An Affordable, Customizable, and Highly Sensitive Metasurface-Based Refractive Index Sensor

Adam J. Ollanik, Isaac O. Oguntoye, George Z. Hartfield, and Matthew D. Escarra
Department of Physics and Engineering Physics, Tulane University, New Orleans, LA 70118, USA
Author e-mail address: aollanik@tulane.edu

Abstract: We demonstrate a compact, metasurface-based sensor. Techno-economic analysis predicts a ~\$2,400 device capable of detecting changes in the refractive index of a liquid of ~$2*10^{-8}$; prototype demonstrates 820% change in transmittance per refractive index unit.

OCIS codes: (160.3918) Metamaterials; (160.4670) Optical materials; (280.1415) Biological sensing and sensors

1. Introduction

The refractive index of liquids can be used as an indicator for a wide variety of useful applications including the measurement of solute or alcohol concentration levels or the monitoring of degradation of oils used in industrial processes. While practical and affordable options exist for these measurements, typically in the form of refractometers or attenuation-based fiber systems, sensors with sensitivities greater than 10^{-5} refractive index units (RIU) tend to be prohibitively expensive for most applications. The high cost of high sensitivity sensors can be largely attributed to the use of spectroscopic or spatially-resolved measurements, which typically rely on interferometric or plasmonic resonance effects. We present here a device based on low-loss dielectric metasurfaces that exhibit resonant reflection. Continuously referenced, single-wavelength intensity measurement enables state-of-the-art refractive index sensitivity at greatly reduced cost.

2. Huygens Metasurfaces, and the Single-Wavelength Measurement Principle

Optical Huygens metasurfaces are known to be low-loss systems [1]. High index dielectric disks encapsulated by a low-index medium support both electric and magnetic dipole resonances, with the spectral location of the resonances independently tunable by geometric array parameters. When these resonances are spectrally overlapped, the system transmits normally incident light of the resonant wavelength with high efficiency. When the resonances are spectrally adjacent, interference between the two produces a peak of high reflectance (Fig. 1a) [2].

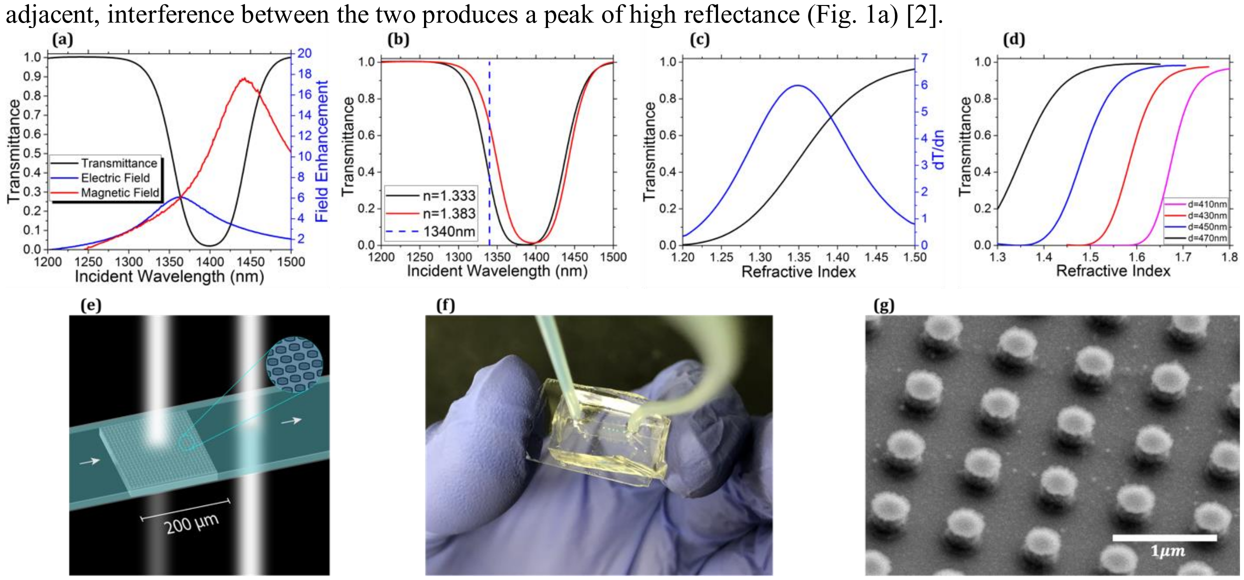

Fig. 1. (a-d) Finite element computational modeling of a metasurface-based sensing device. (a) Transmittance spectrum plotted with electric and magnetic field amplitudes at nanoantenna resonator center, showing spectral locations of dipole resonances. (b) Transmittance spectrum for two values of liquid refractive index, showing shift in reflectance peak. Dashed blue line shows wavelength of single-wavelength measurement. (c) Single wavelength transmittance as a function of liquid refractive index, with derivative plotted in blue. (d) Single wavelength transmittance for four metasurface devices of varied nanoantenna diameter. (e) Schematic of measurement, with metasurface and reference measurement beams depicted. (f) Picture of fabricated microfluidic metasurface-based sensing device. Metasurfaces can be seen as green dots, since they act as a diffractive surface for visible wavelengths. (g) Scanning electron micrograph of a-Si nanoantennas fabricated on a glass substrate.

