SAND2011-8041 C

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3D IR Metamaterial Science and Technology at Sandia National Laboratories

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***Abstract*—Sandia National Laboratories' Metamaterial Science and Technology Program has developed novel HPC-based design tools, wafer scale 3D fabrication processes, and characterization tools to enable thermal IR optical metamaterial application studies.**

Keywords-metamaterials, plasmonics, nanophotonics, LWIR

I. Introduction

Research in electromagnetic metamaterials has steadily increased over the last 10 years, providing enhanced understanding and demonstration of novel physics at shorter and shorter wavelengths. While some evidence of this progress is being seen in radio frequency applications, the question remains: "When will *optical metamaterials* start appearing in device and system applications"? New technology adoption faces many technical and financial challenges to enable the application engineering studies and device demonstrations needed to compel modern device/systems designers to incorporate new material approaches. Among the technical challenges, there is the need to quantify the limits for loss and permeability provided by different approaches, as well as the desire for accurate and flexible design tools, scalable and robust fabrication techniques, and high fidelity metrology. Sandia's Metamaterial Science and Technology program is attempting to address these challenges.

II. Background & Program Goals

In the late 1990's and early-mid 2000's, Sandia pursued a variety of R&D projects in photonic crystals, plasmonics, and other nanophotonics, including some collaborative work on THz metamaterials with Los Alamos National Labs (LANL).

(a)

D_2	E	C_2 (z)	C_2 (y)	C_2 (x)	linear functions, rotations
A	+1	+1	+1	+1	-
B_1	+1	+1	-1	-1	z, R_z
B_2	+1	-1	+1	-1	y, R_y
B_3	+1	-1	-1	+1	x, R_x

(b)

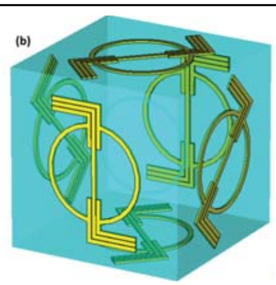

Figure 1. Example of a group-theoretic design of a 3D chiral metamaterial (from [4]).

In 2007, we began considering extensions of this work to applications of thermal infrared (LWIR) metamaterials. However, when we examined the current state of the metamaterial art at these optical frequencies, we found a need for additional scientific insight and infrastructure, especially concerning approaches to realize isotropic large-area 3D metamaterials (rather than "meta-films") and to control and/or reduce the loss associated with resonant metal unit cells. The primary goal of our 3-year (2009-2011) program was to develop the insights, tools, materials and fabrication techniques to help address these needs and enable the maturation of LWIR metamaterial technology into national security applications.

The Metamaterial Science and Technology Program has engaged approximately two dozen researchers on tasks involving: [1][2]

- Developing 3D metamaterial design insights and deployment of our high-performance resources to provide high-fidelity full-field electromagnetic modeling/design capabilities.
- Leveraging the material science and MESA and CINT [3] fabrication facilities at Sandia to develop the materials and process libraries needed to demonstrate new wafer-scale 3D metamaterial fabrication approaches.
- Utilization of the LWIR characterization equipment and expertise developed under prior nanophotonics projects, and development of new tools and analysis techniques.
- Preliminary efforts on extending earlier THz tunable metamaterial work into the optical IR regime.

After 3 years, the program has largely met its goals, developing new insights into the present limits of achievable manipulation of permittivity and permeability, developing new design approaches and highly scalable high-fidelity electromagnetic analysis code tools, creating a library of IR-compatible materials (and their associated deposition/pattern/etch processes), demonstrating two new wafer-scale fabrication approaches for 3D LWIR metamaterials, building two new phase-measuring metamaterial spectroscopy systems, and laying the foundation for a new program in active IR metamaterials.

III. Metamaterial Design and Realization Progress

A. Design and Modelling

Our Design team's work focused on developing the tools and insights to efficiently explore the design space of 3D metamaterials made with metal-resonator and dielectric resonator unit cells, including local interactions of the unit cell structures with the host matrix and substrate materials, methods to align the electric and magnetic resonances, and efficient and accurate full-field modeling of complete devices (composed of of many unit cells).

To study the design of 3D metal unit cells, we have explored an inverse problem approach based on group theory, which can be used to predict electric and magnetic behavior of MM inclusions for any incident field, including the existence and isotropic nature of the electromagnetic constitutive relationship.[4] The work has demonstrated the design and numerical validation of bianisotropic, chiral, and biaxial 3D unit cells.

