Journal of Physics: Conference Series

Refractive Index Sensing Based on Terahertz Spoof Surface Plasmon Polariton Structure

To cite this article: Xinda Chen *et al* 2020 *J. Phys.: Conf. Ser.* **1617** 012008

Journal of Physics: Conference Series **1617** (2020) 012008 doi:10.1088/1742-6596/1617/1/012008

Refractive Index Sensing Based on Terahertz Spoof Surface Plasmon Polariton Structure

Xinda Chen[a], Huaibao Xiao[b], Guizhen Lu[c], Ruiqi Zhao[d]

College of Electronic Engineering, Communication University of China, Beijing, China

[a]chenxinda@cuc.edu.cn

[b]xiaoyuhuai@cuc.edu.cn

[c]luguizhen@cuc.edu.cn

[d]cuc_zrq@cuc.edu.cn

Abstract—Surface plasmon resonance sensing technology has many advantages, such as high sensitivity, no interference to samples and real-time monitoring. It has been widely used in biomedical detection, food safety testing and environmental protection etc. How to increase the measurement sensitivity is a key technology in these applications. In this paper, a stepped surface plasmon resonance sensing structure is proposed, which is easy to be machined. The influence of its structure parameters on the sensing sensitivity is simulated and analyzed. The results show that the sensitivity can be increased to 2.44THz/RIU by optimizing the structure parameters when the refractive index of the liquid to be measured is between 1.33 and 1.36.

1. INTRODUCTION

Surface plasmon resonance (SPR) sensing is an emerging detection technology with high sensitivity, no labeling and fast detection. It has been extensively applied in biomedical, chemical detection and food safety etc [1-3]. SPR sensing technology was first proposed in 1982, Liedberg first applied SPR technology to the field of biosensors, setting a precedent for SPR sensing applications [4]. Since then, SPR sensing technology has developed rapidly. A few years later, C.R.Lavers proposed a waveguide-coupled SPR sensor for detecting water pollution [5]. This technology had also been applied to the liquid concentration sensing, Yu used a phase modulation method to detect different concentrations of NaCl solution and the detection index range was 1.33~1.37 [6]. Binghao.Ng proposed a terahertz SPR sensing structure based on a linear array of subwavelength grooves, with a sensitivity of 0.49 THz/RIU [7]. Yao reported a terahertz SPR sensing based on prism-coupling, and found that the high-mode SSPP-based sensing had a high sensitivity of up to 2.27 THz/RIU [8]. Cennamo.N proposed a D-shaped optical fiber SPR sensor, and found that changing the structure parameters would affect the sensitivity of the sensor [9].

In this paper, a stepped spoof surface plasmon polariton structure based on Otto prism coupling configuration is proposed to analyze the influence of the structure parameters on the sensitivity of the sensor. The reflection curves of different filled analyte are obtained by COMSOL MULTIPHYSICS software, simulating the sensing process of liquid with different refractive index. We analyze the influence of the structure parameters on the sensitivity of the sensor and the results show that the sensitivity of the sensor can be increased significantly by optimizing the structure parameters.

2. THEORY AND MODEL

Surface plasmon polariton (SPP) is collective oscillations caused by the interaction of photons and free electrons of metal. Surface plasmon resonance is excited when the frequency of the incident electromagnetic wave is equal to the oscillation frequency. Spoof surface plasmon polariton (SSPP) is a kind of surface wave excited by a special structure. It has a dispersion relation similar to SPP. Otto prism coupling is a commonly used configuration to excite SSPP [10, 11]. The model of the sensor based on stepped SSPP structure is shown in Figure 1. It is comprised of a coupling prism with high refractive index n_p=1.5163 and a metal film engraved by grooves. H_{gap} is the distance of the gap between the prism and the metal. The gap and grooves are filled with the analyte. Periodic boundary is applied to the propagating direction.

