Refractive Index Sensing Using Cylindrical Photonic Metasurfaces

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***Abstract*—In this work, we propose and analyze a dielectric metasurface based refractometric sensor. The sensor demonstrates dual response in the near-infrared range with sensitivities of 288.2 nm/RIU and 149.7 nm/RIU. By introducing a cylindrical slot in the meta-atom design, we further enhance the sensitivity of one of the resonant modes by 55.4%. Our study details the improvements achieved, showcasing the potential for fine-tuning sensor performance through structural modifications.**

***Index Terms*—metasurface, refractometric sensor, near infrared, meta-atom**

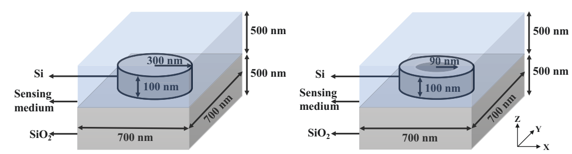
I. Introduction

Photonic metasurfaces, comprising an array of sub-wavelength nanostructures called meta-atoms, provide a novel way to manipulate light at specific wavelengths. By engineering their geometry and functional arrangements on the substrate, metasurfaces can manipulate optical waves with high precision [1]. This precise control makes metasurfaces highly suitable for various applications, including refractive index sensing. Refractometric sensing is pivotal in various fields such as environmental monitoring, food safety inspection, biomedical diagnostics, chemical industries and so on [2].

Dielectric metasurfaces have recently gained prominence for sensing due to low loss, low cost, lower line width, high Q-factor [3]. Here we propose a dielectric metasurface based refractometric sensor in this work. The performance of the sensor is investigated through numerical simulations. Transmission spectrum obtained depicts dual resonance in the wavelength range of 1 μm to 1.7 μm. The presence of such dual resonance offers a significant advantage in sensor technology, as it furnishes multiple options for monitoring changes. Moreover, the stability of the sensor is also enhanced by this dual response. The sensor design is further modified by introducing a cylindrical slot in the meta-atom and its improvement in sensitivity has been investigated.

II. Simulation Setup

The proposed metasurface sensor comprises an array of silicon (Si) scatterers arranged on a silicon-dioxide (SiO_2) substrate. These scatterers are cylindrical-shaped with dimensions of radius 300 nm and height 100 nm, forming a periodic square array with a periodicity (Λ) of 700 nm in the XY plane. Figure 1a and 1b show the schematic diagram of the proposed metasurface sensor unit cell, without and with cylindrical slot. The numerical simulations are conducted with in-plane boundary conditions for normally incident Y-polarized plane wave.



(a) (b)

Fig. 1: Schematic diagram of the metasurface sensor unit cell (a) without slot (b) with cylindrical slot

The refractive index values of Si and SiO_2 have been obtained from [3] and [4], respectively. The thickness of the sensing medium is 500 nm. Initial computations for transmission has been made with air as the background. Further, transmission spectra are computed by changing the refractive index of the sensing medium from 1.33 to 1.49. Later, to improve the sensitivity of the dielectric metasurface sensor, a cylindrical slot of radius 90 nm is introduced as shown in Figure 1b and the sensitivity of the sensor is analyzed. All the numerical simulations are carried out through finite element method (FEM) using COMSOL Multiphysics software.

III. Results and discussion

Figure 2 shows the numerically simulated transmission spectra of the dielectric metasurface sensor. With air as background, for a normally incident Y-polarized plane wave, it unveils two distinct minima at the wavelengths of 1.023 μm and 1.226 μm. To employ this dielectric metasurface sensor for sensing refractive index, we first investigate by varying the refractive index of the sensing medium from 1.33 to 1.49.

As the refractive index of the sensing medium increases, both the resonance modes get shifted to longer wavelengths. Figure 2 also depicts these shifts for various refractive index values of the sensing material. The ratio of the change in resonance wavelength ($\Delta\lambda$) to the change in refractive index (Δn) is termed as Sensitivity (S). The sensitivity of this dielectric metasurface sensor is found to be 288.5 nm/RIU and 149.7 nm/RIU for each respective resonance modes.

