Linear and Nonlinear Properties of Large-Area Metamaterials

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Scientific Thrust Area: Nanophotonics and Optical Nanomaterials

Research Achievement:

Optical lithography has long been the mainstay of the integrated circuit industry, and, despite many and frequent predictions to the contrary, is now widely accepted as the dominant volume manufacturing technology for the next several generations, accessing scales to less than 20 nm (with a 193-nm wavelength!). A major reason for the continued ascendency of optical lithography in manufacturing is its parallel writing capability that scales to large volumes at low cost. The issue with optical lithography for research applications is the extreme cost of modern lithography tools (approaching $40M) and masks which limits research accessibility. In contrast, much of the work in nanophotonics has been carried out with e-beam and related serial lithography techniques that inherently are not scalable. Interferometric lithography (IL) provides the bridge between these two trends [1]. IL uses the interference between a small number (usually two) of coherent beams to produce a maskless periodic pattern. Scales as small as 22-nm half-pitch have been demonstrated [2]. The restriction to periodic pattern arrays is not of major concern for many nanophotonic applications, mix-and-match with conventional, lower resolution, optical lithography techniques provides the additional customization needed for many device applications. Processing can provide more complex structures such as split ring resonators as shown in Fig. 1(a). At the University of New Mexico, we have used IL for a wide variety of nanophotonic structures including: 2D and 3D photonic crystals, metamaterials (Fig. 1(a) shows negative permeability split-rings with ~ 5 μm resonance wavelength) [3], negative index materials (Fig. 1(b)) [4], and plasmonic structures (Fig. 1(c)) [5]. Current efforts focus on inhomogeneous negative-index materials for lensing, active metamaterials for high speed modulators, higher-order nonlinearities in second harmonic generation in plasmonic structures and various approaches to 3D photonic crystals. Progress in these areas will be reviewed.

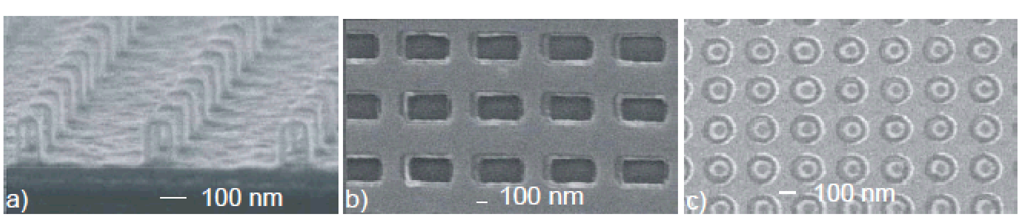

Fig. 1: Large area (> several cm2) nanophotonic arrays fabricated with interferometric lithography. A) Vertical split ring resonators (Au:MgO:Au) providing a negative permeability at ~ 5μm; b) Au:Al_2O_3:Au negative index metamaterial at ~ 2 μm; and c) GaAs-filled Au plasmonic structure for second harmonic generation. Note that all three structures exhibit complexity at the individual nanostructure level as a result of the integration of lithography and processing.

One example of these developments that has strongly benefited from a collaboration with CINT is the demonstration of ultrafast switching in metamaterial structures. Development of all-optical signal processing, eliminating the performance and cost penalties of optical-electrical-optical conversion, is important for continuing advances in Terabits/sec (Tb/s) communications [6]. Optical nonlinearities are generally weak, traditionally requiring long-path, large-area devices [7] or very high-Q, narrow-band resonator structures [8]. Optical metamaterials offer unique capabilities for optical-optical interactions. We have demonstrated 600-fs all-optical modulation at a broadband, negative-index resonance in a fishnet (2D-perforated metal/α-Si/metal film stack) metamaterial. We achieve this ultrafast response – two orders of magnitude faster than previously reported[9] – by accessing a previously unused regime of high-injection level, sub-ps carrier dynamics in α-Si [10-12]. A new, higher-order, shorter-wavelength resonance than previously reported in the fishnet structure is used [3,4], thereby extending device functionality (via structural tuning of device dimensions) over 1.0 – 2.0 μm. Over 20% modulation (experimentally limited) is achieved in a path length of only 116 nm. This device has the potential for Tb/s all-optical communication and will lead to other novel, compact, tunable, sub-picosecond (ps) photonic devices.

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