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# Terahertz Fourier Ptychography for Complex Media Imaging

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**Abstract**—Ptychography is a novel approach that provides the spatial sampling of objects with a resolution that exceeds the diffraction limit. We present our studies to explore the potential of complexity-driven imaging solutions in terahertz frequency regime. Our strategy involves probing media by using a sequence of tilted wavefronts and recording diffraction-limited speckle patterns with a THz imager that has a limited field-of-view. By formulating a phase retrieval optimization problem and utilizing beam propagation methods, we show successful recovery of the spatial variations in the refractive index profile in the complex media.

Keywords—terahertz wavefront shaping, Fourier ptychography, complex media.

## I. INTRODUCTION

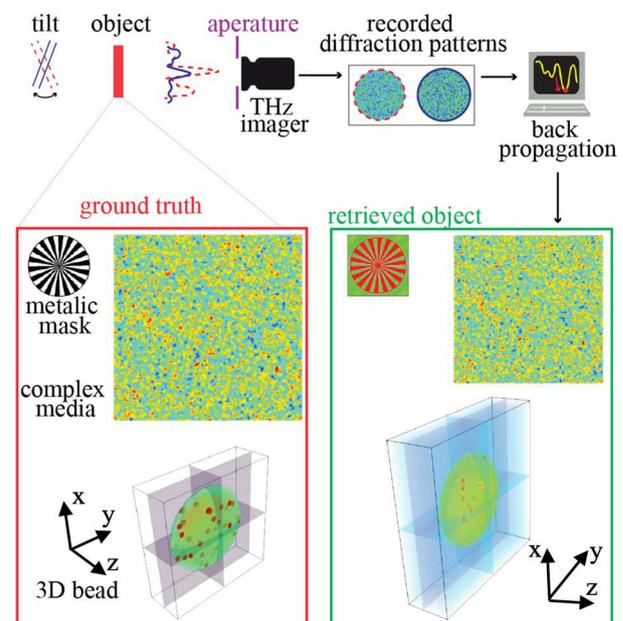
Imaging through complex media poses a current challenge in the field of photonics and other wave domains [1]. The primary factor responsible for this issue is the spatial variation in the refractive index profile of a medium. These variations operate as convolution elements and greatly impede the efficient transfer of information. Moreover, the limiting numerical aperture of the currently accessible terahertz (THz) imaging sensors restricts the space-bandwidth product, frequently leading to the recovery of diffraction-limited, low-resolution images. In order to address these constraints, wavefront-shaping methods have been devised to manipulate the light in various intricate propagation scenarios such as mitigating image distortions caused by scattering [2], [3]. Recently, there have been a considerable amount of study focused on optimizing illuminating wavefront in order to generate target field distributions in both space and time [4]. This is achieved by employing iterative optimization of output using input spatial light modulators [5] or by deterministically evaluating the transmission matrix for the scattering media [6]. Along the same direction, ptychography imaging modalities have been introduced. They combine the shifting of the aperture to achieve high-resolution, extensive field-of-view imaging without major hardware modification of the THz imaging system [7], [8]. The degree of complexity present in the sample, which is only limited to weak scattering regime, still has an impact on the performance of modern state-of-the-art ptychography [9]. Additionally, despite the recent advances in computational imaging in the THz

frequency range, the extension of these modalities for tomographic reconstruction of 3D imaging objects is currently lacking.

## II. BACKGROUND

Here we present THz Fourier ptychography for complexity-driven imaging solutions. As shown in figure 1, the object is probed with a coherent beam incident at several angles, and corresponding scattered fields are collected using THz imaging sensor (typically microbolometer). In such case, we define forward model as,

$$E_{out}^l(r, \lambda) = O_{NA} \langle \mathcal{P}_z \{ T_r E_{in}^l(r, \lambda) \} \rangle \quad (1)$$



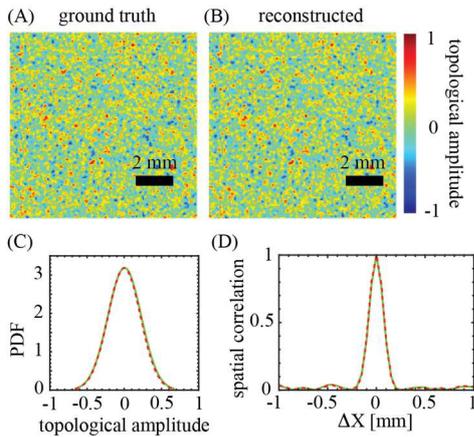
**Fig 1: A conceptual description of the THz Fourier Ptychography complex media imaging system.** Schematics of the numerical simulation, in which the complex media sample is illuminated by a series of tilted wavefronts of THz radiation, and corresponding intensity-only diffraction patterns are acquired using THz imagers (bolometer). The diffraction patterns associated with different angles of illumination are combined to formulate a phase retrieval problem, which is subsequently solved using gradient descent technique.

