Two-photon holographic interference lithography (TP-HIL) for large-area manufacturing of 3D metamaterials

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Metamaterials are artificially structured materials with properties beyond those found in nature. These properties (electromagnetic, acoustic or mechanical) arise due to engineered arrays of elements smaller than the wavelength of interest rather than from the fundamental material. Metamaterials have enormous potential across diverse application areas including antennas for telecommunications, miniaturized optical components, cloaking for defence and energy harvesting [1].

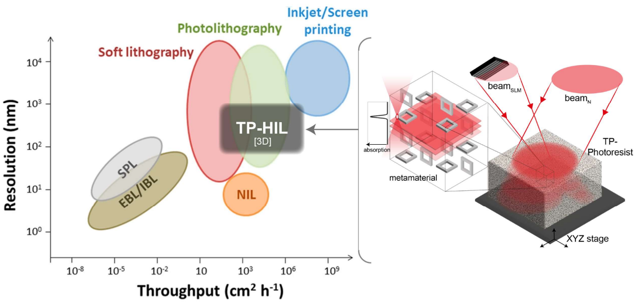

Fig 1. *Feature resolution versus fabrication throughput showing the relative location of various lithographic and printing processes, adapted from [2], with added concept of TP-HIL and envisaged performance metrics.*

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 [2](**Fig 1**), yet no existing approach provides an all-encompassing solution. 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—often variations of hole or line arrays [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. Our system will exploit multi-beam interference lithography—with one or more wavefronts controllable through a high resolution spatial light modulator (SLM)—and two-photon absorption with a tailored photoresist (**Fig 1**). 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.

Student training: The Department of Physics at Exeter has extensive expertise across optical physics and metamaterials, along with providing access to world-class research facilities—including state-of-the-art nanofabrication cleanrooms, high performance electromagnetic simulation software, and laboratories for electro-optical characterization. Dr. C. Williams (Supervisor) develops novel imaging and sensing technologies based on engineering nanoscale light-matter interactions. The student will develop a diverse skillset, including advanced experimental techniques such as nanofabrication processing, optical systems building and electro-optical characterisation, as well as programming skills in electromagnetic modelling, machine learning and lab systems automation. The student will be expected to spend 1 month per annum at the sponsor for knowledge transfer.

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)