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# 用表面等离子体共振原理检测湿度环境

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**摘 要**:采用 Kretschmann 结构激发表面等离子体,利用多孔陶瓷材料 $SiO_2$ 作感湿材料,当外界环境的相对湿度变化时,引起感湿层 $SiO_2$ 的折射率发生相应变化,导致表面等离子体共振角发生偏移.采用有限元法对传感系统在不同感湿层折射率下的反射谱进行了模拟分析,并根据反射谱的共振半峰宽和共振峰深度对金膜的厚度进行优化.研究结果表明:金膜的最佳厚度为 55 nm,反射谱的共振角偏移量与感湿层折射率变化呈线性关系,湿度检测的分辨率高达 0.37%RH,灵敏度达到 0.03°/% RH.该研究对基于表面等离子体共振原理的湿度传感器的研制与应用具有一定意义.

**关键词**:光学传感;表面等离子体共振;有限元法;湿度检测;灵敏度;分辨率;金属膜厚度

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# Humidity Detection Based on Surface Plasmon Resonance

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**Abstract**: A method of humidity detection based on surface plasmon resonance was proposed. Kretschmann structure was applied to excite surface plasmon polarization. Porous ceramic $SiO_2$ was used as the humidity-sensitive material. The refractive index of porous ceramic $SiO_2$ altered as the ambient relative humidity changed, thus leading to a shift of surface plasmon resonance angle. On this basis, the reflection spectrum was simulated and analyzed under different refractive index of humidity-sensing layer by finite element method. Furthermore, the thickness of gold film was optimized in accordance with the full width at half maximum of reflection spectrum and the formant depth. The results show that, the best thickness of gold film is 55 nm, a linear relationship between the shift of surface plasmon resonance angle and the variation of humidity-sensing layer refractive index is got, high resolution of 0.37%RH and high sensitivity of 0.03°/% RH are obtained. The research contributes to the realization and application of humidity sensor based on surface plasmon resonance.

**Key words**: Optical sensor; Surface plasmon resonance; Finite element method; Humidity detection; Sensitivity; Resolution; Thickness of gold film

**OCIS Codes**: 240.6680; 130.6010; 230.0230; 260.0260

## 0 Introduction

Surface Plasmon Resonance (SPR) is collective oscillations of free electrons in solid when stimulated by incident light [1-2]. Surface plasmon waves can propagate in subwavelength structure system, forming highly integrated photonic circuits. The technology is a significant bond between optical field and electrical field

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[3]. It has been attracted high importance and developed at great speed, especially in terms of biomacromolecules and circumstances detection[4], The technology of SPR was used to detect the amine tissue proteins successfully by Byoung Jin-Jeon in 2011[5]. Liu Xia detected pesticide residues by taking the advantage of high sensitivity of SPR technology in 2013[6]. However, the use of SPR in terms of detecting humidity is very rarely reported.

Humidity is closely related to scientific studies, production and living. The maintaining of precision instruments, the storage of grain, printing and dyeing et al have strict requirements for humidity. The traditional humidity sensors are mostly resistive or capacitive sensors based on conductive mechanism of electron and ion. But they are difficult to integrate and meet the precision requirements [7-8]. To overcome the drawbacks of capacitive humidity sensor, optical humidity and temperature sensor based on fiber grating was proposed to improve the sensitivity and stability[9-10], synchronously, high resolution was achieved. Porous ceramic $SiO_2$ was studied and analyzed by Alberto[11] and Wang Zhen-yuan[12], providing foundation for porous ceramic $SiO_2$ as humidity-sensitive material. In the literature, a novel method to detect humidity is put forward and demonstrated. SPR technology is applied to humidity detection for the first time. Thanks to the superhigh sensitivity of SPR to the refractive index variation of porous ceramic $SiO_2$ caused by humidity change, high sensitivity and resolution have been achieved by theoretical analyses and simulation.

# 1 Calculation methods

## 1.1 Mechanical model

The commonly used method for exciting surface plasmons is the Kretschmann prism configuration, initially investigated by Kretschmann and Raether[13], which consists of three layers. The optical layout, composed of a prism, a metal film and a dielectric layer is shown in Fig. 1.

