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Simulation of Periodic 6-Point Shuriken Nano-Structures to Use in SPR Sensors

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ABSTRACT

Surface plasmon resonance or SPR, was first observed on the verge of the twentieth century. In late 60s and early 70s, simple methods to implement and excite surface plasmons were introduced. Since then, numerous applications have been proposed to utilize SPR, from biosensors to optical switches. This is due to the sensitivity of SPR to fine changes in the conditions of the environment (for example temperature or concentration), and its ability to work in real time. It is imperative to design and propose structures with different SPR properties to enable the possibility of tailoring devices to meet the needs of science and technology. The purpose of this study is to investigate nano sensors with a periodic 6-point shuriken structure to excite localized surface plasmons (LSPR). It is shown in this study that the aforementioned sensor can have a sensitivity of up to 600 nm/RIU, using Kretschmann configuration and silver nano particles.

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1. Introduction

Surface Plasmon Resonance or SPR, occurs when the collective vibrations of the free electrons on the surface of a metal (plasmons) is somehow resonated. The frequency which these plasmons tend to vibrate with, is dependent on the refractive index of the adjacent dielectric region. This dependency and the fact that the electric field in SPR condition is highly confined to the interface, is very promising for developing sensors.

Historically, it was Sommerfeld who first theoretically discussed such confined surface waves in 1899 (Maier, 2007). Three years later, Wood observed an anomaly in the reflected spectra of a metal grating (Wood, 1902) which he could not explain. The field was almost dormant until Otto (Otto, 1968), Raether (Bruns & Raether, 1970), and

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Kretschmann (Kretschmann, 1971) separately proposed ways to achieve SPR. However, it was the advent of near field imaging that really helped the field bloom.

Since then, there has been an abundant of application proposed for SPR and several SPR-based devices have been industrialized. Apart from its high sensitivity, real-time monitoring and label-free detecting makes SPR an interesting candidate for scientists and researchers (Chen et al., 2022; Gao et al., 2023; Kruchinin & Vlasov, 1996; Rivero et al., 2012; Rossi et al., 2018; San-Blas et al., 2023; Severs et al., 1993; Sun et al., 2023; Zhao et al., 2023).

As can be seen in Fig. 1, there are three main approaches to achieve SPR: via a prism coupler, metal grating, or using a waveguide or a light fiber. In this research, prism coupling in Kretschmann configuration has been exploited.

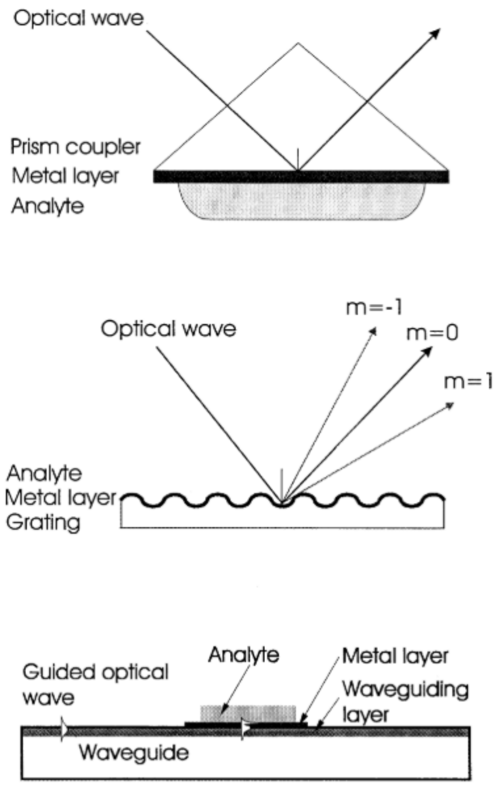

Figure 1. Main approaches to implement SPR (Homola et al., 1999).

2. Material and Methods

In 6-point shuriken structure, silver nanocylinders are placed on the edges of imaginary hexagons. This is basically the hexagonal structure without the center nodes (Fig. 2).

In order to make such structures, a polymerization procedure was designed to synthesize PMMA nano spheres with the radius R. Figure 3, is an AFM picture of the mentioned spheres deposited on a glass slide to be used as a mask.

