

Fabrication of Waveguides and Gradient Index Flat Optics by Nanoimprinting Refractive Index

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Abstract: We report the fabrication of gradient index flat optics and waveguides using the ‘nanoimprinting refractive index’ (NIRI) technique applied to mesoporous silicon substrates. Optical wavefront shaping and waveguiding are demonstrated in the visible and near-infrared respectively. © 2022 The Author(s)

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Modern integrated-optics and flat-optics are typically fabricated through binary processes such as lithography, etching, and/or deposition. However, conventional manufacturing techniques also impose limitations on design flexibility, processing cost, processing time, and optical performance [1]. Overcoming these challenges is crucial to fostering the wide adoption of cost-effective optical components and enabling novel optical structures or flat-optic design regimes which may otherwise be difficult or impossible to realize through conventional techniques [2,3].

Recently, we developed a novel fabrication process known as ‘nanoimprinting refractive index’ (NIRI) [4]. When applied to high porosity mesoporous silicon (pSi) substrates, direct nanoimprinting locally densifies the thin film and permanently reconfigures the local porosity and the refractive index of the subwavelength effective medium as illustrated in Fig 1. In principle this process can be used to pattern the refractive index, $n(x,y)$, on the surface-of-a-chip with a maximum index contrast near $\Delta n \approx 1$ RIU [4]. However, early demonstrations of the NIRI process have so far been limited to refractive index patterning with blank unpatterned stamps or 1D microscale gratings, with optical functionalities not yet demonstrated.

In this work we utilized the NIRI process to separately fabricate: (1) flat gradient index micro-lens arrays, and (2) optical waveguides. The fabrication process for both types of components begins with the electrochemical etching of (100) p-type Si chips in 15% ethanoic hydrofluoric acid. In the initial etching step, a current of 140 mA is applied over an exposed Si area of 2.54 cm² for 34 s. This produces layers of mesoporous silicon ~1.1 μm thick with ~75% porosity. To pattern the on-chip refractive index distribution $n(x,y)$, the porous layer is imprinted with a pre-fabricated silicon or fused silica stamps using a hydraulic press at applied pressures ranging from 50 N/mm² to 160 N/mm². An example stamp for realizing gradient index micro lens arrays is depicted in Fig. 2(a).

After imprinting, the micro-lens samples are oxidized in ambient air for 15 minutes at 500° C to strengthen the mesoporous structure prior surface planarization. Characterization of the interference fringe profiles for red, blue, and green laser wavelengths, Fig. 2(b), were used to extract the gradient index profile. The micro-lens samples are then polished on a vibratory polisher to the desired final film thickness,

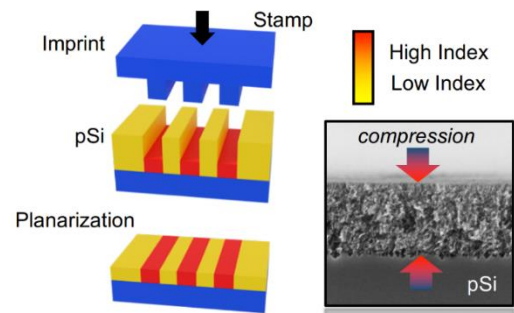


Fig. 1 - Illustration of the nanoimprinting refractive index (NIRI) process. Local compression of a subwavelength effective medium provides tunable refractive index over the range $n = 1.4$ to 2.4 RIU [4].

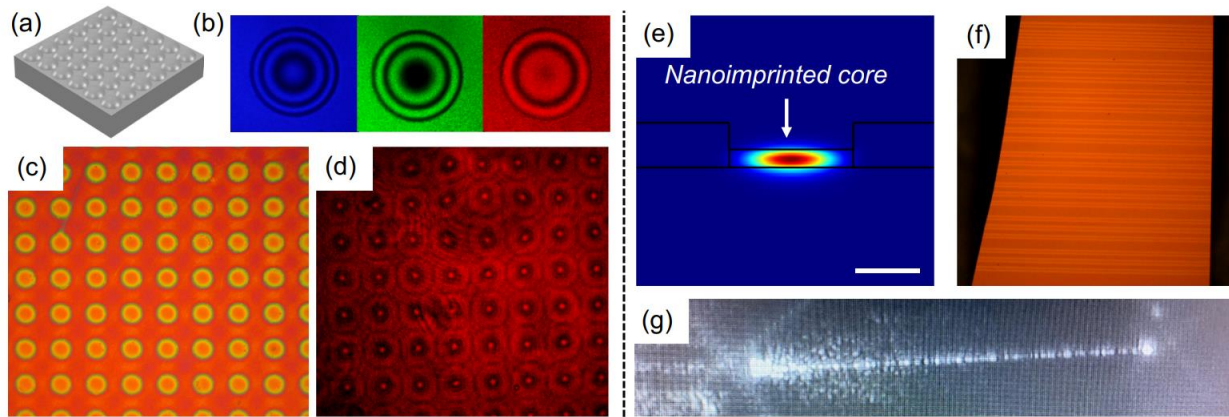


Fig. 2 - (a) Cartoon of a 3D stamp, (b) experimental fringe profiles of patterned gradient index lenses prior to planarization, (c) gradient index micro-lens array after planarization and prior to liftoff, (d) wavefront shaping/focusing at $\lambda_0 = 635$ nm. (e) Mode simulation (scale bar, 1 μm), (f) NIRI patterned waveguide chip after cleaving, (g) top view of an edge coupled ~ 1 mm long waveguide guiding light near $\lambda_0 = 1600$ nm.

typically <400 nm thick. After the micro-lens samples are polished, they are placed back into the electrochemical etch cell where a ~ 6 μm thick mechanical support layer of porous silicon is etched followed by a high current pulse to detach the film from the Si substrate. The imprinted micro-lens arrays are then transferred from the silicon substrate onto an optically transparent substrate for testing. Fig. 2(d) reveals wavefront shaping/focusing as observed upon illumination with a collimated 635 nm laser source.

To support a guided mode after imprinting the waveguide core, Fig. 2(e), the NIRI patterned waveguide samples were placed back in the HF etch cell to etch a ~ 6 μm thick low index cladding. The waveguide samples were thermally oxidized, as above, and then cleaved into roughly 1 mm wide samples for edge coupled waveguide characterization as depicted in Fig. 2(f). Waveguide transmission is then measured with a tunable semiconductor laser ($1560 \text{ nm} < \lambda < 1680 \text{ nm}$). Side view and top view, e.g. Fig. 2(g), infrared imaging was also performed to optimize alignment and visually confirm waveguiding.

In summary, we successfully demonstrated two different types of optical components by directly nanoimprinting porous silicon to modify the refractive index profile $n(x,y)$, referred to as the NIRI process. The scalability of this technique allows for the fabrication of a wide variety of chip scale flat-optic and integrated-optic devices, such as those demonstrated here, on a large scale at low-cost. This process further opens the door to novel flat-optic designs based on non-pixelated and truly flat gradient index surfaces.

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