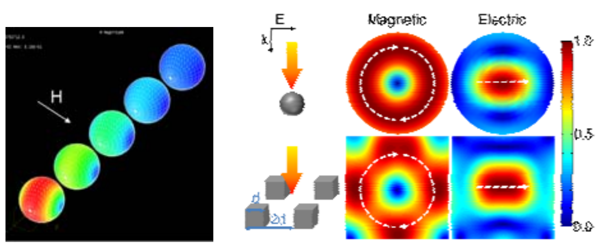

Figure 2. Examples of full-field spherical and cubic dielectric resonator analysis (from [5],[29]).

We have also examined dielectric resonator unit cells as a path to lower-loss 3D IR metamaterials. Various approaches have been explored to design and analyze spherical and cubic dielectric resonator metamaterials, and to align the electric and magnetic resonances that result. [5][6][7] Other work has examined the interaction of both metallic and dielectric resonators with their substrate and host matrix environments, including coupled-resonant behavior. [8][9]

To examine and quantify the accuracy limits of effective media approximations, as well as the effects of boundaries, strong index gradients, and spatial dispersion effects in future metamaterial devices, large-scale simulations which do not require effective media approximations may be necessary. We have explored the use of both commercial (HFSS, CTS, GD-CALC, Lumerical, etc.) and in-house (EIGER and other) codes, and have developed sub-cell circuit models and other approaches which dramatically (>1000x) decrease the computation time and memory needed for this task.[10][11][12][13] These tools are also beginning to be used for initial manufacturing tolerance studies.

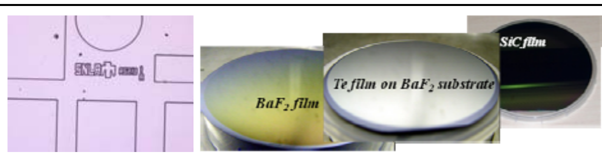

Figure 3. Examples of photpaternable low-loss IR polynorbornene, and BaF_2, Te, and SiC films on wafers.

B. Materials and Processes

To realize these metal and dielectric metamaterial designs, a broad range of "base-materials" may be necessary: various metals, low and high dielectric constant host matrix materials, low-loss IR polymers, etc. The assembly of this "materials library" is further complicated by the need to accurately characterize the properties of the materials in thin-film form, which can vary significantly from that of bulk, or between differing deposition methods.[14] Additionally, to be useful for wafer-scale fabrication, the associated processes for deposition, spinning, photopatterning, etching, and co-integration of the materials must be developed. Our materials team has developed and characterized the IR performance of high-yield thin film wafer-scale processes for a wide range of metals in addition to low and high dielectric constant IR materials, such as low-loss photo-patternable polynorbornene, polyethylene, low-loss barium fluoride, silicon carbide, magesium oxide, germanium, tellurium, lead telluride, and of course the common semiconductor processing polymers (SU-8, PMMA, BCB, polyimide, etc.).[14] [15][16]

C. Wafer-Scale 3D IR Metamaterial Fabrication

The lack of many fabrication techniques for bulk-like metamaterials containing 3D isotropic unit cells for IR operation is a significant barrier to exploration of potential metamaterial solutions and applications. We began our program fabricating single and multilayer "metafilms" (split ring resonator films, fishnet multilayers),[8][9] and "2.5D" IR frequency selective surface absorbers (so called "perfect absorbers").[17][18] That developmental work was crucial for our later demonstrations of 3D IR metamaterial designs using both "conventional" metal unit cell structures, as well as all-dielectric resonator approaches.

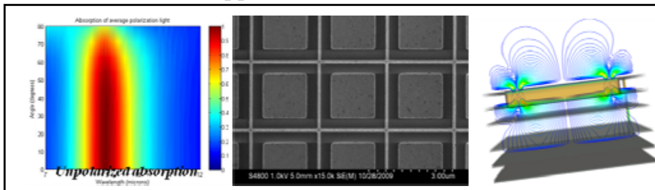

Figure 5. "2.5D" FSS-based metamaterial IR perfect absorber showing polarization and angle insensitive high absorption/emission (from [18]).

Membrane projection lithography (MPL) was invented to demonstrate at micron-scale for the LWIR the "Pendry-cube" metamaterial unit cells previously demonstrated at millmeter-scale for microwave frequencies. MPL creates a patterned membrane suspended over a cavity (the unit cell). Directional evaporation(s) through the patterned membrane results in

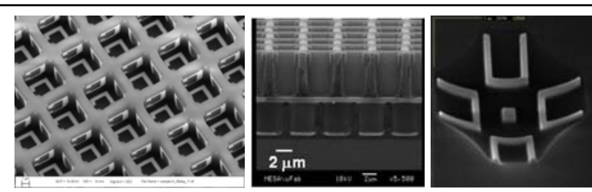

Figure 4. Single- and multilayer Membrane Projection Lithography-based (MPL) resonator and non-resonant (artifical dielectric) materials, Self-Aligned MPL-based tilted antennae absorbers/emitters.

