3D printing technique forms microlenses with adjustable refractive indices

For centuries, scientists have explored how light can be focused and manipulated by controlling the geometries and refractive indices of lenses. Paul V. Braun, Lynford L. Goddard, and colleagues from the University of Illinois at Urbana-Champaign, Mark L. Brongersma at Stanford University, and Kimani C. Toussaint Jr., now at Brown University, have reimagined classical optics at a micron-scale by creating lenses with refractive indices that are tunable in three dimensions. Their new fabrication technique, coined subsurface controllable refractive index via beam exposure (SCRIBE), uses direct laser writing (DLW) inside a porous scaffold, where the refractive index of a polymerized photoresist is spatially tuned by controlling the laser exposure during printing.

The method was used to produce the world's smallest spherical Luneburg lens—a special lens with a unique radial refractive-index profile—that can operate at visible wavelengths. The group demonstrated submicron accuracy over

control of optical properties and geometry. Not only is it a small structure (15 μm diameter), but it also focuses light in a way that cannot be achieved with single-index optical elements. Furthermore, “by having control over the internal refractive index and the shape of the lens during fabrication, we have two independent ways to bend light inside a single lens,” said Goddard in a news release.

As reported in a recent issue of *Light: Science & Applications* (<https://doi.org/10.1038/s41377-020-00431-3>), the novel lithography technique achieved control over lens geometry and refractive index in three-dimensional (3D) space, something previously unattainable by normal DLW. Moreover, the technique's control over refractive index is based on the percentage of the material's pores that are filled with polymer and the spacing between voxels in the material, which are units of tridimensional space. Both porous silicon (PSi) and silicon dioxide (PSiO₂) films were used as porous materials inside which the lenses were printed.

The optics demonstrated by the researchers include the Luneburg lens, achromatic doublets (limits chromatic and spherical aberrations),

3D waveguides, and photonic nano-jet generators. It should be noted that Luneburg lenses have previously only operated at longer wavelengths such as infrared and radio due to the lower resolutions of other fabrication techniques. SCRIBE affords submicron refractive-index resolution and could therefore be used to create Luneburg lenses that can focus visible light. The waveguides created are unique as they develop in three dimensions; light going through the waveguide makes a 90° turn, goes into a coupled resonator, and does a second 90° turn. These waveguides are lossier than commercial waveguides but have the advantage of routing light in 3D space.

Christian Ocier, from the Braun research group (now at Apple, Inc.), when asked about future applications for this technique, says that “stacking diffractive optical elements, maybe with a spacer between each layer, could lead to new optical applications.” Even though the scale for the technique is in the micrometer range, multiple applications can be sought. “Routing light through three-dimensional space, achromats, diffractives, vertical integration, bio-imaging—there are so many possibilities,” says Corey Richards, also from the group. The range of applications suitable for SCRIBE-generated optics may expand as challenges associated with DLW are improved. For example, improving the stitching errors between writing fields could extend the size of printed optics from a few hundred microns to many millimeters.

Refractive index, dispersion, and fluorescence are all optical properties that are tunable with SCRIBE, giving way to possibilities and applications not possible before and opening a way for scientists to continue investigating light–matter interactions.

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Three-dimensional multiphoton image of a subsurface U-shaped waveguide printed in porous SiO₂ coupled to a microring resonator, with coupling ports displaced by 250 μm . Credit: *Light: Science & Applications*.