Optics and Laser Technology 100 (2018) 304–308

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Experimental demonstration of a metal–dielectric metamaterial refractive index sensor

Li Shengyong *, Ai Xiaochuan, Wu Ronghua, Chen Jiajun

Naval Univ. of Engineering, Wuhan 430033, China

ARTICLE INFO

Article history:
Received 22 June 2017
Received in revised form 15 September 2017
Accepted 16 October 2017

Keywords:
Photo-electrochemical
Metamaterial
Absorber

ABSTRACT

A metamaterial equipment is designed and experimental verified in the near-infrared with two reflectivity dips. The metamaterial equipment shows independent of polarization. Simulated results indicate that the reflectivity dip is excited by the coupling of localized surface plasmon (LSP) modes. The metamaterial equipment can work as a refractive index detection sensor with high figure of merit (FOM) value. This proposed metamaterial sensor can be applied in detecting different biochemical liquid.

1. Introduction

The development and application of has gained tremendous interest over the past decades due to their unique electromagnetic properties can be applied in many ways, such as: perfect lensing, negative refractive index, invisibility cloaking [1–4]. These unique electromagnetic properties of metamaterial are mainly excited by the resonating elements of adopted materials. Designing and producing metamaterial with resonance band are applied in depth consequences for chip in a wide range, such as: optical modulators, optical devices, and biosensors [5–7]. Metamaterial equipments can be applied in light controlling or detecting due to their resonant character of the designed unit cell. In the metamaterials research field, design and validation of practical metamaterial devices is becoming more and more importance. At the same time, artificially prepared metamaterial devices can be applied in sensing field, is going far to confirm the feasibility and application prospect of this technology. Therefore, many metamaterial devices are reported or experimentally confirmed [8–10]. In addition, the demand for development of metamaterials is growing [11,12]. The surface plasmon polaritons (SPP) and localized plasmon polaritons (LSP) modes resonance are always defined in the metal–dielectric interface, which are distributed in exponentially decaying fields on both edges. These resonance modes always work as an information or energy carrier at the sub-wavelength level. The excitation of LSP or SPP generally plays an essential role in development metamaterial equipments. Kreibig et al. [13] indicated that the LSP resonance can be excited when the conduction electrons are collective excited in metal layer. Moreover, the LSP resonance always depends on the structural design, structural parameters, and environmental media of the proposed structure [14]. It is found that the property of the designed metamaterial device can be directly impacted by the environmental media due to the changing of the refractive index. Therefore, a refractive index sensing strategy is worth considering based on the environmental media dependence of the designed metamaterial devices [15].

In this paper, a simple structure design metamaterial sensor is proposed and experimental confirmed. Measured results indicate that the reflection dip is excited by the coupling of LSP modes. The proposed metamaterial sensor is very sensitive to the change of the refractive index. Such characteristics show that the proposed metamaterial sensor can be applied for biochemical detection of the refractive index of materials.

2. Structural design, experimental and simulation methods

2.1. Structural design

The designed structure is shown in Fig. 1(a and b). The designed metamaterial sensor has three layers: The top metal layer (gold layer) is patterned with air hole arrays, which works as a resonator. The intermediate dielectric layer is continuous and completely (SiO_2 layer). The bottom layer is a continuous and completely metal layer, which plays as an eliminator. In the proposed metamaterial sensor, the lattice constant of the unit cell is set as "*P*",

* Corresponding author.
E-mail address: jsj_njnu2001@sina.com (S. Li).