where  $r = \sqrt{x^2 + y^2}$ ,  $E_{out}^l / E_{in}^l$  is scattered/input field corresponding to  $l^{\text{th}}$  illumination angle,  $T_r(r, \lambda) = \exp(2\pi i \phi(r, \lambda))$  is transfer function of phase imaging object,  $\mathcal{P}_z$  is free space propagator (using angular spectrum method) and  $\text{O}_{\text{NA}}$  arises due to limited numerical aperture of detection optics and defined as spatial low pass filter with cut-off frequency:  $k_x^2 + k_y^2 < \left(\frac{\text{NA}}{\lambda}\right)^2$ . Further, by collecting scattered field corresponding to all the set of tilted illuminations, we established a nonlinear convex optimization problem and reconstructed spatial variation in the phase profile of the complex media.

We further extend our reconstruction abilities for 3D imaging object in the tomographic fashion. We resort to a well-known model for light propagation applicable to a wider variety of scattering media and wavelength ranges, known as beam propagation method (BPM) [10]. The object will be computationally sectioned in slices, whose thickness approximate the scattering mean free path. Within each slice, light undergoes diffraction and refraction, respectively modelled by free-space propagation and multiplication by a phase mask, which is proportional to the unknown refractive index contrast of the medium. Because the input wavefronts always probe the same volume of the object, the output wavefronts provide redundant information, which can be used to iteratively reconstruct the transmission properties of the sample. Successfully reconstructing the object therefore entails learning its 3D refractive index distribution.

### III. RESULTS

We will introduce our most recent results opening new avenues for THz imaging systems. Initially, to benchmark our imaging method, we introduced metallic mask as an imaging object and obtained high resolution images, as shown in figure 1. In another case of imaging object, we represent complex media by circular complex random Gaussian elements of spatially correlated amplitude-phase transmission function at

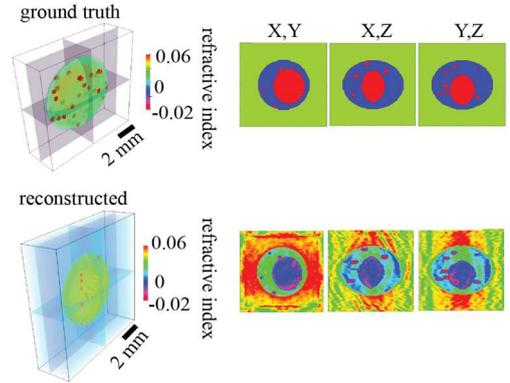


**Fig 2: THz complex media imaging.** (A) Slowly varying random surfaces as a ground-truth imaging object. (B) Reconstructed image of the object. (C) Probability density function in the ground truth (red) and reconstructed object (green). (D) spatial correlation in the ground truth (red) and reconstructed object (green).

the millimeter wavelength scale ( $\lambda = 0.3$  mm). The most obvious consequence is that, numerically, the overall transmission properties are directly connected to the degree of complexity, i.e., spatial correlation in complex media modelling. Quiet interestingly, due to relatively large wavelength scale than the optical frequencies, it is feasible to fabricate an imaging sample with tunable complexity in the

THz frequency range. Therefore, we utilize 3D printed slowly varying random surfaces that function as passive phase-modulating elements. An exemplary random surface ( $\mu = 0, \sigma = 0.5$ ) with a low-pass spatial Gaussian-convolution filter of width 0.1 mm is shown in figure 2(a), which serves as a ground truth imaging object. As a result, illustrated in figure 2(b), our employed technique successfully facilitated the reconstruction of the topological amplitude of a random surface containing subwavelength features.

We will further present reconstruction of 3D THz complex media and discuss the scenario towards tomography. Some preliminary results are shown in figure 3, where our employed technique enabled the retrieval of slice-by-slice variation in refractive index of THz complex media and opens a pathway for non-destructive inspection of the 3D objects. Our full theoretical and experimental investigation will be reported in



**Fig 3: THz complex media tomography.** 3D bead sample and its reconstruction.

detail.

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