All-optical image recognition and processing with plasmonic metasurfaces

M. Papaioannou1, E. Plum1,\*, E. T. F. Rogers1,2, J. Valente1, Nikolay I. Zheludev1,3

1 Optoelectronics Research Centre and Centre for Photonic Metamaterials,  
University of Southampton, Southampton, SO17 1BJ, UK

2 Institute for Life Sciences, University of Southampton, Southampton, SO17 1BJ, UK

3 Centre for Disruptive Photonic Technologies, Nanyang Technological University,  
Singapore 637371, Singapore

We engage the interaction of coherent waves on a thin metamaterial absorber to demonstrate all-optical image recognition and logical operations between images. Our approach is compatible with THz frame rates and single photon energy levels.

A lossy thin film or metasurface of substantially sub-wavelength thickness can be placed at a node or anti-node of a standing wave formed by counter-propagating coherent waves. At the electric field node, negligible light-matter interaction renders the metasurface perfectly transparent, while at the anti-node perfect absorption of incident light is possible. This form of modulation of light with light enables logical operations for all-optical data processing, at arbitrarily low intensities, with 100 THz bandwidth and with diffraction-limited spatial resolution. Here we present the first experimental demonstration of image recognition exploiting the coherent interaction of light with light on metasurfaces. Identification of similarities and differences between two images projected onto either side of an absorbing metasurface is accomplished through the variation of the relative phase difference between the illuminating images, resulting in perfect transmission or perfect absorption of common image features. Therefore, a target image can be identified amongst test images and the degree of image mismatch can be quantified.

We project test and target images on either side of a metasurface absorber, a 60-nm-thick freestanding gold film perforated with a periodic array of split ring apertures. All-optical image recognition is illustrated with test and target images consisting of binary patterns. These could represent optical data streams or patterns such as positive/negative medical test results, winning lottery tickets or correct multiple choice answer sheets. If the target and test images are projected onto the metasurface with a π phase difference, destructive interference of matching image features prevents their absorption and therefore matching features appear much brighter (4x) than those that do not match. In contrast, for in-phase image projection, matching features are absorbed due to constructive interference on the metasurface, resulting in detection of the differences between the images. Such pattern recognition may also be thought of in terms of logical operations between images, where detection of similarities and differences correspond to AND and XOR operations between the test and target images, respectively. The level of agreement between the images (matching bits, positive test result, winning ticket or number of correct answers) can be detected using a photodetector that measures the overall image intensity at node or anti-node, or the phase-dependent intensity fluctuation that is directly proportional to the level agreement.

In summary, we demonstrate all-optical image recognition based on coherent absorption of light by a lossy metasurface for the first time. The technique enables the selective and quantitative detection of similarities and differences between images and between patterns with diffraction-limited resolution. In principle, it can be applied to still and moving images or massively parallel data streams with frame or data rates up to 10s of THz and at arbitrarily low intensities down to a single photon per bit.