Coherent all-optical information processing on metasurfaces

E. Plum[1*], M. Papaioannou[1], A. Xomalis[1], Y. Jung[1], I. Demirtzioglou[1], E. T. F. Rogers[1], K. F. MacDonald[1], P. Petropoulos[1], David J. Richardson[1], and N. I. Zheludev[1,2]

[1] Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, UK

[2] Centre for Disruptive Photonic Technologies and The Photonics Institute, Nanyang Technological University, Singapore

[*]corresponding author: erp@orc.soton.ac.uk

Abstract-Exponentially growing bandwidth requirements of our information society introduce major capacity and energy challenges. We exploit coherent control of light with light on Fano-metamaterials of nanoscale thickness to demonstrate an approach promising massively parallel all-optical information processing at arbitrarily low intensities and with up to 100 THz bandwidth. We experimentally demonstrate parallel all-optical data processing, all-optical pattern recognition and image analysis as well as a fully packaged fiberized metadevice performing several logical operations at GHz bitrates.

Conventional approaches to all-optical information processing rely on nonlinear optical processes to influence one optical signal with another, resulting in tradeoffs between modulation rates and power requirements as fast nonlinearities are weak. However, it is a common misconception that modulation of light with light requires nonlinear optical materials. Consider the interaction between counterpropagating coherent optical signals and a material of substantially sub-wavelength thickness. The thin film can be placed at a node or anti-node of the standing wave formed by the counterpropagating optical signals. At a node, there is no electric field and therefore no light-matter interaction, while constructive interference at the anti-node enhances the light-matter interaction. This linear mechanism allows one optical signal to control absorption of the other almost from 0% to 100%, at arbitrarily low intensities down to the quantum regime and with many THz bandwidth.

We exploit such coherent interaction of light with light on a freestanding gold Fano-metasurface of 60 nm thickness to control intensity of light in spatially distributed optical information channels. Based on optically controlled coherent perfect absorption and coherent transparency of the metasurface (Figure 1), we perform logical operations such as XOR and AND between selected information channels, identify similarities and differences between images, perform pattern recognition by quantifying the similarity between images or data patterns of arbitrary complexity and perform advanced optical image analysis, for example of satellite images to detect the Arctic ice cover, its growth and melting over several decades.

We also demonstrate the first fully integrated data processing metadevice based on coherent interaction of light with light on a gold Fano-metasurface (Figure 2). The fully packaged fibre device is based on a metasurface fabricated on the end face of a polarization maintaining single-mode telecommunications fibre. It can act as an optical logic NOT, XOR and AND gate and has been tested up to GHz frequencies.

In summary, we report a novel, linear approach to all-optical information processing that could deliver orders-of-magnitude improvements in speed and energy efficiency. We illustrate this with a diverse range of experiments ranging from parallel optical processing, recognition and analysis of data and images to demonstration of a fully integrated fiberized metadevice performing various logical operations at least up to GHz data rates.