The dispersion relation of SSPP on the stepped spoof surface plasmon polariton structure satisfies the expression:

$$\frac{\sqrt{k_x^2 - k_0^2}}{k_0} = \frac{W_1}{P} \frac{\frac{W_1}{W_2}\tan(k_0 H_1) + \tan(k_0 H_2)}{\frac{W_1}{W_2} - \tan(k_0 H_1)\tan(k_0 H_2)} \tag{1}$$

Where k_x is the propagation constant, k_0 is the wave vector in vacuum, W_1 and W_2 are the widths of the grooves, H_1 and H_2 are the depths of the grooves.

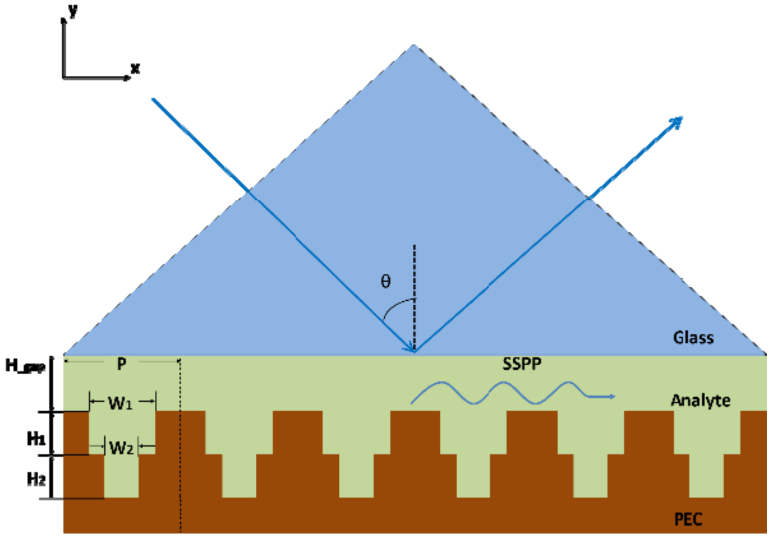

Figure 1. Schematic diagram of the proposed sensor based on THz spoof surface plasmon polariton structure.

Using CST Microwave Studio software, we obtain the dispersive relation curves of the metal film engraved by grooves, as shown in Figure 2. The red line represents the dispersion relation of the light in vacuum, the green line and the yellow line represent the dispersion relation of parallel wave vector with internal incident angles of 45° and 65° respectively. The blue dotted lines represent the fundamental mode and the high mode of SSPP. The dots A, B and C are the intersections between different modes SSPP dispersions and coupling wavevector at 45° and 65° incident angle.

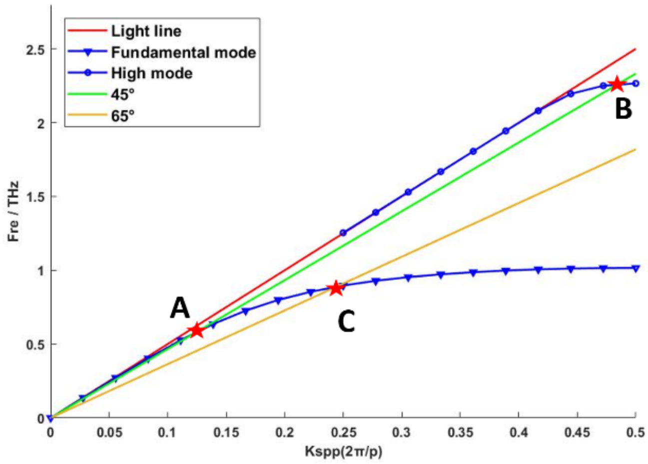

Figure 2. Dispersion relations of the different modes SSPP on the metal film engraved by grooves.

The reflectivity of different modes SPR sensing at the incident angles of 45° and 65° is calculated by using the MULTIPHYSICS software COMSOL, as shown in Figure 3. It can be seen that the resonance frequencies of the fundamental mode and the high mode are 0.63THz and 2.28THz respectively at the incident angle of 45°. Whilst for the case of 65°, there is only the fundamental mode SSPP and the resonance frequency is 0.9THz. The simulation results are consistent with the results in Figure 2, showing that the surface plasmon polariton can be excited successfully by the grooved metal film.