The incident light, p-polarized light falls on the metal layer through the prism with total reflection[14]. There is an evanescent wave with amplitude decaying exponentially normal to the interface under the total reflection. When $k_{x0}=\mathrm{Re}(k_{SP})$, surface plasmons at the interface of the metal and dielectric are excited by the evanescent wave. where

$$n_j=\sqrt{\varepsilon_j} \tag{1}$$

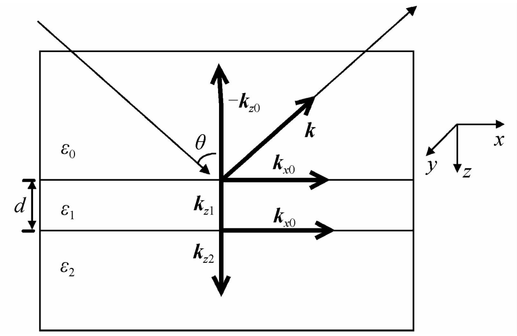



Fig. 1 The schematic view of optical system to excite SPR

$$|\boldsymbol{k}_{SP}|=\frac{\omega}{c}\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2} \tag{2}$$

$$|\boldsymbol{k}_{x0}|=\sqrt{\varepsilon_0}\,\frac{\omega}{c}\sin\theta \tag{3}$$

$\boldsymbol{k}_{x0}$ is the wave number vector of the incident light across the media, $\boldsymbol{k}_{SP}$ is the wave number vector of the surface plasmon, $\varepsilon_0$, $\varepsilon_1$ and $\varepsilon_2$ are the dielectric constants of the prism, the metal film and the dielectric layer respectively, $n_j(j=0,1,2)$ is the refractive index correspondingly, $c$ is the speed of light in vacuum, $\omega$ is the frequency and $\theta$ is the angle of incidence.

As the incident light is p-polarized light, the reflection coefficient $R$ can be got according to the Fresnel equation and the reflectivity equation for single layer

$$R=|r_{012}|=\left|\frac{r_{01}+r_{12}\exp(2\mathrm{i}\,k_{z1}d)}{1+r_{01}r_{12}\exp(2\mathrm{i}k_{z1}d)}\right|^2 \tag{4}$$

where $r_{pq}=\dfrac{n_p^2k_{zq}-n_q^2k_{zp}}{n_p^2k_{zq}+n_q^2k_{zp}}$ represents the reflection ratio of the strength of the electric field at the interface between two adjacent media. $k_{zj}=\sqrt{\left(\dfrac{\omega}{c}\right)^2n_j^2-|\boldsymbol{k}_{x0}|^2}$, $(p=0,1,\ q=1,2,j=0,1,2)$.

Under a certain angle of incidence, $\theta_{SPR}$, the SPR at the interface of the metal and dielectric are excited by the evanescent wave and the minimum reflection intensity can even approach to 0. Porous ceramic $SiO_2$ is recommended as the dielectric layer, so $n_2$ will change as the humidity changing in surrounding. The refractive index $n_2$ can affect the $\theta_{SPR}$. So we can analyze $\theta_{SPR}$ to detect the humidity around.

## 1.2 The characteristic of porous ceramic $SiO_2$

Relative humidity (%RH) refers to the humidity saturation percentage of the air in certain volume[15]. Ceramic $SiO_2$ fabricated by sol-gel method has good sense of humidity. The water adsorption capacity of porous ceramic $SiO_2$ was analyzed using spectrometer by Alberto A H and other researchers. The relationship between the refractive index of porous ceramic $SiO_2$ and relative humidity is shown in Fig. 2.

