☐ **Poster Presentation** ☐ **Oral Presentation** ☐ **Student presentation**

EFFECTIVE MEDIUM METASURFACES USING NANOIMPRINTING OF REFRACTIVE INDEX: DESIGN, PERFORMANCE, AND PREDICTIVE TOLERANCE ANALYSIS

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SUMMARY

We introduce a design method that leverages the nanoimprinting of refractive index (NIRI) to compress a mesoporous silicon (pSi) film to impart a transverse refractive index profile capable of creating arbitrary phase functions. Our design method method is used to design a Fresnel lens which is examined using finite difference time domain (FDTD) analysis. Additionally, possible fabrication errors are examined both individually and holistically using a Monte-Carlo (MC) analysis to assess the effects of fabrication errors on lens efficiency and the results are used to train a neural network (NN) to predict the effects of fabrication errors on process yield.

1. INTRODUCTION

Metasurfaces are 2D artificial structures with engineered properties that have enabled unprecedented control of the degrees of freedom of light in the visible and near infrared regimes (NIR)[1]. While most of the early research into metasurfaces centered around the use of arrays of resonant scatterers, effective medium theory (EMT) provides an alternative method for the design of metasurfaces. Effective medium metasurfaces (EMMs) can be realized by patterning subwavelength dielectric structures and have been realized using a variety of forms ranging from pillars and fins to recesses and holes[2,3]. However, the subwavelength patterning required for visible and NIR wavelengths require the use of direct writing fabrication methods such as EBL, limiting throughput and increasing the cost of the fabricated devices.

Our group has recently shown that direct imprinting of a pSi film can be utilized to directly pattern a spatially variant transverse refractive index profile such that $n(x,y) = n_0 + \Delta n(x,y)$ using the NIRI process as illustrated in Figure 1a[4]. However, before NIRI can be applied to general metaoptic fabrication several factors must still be addressed, including (1) establishing how to design the required stamp, and (2) establishing the theoretical performance as a function of design and fabrication parameters. Here, we demonstrate a method for designing a NIRI-compatible transmissive metalens with full 2π phase control based on experimentally achievable refractive index contrast. We apply inverse design to map the desired meta-optic phase response $\varphi(x,y)$ to both the required EMM refractive index distribution $n(x,y)$ and to the required stamp height profile $s(x,y)$, allowing automated design of arbitrary optics. Additionally, we simulate the performance of one such device using FDTD. Lastly, to investigate process tolerance and real-world manufacturability, we perform a MC simulation and develop a predictive NN model that factors in the primary sources of fabrication variation.

2. EXPERIMENTAL RESULTS AND DISCUSSIONS

To design a stamp to impart an arbitrary phase function into a pSi film, we map three key relationships: (1) effective refractive index n vs. transmitted phase ϕ, (2) effective refractive index vs. film compression, and (3) film compression vs. stamp height. Transmitted phase is calculated using the transfer matrix method (TMM) using an operating wavelength λ_0, a polished final film thickness d, an air top cladding and a substrate refractive index n_{sub}. The post -compression film height h required to achieve $\Delta\phi = 2\pi$ is determined by TMM and corresponds to a maximum film compression $C_{max} = (h_0 - h_{min})/h_0$ and a maximum stamp height $s_{max} = h_0 - h_{min}$. To ensure manufacturability, it is crucial that the maximum compression is less than the initial void fraction, $C_{max} < P_0$.

To design the stamp, the pSi film compression that achieves $\Delta\phi = 2\pi$ is discretized into a depth vector **d** with i discrete values such that $0 \le d_i \le d_0$. The compression required to produce each value of **d** is used to create a refractive index vector **n** using the three-component Bruggeman model and TMM is used to generate a phase vector **p**. The desired optic is represented as a phase function $\phi(x,y)$. Each point of the $\phi(x,y)$ is iterated through using a nearest-neighbor approach to map the phase values in $\phi(x, y)$ to those in **p**. The resultant map is then matched to its corresponding value in **n** and the associated film height required to create $n(x,y)$.