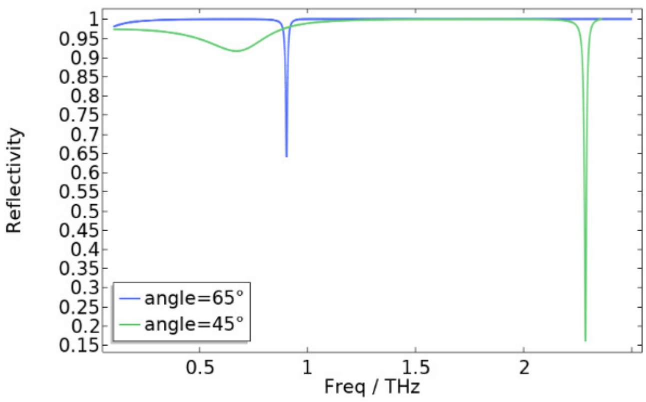

Figure 3. The reflection curves at the incident angles of 45° and 65° when the filling analyte is vacuum.

3. SIMULATION RESULTS AND ANALYSIS

In order to meet the condition of total reflection, the incident angle is set as 65° when the refractive index of the filled analyte is between 1.33 and 1.36. The gap distance mainly affects the reflectivity at resonance, but hardly affects the resonance frequencies, so we fix the gap distance to 200um. Other parameters are initially set as P=60um, W_1=30um, H_1=H_2=35um. Firstly, the effect of the values of W_1 and W_2 on the sensitivity is analyzed. Using the MULTIPHYSICS software COMSOL, we obtain the reflection curves when the values of W_1:W_2 are 3:1, 2:1 and 3:2 respectively. The relations of the resonance frequencies and the refractive index in the three cases can be expressed as: $f_{3:1} = -2.0n_d + 4.31$, $f_{2:1} = -2.13n_d + 4.53$, $f_{3:2} = -2.07n_d + 4.50$. Where f is the resonance frequencies, n_d is the refractive index of the analyte. Obviously, the sensitivity is the highest when W_1:W_2=2:1, as the simulation results are shown in Figure 4.

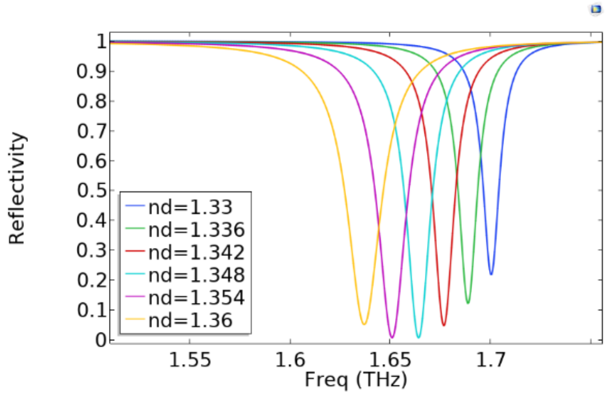

Figure 4. Reflection curves of filled with different refractive index analyte when $W_1 : W_2 = 2:1$.

Secondly, the effect of the values of the width W_1 and the period (P) on the sensitivity is analyzed. We obtain the reflection curves when the values of W_1:P are $1:3$, $1:2$ and $2:3$ respectively. The relations of the resonance frequencies and the refractive index can be expressed as: $f_{1:3} = -2.27n_d + 4.76, f_{1:2} = -2.13n_d + 4.53, f_{2:3} = -1.98n_d + 4.32$. It confirms that the sensitivity is the highest when W_1:P=1:3, as the simulation results are shown in Figure 5.

