal-dielectric-metal surface plasma nanostructure is proposed, the structure of which is mainly composed of three layers, the top layer is a periodic double nanorod, the middle layer is the substrate, and the bottom layer is the metal reflective layer. Firstly, the time domain finite difference method is used to excite the surface plasmon resonance according to the impedance matching principle, and the peak of the absorption spectrum of the sensor is increased by optimizing the structural parameters. Secondly, the sensitivity and quality factor of the sensor are calculated by changing the refractive index of the medium around the structure. Compared with other narrow-band absorbers, the periodic structure of the absorber designed herein is a square nanorod, which has the characteristics of simple preparation under the characteristics of high absorption, creating conditions for the large-scale and large-volume production of metamaterials in the future and shortening its production cycle.

2. Simulation structure and calculation method

The absorber designed herein is based on a thickness of t_1 = 30 nm of silica as a substrate, and a metal reflective layer is provided under the substrate, the thickness of which is t_2 = 50 nm, the material is gold, and the upper surface of the substrate is plated with a periodic two-line structure, as shown in **Figure 1a**. The two-line structure period is p_x = 700 nm and p_y = 1 mm, as shown in **Figure 1b**. The array cell consists of two rectangular nanorods, *w* = 80 nm wide and *t* = 100 nm in the *z* direction, where the length of the nanowires is *L* and the spacing between the two nanowires is *g*. The plane wave with a wavelength of 0.2–3 mm of the incident light wave is polarized along the *y* direction and propagates in the negative direction of the *z*-axis to the two-line structure structure. Simulation space settings: the *x* and *y* directions set periodic boundary conditions, while the *z* direction is set to perfectly match the layer. During the calculation, the refractive index of the gold model was modeled JC and SiO_2 adopts palick model.

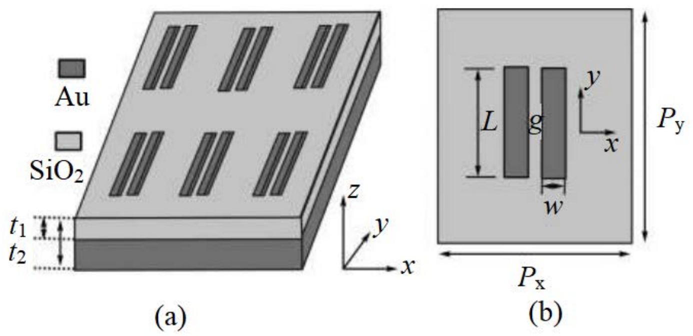

Figure 1. (**a**) Three-dimensional illustration of the double nanorods perfect absorber; (**b**) top view of unit cell.

Based on Maxwell's equations, the absorption spectral characteristics and refractive index sensitivity characteristics of the sensor are simulated by using the time domain finite difference method. According to the energy conservation of light waves, the absorption rate of the structure is A = 1-R-T, where R is the reflectivity of light and T is the transmittance of light. In order to improve the absorption rate of the structure to a certain range of light waves, it mainly starts from the following two points. First of all, reduce the reflectivity of the structure; according to the principle of impedance matching, adjust the parameters of the top structure of the sensor, so that the resistance of the sensor is approximately equal to the resistance in free space, so that the reflectivity of the sensor is close to 0. Secondly, the transmittance of the structure is reduced T, and a metal layer is added as a reflective layer under the medium, thereby reducing the transmittance coefficient of light waves passing through the sensor S_{12}.

