10th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics – Metamaterials 2016
Crete, Greece, 17-22 September 2016

Metasystems for All-optical Recognition and Processing of Images and Data

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***Abstract* – All-optical image recognition and data processing is accomplished by engaging the effectively nonlinear coherent wave interaction on a thin absorbing metasurface. This approach relies on coherent perfect absorption and perfect transmission of matching image features and it is compatible with single-photon intensities and THz frame rates.**

I. INTRODUCTION

We perform image and data processing by exploiting the effective nonlinearity of a system where a lossy thin film or metasurface of subwavelength thickness is translated between nodes and antinodes of a standing wave. Negligible light matter interaction renders the metasurface perfectly transparent at the electric field node, while at the anti-node incident light is perfectly absorbed [1]. Such control of light with light can be used for logical operations between optical signals and therefore enables all-optical data processing, at arbitrarily low power, with 10s of THz bandwidth [2]–[4].

Here we report the first experimental demonstration of a metasystem for all-optical image recognition and processing of images and data based on coherent interaction of light with light on metasurfaces. The "Correct Image" is compared to an "Image Under Test" by projection on opposite sides of an absorbing metasurface (Fig. 1). Coherent light matter interaction will take place across features that are common in the two images.

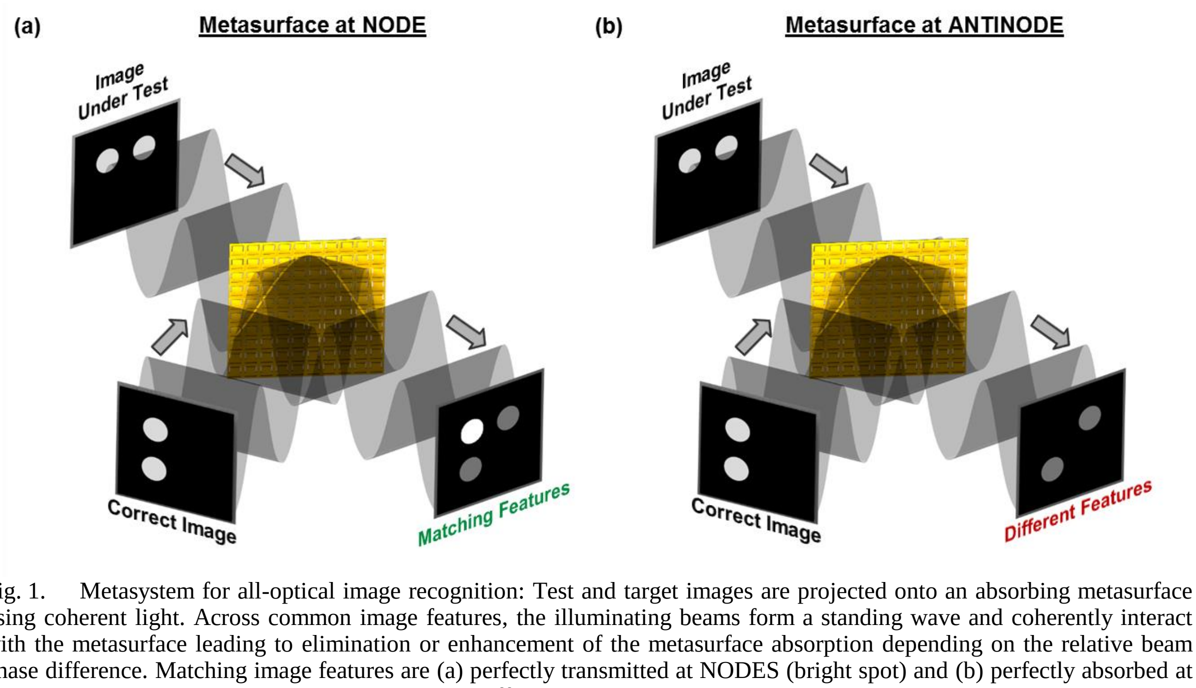

Fig. 1. Metasystem for all-optical image recognition: Test and target images are projected onto an absorbing metasurface using coherent light. Across common image features, the illuminating beams form a standing wave and coherently interact with the metasurface leading to elimination or enhancement of the metasurface absorption depending on the relative beam phase difference. Matching image features are (a) perfectly transmitted at NODES (bright spot) and (b) perfectly absorbed at ANTINODES revealing the (a) similarities and (b) differences between the images at the output.

Therefore, if the metasurface is located at an electric field node, common features will reach the output without attenuation, thus revealing the matching features between the images (Fig. 1a). On the other hand, at the antinode, common image features will be perfectly absorbed and therefore only the differences between the images will be detected at the system output (Fig. 1b). Consequently, the correct image can be identified amongst a set of test images based on quantitative data that reveal the degree of image mismatch.

II. RESULTS

All-optical coherent image processing and recognition is performed experimentally by exploiting the properties of a metasurface consisting of a free-standing gold film of sub-wavelength thickness perforated with a periodic array of split ring resonators. The metasurface absorbs close to 50% of a single illuminating beam. The correct image and a test image are projected on either side of the metasurface. A CCD camera at the system output gathers the output light by imaging the metasurface plane.

