Design and Prototyping of a Portable Metasurface-Based Refractive Index Sensor

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Abstract: Demonstration of nanophotonic platform for metasurface-based refractive index sensing. Prototype results indicate that dramatic cost (~$5,000) and scale (e.g. portable, handheld) reductions are attainable in comparison to existing technologies with comparable sensitivity (Δn= 10^{-6}). © 2020 Optical Society of America

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1. Introduction

Refractive index sensing is used widely across many industries to determine concentrations of key solutes in a liquid solution. The most precise sensors cost upwards of $100,000 for a surface plasmon resonance-based spectroscopic device. This technology can be reimagined with the same sensitivity but at a fraction of the cost and size, allowing for the overall resolution of sensing available to smaller businesses in the food industry or medical practices to increase by 2-4 orders of magnitude to a Δn of 10^{-6} to 10^{-8}. We are investigating novel means to reduce >90% of the cost of highly sensitive refractive index measurements by developing an integrated, metasurface-based sensor utilizing single wavelength measurements on a microfluidic, temperature stabilized photonic chip (see Fig. 1b for schematic).

2. Device

2.1 Nanophotonic Design and Fabrication

All-dielectric Huygens metasurfaces are nanoscale antenna arrays designed to utilize both electric and magnetic field resonances to locally impart sudden phase shift and/or amplitude change to impinging light [1]. These nanophotonic structures may be designed to transition from transmissive to opaque device functionality depending on the refractive index of their encapsulant [2]. When considering a single wavelength system, this spectral resonance shift is interpreted as a change in transmittance that can be related to very small refractive index changes via computational modeling (see Fig. 1a). The spectral location of the resonance (in this case, a dip in transmission through the metasurface) is dependent on antenna material (amorphous silicon) and geometry and thus, has been selected by designing the height, diameter, and center to center space of each nanoantenna. The sensor design includes the ability to measure three metasurfaces with varying resonance in order to enhance the detection range and capabilities. Here we demonstrate fabrication of these sensing metasurfaces by electron beam deposition, electron beam lithography and reactive ion etching, as shown in Fig. 2a.

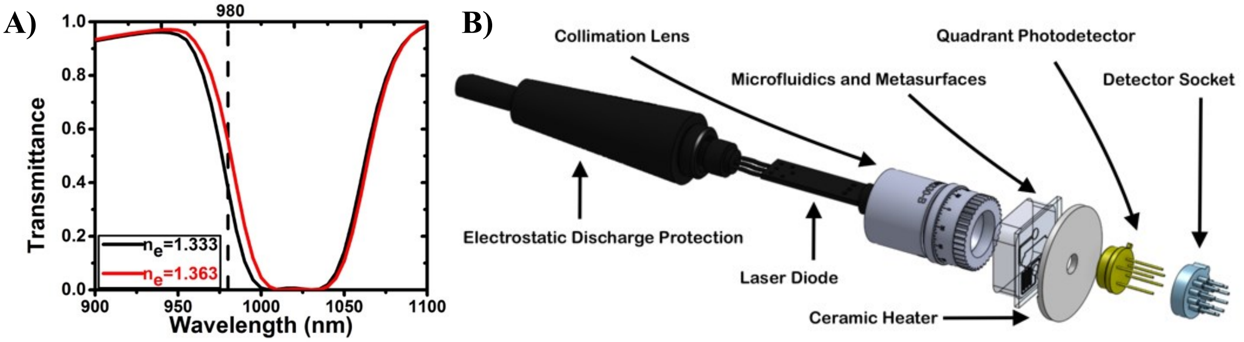

Fig. 1. A) Finite element model of the transmittance spectrum demonstrating nanoantenna resonance shift with changing encapsulant index. B) Computer aided design modeling of sensor architecture showing the microfluidic and optical systems.

2.2 Microfluidic Design and Fabrication

Microfluidic design consists of an inlet tubing connection that leads to a temperature stabilizing channel before passing into a large metasurface channel and then to an outlet tube. For fabrication, an SU-8 stamp was patterned on to a silicon wafer using photolithography. Polydimethylsiloxane (PDMS) is then cast on the wafer resulting in 100 μm

deep channels. In parallel to this process, a chromium reflection mask is fabricated around the metasurfaces using photolithography and electron beam evaporation to block all other light from reaching the photodetector, decreasing the perceived transmittance change. Oxygen plasma is used to permanently bond PDMS channels over the metasurface and reflection mask. Water aided bonding is employed to increase alignment time and precision of the microfluidic bond.