https://doi.org/10.1016/j.optlastec.2017.10.013
0030-3992/

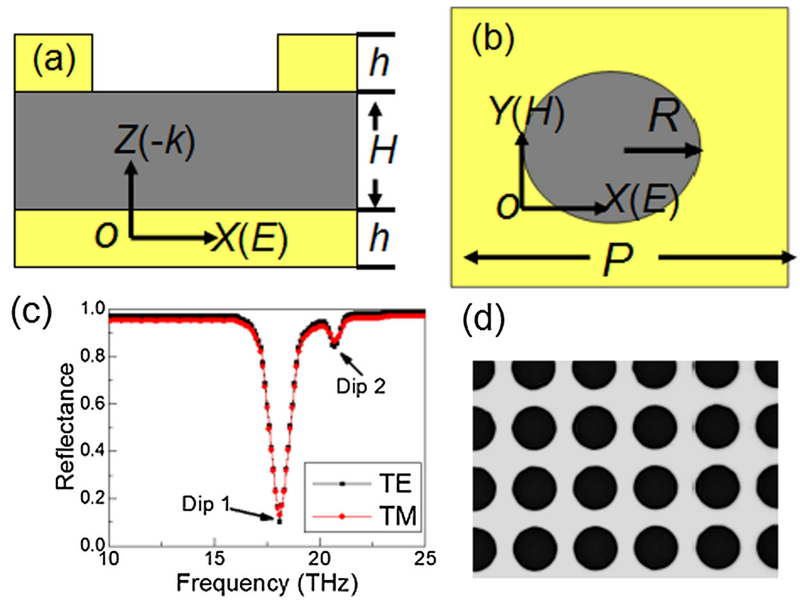

Fig. 1. (a) The side view of unit cell. (b) The top view of unit cell. The yellow part is gold layer, the gray part is dielectric layer. (c) Measured reflection spectra at TM and TE configurations. (d) Optical images of samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the thickness of two metal layers is given by "h", the thickness of the dielectric layer is set as "H", respectively. Dimensional parameter of unit cell is shown in Table 1. In our simulations, two ideal electric conductor planes are applied on two boundaries of the unit cell along the x-axis, while two ideal magnetic conductor planes are applied on boundaries of the unit cell along the y-axis [16], as shown in Fig. 1(a and b).

2.2. Experimental and simulation methods

2.2.1. Experimental methods

The proposed metamaterial sensor is fabricated as following: the bottom gold layer is deposited on a substrate (low pressure chemical vapor deposition). A SiO_2 layer is deposited on the bottom gold layer as an intermediate dielectric layer (plasma-enhanced chemical vapor deposition). Then, the top gold layer is also deposited on the SiO_2 layer (low pressure chemical vapor deposition). Finally, air hole arrays are defined through regular electron-beam lithography. A Bruker Optics Equinox spectrometer is used to measure the reflection spectra. Two reflectance dips are achieved, which are at 18.0 THz and 21.0 THz, respectively, as shown in Fig. 1(c). The optical images of samples are achieved through Leica DM2700H, as shown in Fig. 1(d). The achieved area of samples is $3 \times 3\ mm^2$. These reflectance dips reach to 10% and 81%, respectively.

2.2.2. Simulation methods

To investigate the electromagnetic resonant behavior of the proposed metamaterial sensor, numerical simulations are performed through employing the software Ansofts HFSS 13.0. In these simulations, the SiO_2 layer is given as 2.1025 [17]. On the one hand, all of gold layers follow the Drude model:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\omega\gamma_D} \quad (1)$$

Table 1
All of dimensional parameters.

Parameter	P	R	H	h
Value (μm)	10	3.5	0.35	0.2

here, $\gamma_D = 9 \times 10^{13}\ s^{-1}$ is the collision frequency, while the $\omega_p = 1.37 \times 10^{16}\ s^{-1}$ is the plasma frequency [18]. On the other hand, there is a natural difference between experimental results and simulation results. A reported work indicates that the plasma frequency of the gold layer is higher than that of the bulk gold in simulations due to the grain boundary and surface scattering effects [18]. Therefore, it is important to optimize the simulated plasma frequency before revealing the physical mechanism of the metamaterail sensor in simulations. Fig. 2 shows the simulated reflectance spectra with 1.0, 1.7, and 2.4 times of damping constants under TE polarizations. Three different amplitudes of reflection valley are obtained. For 1.0 time of plasma frequency, the reflectance dip around 18.0 THz reaches to 31%. For the 1.7 times case, the reflectance dip is reduced to 10.5%, which is consistent with the experimental results, see the black curve in Fig. 2. It is indicate that the 1.7 times plasma frequency is the optimized parameter. Further, for the 2.4 times case, the reflectance dip is increased to 22.3%, as shown in Fig. 2. These results in Fig. 2 indicate that both the optimization of simulation results and the strong narrow-band resonance can be obtained under 1.7 times damping constant of the bulk gold layer. It is difference with that in literature [18], in which the optimized damping constant is equal to three times. These

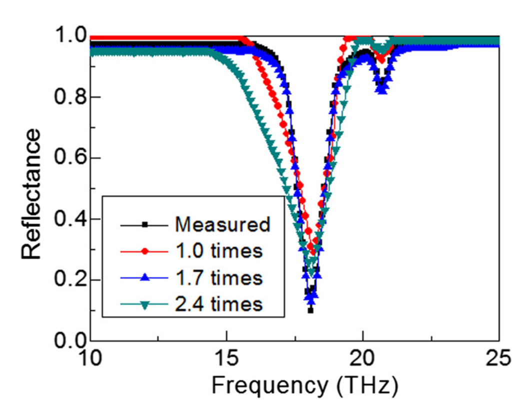

Fig. 2. Simulated reflection spectra with different times of damping constants. The black curve is the measured reflection result.