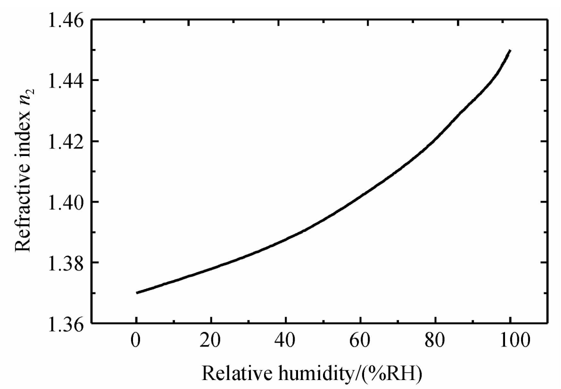



Fig. 2 The relationship between refractive index of porous ceramic $SiO_2$ and relative humidity

## 2 Results and discussions

We use porous ceramic $SiO_2$ as the third layer in this simulation, the wavelength of the incident light in free-space is taken to be $\lambda=632$ nm, because of the high sensitivity at shorter wavelength[16-17]. The prism is BK7 with high transmissivity and the refractive index is $n_0=1.515$[18]. The relative permittivity of Au at $\lambda=632$ nm is $\varepsilon_1=-9.5093+1.2175i$[19]. The refractive index of porous ceramic $SiO_2$ under different relative humidity is got according to Fig. 2. In Fig. 3 we show the magnetic distribution ($x$-$y$ plane) at resonance by Comsol Multiphysics analysis [20]. Note that we have imposed periodic boundary condition on both up and down boundaries for a better representation of the plasmon. The right diagram is a color scaled image of the magnetic field while the inset is the corresponding 3D plot of the magnetic field distribution across the materials.

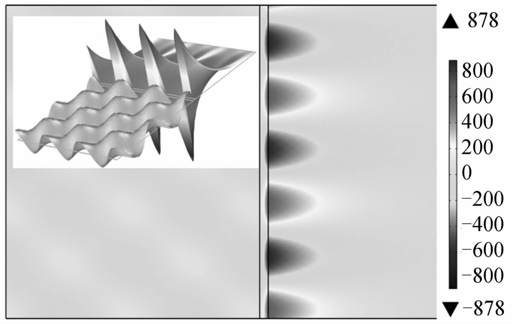
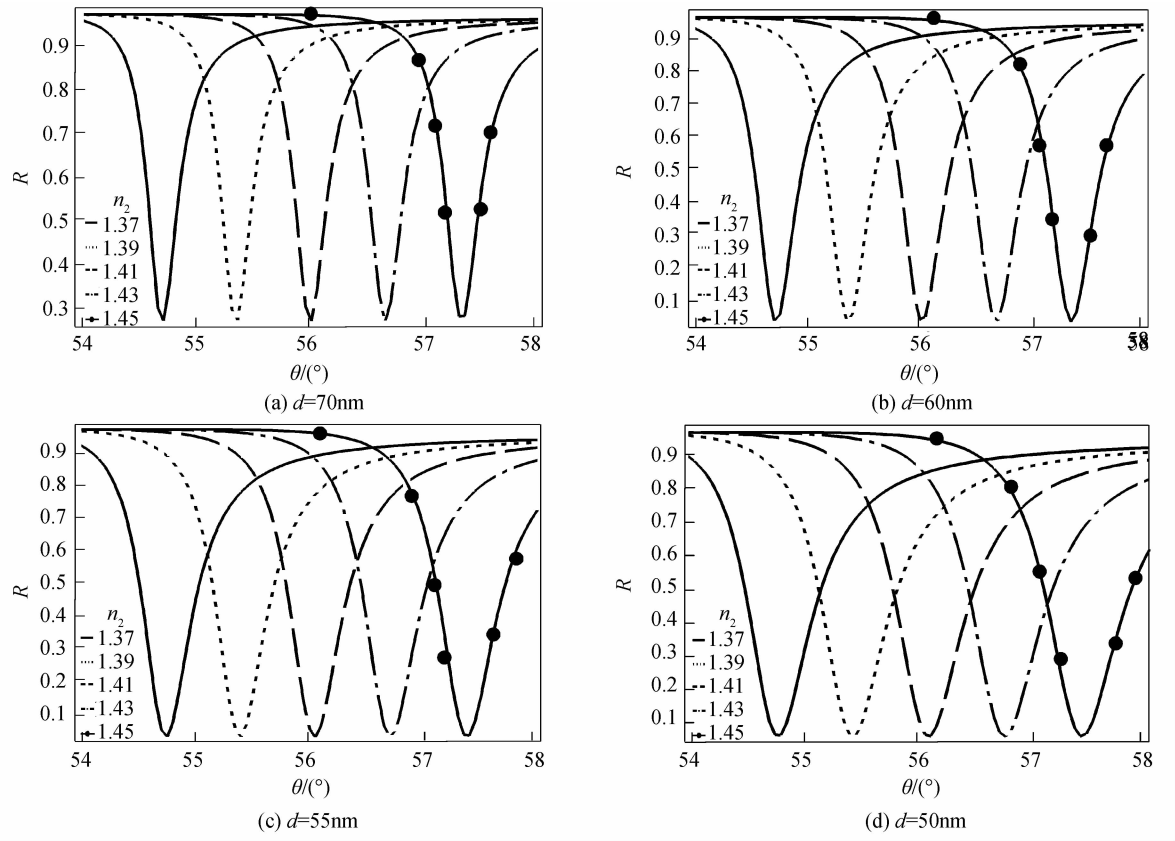