2.3 Sensor Prototyping

All-dielectric silicon-based Huygens metasurfaces were designed to resonate in the near-infrared, allowing us to use an off-the-shelf, 980 nm source for only $28. A four-quadrant photodetector is used to isolate the signal passing through three metasurfaces and one blank reference channel. Considerations for housing design include optical alignment and vibration stabilization. The laser and photodiode are fixed in opposing holders mounted on cage rods, preventing motion relative to one another. A sample holder is designed to allow for the metasurfaces to be aligned to the optical system. The components are then encased in a sleeve preventing interference from ambient light. The usage of expensive and bulky lab equipment has been reduced by directly powering the laser and control systems with wall plug-in AC-DC adaptors. An $85 PID controller is used for temperature control wired to a resistive ceramic heater mounted in the photodetector housing. A four-channel oscilloscope for voltage measurements can be replaced with an off-the-shelf Delphin Datalogger that allows for low noise voltage and temperature monitoring for ~$2,000.

3. Experimental Results

Testing requires optical transmission measurements taken through two fluids of differing refractive index. In order to determine an absolute concentration of a solute in water, pure deionized water must be used as the reference solution. One fluid is injected into the microfluidic channel and temperature and pressure stabilized. A photodiode voltage measurement is recorded and then a pocket of air is injected, followed by the second fluid. Light passing through metasurfaces is referenced with an empty (no metasurface) channel to obtain relative transmittance. Comparing measured results (Fig. 2b, measured sensitivity of 6.04 T/RIU) to COMSOL finite element modeling (sensitivity of 5.8 T/RIU) shows a good fit for a sample of .15M saline with a Δn of .0019 RIU relative to deionized water. Currently, the prototype with externals included costs ~$5,000 and fits inside a small shoebox (see Fig. 2c).

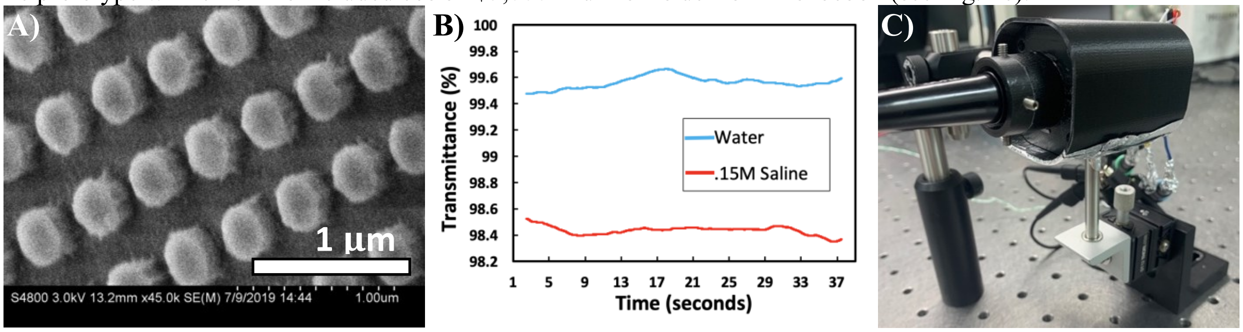

Fig. 2. A) Scanning electron microscope image of silicon nanoantenna array on glass substrate. B) Experimental measurement on water and .15M saline depicting a transmittance change of .01148 corresponding to a Δn of .00198 RIU. This gives an experimental sensitivity of 6.042 T RIU^{-1}. Data plotted with rolling average over 5 second window with very low noise, allowing for measurement of much smaller Δn in upcoming experiments. C) Experimental sensor prototype set up for testing.

4. Conclusions

An ultra-high sensitivity metasurface based sensor has been prototyped, showing model verification measurements have been repeatably achieved and device scalability has been dramatically improved to eliminate the requirement of costly and cumbersome lab equipment. The addition of the low noise Delphin Datalogger is anticipated to allow upcoming measurements with $\Delta n=10^{-6}$, showing that leading sensitivity may be attained at a fraction of the cost of existing technologies. Work is in progress toward measurement of lower Δn fluids, system integration, and testing with medically relevant fluids.

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5. References

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