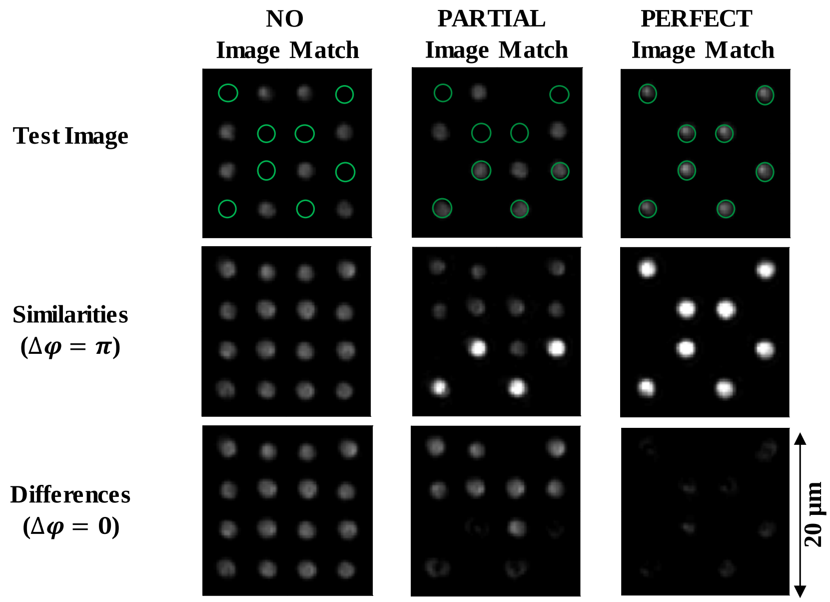

Figure 1. Pattern recognition. Test images (row 1) are compared to a target image (green circles) by projection onto opposite sides of a lossy metasurface using coherent light of 790 nm wavelength. Depending on the optical phase difference Δφ on the metasurface, overlapping image features are perfectly transmitted (row 2) or fully absorbed (row 3), revealing similarities and differences.

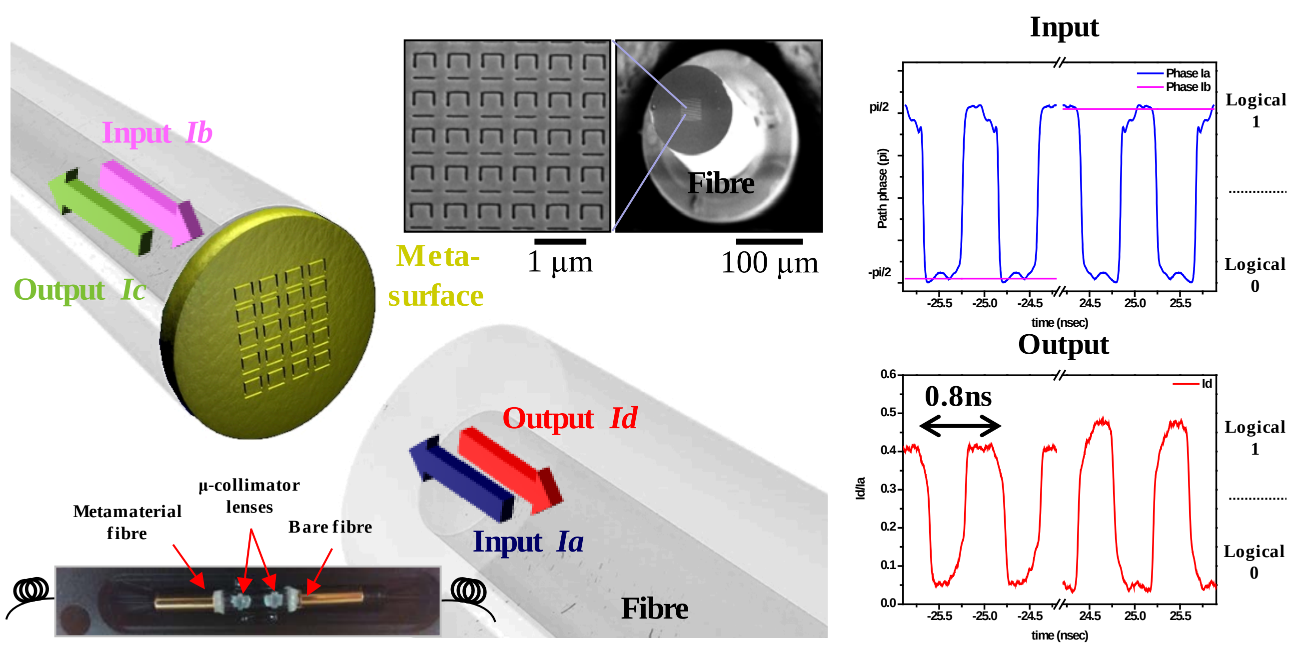

Figure 2. Data processing metadevice based on coherent interaction of input light beams *Ia* and *Ib* on a 70-nm-thick plasmonic metamaterial absorber fabricated on the end face of a single-mode telecoms fibre (1550 nm wavelength). Insets show the nanostructured fibre end and the assembled metadevice. Measurements show an all-optical XOR operation between phase-modulated signals at a data rate of 1.2 GHz: High output (logical 1) results from opposite input bits and low output (logical 0) results from identical input bits.