Humidity sensor based on perfect metamaterial absorber

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Abstract

We proposed a humidity sensor based on perfect metamaterial absorber. The sensor is composed of three layers, which are metallic particle array on the top, porous silicon in the middle layer and metallic film at the bottom. It is shown that the resonant wavelength displays significant red-shift with the increasing effective permittivity of porous silicon, which is influenced by the filling fraction of water condensation. Furthermore, the simulation results indicate that the refractive index sensitivity of absorber is high to 249 nm/RIU, which makes our structure be an ideal candidate for evaluating the humidity of environment.

I. INTRODUCTION

Since Smith et. al first experimentally realized the meta-materials (MMs) with simultaneous permittivity and permeability at microwave frequency [1], MMs are widely used to realize some interesting and fascinating devices, such as perfect lenses [2], photodetector [3], transistors [4,5,6], nanocavity [7] and absorbers [8,9]. Among the devices, plasmonic absorber is one of the most important and successful applications because of its ultra-strong ability of absorbing electromagnetic waves and freely tuning the absorption wavelength. On the other hand, it is known that MMs can be regarded as homogeneous medium with the complex permittivity $\varepsilon=\varepsilon'+i\varepsilon''$ and permeability $\mu=\mu'+i\mu''$ when the unit cell of MMs is much smaller than the wavelength of incident wave [10]. Therefore, the absorption wavelength is quite sensitive with the material composition, which can be utilized to make sensor. For example, Liu et. al proposed a plasmonic sensor base on absorber in detecting the refraction index variation of environment [11].

In this paper, we have proposed a humidity sensor based on perfect absorber. According to the effective medium approximation, the effective permittivity of porous silicon is mainly determined by the filling fraction of water condensation. The calculated results show that the increasing dielectric constant in the middle layer of sensor induces significant red-shift of the absorption wavelength of absorber. Moreover, It is found that refractive index sensitivity high to 249 nm/RIU.

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II. Numerical model and simulations

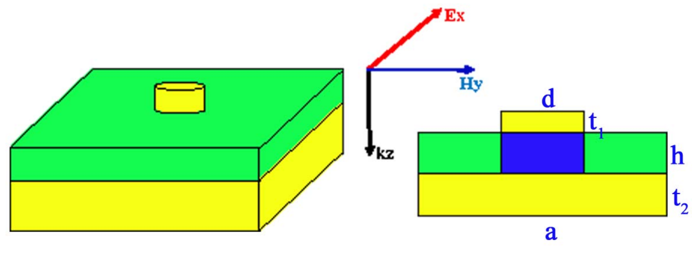

Figure 1. (Color online) Schematic of the metamaterial absorber cell structure

Fig. 1 shows the basic scheme of the metamaterial absorber. It is composed of three layers. The top layer is an array of cylindrical gold particles. The middle dielectric layer consists of two parts. The middle part under the gold particle (blue part) is solid silicon while the other part (green part) is porous silicon. The bottom layer is a thin gold film.

The parameters of the sensor structure are as follows. The diameter and thickness of gold particle are d=200 nm and t_1=20 nm. The thickness of silicon in the middle layer is h=60 nm, and the thickness of gold film is t_2=200 nm while the lattice constant is a=600 nm. The permittivity of gold is described by Drude model [12]: $\varepsilon_m=\varepsilon_0\{1-\omega^2_p/\omega(\omega+i\gamma)\}$. Here, ε_0 is the permittivity of the vacuum, the plasma wavelength ω_p $=1.37\times10^{16}\,s^{-1}$, ω is the angle wavelength of the incident wave, and the damping rate γ = $4.08\times10^{13}\,s^{-1}$. Due to the surface scattering and boundary effects in thin film, the damping constant employed in simulation is three times of the bulk value. The relative permittivity of the silicon is 11.7. However, since the porous silicon possesses the property of absorbing water, its dielectric constant can no longer be viewed as constants. The effective permittivity of porous silicon layer can be estimated by using an effective medium approximation, which assumes that the macroscopic system is homogeneous, and is expressed as follows

$$f_1\frac{\varepsilon_1-\varepsilon_e}{\varepsilon_1+2\varepsilon_e}+f_2\frac{\varepsilon_2-\varepsilon_e}{\varepsilon_2+2\varepsilon_e}+f_3\frac{\varepsilon_3-\varepsilon_e}{\varepsilon_3+2\varepsilon_e}=0$$

Where ε_1, ε_2 and ε_3 are the relative permittivity of air, silicon and water, respectively. f_1, f_2 and f_3 are the volume

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fraction of air, silicon and water, respectively. ε_e is the effective permittivity of the aggregate. In order to investigate the characteristics of sensor, the reflection spectra are simulated with the 3D FDTD method based on *EastFDTD* software [13].