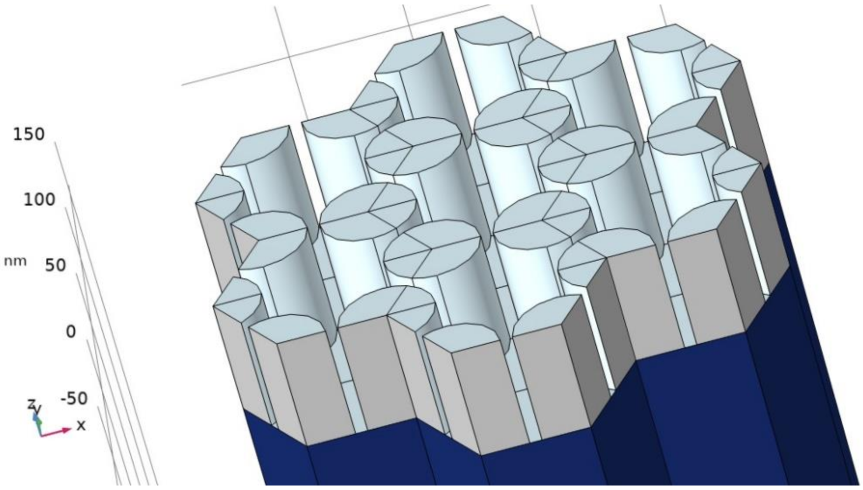

Figure 2. Schematics of the 6-point shuriken structure. The silver pillars are nano particles and the navy-blue substrate is the prism. The picture includes seven adjacent simulation cells.

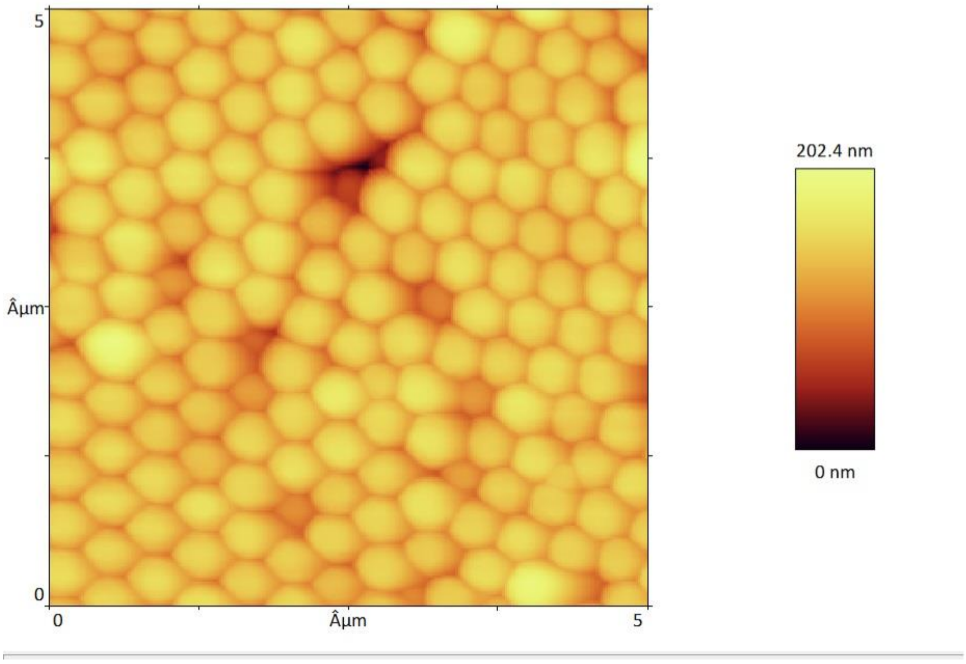

Figure 3. AFM picture of deposited PMMA nano spheres.

Next, silver is coated on the mask and PMMA spheres are washed off using acetone. Figure 4 shows the remaining structure. Note that one of the spheres had not been washed off and can be seen in the picture. The last step is baking the remaining structure so that the coated silver segregates and forms cylinders. For a given R, the amount of coating and baking, determine the radius of cylinders (r) and their height (h_M) (Fig. 5). The synthesizing process and the procedure of building sensors are still being optimized.