$$S_{11} = \frac{Z_1 - Z_0}{Z_1 + Z_0} \quad (1)$$

$$Z_1 = \sqrt{\varepsilon_1}\sqrt{\mu_1} \quad (2)$$

$$Z_0 = \sqrt{\varepsilon_0}\sqrt{\mu_0} \quad (3)$$

Where S_{11} represents the reflection coefficient of the structure, Z_1 represents the equivalent impedance of the structure, Z_0 represents the impedance of a free space. Reflectance $R = S_{12}$, in order to obtain a small enough reflectivity, adjust the parameters of the metamaterial structure, so that the equivalent impedance of the structure and the free space impedance Z_0. Approximately equal, so that S_{11} tends to zero. Among them, ε_1, ε_0 represents the equivalent dielectric constant of the structure and the dielectric constant in vacuum, respectively. The equivalent permeability and vacuum permeability of the structure are represented, respectively. Based on the above two adjustments, when L = 600 nm, g = 140 nm, w = 80 nm, the two-line structure produces a local surface plasmon resonance at wavelengths of 12 μm and 23 μm, the near field is enhanced, and the absorption rate is up to 99.96%, so that the absorption coefficient of the structure gets the optimal value. As shown in **Figure 2a**, the absorption rate of a single nanowire structure is lower than that of a double nanowire structure. From **Figure 2b** and **Figure 2c**, it is found that the absorption spectrum has two peaks, and absorption enhancement is achieved at both wavelength positions. Among them, the larger peak is at 12 mm, which is the resonance mode of the oscillation excitation of the electric dipole oscillation in the local area of the structure, because the direction of the electric field strength of the left and right nanorods is consistently reinforced, and the sub-peak is the near-field coupling between the two nanorods, resulting in a larger absorption rate at the wavelength of 23 mm.

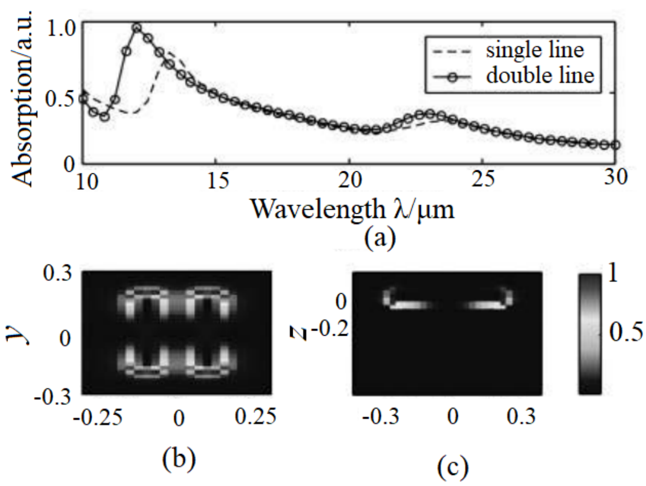

Figure 2. (**a**) Absorption spectrogram; (**b**) electric field diagram of absorption spectrum peak in *x-y* plane; (**c**) electric field diagram with absorption spectrum peak in *y-z* plane.

3. Effect of structural parameters on absorption spectral characteristics

The effect of vertical nanorod length L on the absorption spectral characteristic curve of the sensor was investigated. The distance between two vertical nanorods is g_2 = 140 nm, change the length of the vertical nanorods, and investigate their effect on the sensor absorption spectrum, as shown in **Figure 3**.

23 μm corresponds to absorptivity of 99.6% and 40%. As L continues to increase from 600 to 800, the two peaks of the absorption spectrum are redshifted, and the larger peak value decreases to 93%. It can be seen that when L = 600 nm, w = 80 nm, and g = 140 nm, the absorption rate value of the double nanorod structure is the largest.

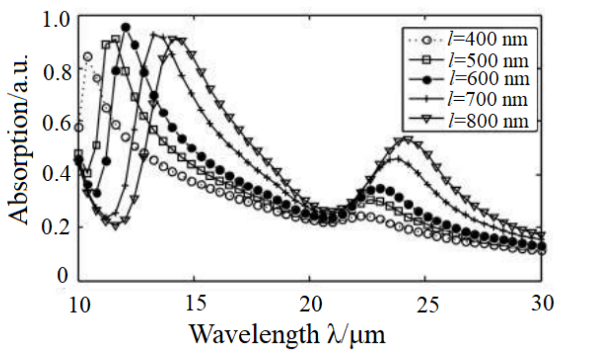

Figure 3. Influence of nanorods length on absorption spectrum.

