Fabrication of Near-Unity Index Hollow-Core Nanopillar Arrays with Tunable Optical Anisotropy

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Low refractive index materials are essential in nanophotonic applications where optical performance is determined by the refractive index contrast between adjacent material, such as in distributed Bragg reflectors (DBRs) [1]. Accordingly, significant effort has focused on developing scalable, mechanically stable coatings and artificial media with refractive indices approaching unity [2]. Our prior work presented at EIPBN 2025 demonstrated highly ordered, thin-shell nanolattice structures exhibiting low and tunable refractive indices through 3D nanolithography coupled with precise control of shell thickness [3]. Nevertheless, further optimization of the fabrication process is needed to mitigate defect formation, reduce optical scattering, and improve optical performance.

In this study, we investigate the optical response of periodic thin-shell nanopillar arrays fabricated by interference lithography. The goal is to enable cylindrical elements consisting of thin shell and hollow core that has high porosity, low refractive index, and high optical anisotropy. Square-lattice photoresist templates were fabricated by Lloyd's mirror interference lithography (IL) using a 325 nm laser on Si substrate coated with an antireflection layer (**Fig. 1a**). A conformal Al_2O_3 was then deposited by atomic layer deposition (ALD), followed by annealing at 550° for 4 hr to remove the polymer template and form hollow thin-shell nanopillars. The resulting hollow-core structures were examined by scanning electron microscopy (SEM), as shown in **Figure 1(b)**.

The effective optical constants of the arrays were characterized by variable-angle spectroscopic ellipsometry (VASE). The measured Ψ and Δ spectra were fit simultaneously using a uniaxial Cauchy dispersion model with a Si substrate layer (**Fig. 2**). The extracted refractive index dispersions exhibit dielectric behavior and near-unity index values, while the observed anisotropy is attributed to the pillar geometry. The dependence of the ordinary (n_o) and extraordinary (n_e) refractive indices on duty cycle and period was systematically evaluated (**Fig. 3**) and compared with finite difference time domain (FDTD) simulations of idealized structures. Both n_o and n_e increase with duty cycle, and the experimentally extracted indices show good agreement with the FDTD results, supporting the uniformity and reproducibility of the IL-based fabrication process.

We have demonstrated a scalable route to highly uniform thin-shell nanopillar arrays with ultralow effective refractive indices and geometry-induced optical anisotropy. Future work will establish a predictable model that relates geometrical parameters to the effective refractive indices and birefringence. We will present the detailed fabrication process, optical modeling, and experimental characterization.

References:

[1] Miguel Anaya, Hernan Miguez and et al. *J. Mater. Chem. C, 2016, 4, 4532-4537*
[2] Jinwoo Song, Heung Soo Kim and et al. *Journal of Materials Research and Technology, 2025, Vol. 39, 2926-2938*
[3] Vijay Anirudh Premnath, Kwon Sang Lee, and Chih-Hao Chang. *Optics Express, 2025, Vol. 33, 15304*

Figures:

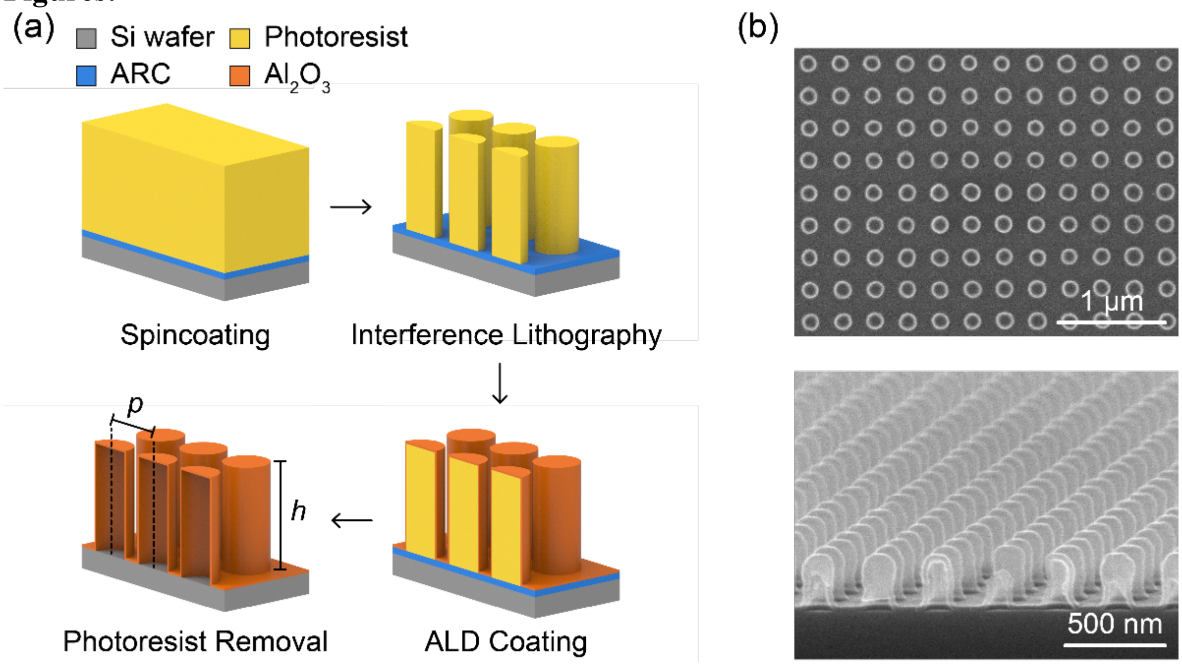

Figure 1. (a) A schematic of the fabrication for thin-shell nanopillar arrays, with p indicating the period and h the structure height. (b) SEM images of a periodic hollow nanopillar array. The period is 300 nm and the shell thickness is 20 nm.

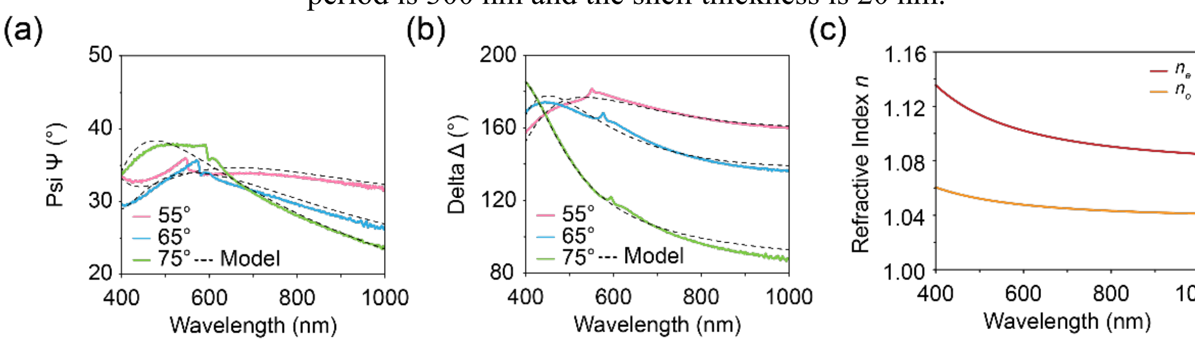

Figure 2. (a, b) Experimental ellipsometric dispersion spectra (Ψ and Δ) and fitted Cauchy model curves obtained at three incidence angles. (c) The corresponding refractive index dispersions, showing the ordinary (n_o) and extraordinary (n_e) indices.

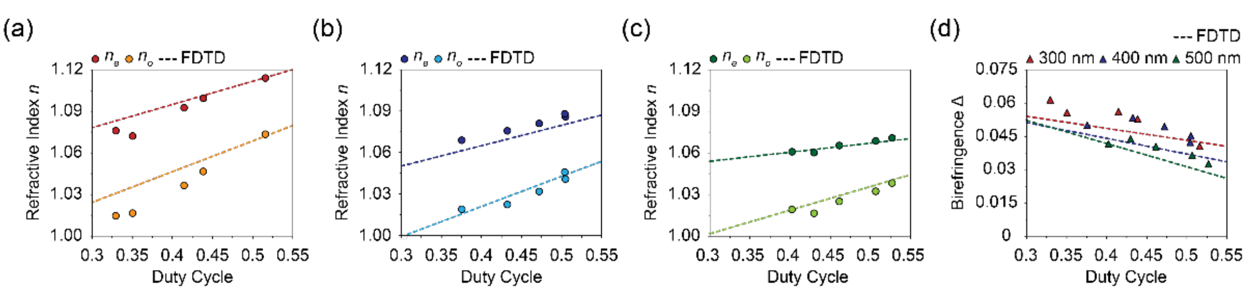

Figure 3. Ordinary (n_o) and extraordinary (n_e) refractive indices of thin-shell nanopillar arrays as a function of duty cycle for three lattice periods: (a) 300 nm, (b) 400 nm, and (c) 500 nm. (d) The resulting out-of-plane birefringence (Δ), plotted versus duty cycle for each period.