12th International Congress on Artificial Materials for Novel Wave Phenomena – Metamaterials 2018
Espoo, Finland, Aug. 27th – Sept. 1st, 2018

A Fiberized Metadevice for Ultrafast All-optical Signal Processing and Picosecond Dark Pulse Generation

A. Xomalis [1,2], I. Demirtzioglou [2], Y. Jung [1], E. Plum [1,2], C. Lacava [1], P. Petropoulos [1], D. J. Richardson [1], and N. I. Zheludev [1,2,3]

[1] Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
[2] Centre for Photonic Metamaterials, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
[3] Centre for Disruptive Photonic Technologies, The Photonics Institute, Nanyang Technological University, Singapore 637371, Singapore
E-mail: ax1c15@soton.ac.uk

Abstract – **We report a fiberized metadevice for all-optical signal processing based upon coherent modulation of absorption. The integrated metadevice is based on a plasmonic metamaterial absorber of nanoscale thickness fabricated on the core area of an optical fibre, and designed to operate over the entire telecoms C-band. We demonstrate signal processing operations analogous to logical functions at data rates ranging from kbit/s up to Gbit/s, with energy consumption as low as few fJ/bit, controlled absorption and transmission of picosecond pulses and generation of 1 ps 'dark pulses'. We anticipate that such THz bandwidth metadevices may provide solutions for quantum information networks as well as orders-of-magnitude improvements in speed and energy consumption over existing nonlinear approaches to all-optical signal processing in coherent information networks.**

I. INTRODUCTION

Energy-efficient ultrafast all-optical signal processing may contribute to solving growing bandwidth and energy challenges in optical telecommunications. However, conventional solutions for all-optical data processing rely on nonlinear optical materials that require sufficient intensity to achieve a significant nonlinear response and face trade-offs between bandwidth and speed [1-2]. In contrast, it was shown that an effective nonlinearity may be derived from linear interaction of light with light [3]. The coherent interaction of light with an absorber of nanoscale thickness can facilitate high-contrast modulation of one optical signal with another, ultimately with few-femtosecond response times [4] and at arbitrarily low intensities down to single photons [5]. The functionality of the metadevice reported here is based on linear interaction of two mutually coherent signals α and β on a planar metamaterial absorber that produces two output signals γ and δ (Fig. 1a). Mutually coherent input signals of similar intensity produce a standing wave within the metadevice. As the metamaterial absorber of 70 nm thickness is thin compared to the operation wavelength (1530-1565 nm), it can be located at an electric field node or antinode of the standing wave resulting negligible or enhanced light-metasurface interaction and thus, low or high absorption, respectively. In principle, absorption can be modulated from 0 % to 100 % in this way. Here we demonstrate experimentally that such coherent control of absorption of light with light enables all-optical signal processing with at least 1 Tbit/s bandwidth. We demonstrate signal processing analogous to logical functions (NOT, XOR, AND), controlled transmission and absorption of 1 ps optical pulses and generation of 1 ps dark pulses within a fibre-optic metadevice.