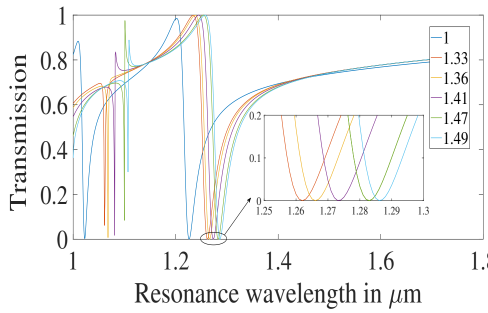


Fig. 2: Transmission spectra of metasurface sensor with air as background and with five different RI of the sensing medium

In order to improve the sensitivity of the sensor, a cylindrical slot of radius 90 nm is introduced at the center of the meta-scatterer. Due to the presence of this slot, the area of contact between the dielectric metasurface sensor and the surrounding sensing medium increases. This leads to an augmentation of the electric field in the slotted region, thereby achieving better sensitivity. Figure 3 depicts the simulated transmission spectrum of the slotted metasurface sensor. With air as the background, it shows dual resonance at the wavelengths of 1.018 μm and 1.094 μm . The resonance at lower wavelength and higher wavelength shall be henceforth referred as mode 1 and mode 2, respectively. When the slot is introduced, both the modes 1 and 2 gets shifted to lower wavelengths. Mode 2 experiences more blue shift when compared to mode 1.

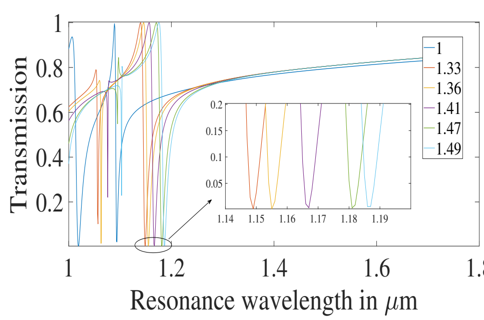


Fig. 3: Transmission spectra of modified metasurface sensor with air as background and with five different RI of the sensing medium

To employ refractive index sensing using this slotted metasurface, the RI of the sensing medium is varied from 1.33 to 1.49 similar to the one shown in Figure 2. The resonances of both the modes get shifted to longer wavelengths when the RI of the sensing material increases. Additionally, the wavelength separation between both the modes get reduced. The sensitivities of this slotted sensor are 288.2 nm/RIU and 232.7 nm/RIU for each mode, respectively. The resonance mode wavelength shift for five different values of refractive index of the sensing medium is shown in Figure 4.

The enhancement in the field depends on the radius of the cylindrical slot. Table I shows the sensitivity of the dielectric metasurface sensor without slot and for sensor with different slot radii. It may be observed that, there is no improvement in the sensitivity of the mode 1 even after the introduction of a cylindrical slot. However, the sensitivity of mode 2 improves significantly with the addition of the slot. A slot radius of 50 nm yields sensitivity of 185.7 nm/RIU for mode 2. When the slot radius is increased to 70 nm, sensitivity of mode 2 increases to 211.3 nm/RIU. Remarkably, for a 90 nm slot radius, the sensitivity of mode 2 improves by 55.4%. These findings indicate that while mode 1 remains unaffected by the cylindrical slot, the optimization of the slot radius can significantly enhance the sensitivity of mode 2, highlighting the potential for fine-tuning sensor performance through structural modifications.

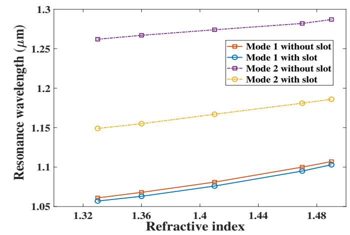


Fig. 4: Sensitivity of dielectric metasurface sensor with and without slot

TABLE I: Sensitivity(nm/RIU) for various values of slot radius

	Mode 1	**Mode 2**
Without slot	288.5	149.7
With slot of radius 50 nm	288.2	185.7
With slot of radius 70 nm	288.5	211.3
With slot of radius 90 nm	288.2	232.7

IV. Conclusion

A dielectric cylindrical metasurface based refractive index sensor is numerically simulated and shown to exhibit dual resonance in the near infrared wavelength regime 1 μm to 1.7 μm. The resonance modes of the metasurface sensor gets shifted to longer wavelengths when the RI of the sensing medium is varied from 1.33 to 1.49. We have also investigated the performance of the sensor when a cylindrical slot is introduced. The study clearly demonstrates that while the addition of a slot to the metasurface does not influence the sensitivity of mode 1, it significantly enhances the sensitivity of mode 2.

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