Fig. 3 Magnetic field of the $H_z(x,y)$ at the resonance angle

The thickness of gold film, which not only determines the appearance of SPR phenomenon, but affects the detection resolution and accuracy directly, is a key parameter of SPR sensor. The curves in Fig. 4 show the simulated reflection spectra under the condition that the gold film thickness is from 40 to 70 nm.



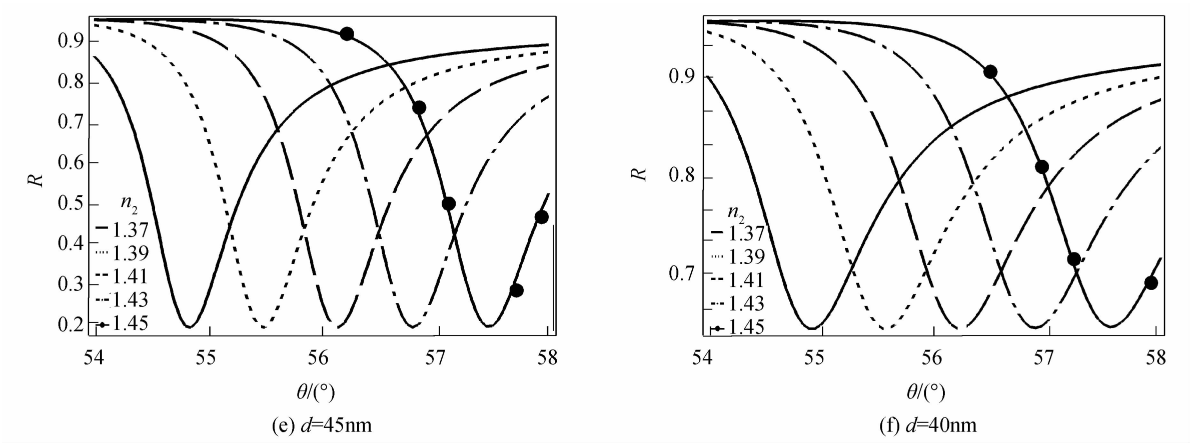



Fig. 4 The relationship between the reflectivity and angle of incidence under different $d$

From the plots of Fig. 4, it can be seen that the thinner the gold film is, the broader the SPR spectrum peak is. The width of peak can be calculated by Full Width at Half Maximum (FWHM). Larger FWHM can result in lower detection resolution and deeper dip will contribute to higher accuracy. But when the gold film is thicker than 70 nm, the dip will diminish in depth. The effect of $d$ on the characteristics of reflection spectra is shown in Fig. 5. Inset of Fig. 5 shows detailed representation of the characteristics of dip when $d$ changes from 50 nm to 60 nm with a step of 1 nm, in order to achieve optimized $d$. We obtain that, the thickness around 55 nm is the best chosen because the dip reaches about 0 and keeps sharp, from these curves.