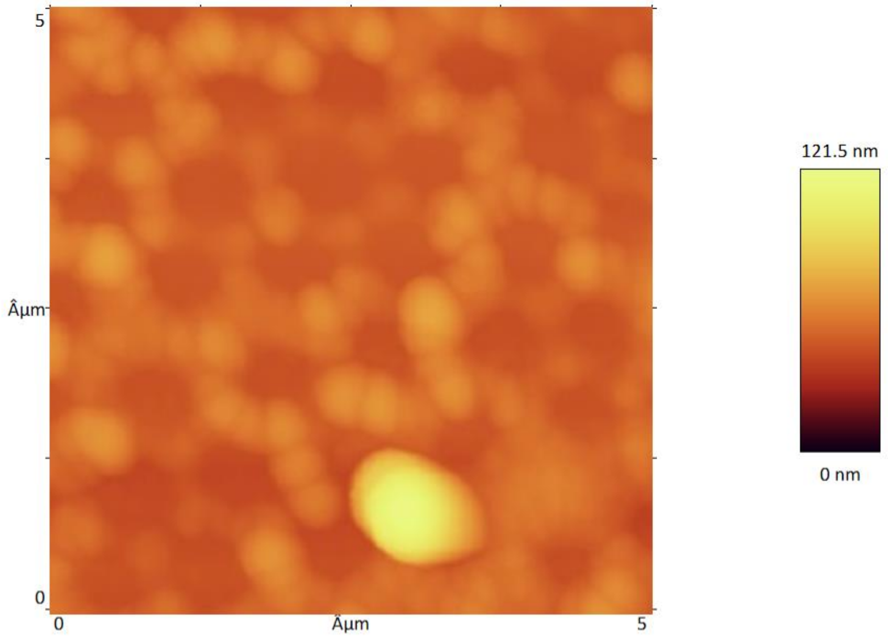

Figure 4. The structure after removing the spheres. The picture is digitally enlarged for a better view. The size of the silver particles (faint yellow) is about 25 nm. Note that one of the spheres had not been washed off.

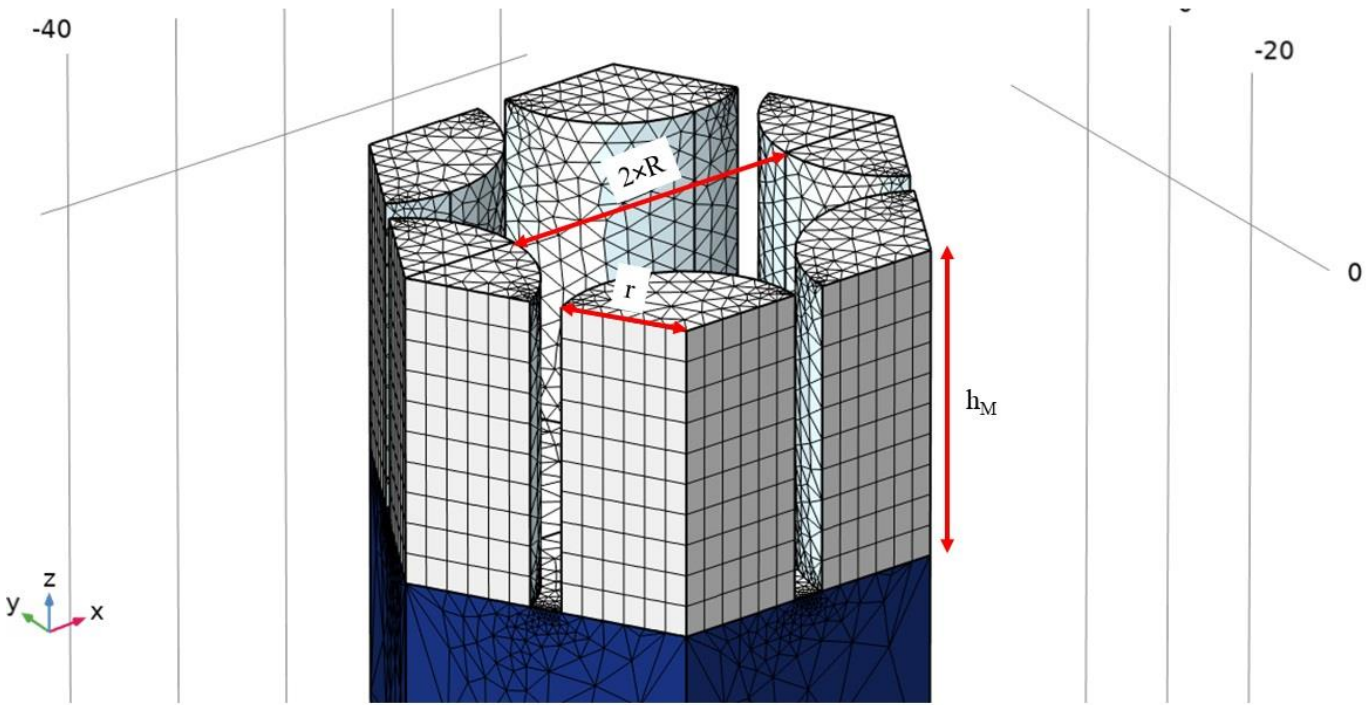

Figure 5. Schematic view of the simulation cell and the geometry parameters.