The resonances, and therefore the reflectance peak, are highly sensitive to the refractive index of the encapsulating material. By encasing a metasurface in a microfluidic channel, a flowing liquid may be used as the encapsulating material (Fig 1f). A change in the refractive index of the encapsulating liquid results in a spectral shift of the reflectance peak (Fig. 1b). This effect may also be used for selective detection of specific proteins [3]. If a single wavelength of light is incident on the metasurface, spectral shift of the reflectance peak translates to transmittance modulation of that wavelength (Fig. 1c). The Huygens metasurface system is highly adaptable, and metasurface array parameters (primarily nanoantenna diameter) may be tuned to allow refractive index sensitivity to various ranges (Fig. 1d). To account for changes in transmissivity or absorptivity of the liquid, a reference measurement is made (Fig. 1e) [2].

3. Experimental Demonstration

Metasurfaces are fabricated by deposition of an a-Si film on glass, followed by patterning of polymer resist by electron beam lithography, deposition of an Al_2O_3 etch mask, reactive ion etching of the silicon film, and removal of the etch mask (Fig. 1g). Microfluidic channels are fabricated through creation of an SU-8 stamp on a Si wafer, followed by curing of PDMS on top of the stamp and subsequent lifting of the PDMS disk from the wafer. The PDMS microchannel chip is attached to the metasurface chip through O_2 plasma bonding, with the channels carefully aligned over metasurfaces. Spectral measurements demonstrate a spectral sensitivity of the reflection peak of 323nm/RIU and a single wavelength response of 8.2 (820%) change in transmittance per RIU (T/RIU) (Fig. 2a). Demonstrations of the single wavelength measurement were performed for saline solution (Fig. 2b).

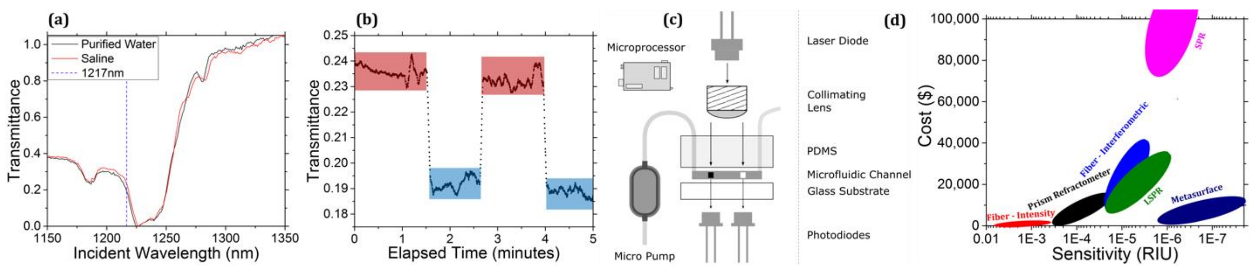

Fig. 2. (a) Experimental measurement of transmittance spectrum for metasurface sensing device with water and saline solutions. (b) Single-wavelength transmittance through metasurface device with water (blue boxes) and saline (red boxes) solution, representing an index difference of 0.0062. (c) Schematic of prototype sensor device. (d) Cost and sensitivity of refractive index measurement for leading sensing technologies. Metasurface-based sensing devices could disrupt current market trends.

3. Techno-Economic Analysis and Prototype Development

The detection limit (or sensitivity) of the device is described by equation (1), where $\frac{\Delta V_{limit}}{V}$ reflects the accuracy of the voltmeter used for the measurement and T is transmittance, evaluated at T=0.8 representing the more-demanding measurement case where absolute optical power is high relative to the change in optical power.

$$\frac{\Delta V_{limit}}{V} = \frac{\Delta P_{limit}}{P} = \frac{S*\Delta n_{limit}}{T} \rightarrow \Delta n_{limit} = \frac{\Delta V_{limit}}{V}\frac{T}{S} \quad (1)$$

For the measured metasurface sensitivity of 8.2 T/RIU, a detection limit of $\Delta n=2*10^{-8}$ should be achievable using affordable, off-the-shelf components. A cost analysis was performed, using conservative estimates of nanofabrication costs to predict a sensor cost of ~$2,400. A prototype of this device is under construction (Fig. 2c). A comparison of the detection limit and cost of this technology and state-of-the-art technologies is shown in Fig. 2d [2].

4. Conclusion

Design, experiment, and analysis of a metasurface-based refractive index sensing device costing ~$2,400 and sensitive to changes on the order of $2*10^{-8}$ is presented. Experimental validation shows sensitivity of 323nm/RIU and a single wavelength response of 8.2 T/RIU. Robust, compact sensor prototyping is underway.

This work is supported in part by the National Science Foundation (DMR-1654765).

5. References

[1] Manuel Decker, *et al., Advanced Optical Materials,* 3, 6 (2015)
[2] Adam Ollanik, *et al., Advanced Materials Technologies (2018)*
[3] Ozlem Yavas, *et al., Nano Letters,* 17, 7 (2017)