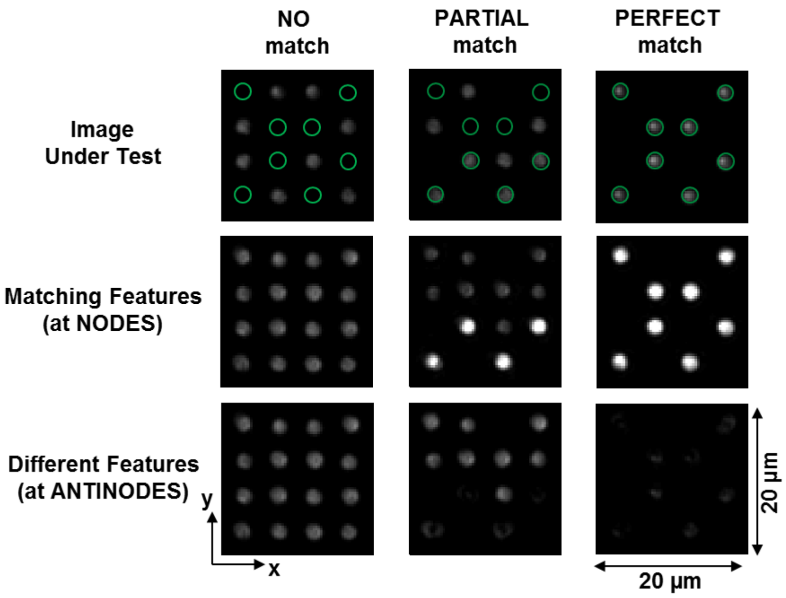

Fig. 2. Experimental image recognition. Test images (1st row) are compared to the correct image (correct spot positions indicated by green circles) on an absorbing metasurface using coherent light of 785 nm wavelength. Overlapping image features are perfectly transmitted (2nd row) or fully absorbed (3rd row) depending on the position of the metasurface with respect to the standing wave. Variation of the relative beam phase difference controls the spatial intensity distribution (2nd and 3rd row) at the output. The cases of NO match (1st column), PARTIAL match (2nd column) and PERFECT match (3rd column) are shown. All images are presented on the same grayscale.

In our experimental demonstration of all-optical image recognition, we compare binary patterns of bright features occupying 8 out of 16 possible positions. We aim to identify the correct image pattern (designated by green circles in Fig. 2) amongst a set of test images with 8 bright features each. Here we show results for test images corresponding to 0%, 50% and 100% pattern match (1st row in Fig. 2). Any optical data streams, from images of multiple choice answer sheets and lottery tickets to medical test results and fibre communication channels could be represented in this form. Absorption of matching image features is negligible due to destructive interference if the test image and the correct reference image are projected onto the metasurface with a phase difference of π (metasurface at a node) and therefore matching dots appear bright (2nd row in Fig. 2). In contrast, the metasurface absorbs overlapping image features completely if the images are projected in phase resulting in constructive interference (metasurface at an antinode), thus only the different image features are detected by the camera (3rd row in Fig. 2). This process can also be described in terms of logical operations between images where matching feature detection corresponds to the AND operation between the two images, while the different image features are revealed via the XOR operation.

Alternatively, the overall detected power when the metasurface is positioned at a node or antinode can be used to identify the correct image and to measure the degree of image agreement. Integration of the overall intensity of the images acquired by the CCD camera (2nd and 3rd row of Fig. 2) results in different optical power at node and antinode when the test image matches the reference image at least partially (dot points in Fig. 3). The detected power follows the theoretical predictions (solid lines in Fig. 3). Moreover, the phase-dependent power fluctuation (indicated by arrows in Fig. 3) is directly proportional to image agreement. Following this analysis, all-optical data and image recognition can be accomplished by replacing the CCD camera with a simple photodetector and monitoring the output power level or/and the level of power fluctuation between nodes and antinodes.

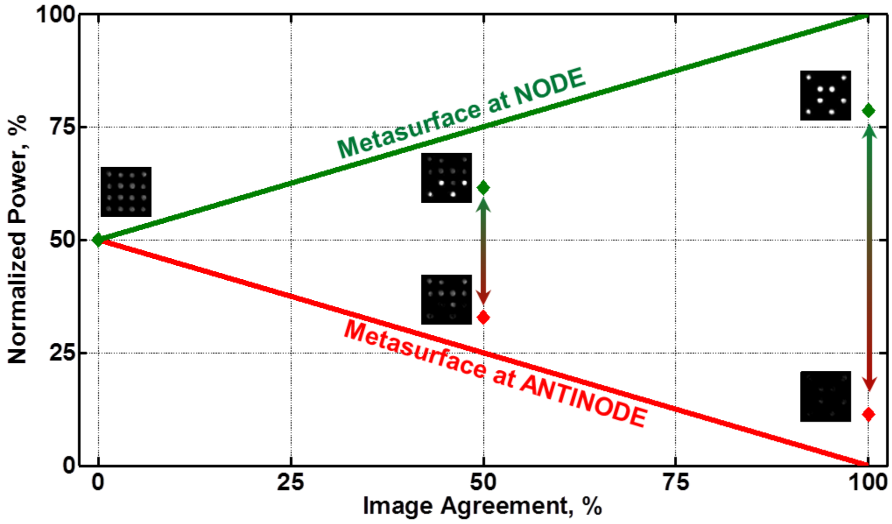

Fig. 3. Quantitative image recognition based on the overall detected power. Theoretical (solid lines) and experimental (dots) integrated image intensity, when the metasurface is positioned at a standing wave node (green) or antinode (red). The normalized power $P/(2P_{0\%})$ is shown where $P_{0\%}$ is the image power for 0% agreement.

III. CONCLUSIONS

In summary, we demonstrate the first experimental metasystem for all-optical image and data recognition and processing based on coherent absorption of light by a lossy metasurface. Matching and different image features are selectively and quantitatively detected by our diffraction-limited configuration. In principle, 10s of THz data rates can be achieved and quantum-level intensities can be used. Furthermore, our technique can be applied to still and moving images as well as massively parallel data streams.

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