Using the method described above, a Fresnel lens of radius 100μm and focal length f = 125μm was designed for an operating wavelength of $\lambda_0 = 532$nm. Lens performance is assessed using FDTD simulation to determine the focusing efficiency η, focal distance f_{actual}, and full width half max (FWHM), which is determined to be 0.952, 125.14μm and 0.98μm, respectively. These results are used as a baseline to examine the effects of three possible manufacturing defects: incorrect post-polish height, incorrect imprinting depth, and incorrect stamp height in a range extending from $0.8\kappa \le \kappa \le 1.2\kappa$, where κ is the ideal value for the lens characteristic being examined. A MC simulation of N = 5000 lenses with all three defects individually randomized in the range described is undertaken and the lenses divided into pass/fail categories, where a passing lens has $\eta \geq 0.9$ with a FWHM ≤ 1µm. Correlation between the errors in the lenses are determined, shedding light on the combined effects of the errors on lens performance. Passing lenses demonstrate a mean η of 0.94 and σ_{eta} = 0.016, a mean f_{actual} of 125.13µm with σ_{focal} = 71.50nm, and a mean FWHM of 99.11nm with σ_{fwhm} = 9.94nm.

The results of the MC provide useful data relating the various errors simulated to overall lens performance which is used to train a NN to predict η for error values not examined during the MC. In addition to predicting η for a given set of input values, a similar architecture can be used to determine fabrication constraints necessary to offset known errors; for example, a stamp height error determined by profilometry prior to lens fabrication may be offset by adjusting the post-polish planar optic thickness.

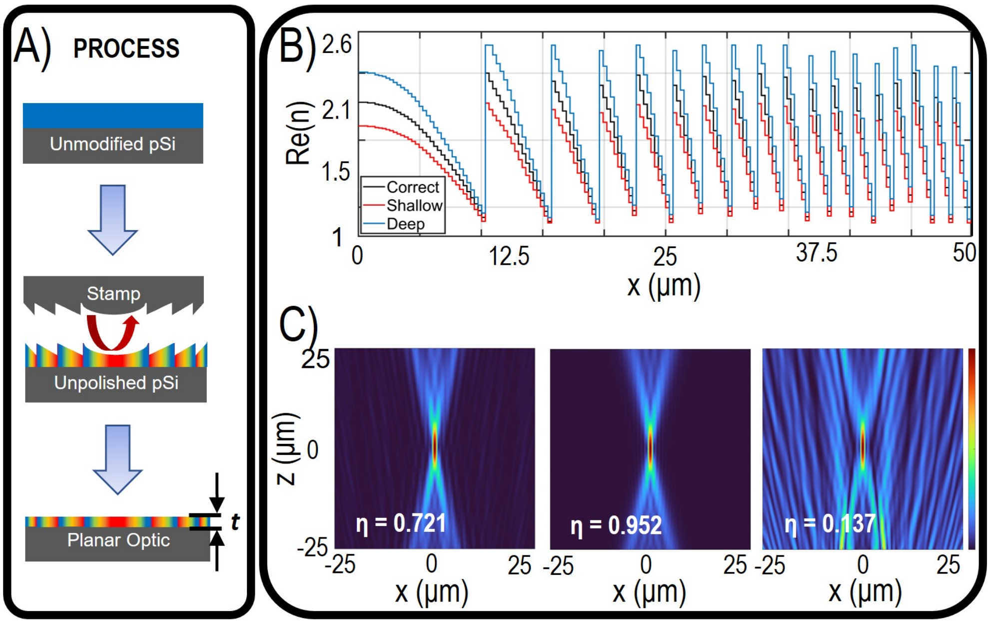

Figure1: (a) The NIRI process flow, in which an unpolished film of pSi on a Si substrate is first stamped with a pattern to impart a transverse refractive index profile, then polished to a specific thickness to produce a planar effective medium metasurface. (b) Calculated real refractive index for a 1D radial slice of an unannealed version of the proposed lens when a properly fabricated stamp has been imprinted to a correct depth (black), too shallowly (red) and too deeply (blue) into the pSi layer. (c) Normalized electric field intensity in a 25µm² box about the focal points of the proposed NIRI lenses. From left to right, a shallow imprint, a correct imprint, and a deep imprint are demonstrated. The focusing efficiency η is given in the bottom right corner of each image.

3. CONCLUSIONS

We successfully demonstrated a method for the design of planar EMM operating in the visible regime. We demonstrate that NIRI is capable of imparting a 2π phase range and a method for creating arbitrary stamp designs is introduced. An ideal lens is examined using FDTD and the effects of fabrication errors are explored to gain insight into the real-world manufacturability of a NIRI EMM. Finally, the MC results are used to create a NN that can predict the focusing efficiency of a lens given a series of fabrication errors, suggesting that the NIRI method represents an alternative, low-overhead, easily parallelized alternative to serial optics fabrication methods such as EBL.

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