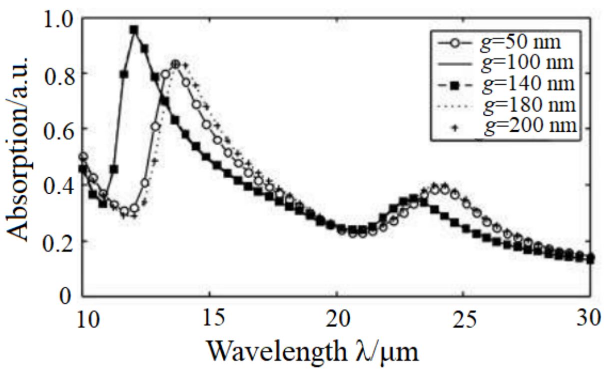

Figure 4. Influence of the distance between nanorods on absorption spectra.

The effect of the spacing g between double nanorods on the absorption spectral characteristic curve of the sensor was investigated. The length of the vertical nanorod L = 600 nm, the distance between the two vertical nanorods g = 50 nm, change the spacing of the double nanorods, and investigate its effect on the sensor absorption spectrum, as shown in **Figure 3**. When g increases from 50 nm to 140 nm, the wavelength corresponding to the two peaks in the absorption spectrum changes blue, and the corresponding absorption rate of the larger peak increases from 85% to 99.6%. When g continues to increase from 140 nm to 200 nm, the wavelength corresponding to the two peaks in the absorption spectrum is redshifted, and the corresponding absorption rate of the larger peak decreases from 99.6% to 84.5%. It can be seen that when L = 600 nm, g = 140 nm, and w = 80 nm, the absorption rate value of the structure is the largest, reaching 99.6%.

4. The influence of the spatial medium on the refractive index sensitivity characteristics of the sensor

When the oscillation frequency of the free electrons on the surface of the metal nanostructure is consistent with the frequency of the incident wave, the surface plasmon resonance phenomenon will be generated, and the near field of the metal nanostructure will be significantly enhanced. As the refractive index of the space medium occurs, the wavelength corresponding to the surface plasmon resonance moves. Therefore, this principle can be used as a refractive index sensor to detect changes in the refractive index of an object, as shown in **Figure 5**.

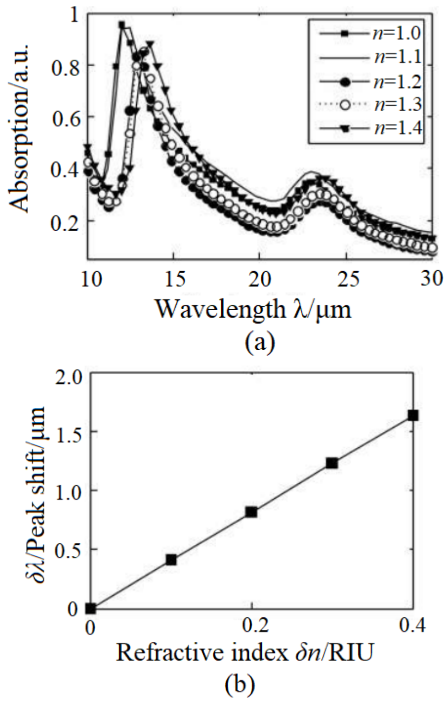

Figure 5. (**a**) Influence of refractive index n on absorption spectrum; (**b**) relationship between the change of refractive index n in the external environment and the change of large peak wavelength of absorbed light wave.

Keep the structural parameters L = 600 nm, g = 140 nm unchanged, change the refractive index of the spatial medium around the sensor, and investigate the influence of the spatial medium on the refractive index sensitivity characteristics of the sensor The external refractive index n = 1.0, 1.1, 1.2, 1.3, 1.4, the wavelength corresponding to the larger peak in the absorption spectrum of the structure is shown in the figure. As shown in **Figure 5a**, the resonant wavelength is redshifted as the refractive index value increases. In **Figure 5b**, the change of the external refractive index is the abscissa, and the change of the wavelength corresponding to the peak of the absorption spectrum is plotted on the ordinate. Through data fitting, the sensitivity S of the sensor at the corresponding wavelength is obtained as 4,008 nm/RIU. When the wavelength measurement resolution is 0.1 nm, the theoretical resolution of the sensor is 2.5×10^{-5} RIU. As the surrounding refractive index increases, the peak wavelength of the absorption rate is redshifted, indicating that high-sensitivity gas detection can be achieved using this design.

