All-optical Image Recognition and Processing with Plasmonic Metasurfaces

Maria Papaioannou[1], Eric Plum[1], Edward T. F. Rogers[1, 2], João Valente[1], B. Gholipour[1], and Nikolay I. Zheludev[1, 3]

[1]*Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, SO17 1BJ, UK*
[2] *Institute for Life Sciences, University of Southampton, Southampton SO17 1BJ, UK*
[3]*Centre for Disruptive Photonic Technologies and The Photonics Institute, Nanyang Technological University, Singapore 637371, Singapore*
Author e-mail address: erp@orc.soton.ac.uk, niz@orc.soton.ac.uk

Abstract: We engage effective nonlinearity of the coherent wave interaction on a thin metamaterial absorber to demonstrate all-optical image recognition and logical functions that in principle can be performed at THz frame rates and quantum-limited intensities.

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1. Introduction

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 allows the realization of logical operations between optical signals for all-optical data processing, at arbitrarily low intensities, with 10s of 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 beam phase difference ($\Delta\varphi$) and results in perfect transmission (Fig. 1a) or perfect absorption (Fig. 1b) of common image features, where coherent interaction occurs. Therefore, a target image can be identified amongst a set of test images and the degree of image mismatch can be quantified.

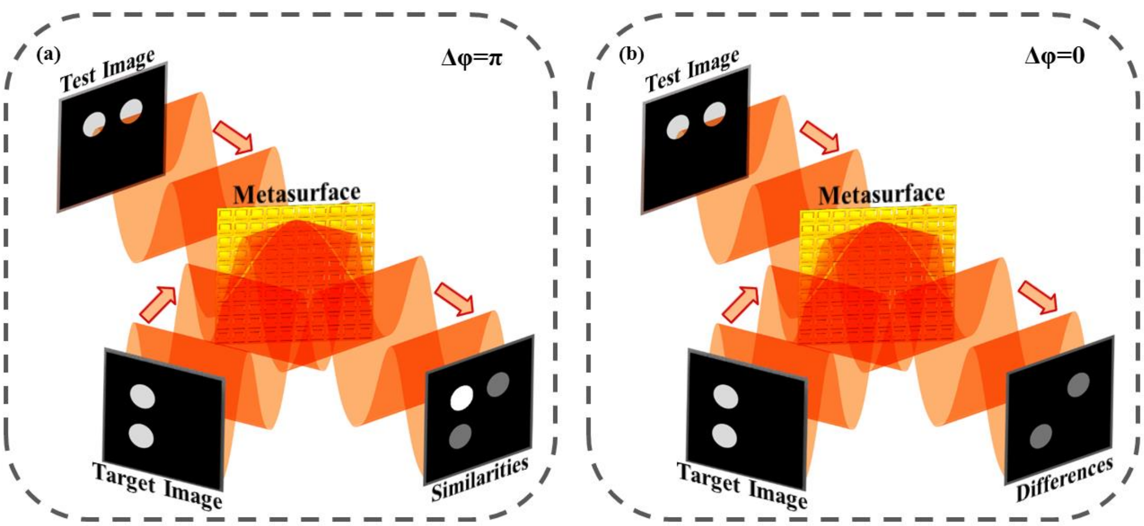

Fig. 1. Basic concept of coherent image recognition: Test and target images are projected onto an absorbing metasurface using coherent light. Across common features of test and target images, illuminating beams coherently interact with the metasurface via the formation of a standing wave. This results in elimination or enhancement of the metasurface absorption across overlapping features depending on the relative beam phase difference ($\Delta\varphi$). (a) For $\Delta\varphi = \pi$ similarities between the two images are perfectly transmitted (bright spot). (b) In contrast, for $\Delta\varphi = 0$ common image features are perfectly absorbed resulting in an output image that reveals only the differences between the two images.

2. Results

In our experimental configuration of all-optical coherent image processing the test and the target images are projected on either side of the metasurface. For illumination of only front or back of the metasurface, absorption is close to 50%. The metasurface is a freestanding gold film which has been perforated with a periodic array of split ring resonators. A CCD camera is employed at the system output to image the metasurface and collect the output light.

