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Nonlocal metasurfaces and thin film devices for all-optical image processing and phase contrast imaging

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Abstract: Metasurfaces and tailored thin film devices can manipulate images and extract information from optical fields in the object plane, leading to a significant reduction in size compared to other optical approaches. Here recent progress in extending and utilizing the range of information obtainable using these devices will be presented.

It is well-known that optical systems can perform image processing in the Fourier plane, but currently computational methods are more commonly employed for tasks such as edge detection, object identification, and image enhancement. The latter approaches, however, rely on the capture of information with a digital camera discarding phase information, and the resources required scale as the amount of information being processed. Hence, there is an ongoing interest in being able to perform operations directly at the sensor level. Furthermore, Frits Zernike demonstrated that the inclusion of phase plates as spatial filters using Fourier methods permitted visualization of essentially transparent objects such as unstained biological cells [1]. While there are advanced computational methods to extract phase information from intensity images, these methods can be slow and computationally intensive and are orthogonal to the drive to the sensor-level processing. Well-established all-optical Fourier and other image processing and phase contrast imaging methods, however, usually require large and sometimes costly optics. With the push for more compact optical components and advances in nanooptics, there is an emerging interest in all-optical image processing taking advantage of the unique capabilities of metasurfaces [1-4] and thin film devices [5-6].

Traditional spatial frequency filtering involves introducing a mask into the focal plane of a lens taking advantage of its Fourier transforming property to independently manipulate contributions to the angular spectrum of the optical wavefield. This approach places a lower bound on the axial extent of the system due to the introduction of lenses and propagation distances. Nonlocal approaches, on the other hand, involve the direct manipulation of the spatial frequency content of the field by using a device that has a reflectance or transmittance sensitive to the angle of incidence of a plane wave. This directly modifies the amplitude and/or phase of a given angular spectrum component of the field. Not only does this present a more compact optical system but permits flexibility in positioning the device [7]. Concepts leveraging known light-matter interactions or inverse design methods can be used to develop metasurfaces with a tailored angular dispersion and, hence, perform a particular operation [2,3]. Specifically, there is considerable scope for the development of compact devices that can generate enhanced contrast images of transparent objects. Indeed, we have previously shown that an off-the-shelf notch filter [8] or a metal-insulator-metal Salisbury screen [9] can perform edge detection and phase contrast imaging of unstained biological samples in, respectively, transmission and reflection. We also used a resonant waveguide grating in transmission [10, 11] to generate phase contrast images of unstained HeLa cells. Our recent research has focused on dynamically modifying the imaging modality without removing the metasurface by changing the polarization of the incident field [12] or using phase change materials [13].

This presentation will focus on recent results utilizing inverse design strategies [14] to produce spatial frequency selective metasurfaces, tailored thin film devices and the introduction of tunable materials to modify image processing operations. Wavelength and polarization multiplexed information extraction from an optical wavefield will also be discussed and applications to quantitative phase imaging presented.

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