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Implosion Fabrication as a Platform for Three-Dimensional Nanophotonics

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Abstract: We investigate Implosion Fabrication, a technique which prints arbitrary 3D nanostructures, as a new platform for nanophotonics. We show that optical properties of printed materials are tunable by characterizing the reflectivity of printed silver.
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Three-dimensional nanophotonic platforms are essential to unlock a plethora of new opportunities. While well-established nanofabrication technologies have enabled the field of nanophotonics to expand quickly, traditional lithography methods are restricted to patterning structures in a plane, i.e. in two-dimensions. This imposes significant limitations on the design space of possible devices. In recent years, two-photon lithography (TPL) has become a popular technique to print three-dimensional (3D) forms in a polymer resin. A variety of 3D optical structures have been demonstrated in polymers [1], metals [2] and high dielectric materials like silicon [3]. However, TPL methods do not allow for self-supported nanostructures or arbitrary 3D shapes like metallic wires arranged in a discontinuous pattern, i.e. plasmonic gratings. Also, the fabrication of optical devices operating in the visible range using these methods remains quite challenging. A recent development which addresses this issue is the technique of Implosion Fabrication (ImpFab) [4], which can be used to print 3D structures inside a hydrogel which shrinks 10-fold when dehyrdrated.

In this work, we investigate ImpFab as a platform for creating high-resolution optical structures with feature sizes compatible with visible range. We show that fabrication parameters influence the density of the deposited material, which in turn controls the material's effective refractive index. We also discuss how this technology is ideally suited for new plasmonic devices, fabricating a plasmonic grating as an example. Our work lays the foundation for a versatile platform for creating a new class of multi-functional optical heterostrutures which have so far remained unrealizable.

The fabrication methodology of ImpFab is depicted in Fig.1(a). A hydrogel is cast using a solution of sodium acrylate, acrylamide and bisacrylamide, which is expanded using water. The gel is then washed with a functionalized cyanine dye. Dye molecules are attached to the gel's backbone through illumination by a commercial two-photon microscope, creating a three-dimensional pattern within the hydrogel. The gel is then thoroughly washed with water to remove the dye that has not been bound to the gel backbone. Through a series of conjugation steps, gold nanoparticles are bound to the gel's patterned regions. These gold particles are used as seeds to grow larger

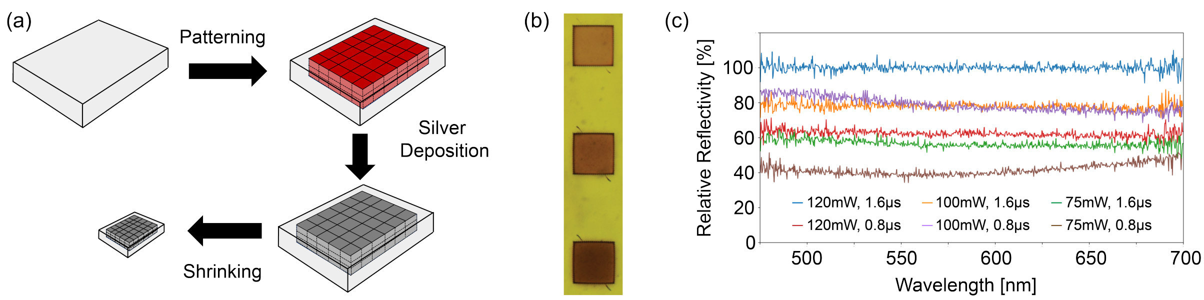

Fig. 1. (a) Sketch of Implosion Fabrication process. (b) Transmission microscope image of fabricated silver patches ($50\,\mu m \times 50\,\mu m \times 5\,\mu m$). (c) Measured relative reflectivity of silver patches.

silver nanoparticles using a mixture of silver ions and a reducer. The gel is then dehydrated using salt solutions which shrinks the gel by a factor of 10, while maintaining the aspect ratio of the patterned structure, resulting in a high resolution three-dimensional silver nanostructures.

The ability to achieve high resolution with low disorder makes the platform uniquely well-suited for creating optical nanostructures. The technology's strength is that one can write 3D patterns using standard TPL systems with low resolutions and achieve high-resolution patterns after shrinking. Through this method, gratings or photonic crystal cavities become possible throughout the visible spectrum. Moreover, the fabrication technique may even enable the fabrication of 3D optical structures that can operate in the ultraviolet range, which have so far been difficult to achieve.

In order to establish ImpFab as a platform for optical devices, we have investigated how the optical properties of silver nanostructures depend on fabrication parameters. We patterned and deposited square patches of silver with 5 µm thickness, varying patterning laser power between 75 mW and 120 mW, and dwell time per pixel between 0.8 µs and 1.6 µs. Figure 1(b) shows a transmission microscope image of silver patches patterned with different light intensities. The image shows that the patterning parameters influence the silver density. We confirm this by measuring the relative reflectivity of silver patches fabricated with a variation of printing conditions using a reflective microscope setup, see Fig. 1(c). All reflectivities are plotted relative to the silver patch with the highest absolute reflectivity (blue sample). The absolute reflectivity of the blue sample was measured to be $\sim 5\%$.

Interestingly, silver's relative reflectivity measurements indicate that we can control its effective index by varying fabrication parameters. This is especially interesting when considering the deposition of high-index dielectric nanoparticles, i.e. Silicon, which opens the possibility to create structures with an index that is a function of position. Such a capability is essential for realizing devices such as planar lenses with gradient index, new photonic crystals, and guiding structures engineered with new degrees of freedom for mode indices.

As an application of this technique, we have used this ImpFab platform to fabricate plasmonic gratings. We have fabricated gratings with groove sizes between 150 nm and 800 nm. Figure 2 shows images of a silver grating with a groove size of 600 nm taken with a microscope . The image shows the fidelity of the patterned grating geometry is maintained through silver deposition and shrinking of the hydrogel. Such a structure may display interesting plasmonic properties that vary with silver concentration and can be tuned in fabrication. In the future, reflection and transmission measurements of these optical gratings will enable us to complete a more detailed study of the optical properties of the deposited silver (i.e. permittivity and absorption as a function of frequency).

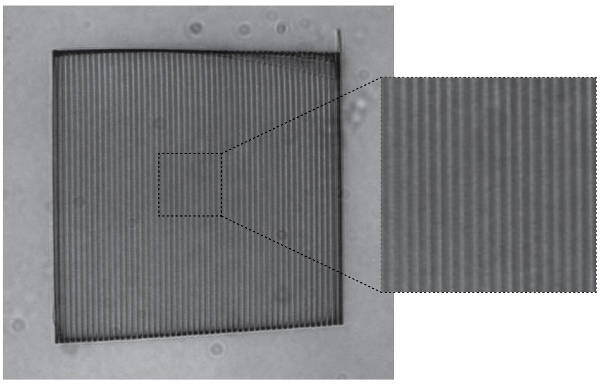

Fig. 2. Microscope image of a 3D silver grating with groove spacing of 600 nm.

In summary, we report on the optical properties of silver structures fabricated with Implosion Fabrication technology and discuss promising opportunities to control the deposited materials' effective refractive index by varying fabrication conditions. Broadly, we anticipate that ImpFab will allow for the realization of a wide variety of 3D multi-material and multi-function optical devices.

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