The improvement of figure of merit with infrared perfect absorber for plasmonic resonance sensing

G.H. Li[a], X. Wu[b], Y. Jiang[b], C. X. Shao[b], L. J. Huang[a], X. S. Chen[a, *], W. D. Hu[a], and W. Lu[a, *]
[a] National Lab for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, 500 Yutian Road, Shanghai, China 200083
[b] Fundamental Science on EHF Laboratory, University of Electronic Science and Technology of China, No.2006, Xiyuan Ave, West Hi-Tech Zone, Chengdu, China 611731
xschen@mail.sitp.ac.cn, luwei@mail.sitp.ac.cn

***Abstract*-We present an infrared perfect absorber which combines gold nanobars and a photonic microcavity. By adjusting the structural geometry, this device is utilized for refractive index sensing. For proper designed structural parameters, it can yield more than 99% absorbance in the near-infrared frequency regime. Our work directly investigate the effect of geometry on sensing performance and it can sever as a model of coupling between localized surface plasmon within nanoparticles and propagating surface plasmon along planar metal layer for sensing applications with a perfect absorber.**

I. INTRODUCTION

When the interface of the metallic structure is large enough, the plasmon, which is attributed to the strong interaction between the conduction electrons and incident electromagnetic field, can propagate in the form of oscillating charges wave, and this is referred to as propagating surface plasmon (PSP). Contrary to the PSP, the localized surface plasmon resonance (LSPR) is within a subwavelength metallic nanostructure. Due to the localized property and the near-field enhancement, surface plasmons have significant applications including near-field optical microscopy [1], surface enhanced Raman spectroscopy (SERS) [2], and sensing devices [3]. Moreover, some special physical mechanisms, such as the classical analog of electromagnetically induced transparency or perfect absorbance [4], are explored for more prospective applications [5].

The LSPR strongly depends on the shape, composition, size, light polarization and surrounding dielectric environment. Particularly, the latter dependence opens a way toward refractive index sensing which can detect small quantities preferably down to single molecules. Recently, different plasmonic structures, such as nanoshells, nanospheres and etc, are proposed to detect the large spectral shift for changes in refractive index [6, 7]

For plasmonic sensors, the sensitivity (S) is commonly defined in terms of the change or shift in a measurable parameter, typically resonant wavelength, for detection of per refractive index. Another factor charactering the performance is the full width at half maximum (FWHM) which is strongly dependent on the shape and size of the nanoparticles. It was mentioned that the linewidth narrowing is potentially helpful to improve the performance of the LSPR sensors. Generally, there defines an overall performance parameter of the plasmonic sensor as figure of merit (FOM), FOM=S/FWHM. However, a second FOM* is proposed by defining FOM*= $[(dI/dn)/I]_{\max}$ for a practical way since the intensity change dI is much easier to detect in experiment at a fixed wavelength λ_0 induced by a refractive index change dn rather than that of the wavelength[8, 9].

In this paper, we present a novel plasmonic sensor with the help of an infrared perfect absorber. This device can yield more than 99% absorbance in the simulation. The geometry parameters have great influence on the sensing performance. However, the spacer thickness is of particularly importance to the performance of absorbance efficiency and consequently affects the sensing qualities. The mechanism of LSP and PSP interaction is proposed to demonstrate this phenomenon.

II. SIMULATION MODELS AND DEVICE STRUCTURE

The schematic geometry of the infrared perfect absorber is illustrated in Fig. 1. The large gold planar bottom layer and the top an array of periodic gold nanobars are sandwiched by the microcavity, which is filled with SiO_2. The unit cell of the nanobars is composed of two bars with the same parameters. The test liquids or gases are channeled or diffused over the period gold nanobars. This structure has dimensional parameters of bar length (L), bar width (W), bar thickness (T), bar gap distance (D), the lattice constant in x axis (P1) and in y axis (P2), the dielectric spacer thickness (H), and planar gold layer thickness (G) [10].

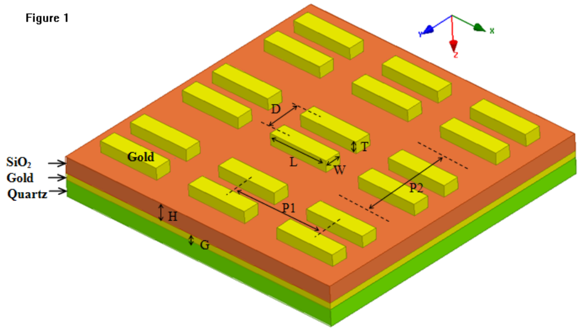

Fig. 1: (colour online) Schematic of the sensing structure and the coordinate setup configuration. The whole structure is placed on the quartz substrate

For the existence of bottom layer, the transmittance of the absorber is almost totally eliminated in the near-infrared (NIR) regime and then the absorbance can be calculated by 1-R (R is

978-1-4673-1604-0/12/$31.00 ©2012 IEEE

the resonant reflectance intensity). Consequently, the perfect absorber can be achieved just by pursuing zero reflectance dip intensity through the following approaches, adopting different nanoparticle shapes, changing the lattice constant or rationally designing the other structure dimensions. Among these choices, optimizing the spacer thickness offers a simple and efficient method to reach the nearly absolute absorbance.

Here, we take advantage of a 3D-FDTD commercial software(from Dongjun Information Technology Co.,Ltd.) to carry out our calculations. With this FDTD method the electric and magnetic fields are temporally separated by half time step, and also are spatially interlaced by half mesh cell. The periodic boundary conditions are imposed in the x and y directions.