5. Conclusions

In this paper, a two-nanowire structure metamaterial perfect absorber is designed, and the spectral characteristics of the absorber, the electric field distribution at the formant of resonance and its refractive index sensing characteristics are studied by the time domain finite difference method, and the influence of structural parameters on the absorption spectrum and sensing characteristics is analyzed. The absorber designed in this paper has a high absorption rate, mainly for the following three reasons.

First, when the incident light is illuminated vertically onto the surface of the absorber, the interaction between the two nanowires of the structural layer makes the local electric field enhanced. Second, a local plasma resonance is generated between the structural layer and the dielectric layer, which makes the electric field enhanced. Finally, the basal layer of the absorber can reflect the incident light, and the light local is localized between the media layer and the substrate, which greatly improves the absorption rate of the absorber. By changing the structural parameters can adjust the absorption rate of the absorber, the peak position and its sensing characteristics, the absorber designed herein has two absorption peaks, at the wavelength of 12 mm and 23 mm, the absorption rate reaches 99.6% and 60%, respectively, where the sensitivity near the wavelength of 12 mm reaches 4,008 nm/RIU. Therefore, the double nanowire metamaterial structure perfect absorber designed in this paper can achieve a measurement resolution of 10^{-5} magnitudes, which provides a certain foundation and support for the plasmon hypersurface structure in terms of refractive index sensor.

Conflict of interest

The authors declared no conflict of interest.

Acknowledgement

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References

1. Pendry JB, Negative refraction makes a perfect lens. Physical Review Letters 2000; 85(18): 3966–3969.
2. Fang N, Lee H, Sun C, *et al.* Sub-diffraction-limited optical imaging with a silver superlens. Science 2005; 308(5721): 534–537.
3. Schurig D, Mock JJ, Justice BJ, *et al.* Metamaterial electromagnetic cloak at microwave frequencies. Science 2006; 314(5801): 977–980.
4. Iwaszczuk K, Strikwerda AC, Fan KB, *et al.* Flexible metamaterial absorbers for stealth applications at terahertz frequencies. Optics Express 2012; 20(1): 635–643.
5. Landy NI, Sajuyigbe S, Mock JJ, *et al.* Perfect metamaterial absorber. Physical Review Letters 2008; 100(20): 207402.
6. Pan W, Yu X, Zhang J, *et al.* Absorption Characteristics analysis of Terahertz metamaterial absorber based on double-open square sheet. Applied Laser 2016; 36(3): 346–350.
7. Mo M, Wen Q, Chen Z, *et al.* Ultra-wideband polarization insensitive terahertz absorber based on truncated cone structure. Chinese Journal of Physics 2013; 62(23): 237801.
8. Liu N, Mesch M, Weiss T, *et al.* Infrared perfect absorber and its application asplasmonic sensor. Nano Letters 2010; 10(7): 2342–2348.
9. Lou W, Shen T, Liu H, *et al.* Fiber optic transverse pressure sensor based on long-cycle fiber grating and butterfly cone. Optoelectronics & Lasers 2016; 27(11): 1145–1148.
10. Xu H, Hu L, Lu Y, *et al.* Dual-band metamaterial absorbers in the visible and near-infrared regions. Journal of Physical Chemistry C 2019; 123(15): 10028–10033.
11. Wang S, Sun X, Ding M, *et al.* The investigation of an LSPR refractive index sensor-based on periodic gold nanoringsarray. Journal of Physics D: Applied Physics 2018; 51(4): 045101.
12. Xu J, Zhao Z, Yu H, *et al.* Design of triple-band metamaterial absorbers with refractive index sensitivity at infrared frequencies References and links. Optics Express 2016; 24(22): 25742–25751.
13. Wang B, Koschny T, Soukoulis CM. Wide-angle and

polarization-independent chiral metamaterial absorber. Physical Review B 2009; 80(3): 033108.
14. Tuong PV, Park JW, Rhee JY, *et al.* Polarization-insensitive and polarization-controlled dual-band absorption in metamaterials. Applied Physics Letters 2013; 102(8): 081122.
15. Lu X, Zhang L, Zhang T. Nanoslit-microcavity-based narrow band absorber forsensingapplications. Optics Express 2015; 23(16): 20715–20720.