Different values of R, r, and h_M lead to different SPR behavior which should be investigated. In order to minimize the number of experiments, and thus, the expenses, computer simulation was used to model and design optimum structures suited for different needs. Here, finite element method (FEM) was used to investigate the SPR response.

3. Results and Discussions

The structure with R = 25 nm, r = 20 nm, and h_M = 50 nm, is reported in this paper. First, to find the angle of incident (AoI) to work with, at wavelength = 600 nm, AoI was scanned from 40° to 89° (Fig. 6).

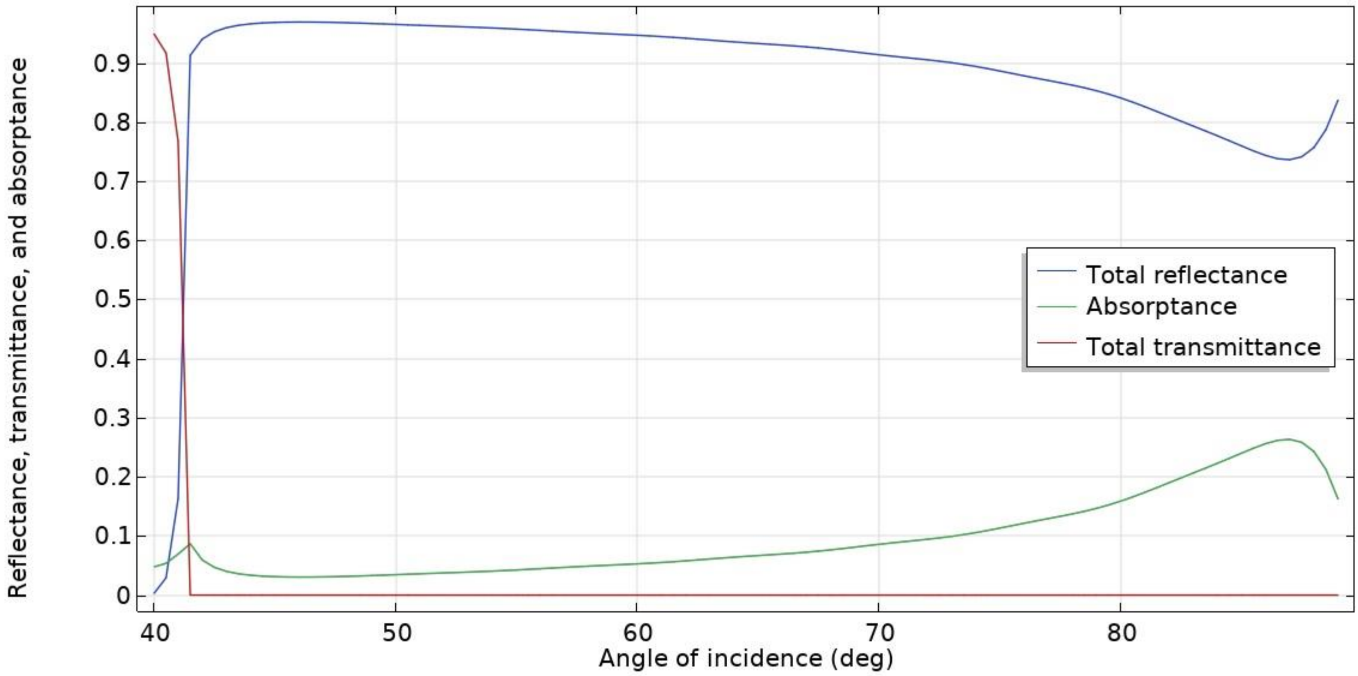

Figure 6. AoI sweep at λ=600 nm.

Although, the SPR occurs at an angle greater than 65°, AoI was set to 65 due to the limitations imposed by the available spectrometer at Amjad SPR Lab. After that, a wavelength sweep was conducted at this AoI to find the wavelength dependency of the reflectance of the structure for several refractive indices of the sample contacting the sensor.

It can be seen from Figure 7, that in the visible band, reflectance has three major SPR dips at AoI = 65° (the minimums between 410 and 420 nm are dominated by the absorptance of the silver nano particles).

It also shows that, even though the first dips have a smaller full width at half maximum, the red shift is more significant in the second and third sets. Interpreting this into sensitivity, this means that for this sensor, at AoI = 65°, for the 1st, 2nd, and 3rd sets, sensitivity is approximately 120, 600, and 450 nm/RIU, respectively. As a comparison, the SPR sensor developed by (San-Blas et al., 2023), had a sensitivity of 518 nm/RIU for an aqueous analyte. In their work, LIPSS was used to make gold metal grating needed to implement SPR.