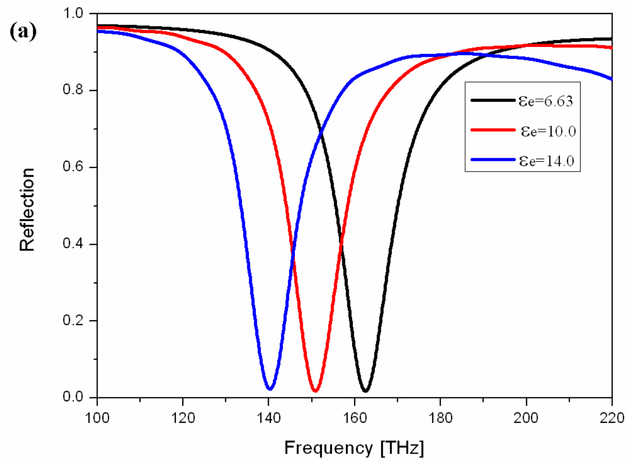

Figure 2. (Color online) Reflection spectra of structure for effective permittivity of porous silicon ε_e=6.63, 10.0, and 14.0, respectively.

Fig. 2 presents the reflection spectra of the absorber with the electric field polarization as shown in Fig. 1 at normal incidence when the effective permittivity of porous silicon is ε_e = 6.63, 10, and 14, respectively. For the case of ε_e = 6.63, which also corresponds to the situation that the porosity is 0.34 and filling fraction of water condensation f_3 is 0, we can find the resonant frequency located at 162.5 THz. If the effective permittivity is increased to 10 (filling fraction f_3 = 28%), the resonant frequency moves to 150.8 THz. With the effective permittivity increasing to 14 (f_3 = 53%), the resonant frequency decrease to 140.2 THz. Thus, our design has good performance in humidity sensing.

Fig. 3 displays the resonant frequency as a function of the effective permittivity. It can be clearly seen that the resonant wavelength exhibits significant red-shift with the increasing permittivity of porous silicon. Furthermore, we have fitted the resonant wavelength λ_R of the absorber and the effective refractive index n_e , The function can be expressed as: $\lambda_R = 249n_e + 1220$, where the unit of λ_R is nm. Therefore, the refractive index sensitivity of structure $(\Delta\lambda_R / \Delta n_e)$ is high to 249 nm/RIU.

III. Conclusion

In this paper, a humidity sensor based on metamaterial absorber has been proposed and investigated. The results shown that the resonant wavelength of absorber can be flexibly tuned by the variation of effective permittivity for porous silicon, which is determined by the filling fraction of water condensation. The refractive index sensitivity of structure is as high as 249 nm/RIU.

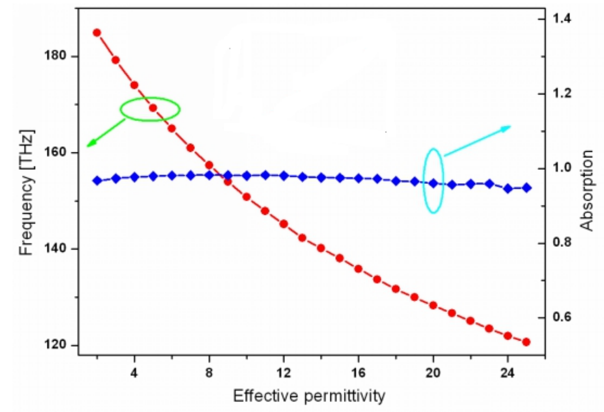

Figure 3. (Color online) Resonant frequency and maximum absorption versus different dielectric constants of porous silicon

Acknowledgments

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