All-Dielectric Metasurface Refractive Index Sensor with Microfluidics

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Abstract. Magnetic resonance and electrical resonance can be excited simultaneously by the incident light source in high refractive index all-dielectric metasurfaces. They can manipulate light waves to a certain extent and can be used in many fields. Silicon is widely used in all-dielectric metasurfaces due to its high refractive index and low loss in near infrared range. In this paper, we use silicon nanodisk structure as refractive index sensor and PDMS microfluidic channels as detection channels to realize liquid refractive index sensing. The magnetic resonance peak of the nanodisk structure is selected for sensing. The position of the magnetic resonance is shifted in the transmission spectrum with the change of the refractive index of the surrounding environment. When the refractive index increases, the resonance peak moves towards the long-wave direction, resulting in red shift, and vice versa. In this paper, the shift of resonance peak reaches 230 nm RIU⁻¹.

1. Introduction

In recent years, all-dielectric metasurface has become a research hotspot because the magnetic resonance and electrical resonance can be stimulated simultaneously by a broadband light source [1-4]. Through the multi-dimensional adjustment of electric and magnetic resonance, many excellent properties can be realized, including huygens metasurface [5] and far-field directional control. Different from the metal metasurface based on local surface plasmon resonance (LSPR), the resonance in the all-dielectric metasurface mainly comes from the polarization of the material under incident light irradiation and the internal displacement current generated inside due to the lack of free moving valence electrons. And this resonance can occur on very small scales. It is found that the resonance between the incident light and the all-dielectric metasurface can also be achieved at the size of as small as 10nm. Considering the broadband characteristics of resonance and the coupling characteristics with incident light, the all-dielectric metasurface can achieve good performance in the field of photovoltaic absorption and efficient absorption.

In a two-dimensional plane, the periodic metasurface is usually composed of the same structural units arranged according to unity. There are also metasurface composed of different structural unit sizes or non-uniform arrangements [6, 7]. The size of ultrathin structural units usually used in the design of metasurface is smaller than the characteristic wavelength. The electromagnetic properties of the metasurface composed of the same structural units are usually determined by the electromagnetic properties of the individual structural units constructed. The use of metasurface can be used to control the properties of electromagnetic waves, such as amplitude, phase, and polarization. Before analysing the electromagnetic properties of the metasurface, it is necessary to analyse the electromagnetic properties of a single structural unit. The examples of metasurface in this paper are all metasurface composed of the same structural units.
Refractive index sensor has a wide range of applications in modern society, from food safety to medical diagnosis, and can be used to conduct qualitative research on liquids through refractive index sensor. In the field of food safety, fiber optic sensing is often used to detect food impurities. In biosensors and medical applications, advanced refractive index sensing systems often rely on the use of surface plasma resonance (SPRs) \[8, 9\]. Recent researches have shown that the refractive index sensor based on all-dielectric metasurface can integrate the complex refractive index detection system into a single chip, which can reduce the detection cost and time. Such refractive index sensors can detect the refractive index of liquids and the presence of proteins.

In this article, we introduce a kind of refractive index sensor consists of silica nano-disk array and PDMS microfluidics, the magnetic resonance peak will shift with the change of the surrounding liquid refractive index. We use microfluidic channels to achieve convenient, fast and sufficient refractive index sensing. The shift of resonance peak reaches 230nm RIU\(^{-1}\).

2. Methods

2.1. Fabrication of Nano-Disk Structure

The overall steps of the samples fabrication can be divided into four steps, in turn for the layer coating, the electron beam exposure (EBL), the development and the reaction particle etching (RIE). Fig. 1 shows the SEM image of the fabricated all-dielectric metasurface sensor with square arrays of Si disks on a SiO\(_2\) substrate under the illumination of a y-polarized near-infrared light, where the radius \(r = 371\) nm, gap \(g = 225\) nm, and periodicity \(P = 967\) nm.

![Figure 1](image-url)

**Figure 1.** The SEM image of fabricated metasurface (\(r = 371\) nm, \(g = 225\) nm and \(P = 967\) nm)

2.2. Fabrication of PDMS Microfluidic Channels

Mix the PDMS matrix and curing agent at a ratio of 10:1, stir the liquid with glass rod for about 30 minutes until they are intensively mixed. At this time, there will be many bubbles in the liquid. After the bubbles are removed by vacuum pump, the PDMS is poured on the mould of the microfluidic channel, and then the whole device is placed on the hot table at 150°C and heated for 3 minutes until the PDMS solidifies. PDMS were then peeled off from the mould, the chips were cut to the required size with a knife, and then PDMS was covered on the metasurface, which was then sealed with PDMS and heated to solidify to obtain the metasurface with a microfluidic channel.
2.3. Optical Measurements
The transmission spectra under normal incidence is measured by AQ-6315A spectrometer. The substrate without structure is used as the reference for measuring the transmittance.

2.4. Numerical Simulations
Finite-difference time-domain method (FDTD Solutions v8.15, Lumerical) is used to compute the optical responses of Si metasurface sensor. The spectral range in the simulation ranges from 1400 nm to 2000 nm. The overall structure is illuminated by plane waves propagating along the z-axis.

3. Results

3.1. Simulations Results
The metasurface consist of Si nano-disk array and SiO2 substrate. We set the height of disks h =220nm, radius r =375nm, periodicity P =960nm. While setting the surrounding refractive index as 1, the transmission spectra as Fig. 2 blue line shows 2 transmission peaks, the peak at around 1.5μm is caused by magnetic resonance, and the other is caused by electrical resonance. Change the refractive index and the results shows in Fig. 2, both resonances will shift. This property proves that the nano-disk metasurface is a good candidate for refractive index sensor.

![Figure 2](image)

**Figure 2.** The FDTD simulation results of transmission spectra. n varies from 1 to 1.4

3.2. Experiment Results
We use PDMS polymer to fabricate the microfluidic channels, microfluidic channels are connected to the outside world by pinheads, and the other side of pin is connected by rubber tubes. Set the chip on the objective table and the liquid is pumped into the microfluidic channels by a pump, so we can measure the transmission peak without moving the chip which make the procedure much more convenient.

We experimented with glucose solutions of different mass fractions as different mass fraction of glucose solution corresponds to different refractive index of liquid. Liquid of different refractive index flows in the microfluidic channel during the measurements. And Fig. 3 depicts the transmission
spectra. The magnetic resonance peak shifts with the change of surrounding liquid refractive index, and the peak present red shift as the refractive index increase. The sensitivity can reach 230nm RIU$^{-1}$.

Figure 3. The measured transmission spectra

4. Conclusion
We present a new kind of refractive index sensor which was assembled in a chip. We used all-dielectric metasurface which exhibits both magnetic resonance and electrical resonance to manipulate light. The Si nano-disk structure is a great candidate for metasurface due to its large refractive index and low optical loss in near infrared. Our metasurface shows a strong magnetic resonance peak at around 1.5μm in a vacuum. While changing the refractive index of the surrounding liquid, the transmission peak will shift to at around 1.6μm, the sensitivity reaches approximately 230nm RIU$^{-1}$ which is much sensitive than other refractive index sensor. Compare with traditional refractive index sensors, our device is cheap and convenient to use.

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6. References
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