3D optical metamaterial manufacturing using two-photon holographic interference lithography

Dr. Calum Williams

Centre for Metamaterials Research and Innovation, University of Exeter, EX4 4QL, United Kingdom

Metamaterials are artificially structured materials with properties beyond those found in nature.[1] These properties (electromagnetic, acoustic or mechanical) arise due to engineered sub-wavelength elements. Large-area manufacturing of metamaterials is challenging. The complex nature of metamaterials presents demanding process requirements such as: accurate sub-wavelength geometries which are heterogeneous and sub-wavelength, multi-material, large-area and in produced in rapid timeframes. A plethora of lithographic and printing technologies exist (**Fig 1,** *left*), yet no existing approach provides an all-encompassing solution.[2] For example, there are often significant tradeoffs: ultrahigh resolution (<10 nm) direct-write patterning is often exorbitantly expensive and low throughput (i.e. e-beam lithography); or, high throughput, low cost and high resolution patterning is often pattern inflexible (i.e. roll-to-roll nanoimprint lithography) such that only one design is imparted.

Two photon polymerisation lithography (TPL) is an attractive technique used to accurately *direct-write* 3D structures in polymers through the intrinsic nonlinearity of multiphoton absorption—near-infrared femtosecond pulses trigger solidification confined to only the focal volume (voxel). In this way, it is often considered to be a *3D printer* on the nano-and-micro scale.[3] Unfortunately, it's low throughput ('one voxel at a time'), thereby limiting its use to low volume manufacturing. In contrast, *holographic interference lithography* (HIL) can create periodic (long range order) over large areas through the interference of two or more wavefronts. The photoresist is exposed in the *3D volumes* of constructive interference over large areas, however the patterning can be inflexible.[4]

In this project, we will combine the advantages of TPL and HIL to develop two-photon holographic interference lithography (TP-HIL) for large area manufacturing of 3D metamaterials. We will exploit multi-beam interference lithography—with one or more wavefronts controllable through a high resolution spatial light modulator—and two-photon absorption with a tailored photoresist (**Fig.1,** *right*). This will look to increase throughput (parallelisation) while maintaining high resolution pattern complexity. Further, we will investigate novel multi-material polymers /resists, for both resolution enhancement and non-polymeric final structures, for example: metal-nanostructure-loaded polymeric structures for two-photon initiated metal salt reduction, which has been shown to produce 3D metallic nanostructures. The envisaged system will have high resolution (<100 nm) direct-write 3D manufacturing capability but at the throughput comparable to parallelized lithographic systems.

The research spans fundamental optical physics, materials science, through to applications, and the student will develop a diverse skillset during the PhD project, including: computational optics, electromagnetic simulation (incl. *Lumerical FDTD* and *COMSOL*), nanofabrication within a state-of-the-art cleanroom, systems construction, electro-optic systems characterisation, and advanced data analysis.

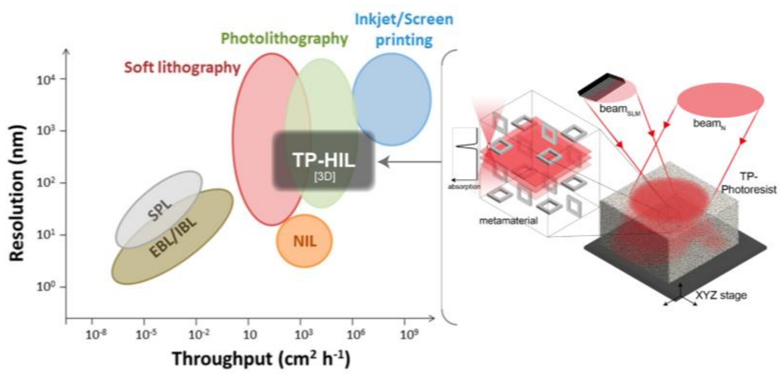

Fig 1. *Feature resolution versus fabrication throughput showing the location of various lithographic and printing processes, adapted from [2], with added concept of TP-HIL and envisaged performance metrics.*

References

[1] Kadic, M. et al. Nat Rev Phys 1, 198–210 (2019)
[2] Fruncillo, S., et al.,ACS Sensors. 6 (6), 2002-2024 (2021)
[3] Zhou, X. et al., AIP Advances 5, 030701 (2015)
[4] Lu, C. and Lipson, R. Laser & Photon. Rev., 4: 568-580 (2010)