Highly Sensitive Refractive Index Sensing with Silicon-Based Dielectric Metasurfaces

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Abstract: We design and simulate microfluidic refractive index sensors based on optical dielectric metasurfaces comprised of resonant silicon nanoantennas. Sensitivity as high as $<10^{-7}$ RIU is modeled; experimental realization is in progress with biomarker of interest

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1. Introduction

Dielectric metasurfaces have been demonstrated to perform a variety of optical applications, including wavefront shaping, with high efficiency. Huygens source metasurfaces, comprised of nanoantenna elements supporting spectrally overlapping electric and magnetic dipole resonances, are capable of highly efficient performance, while the low aspect ratio of elements eases fabrication requirements. Easy, CMOS compatible fabrication, coupled with affordable and non-toxic material systems (Si, SiO_2, PDMS) opens doors for the development of affordable, high performance, specialized optical devices. The micrometer size scale of metasurfaces makes them an ideal option for lab-on-a-chip and other integrated optical applications. Although the high sensitivity of Huygens source dielectric metasurfaces can make wavefront shaping applications difficult, it makes them a good platform for devices with dynamic performance.

2. Highly Sensitive System

Huygens source, all-dielectric metasurfaces are particularly well suited for dynamic performance, in both active and passive configurations. Differing sensitivities of the electric and magnetic dipole resonances (Fig. 1a), as well as significant inter-element coupling, amplify the sensitivity. A reflective metasurface is a good platform for demonstration of this sensitivity, as the scattering condition for high reflection is quite sensitive to metasurface parameters [1] (e.g. antenna diameter, Fig. 1b). From this initial condition, 80% absolute modulation of transmitted light can be achieved by changes of ~5% in the refractive index of either the nanoantenna elements or the encapsulating medium, or by changes of ~10%-15% in any of the geometric parameters of the array (Fig. 1c). Although a variety of methods and materials are capable of varying geometric parameters, including mechanical stretching or utilization of piezoelectric materials, mechanical movement adds undesired complexity to a device.

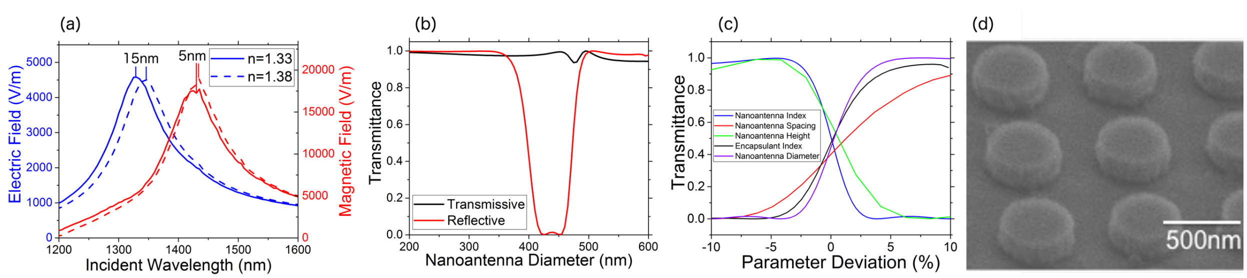

Fig. 1. (a) Spectral locations of electric and magnetic dipole resonances are plotted for two indices of refraction of the encapsulant layer. Spectral shifts are shown. The electric resonance is significantly more sensitive to this change, amplifying the sensitivity of the metasurface in general. (b) Transmittance as a function of nanoantenna diameter for a transmissive array (black line) and a reflective array (red line). While the transmissive array is highly transmissive over a large range of diameters, the reflective array is only reflective within a narrow range; at the limits of this range, the reflectance of the array is highly responsive. (c) Transmittance as a function of parameter variation for critical geometric and material array parameters. For each parameter, 0% deviation is defined by the peak of sensitivity. (d) SEM image of Si nanoantenna elements.

For practical devices, variation of material properties is preferred. Our parallel work has focused on the design of optical modulators based on vanadium dioxide nanoantennas, in which refractive index of the nanoantennas and corresponding optical response vary steeply in response to heat, or electrical or optical stimulus. Here, we take advantage of high sensitivity to refractive index of the encapsulating material for microfluidic sensing applications.