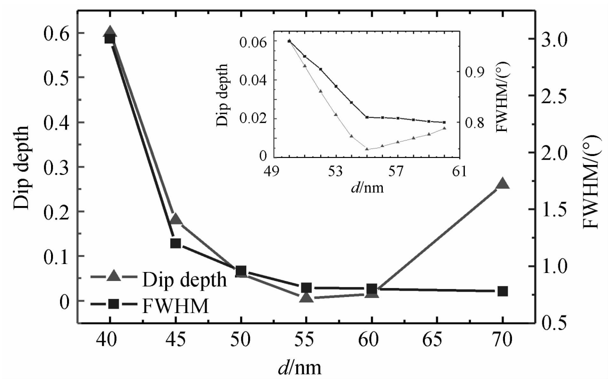



Fig. 5 The effect of $d$ on dip

Then the $d=55$ nm was taken to calculate the sensitivity of the humidity sensor. From Fig. 4(c), we can see that the bigger the relative permittivity $n_2$ is, the larger the angle $\theta_{\mathrm{SPR}}$ will be. Fig. 6 shows the effect of $n_2$ on the resonance angle $\theta_{\mathrm{SPR}}$. The red line is obtained from the analytical solutions using Eqs. (1), (2) and (3) in the range from $n_2=1.35$ to $n_2=1.45$, and the black diamonds are obtained directly from the results of the Comsol simulation. The simulation and the analytical expressions show good agreement. A linear relationship between $\theta_{\mathrm{SPR}}$ and $n_2$ is got in the range from $n_2=1.37$ to $n_2=1.45$ used for humidity detection.

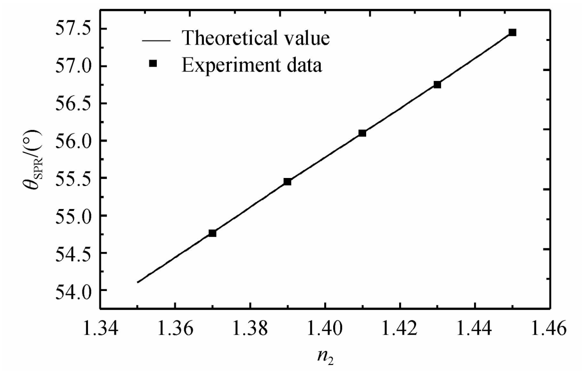



Fig. 6 The effect of refractive index $n_2$ on $\theta_{\mathrm{SPR}}$ detection

According to the functions of $n_2$ with $\theta_{\mathrm{SPR}}$ and relative humidity, we obtained the relationship of $\theta_{\mathrm{SPR}}$ with relative humidity shown in Fig. 7.

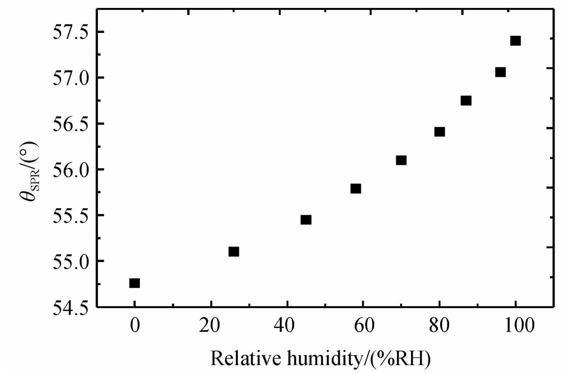



Fig. 7 The relationship between $\theta_{\mathrm{SPR}}$ and relative humidity

The result clearly indicates that within the scope of humidity changing, 0% RH ~ 100% RH, the $\theta_{\mathrm{SPR}}$ shifts significantly, ranging from 54.76° to 57.46°. At present the detection limit of angle resolution is 0.01°, so the resolution of this humidity sensor, 0.37%RH, has been achieved. This resolution significantly exceeds 1%RH~2%RH, which is the resolution of capacitive humidity sensors. Under the optimal conditions, a sensitivity of the humidity sensor of 0.03°/% RH is calculated.

# 3 Conclusion

In this research, SPR-based sensor is applied to detect relative humidity in surrounding. When the thickness of gold film is around 55 nm, the sensor has ideally high resolution and sensitivity. We anticipate that the proposed method will be developed and become a promising candidate for highly sensitive humidity detection format.

**References**

[1] BRONGERSMA M L, SHALAEV V M. The case for Plasmonics[J]. *Science*, 2010, **328**(5977): 440-441.