4. Conclusions

In this study, 6-point shuriken structure is proposed as an interesting flexible framework to build SPR nano sensors. It can be built at large scales with low cost. It was shown that for a case of R = 25 nm, r = 20 nm, and h_M = 50 nm, at AoI = 65°, SPR occurs at three different wavelengths in the visible band and the sensitivity of the device can reach to about 600 nm/RIU.

Next, other geometries and materials should be investigated so that the sensor would be able to work for a wider range of refractive indices. Furthermore, different ligands should be implemented in the proposed sensor. Last but not least, the sensor must be put to trial in the laboratory and the simulation results should be compared with experimental ones.

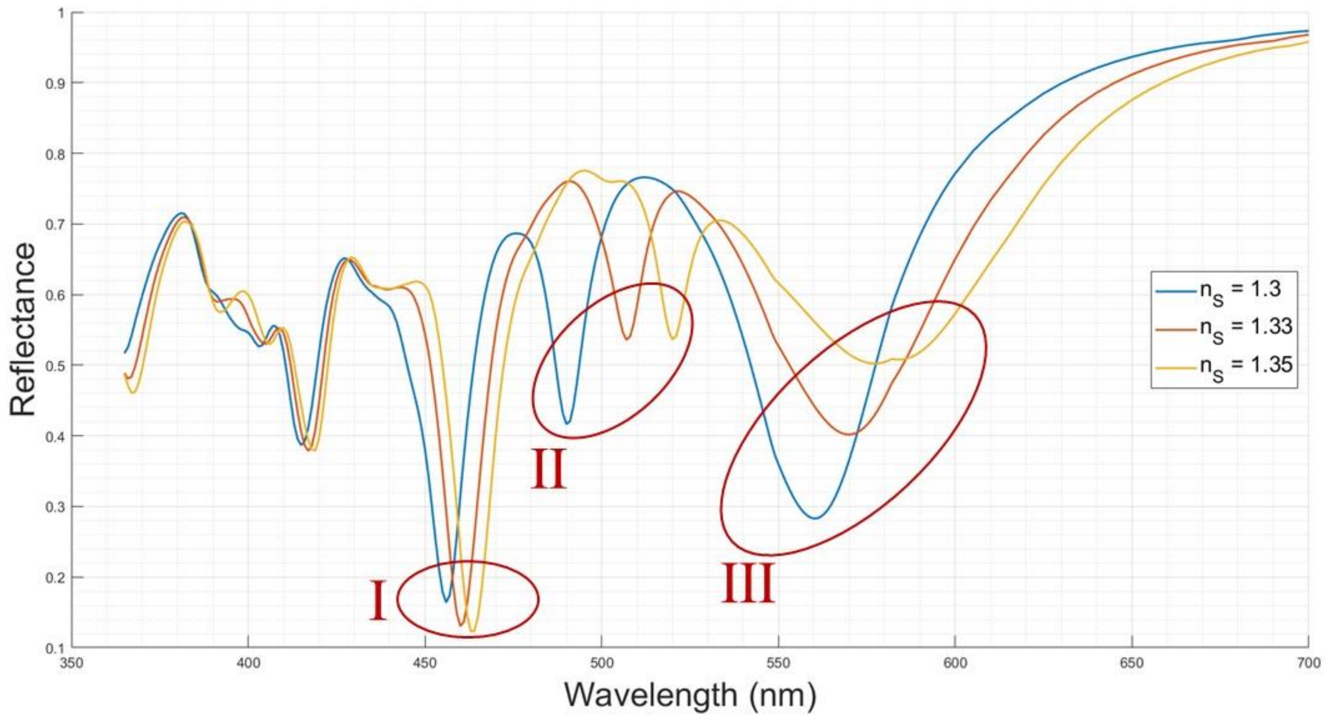

Figure 7. Wavelength dependency of reflectance for different refractive indices (1.3, 1.33, and 1.35) shows three major dips in the visible band.

Acknowledgment

Some of the simulations presented here, were conducted on the computational node at Prof. Akhlaghi's Lab at IASBS. This study was presented in the fourth 'international conference on light and light-based technologies (ICLLT)' in Gazi University in May 2024.

Declaration of Competing Interest and Ethics

The authors declare no conflict of interest. This research study complies with research publishing ethics. The scientific and legal responsibility for manuscripts published in OPS Journal belongs to the authors.

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