III. RESULT AND DISCUSSION

The geometry parameters are systemically optimized and the reflectance dips are gradually moving to the ground of zero intensity. The Fig. 2 shows the reflectance spectrum as a function of key variable spacer thickness.

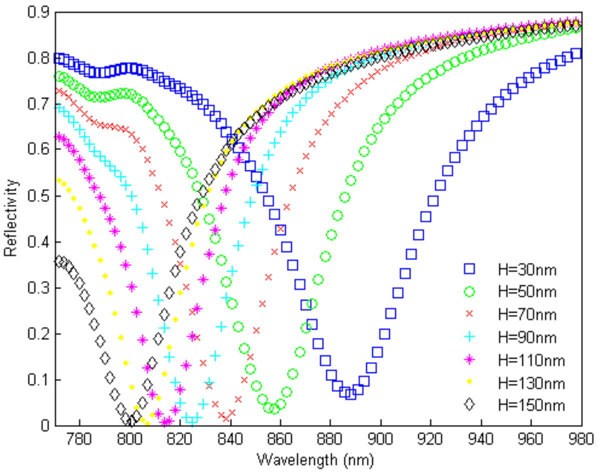

Fig. 2: (colour online) Simulated reflection spectrum of the sensing structure as a function of dielectric spacer thickness from H=30nm to H=150nm for 25%-solution of glucose in water. Within the large thickness range the structure obtains high absorbance efficiency.

As shown in the figure 2, there appear a series of strong reflectance dips. Here we emphasize that the shape of the spectrum is becoming more and more asymmetric as the spacer thickness increases. The intensity of short wavelength part is decreasing to less than half of the long wavelength part. Considering the FWHM values are obtained from the Lorentz fitting for the plasmon resonance, the reflection spectrum are not carried out for thickness more than 150nm. However, it becomes symmetric again for thickness more than about 300nm, but the FWHM is more than twice wider than that shown in figure 2. Based on the above discussion, we will not talk about the thickness more than 150nm.

To have a look at the periodicity effect on the absorbance efficiency, we calculate it and show in table 1. It can be seen that the periodicity of 500nm*500nm achieves the best sensing performance. The dip intensity is about zero and the FWHM and FOM* all satisfy the demand for sensing quality.

TABLE 1

The periodicity effect on the absorbance efficiency

Periodicity (nm*nm)	Resonant Wavelength (nm)	Resonant Intensity (arb.)	FWHM (nm)	FOM* (arb.)
440*440	792	0.0546	45	30
440*500	786	0.0369	47	42
500*440	851	0.0128	44	155
500*500	824	0.00627	40.8	357
500*600	830	0.00181	*	158
600*500	946	0.124	45	46
600*600	936	0.1518	43	87

* The reflection spectrum does not follow the Lorentz shape.

IV. CONCLUSION

Through the optimization of geometry parameters, we take the inevitable losses to advantage and design a novel plasmonic infrared sensor. It can yield more than 99% absorbance in the near-infrared frequency regime. The FWHM and FOM* are achieved both excellent.

ACKNOWLEDGEMENTS

This work was supported in part by the State Key Program for Basic Research of China grants 2007CB613206, the National Natural Science Foundation of China grants 10725418, 10734090, 10990104, and 60976092, the Fund of Shanghai Science and Technology Foundation grant 09DJ1400203, 09ZR1436100, 10JC1416100, and 10510704700. Also thanks to the Longwen Scholarship for his support..

REFERENCES

[1] T. Kalkbrenner, U. Hakanson, A. Schadle, S. Burger, C.Henkel, and V. Sandoghdar, "Optical microscopy via spectral modifications of a nanoantenna," Phys. Rev. Lett. 95, 200801, 2005.

[2] F. Hao and P. Nordlander, "Plasmonic coupling between a metallic nanosphere and a thin metallic wire," App. Phys. Lett. 89, 103101, 2006.

[3] Jian Ye, Pol Van Dorpe, "Improvement of the figure of merit for gold nanobars array plasmonic sensors." Plasmonics 10, 665-71, 2011.

[4] Liu N, Mesch M, Weiss T, Hentschel M, Giessen H, "Infrared perfect absorber and its application as plasmonic sensor," Nano Lett. 10 2342-48, 2010.

[5] G.H. Li, X.S. Chen L.J. Huang, J. Wang, W.D. Hu, W. Lu, "The localized near-field enhancement of metallic periodic bowtie structure: an oscillating dipoles picture" Phys. B 407, 2223, 2012.

[6] C. Soennichsen, and A.P. Alivisatos, "Gold nanorods as novel nonbleaching plasmon-based orientation sensors for polarized single-particle microscopy" Nano Lett. 5 301-04, 2005.

[7] J.B. Lassiter, J. Aizpurua, L.I. Hernandez, D.W. Brandl , L. Romero, S. Lal, J.H. Hafner, P. Nordlander, and N.J. Halas, "Close Encounters between Two Nanoshells" Nano Lett. 8 1212-18, 2008

[8] L.J. Sherry, S.H. Chang, G.C. Schatz, R.P. Van Duyne, B.J. Wiley, and Y. Xia, "Localized surface plasmon resonance spectroscopy of single silver nanocubes" Nano Lett. 5 2034-38, 2005

[9] J. Becker, A. Trügler, A. Jakab, U. Hohenester, and C. Sönnichsen, "The optimal aspect ratio of gold nanorods for plasmonic bio-sensing " Plasmonics 5 161-67, 2010

[10] G.H. Li, X.S. Chen, O.P. Li，C.X. Shao, Y. Jiang，L.J. Huang, B. Ni, W.D. Hu, and W. Lu "A novel plasmonic resonance sensor based on an infrared perfect absorber" J. Phys. D: Appl. Phys. In press.