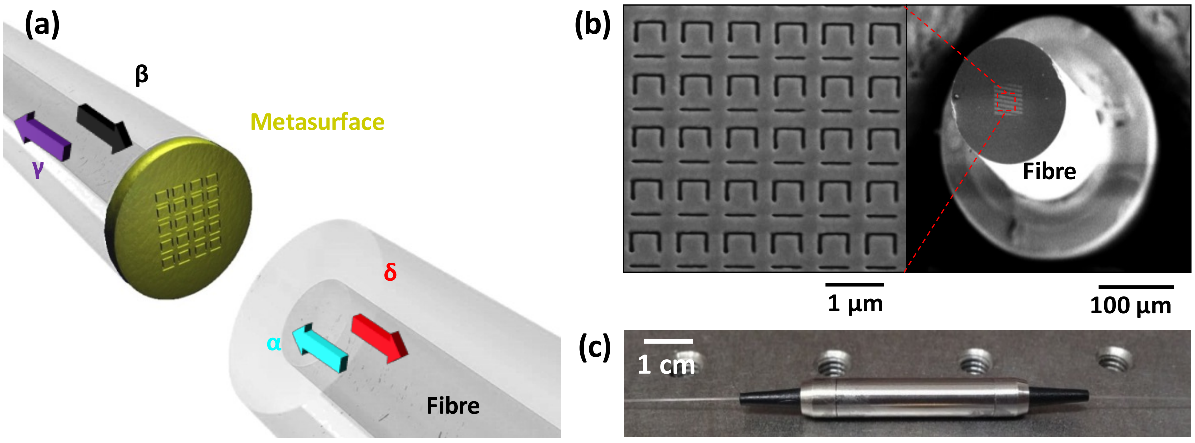

Fig. 1. A fibre-optic metadevice based on coherent absorption. (a) Coherent optical signals α and β interact in a plasmonic metamaterial absorber resulting output signals γ and δ. (b) Scanning electron micrograph of the metamaterial absorber, which has been fabricated directly on the end face of an optical fibre. (c) The packaged fibre metadevice.

II. Experimental results

The plasmonic metamaterial absorber was fabricated by gold deposition and focused ion beam milling directly on the end face of a standard polarization-maintaining single-mode telecommunication fibre. The metamaterial structure is 25 x 25 μm^2 in size and fully covers the fibre core area (Fig. 1b). The metamaterial-covered fibre was coupled to a second cleaved optical fibre using antireflection-coated microcollimator lenses and packaged in a stainless steel enclosure to create a robust pigtailed fibre device (Fig. 1c) that is compatible with standard telecommunication components.

All-optical signal processing functions analogous to logical operations were realized at bitrates from few kbit/s up to 40 Gbit/s by combining mutually coherent phase-modulated or intensity-modulated signals α and β within the metadevice. For example, a NOT function for intensity-modulated data α has been realized based on constructive interference with a continuous wave input β on the metasurface. In this case, each input pulse α will trigger absorption resulting in low outputs, while absence of signal α will allow light from input β to reach the outputs, resulting in signal inversion. Fig. 2a shows a signal α "1011" that is inverted to an output signal "0100" at a bitrate of 40 Gbit/s. Similarly, we have used one optical signal to trigger absorption or transmission another to realize all-optical XOR and AND functions.

However, the metadevice is capable of processing coherent optical signals at much higher bitrates than 40 Gbit/s. This is illustrated by Fig. 2b, which shows that a 1 ps pulse α can be switched with another 1 ps pulse β (top). Destructive interference of the mutually coherent pulses on the metasurface causes both pulses to be transmitted (middle), while constructive interference causes both pulses to be absorbed. Controlled transmission and absorption of 1 ps pulses was observed throughout the telecommunications C-band from 1530 nm to 1560 nm wavelength (inset). Such all-optical switching of 1 ps pulses indicates that the metadevice has a bandwidth of at least 1 Tbit/s.

Interesting opportunities for pulse shaping arise from interaction of mutually coherent signals of different shape within the metadevice. Fig. 2c illustrates this for a 1 ps pulse α (top left) that triggers coherent absorption of part of a 6 ps pulse β (top right), resulting in formation of a 1 ps dark pulse (bottom). Our results indicate that coherent absorption in a plasmonic metamaterial absorber may be used to convert an arbitrary sequence of bright pulses into dark pulses.

We note that the all-optical switching response time of the plasmonic metamaterial absorber corresponds to the plasmon relaxation time and thus the bandwidth of coherent absorption can reach tens of THz. The bandwidth of our fiberized device may be as high as several THz and is limited by pulse broadening due to fibre dispersion, rather than the plasmonic metamaterial.