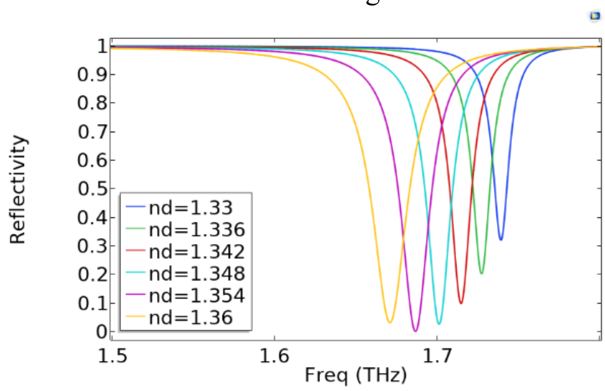

Figure 5. Reflection curves of filled with different refractive index analyte when W_1:P=1:3.

Finally, the effect of the depths (H_n, n=1,2) on the sensitivity is analyzed, but we only consider the same depth of the upper and lower grooves (H_1=H_2). The depths are set as 35, 40 and 50 respectively. The relations of the resonance frequencies and the refractive index in the three cases can be expressed as: $f_{35} = -2.27n_d + 4.76$, $f_{40} = -2.35n_d + 4.69$, $f_{50} = -1.96n_d + 3.87$. It confirms that the sensitivity is the highest when H_1=H_2=40um, as the simulation results are shown in Figure 6.

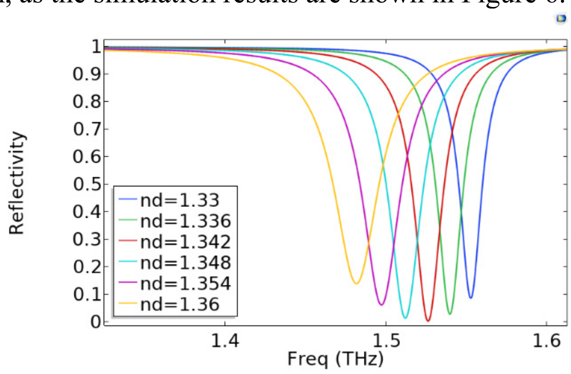

Figure 6. Reflection curves of filled with different refractive index analyte when H_1=H_2=40um.

According to the analysis above, the sensitivity of the SPR sensor is greatly affected by the widths (W_n) and depths (H_n). The maximum sensitivity, which is 2.44THz/RIU, is achieved when the structure parameters are set as, W_1=20um, W_2=10um, H_1=H_2=40um. Figure 7 displays the simulation results of the optimized structure. The relation of the resonance frequencies and the refractive index can be expressed as, $f_{opt} = -2.44n_d + 4.80$. Figure 8 demonstrates the resonance frequencies along the refractive indices, which can compare the initial sensitivity with the optimized sensitivity more intuitively. It confirms that the sensing sensitivity is significantly increased by optimizing the structure parameters.

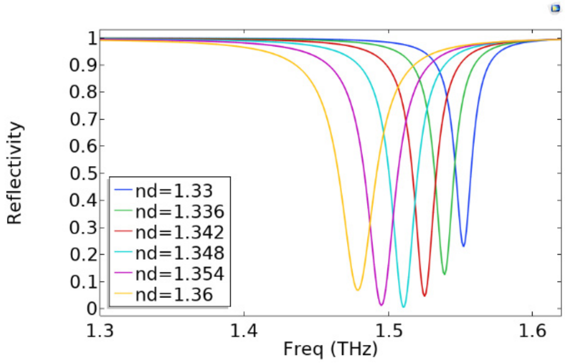

Figure 7. Reflection curves of filled with different refractive index analyte after optimized structure parameters.

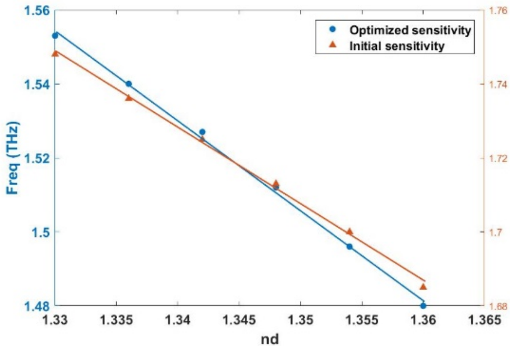

Figure 8. The relation between the resonance frequencies and the refractive index.