3. Refractive Index Sensing of Liquids and Gasses

Refractive index of liquids and gasses can be used as an indicator of solute concentration or the existence of impurities or biomarkers, as well as variation in temperature and pressure. Nano-patterned surfaces [2] and volumes [3] have proven capable of this type of measurement, with demonstrations performed for both plasmonic and dielectric systems. These demonstrations tend to rely on the spectral shift of an extinction or transmittance peak, typically on the order of several nanometers or less, thereby relying on high resolution spectrometers to make the measurement. In pursuit of a cheap and simplistic, yet highly sensitive refractive index sensor, we are developing a device with a steep single-wavelength transmittance response to varying refractive index of the encapsulant layer. Experimental verification is in progress (Fig. 1d), and expected to be completed in the near future. The device consists of a silicon metasurface on a fused quartz substrate (Fig. 2c). A microfluidic channel carries fluid over the metasurface, with the fluid acting as the encapsulating layer. A simple laser/photodetector setup measures transmittance through the metasurface, variation of which can be used to detect changes in the refractive index of the fluid. A simultaneous transmittance measurement may be made in an adjacent channel with no metasurface present. This measurement acts as a control, accounting for any changes in absorption of the fluid caused by changes in solute concentration. We have modeled this device using a finite element package (COMSOL). Using water as an example fluid, a sensitivity of >20% change in relative transmittance per 1% change in refractive index is observed (Fig. 2a). With a standard amplified InGaAs photodetector (100 pW sensitivity) and a 1 mW input signal, a refractive index change of $<10^{-7}$ could be detected in water. Although the refractive index range of the measurement is not large, roughly 0.1 RIU, this range is easily adjustable (Fig. 2b) by varying nanoantenna diameter. The footprint of these metasurface devices is small and scalable, having a lower limit of several microns; this allows a single microfluidic chip to contain many metasurfaces, each tuned to a different refractive index or wavelength range. This refractive index sensitivity is experimentally verified by coupling to a microfluidic volume flowing e.g. calcium dissolved in a buffered saline solution. Calcium is a critical biomarker, as its presence in blood serum affects heart and skeletal muscle contractility, nervous system function, blood clotting, and bone mineralization [4].

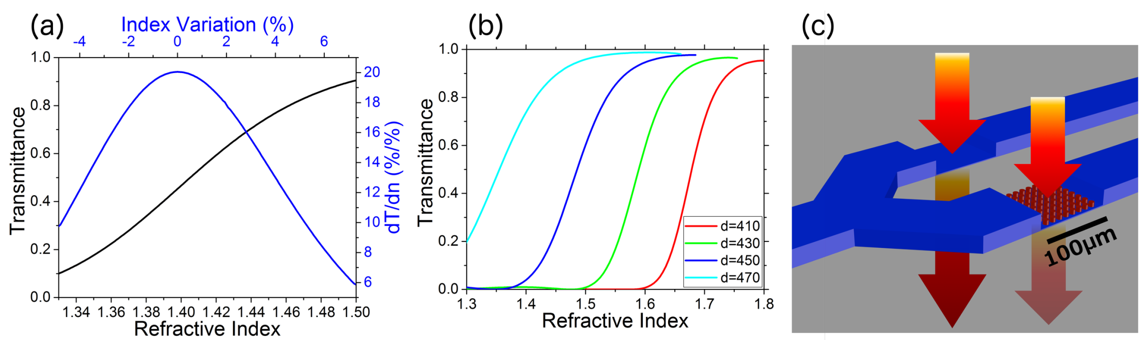

Fig. 1. (a) Transmittance as a function of the refractive index of water-based solution (black line), and the derived sensitivity (blue line). At the most sensitive point, a 1% change in refractive index corresponds to a 20% change in transmittance. (b) Transmittance curves for several metasurfaces with varied nanoantenna diameter. The region of refractive index sensitivity is easily and precisely adjustable. (c) Schematic of the metasurface sensing device. Variation in the refractive index of a fluid flowing through a microfluidic channel is characterized by modulation of light transmitted through the metasurface (right). Changes in absorption of the fluid are accounted for by a simultaneous measurement made in an adjacent channel (left).

4. Conclusions

The high sensitivity of Huygens source metasurfaces, in tandem with their small size, safe and affordable material requirements, and easy fabrication, makes them an ideal platform for sensing applications. We have designed and modeled a spectrometer-free device capable of detecting changes in the refractive index of a fluid smaller than 10^{-7} RIU.

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5. References

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