[2] CIRACI C, HILL R T, MOCK J J, *et al*. Probing the ultimate limits of plasmonic enhancement[J]. *Science*, 2012, **337**(6098): 1072-1074.

[3] BERINI P, DE L I. Surface plasmon-polariton amplifiers and lasers[J]. *Nature Photonics*, 2012, **6**(1): 16-24.

[4] MAREK P, HANA S, PAVEL K. High-resolution biosensor based on localized surface plasmons[J]. *Optics Express*, 2012, **20**(1): 672-680.

[5] BYOUNG J J, MOO H K , JAE C P. Application of a functionalized parylene film as a linker layer of SPR biosensor [J]. *Sensors and Actuators B*, 2011, **154**(2): 89-95.

[6] LIU Xia, LI Lei, LI Wen-jin, *et al*. Research progress on the detection of pesticide residues by surface plasmon resonance sensor[J]. *Journal of Food Safety and Quality*, 2013, **4** (2): 321-327.

[7] BAYHAN M, KAVASOGLU N A. A study on the humity sensing properties of ZnCr2O4-K2CrO4 ionic conductive ceramic sensor[J]. *Sensors and Actuators B*, 2006, **117**(1): 261-265.

[8] WU Da-jun, TANG Qi, YANG Shan-shan, *et al*. Development of a novel humidity sensor by the MEMS technology[J]. *Micronanoelectronic Technology*, 2013, **50** (9): 570-575.

[9] TANG Jie-yuan, CHEN Zhe, LUO Yun-han, *et al*. Side polished SMS fiber sensor[J]. *Acta Photonica Sinica*, 2013, **42**(10): 1187-1192.

[10] LUO Yun-han, MAO Pei-ling, CHEN Chao-ying. Side-polished fiber coupled plasmon resonance based on triangle nano-rod array[J]. *Acta Photonica Sinica*, 2015, **44**(4): 0406004.

[11] ALBERTO A H, HEREDERO R L, EUSEBIO B. Dsorption of water on porous vycor glass studied by ellipsome-try[J]. *Applied Optics*, 2001, **40**(4): 527-532.

[12] WANG Zhen-yuan, GU Zheng-xian. Optical humidity-sensitive mechanism based on refractive index variation[J]. *Transducer and Microsystem Technologies*, 2009, **28**(5): 68-71.

[13] KUMAR S, SHARMA G, SINGH V. Effect of a graded optical layer on surface plasmon resonance sensor[J]. *Optics Communications*, 2014, **313**: 436-440.

[14] LEVESQUE Q, MAKHSIYAN M, BOUCHON P, *et al*. Plasmonic planar antenna for wideband and efficient linear polarization conversion[J]. *Applied Physics Letters*, 2014, **104**(11): 111105.

[15] ZHANG Yun-shan, QIAO Xue-Guang, SHAO Min, *et al*. Humidity sensor based on waist-enlarged fiber tapers cascade structure[J]. *Acta Photonica Sinica*, 2015, **44**(3): 0328004.

[16] LUCA S. Enhancement of four reflection shifts by a three-layer surface-plasmon resonance[J]. *Physical Review A*, 2012, **86**(5): 05580.

[17] EVLYUKHIN A B, BOZHEVOLNYI S I. Surface plasmon polariton guiding by chains of nanoparticles[J]. *Laser Physics Letters*, 2006, **3**(8): 396-400.

[18] CHEN Xiao-long, LUO Yun-han, XU Meng-yun, *et al*. Refractive index and temperature sensing based on surface Plasmon resonance fabricated on a side polished fiber[J]. *Acta Optica Sinica*, 2014, **34**(2): 0206005.

[19] ZUPPELLA P, TOSATTO S, CORSO A J. Graphene-noble metal bilayers for inverted surface plasmon resonance biosensors[J]. *Journal of Optics*, 2013, **15**(5): 055010.

[20] LEE C, TAME M, NOH C, *et al*. Robust-to-loss entanglement generation using a quantum plasmonic nanoparticle array[J]. *New Journal of Physics*, 2013, **15** (8): 083017.