The sensitivity of this sensor is better than that reported in similar devices [8, 12, 13]. For example, a prism coupled terahertz SPR sensor technology reported by Yao HZ has a sensitivity of up to 2.27 THz/RIU [8], the comparison between the result and ours is shown in Figure 9. Thus, the stepped spoof surface plasmon polariton structure based on Otto prism coupling configuration approach very promising for the refractive index sensing.

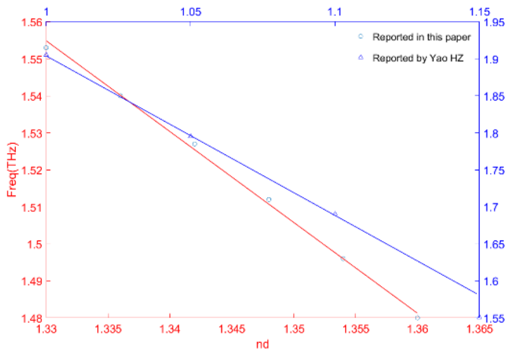

Figure 9. The comparison of sensitivity reported in this paper with that reported in similar devices [8].

4. CONCLUSION

In summary, the influence of different structure parameters on the sensing sensitivity is analyzed by using the numerical simulation method. The results show that the sensitivity of the SPR sensor is greatly affected by the widths and depths of the grooves. The sensing sensitivity can be increased to 2.44THz/RIU by optimizing the structure parameters when the refractive index range of the liquid to be measured is between 1.33 and 1.36. In addition, the change of liquid concentration will lead to the change of refractive index, so the technology can also be applied to the sensing of liquid concentration.

REFERENCES

[1] D M. Sensing with Terahertz Radiation [J]. 2003.
[2] BHATIA. Surface-plasmon-resonance-based fiber-optic refractive index sensor: Sensitivity enhancement [J]. Applied Optics, 2011, 50(14): 2032-6.
[3] TONG L, ZHANG S, ET AL. Recent Advances in Plasmonic Sensors [J]. Sensors, 2014, 14(5): 7959-73.
[4] NYLANDER, LIND T. Gas detection by means of surface plasmon resonance [J]. Sensors and Actuators, 1983, 3(79-88).
[5] LAVERS CRWJS. A waveguide-coupled surface-plasmon sen-sor for an aqueous environment [J]. Sensors and Actuators B (Chemical), 1994, 22(1): 75-81.
[6] YU X, DING X, ET AL. Spatial phase modulation protein chip de-tection based on SPR sensing [J]. Chinese Journal of Scientific Instrument, 2009, 30(6): 1134-9.
[7] NG B W J, HANHAM S M, ET AL. Spoof Plasmon Surfaces: A Novel Platform for THz Sensing [J]. Advanced Optical Materials, 2013, 1(8): 543-8.
[8] YAO H Z S. High-mode spoof SPP of periodic metal grooves for ultra-sensitive terahertz sensing [J]. Optics Express, 2014, 22(21): 25149.
[9] CENNAMO N, PESAVENTO M, MARIA L D, et al. Comparison of different photoresist buffer layers in SPR sensors based on D-shaped POF and gold film; proceedings of the 25th International Conference on Optical Fiber Sensors, F, 2017 [C].
[10] FERNáNDEZ-DOMíNGUEZ AI, MORENO E, MARTíN-MORENO L, et al. Terahertz wedge plasmon polaritons [J]. Optics Letters, 2009, 34(13): 2063-5.
[11] WILLIAMS CRASR, MAIER S A, ET AL. Highly confined guiding of terahertz surface plasmon polaritons on structured m etal surfaces [J]. Nature Photonics, 2008, 2(3): 175-9.
[12] CHEN L, YIN H, et al. Ultra-sensitive fluid fill height sensing based on spoof surface plasmon polaritons [J]. Journal of Electromagnetic Waves & Applications, 2017, 1-12.