Fig. 2 illustrates all-optical image recognition based on a target image consisting of a binary pattern of bright dots occupying 8 out of 16 possible locations (indicated by white circles in column 1). Test patterns also have 8 bright dots each, at positions that correspond to 0%, 50% and 100% pattern matching with respect to the target image (column 1). These could represent, for instance, lottery tickets, multiple choice answer sheets or optical data streams. If the target and test images are projected onto the metasurface with a phase difference of π, destructive interference of matching image features prevents their absorption and therefore matching dots appear bright (column 2). In contrast, if the images are projected in phase, matching image features interfere constructively on the metasurface. This results in complete absorption of light across the matching dots, and therefore only the differences between the images are detected by the camera (column 3). Such pattern recognition may also be thought of in terms of logical operations between images, where the detection of similarities corresponds to a logical AND operation between the test and target images, while the detection of differences corresponds to an XOR operation. In pattern recognition applications, a simple photodetector can replace the CCD camera and the level of agreement (winning ticket, number of correct answers or matching data bits) can be derived from the overall detected intensity at node or anti-node, or from the phase-dependent intensity fluctuation that is directly proportional to the number of matching dots.

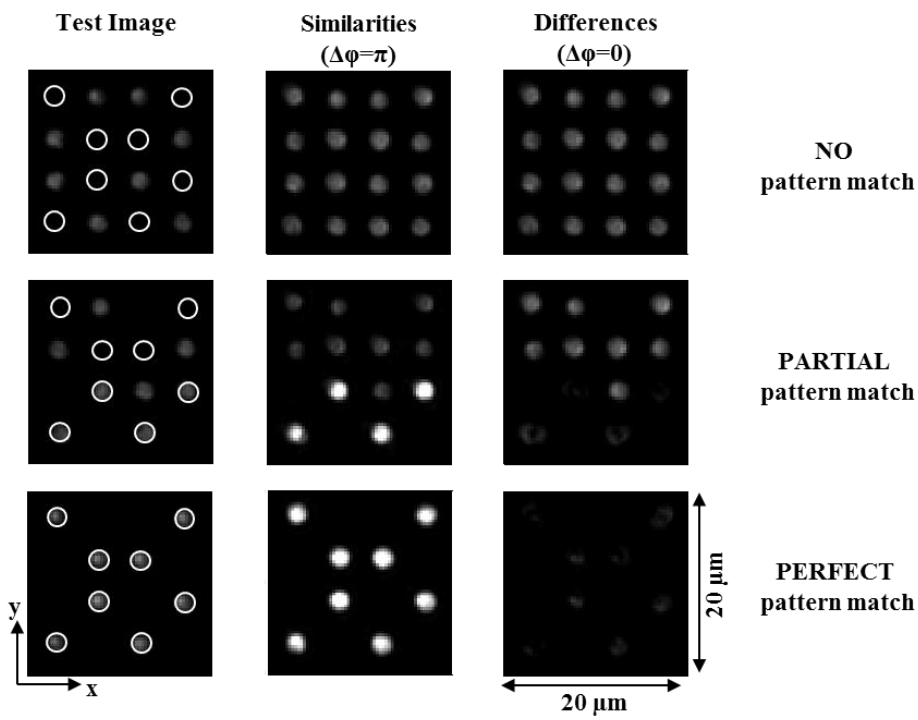

Fig. 2. Quantitative image recognition. A test image (column 1) and a target image (indicated by white circles) are projected onto either side of an absorbing metasurface using coherent light of 785 nm wavelength. Overlapping features of test and target images are perfectly transmitted (column 2) or fully absorbed (column 3) depending on the phase difference Δφ between the illuminating beams. Δφ controls the spatial intensity distribution (columns 2, 3) of the detected image which clearly reveals the cases of NO pattern match (row 1), PARTIAL pattern match (row 2) and PERFECT pattern match (row 3). All images are presented on the same grayscale.

3. Summary

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 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.