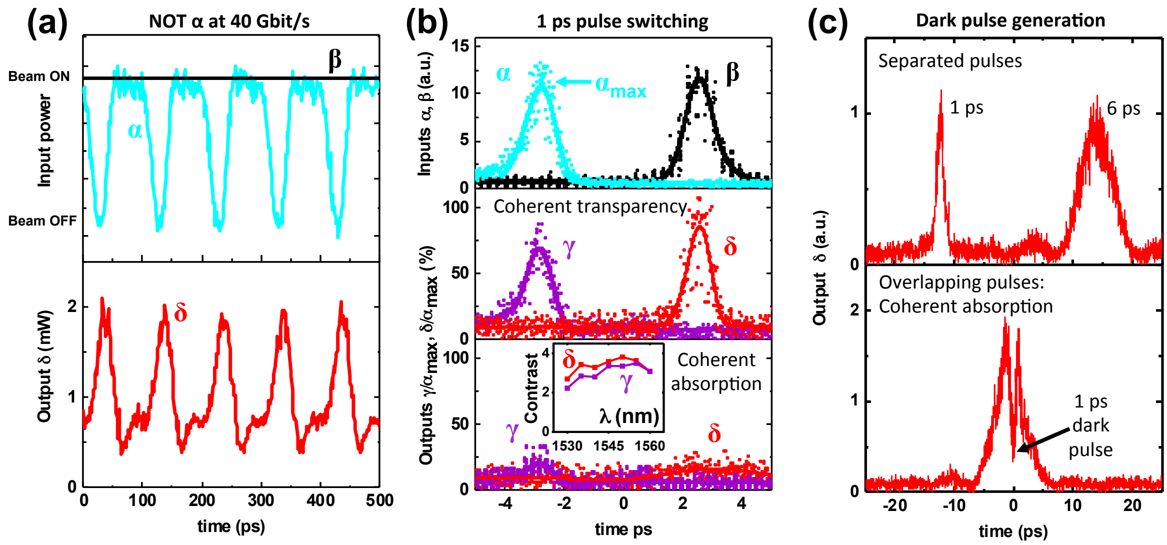

Fig. 2. All-optical signal processing based on coherent absorption at 1550 nm wavelength. (a) Logical function NOT α recorded at a data rate of 40 Gbit/s. Input signals α and β (top) and output signal δ (bottom). (b) All-optical switching with mutually coherent 1 ps pulses α and β (top) corresponding to a bandwidth of 1 Tbit/s. Destructive interference on the metasurface results in transmission of both pulses (middle), while constructive interference results in absorption of both pulses (bottom). The inset shows the modulation contrast for the outputs (γ and δ) between 1530 and 1560 nm wavelength. (c) Constructive interference of mutually coherent pulses of 1 ps (gate pulse α) and 6 ps (carrier pulse β) duration (top) results in generation of a 1 ps dark pulse (bottom) within a 6 ps pulse envelope due to coherent absorption.

III. Conclusion

In summary, we report signal processing from kbit/s to Tbit/s based on coherent absorption in a fully packaged fiberized metadevice containing a plasmonic metamaterial absorber. We demonstrate all-optical NOT, XOR and AND logical functions, switching of 1 ps pulses, pulse shaping and 1 ps dark pulse generation with energy consumption as low as few fJ/bit. We anticipate that several Tbit/s bandwith and sub-fJ/bit energy consumption will be achievable, promising applications in fast and energy-efficient all-optical information processing, coherent quantum information networks, pulse shaping, dark soliton generation and arbitrary dark pulse pattern generation at 1 Tbit/s and beyond.

Acknowledgement

This work is supported by the UK's Engineering and Physical Sciences Research Council (grants EP/M009122/1 and EP/P003990/1) and the MOE Singapore (grant MOE2011-T3-1-005).

References

[1] R. W. Boyd, *Nonlinear Optics*, 3rd ed., MA, USA: Academic Press, 2008
[2] V. R. Almeida, C. A. Barrios, R. R. Panepucci, and M. Lipson, "All-optical control of light on a silicon chip," *Nature* vol. 431, p. 1081–1084, 2004.
[3] X. Fang, K. F. MacDonald and N. I. Zheludev, "Controlling light with light using coherent metadevices: all-optical transistor, summator and invertor," *Light Sci. Appl.*, vol. 4, p e292, 2015.
[4] V. Nalla, J. Valente, H. Sun and N. I. Zheludev, "11-fs dark pulses generated via coherent absorption in plasmonic metamaterial," *Opt. Express* vol. 14, p. 868–870, 2016.
[5] T. Roger, S. Vezzoli, E. Bolduc, J. P. Valente, J. J. F. Heitz, J. Jeffers, C. Soci, J. Leach, C. Couteau, N. I. Zheludev, and D. Faccio, "Coherent perfect absorption in deeply subwavelength films in the single-photon regime," *Nat. Commun.* vol. 6, p. 7031, 2015.