Surface plasmon resonance sensor based on core-shell metal nanorods

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Abstract. A surface plasmon resonance (SPR) sensor based on core-shell metal nanorod arrays for ultra-sensitive refractive index sensing applications is proposed using three-dimensional finite element method. Simulation results show that the absorptance (A) of the proposed structure can be reached A=90.0% which is about 3.5 times enhancement compared to its solid counterpart (A=25.57%). Result shows that the sensitivity can be obtained as high as 700.00 nm/RIU (RIU is the refractive index unit). The proposed SPR sensor could be a desirable candidate for applications in nanophotonic devices.

1. Introduction
Surface plasmon resonance (SPR) sensor have been attracted great attention for their fascinating properties due to their behaviour of absorbing and enhancing electromagnetic (EM) waves in nanophotonic field [1-6]. Recently, many research groups have made their efforts to enhance the absorption in plasmonic nanostructures for refractive index (RI) sensing applications [7,8]. SPR sensors require being designed with simple and tunable in near infrared if they are to be successfully implemented in sensor applications. Many SPR RI sensors using core-shell nanostructures have been proposed [9,10]. However, the RI sensitivity of the SPR sensor based on core-shell nanorods connected with crossing veins has been investigated less before.

In this paper, a new type of SPR sensor based on silver-shell nanorod arrays connected with crossing veins, which provides a connected resonance bridge between silver-shell nanorods and veins compared to its counterpart without the crossing veins, has been proposed and investigated using three-dimensional (3-D) finite element method (FEM) and the numerical results of coupled silver nanorods without the crossing veins are included for comparison.

2. Simulation method and model
The numerical simulation of the proposed structure was performed using 3-D FEM (COMSOL Multiphysics [11]). The silver permittivity data is obtained from Ref. [12] and the absorptance (A) is calculated from 1-reflectance (R)-transmittance (T). The sensitivity (S) can be calculated as $S=\Delta \lambda /\Delta n$ [13-15], where $\Delta \lambda$ is the shift of resonant peak wavelength of absorptance and $\Delta n$ is the RI difference. Figs. 1(a) and (b) depict the unit cell of proposed structures without and with crossing veins, respectively. The case with veins is composed of four silver nanorods connected by silver crossing veins at central part placed on the surface of a uniform silver film. The reason why the proposed sensors are based on core-shell structures is due to the capacitance and inductance effects can be
simultaneously induced in the designed sensor. The structural parameters of the proposed SPR sensor are denoted as period \( (P) \), height \( (h) \), length \( (w) \), gap distance \( (g) \), vein thickness \( (t) \) and the thickness of bottom Ag film \( (s) \), respectively.

**Figure 1.** A truncated view of the proposed SPR sensor structure (a) without and (b) with crossing veins.

### 3. Results and discussion

Figure 2 shows the optical spectra of the designed structures without (dashed lines) and with (solid lines) the crossing veins. The values of \( P, h, d, g, t \) and \( s \) are fixed at 470 nm, 100 nm, 60 nm, 80 nm, 10 nm and 100 nm, respectively. As shown in Figs. 2, the difference of peak/dip of absorptance/reflectance/transmittance spectra can be attributed to that of different SPR effect generated in the proposed structure. A remarkable peak/dip occurred at 780 nm for the case with crossing veins and a much weaker one at 1010 nm for the case without crossing veins. There is a huge difference between the two cases because of the vein effect has a dominant influence on plasmon resonance in the proposed structure. Note that the absorptance \( (A) \) of the case with veins can be reached \( A=90.00\% \) which is about 3.5 times enhancement compared to its solid counterpart without veins \( (A=25.57\%) \).

The electric field intensity \( (|E|, \text{V/m}) \) distributions of the unit-cell structures at resonances for the cases without crossing veins and with veins are displayed in Figs. 3(a) and (b), respectively. It can be seen that the \( |E| \) profile of the case with veins is much higher than that of the case without veins, which is strongly confined in the gap vicinity of Ag nanorods and the surface of veins. In addition, an enhanced distribution of \( |E| \) can be extended around their outer sides. The gap and edge enhancement profiles in the case with crossing veins indicate that the hybrid surface, cavity and gap modes were stimulated by the incident EM waves coupled with the proposed structure.

To investigate the difference of the proposed structures without and with crossing veins, the surrounding RI of \( n=1.0, 1.20 \) and \( 1.40 \) are examined as shown in Figs. 4(a) and Figs. 4(b), respectively. There is a remarkable redshift of each mode when the RI is varied from 1.0 to 1.4. The calculated sensitivity can be achieved up to 700.00 nm/RIU. The magnitude of absorptance of the cases without veins is much less than that of the cases with veins because of the cases without veins possesses the less gap and cavity modes among Ag nanorods [16-18]. The absorptance \( (A) \) in the cases with crossing veins will be beneficial for plasmonic sensing application. The physical inference for these redshifts of the cases with crossing veins is due to the effective increase in capacitance and inductance of the resonant structure [19] lead to the increase in the RI of the surrounding media.
Figure 2. Reflectance (R), Transmittance (T) and Absorptance (A) spectra of the designed SPR sensors without and with the connected crossing veins.

Figure 3. Electric field intensity (|E|, V/m) for the case (a) without crossing veins (at $\lambda_{\text{res}}=1010$ nm) and (b) with crossing veins (at $\lambda_{\text{res}}=780$ nm), respectively.

4. Conclusions
In this paper, a new type of SPR sensor based on core-shell silver nanorod arrays with the crossing veins and compared the optical performance with its counterpart without the crossing veins is proposed and investigated using 3-D FEM. Results show that a huge difference of absorptance between the case with and without crossing veins can be found because of the vein effect has a dominant influence on plasmon resonance in the proposed structure. The absorptance of the case with crossing veins is nearly perfect which is much higher than the case without veins. The calculated sensitivity can be achieved up to 700.00 nm/RIU. The proposed structure could be a promising candidate for applications in the SPR sensors and the nanophotonic devices.
Figure 4. Absorptance spectrum of the case with veins by varying the surrounding RI of $n=1.0$, 1.2 and 1.4, respectively. Where black dashed line denotes the case without veins.

5. References
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