deposition of a replica of the membrane pattern on the interior face(s) of the cavity.[19][20][21] The wafer-scale process can be repeated to create multilayer, "optically thick" 3D metamaterials.[22][23] Non-resonant structures may be printed to enable lower-loss "artificial dielectrics", and the cavity walls may be shaped or tilted to enable angularly selective absorption or emission, or other interesting effects.[24][25]

All-dielectric 3D metamaterials were developed under this program as a means of providing a low-loss path to manipulating both the magnetic and electric optical response. These dielectric resonator metamaterials must be fabricated from low-loss, high dielectric constant materials, which are plentiful in the microwave regime,[26][27] but are significantly more problematic at optical frequencies. After considering and characterizing a variety of materials, we have concentrated on Ge, Te, and TePb.[28][29] For example, Tellurium resonators arrayed on a Barium Fluoride substrate exhibit a magnetic resonance near 10 um wavelength and an electric resonance at a slightly shorter wavelength. The retrieved effective parameters indicate a negative permeability (permittivity) in the vicinity of the magnetic (electric) resonance.

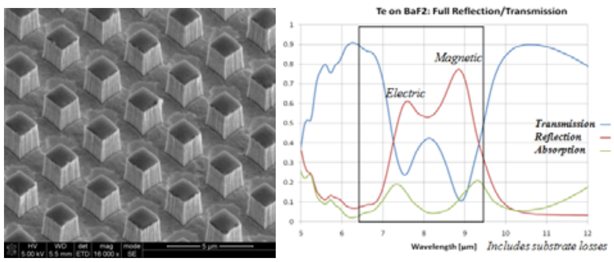

Figure 7. Te dielectric resonator optical metamaterial showing distinct electric and magnetic resonances in the LWIR (from [29]).

D. Test and Characterization

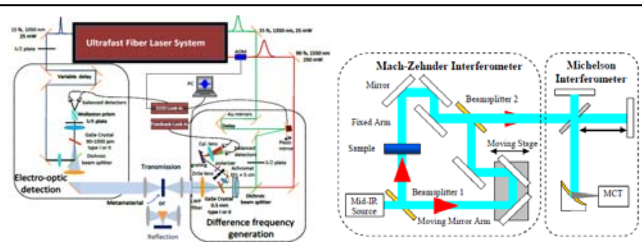

Figure 6. Phase-measuring IR metamaterial spectroscopy: IR Time Domain Spectroscopy (TDS) system, and IR Tandem InterferometricsSpectroscopy (TIS) system (from **Error! Reference**

Accurate characterization and parameter retrieval is a crucial aspect of the development of these metamaterials, and a variety of tools are being deployed, including both commercially available FTIR and IR ellispsometry, as well as custom-built tandem interferometric FTIR and ultrafast IR time-domain spectroscopy. At optical wavelengths, electric field resolved detection is difficult and metamaterial characterization is often done with FTIR, which unfortunately yields no information on the transmitted or reflected phase. However, the complex dispersion properties of 3D metamaterials ideally are retrieved from complex transmission and reflection measurements, and thus measurement of the absolute phase of advanced metamaterial systems is highly desirable. Additionally, access to the full electric field of IR transients can provide direct insight to the metamaterial response in both amplitude and phase, and may be crucial to developing three-dimensional resonant metamaterial composites or materials exhibiting electromagnetically induced transparency for slow light applications. To address these needs, we have developed two IR metamaterial phase-measuring spectroscopic analysis systems: an ultrafast electrooptic sampling IR Time Domain Spectroscopy (TDS) system, and a Tandem Interferometric Spectroscopy (TIS) system. Both are in use characterizing our IR metamaterials.

E. Tunable / Active Metamaterials

While the primary focus of the last three years was on passive metamaterials, this team has leveraged prior THz frequency work with LANL and ongoing work at CINT to make progress on demonstrating active tunable IR metamaterials.[32][33][34] This work on active metamaterials will continue under a new 3-year program at Sandia.

IV. Conclusions

Due to space constraints, this review only presents results from the Sandia metamaterials program (hence the lack of other references). This work represents a first step toward the development of low loss infrared metamaterials suitable for device applications. Similarly groundbreaking work is taking place in many leading universities, industrial groups, and government labs: this exciting field is well poised to move from a discovery science phase to application engineering studies.

Acknowledgments

The results presented in this overview are due to the ongoing efforts of the outstanding researchers listed as authors of the references, and we would also like to acknowledge the stimulating and productive academic, industrial, and government collaborations we've enjoyed during this work. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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