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Microfabrication of self-assembling elements for 3D negative-index materials

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A planar microfabrication process creates arrays of self-assembling nonplanar elements suitable for three-dimensional negative-index materials (3D-NIMs).

Negative-index materials (NIM) are a new class of materials (metamaterials) with simultaneous negative permittivity, ϵ, and negative magnetic permeability, μ, as analyzed by Victor Veselago.[1] This unconventional electromagnetic property allows unique and exotic applications, such as new designs in airborne radar, "perfect" thin-slab lenses with sharper images than conventional diffraction limits allow,[2,3] higher-resolution magnetic-resonance imaging, miniature antennas, and high-power communication-signal modulation.

One key strategy for engineering NIMs is constructing a periodic array of composite elements. These elements comprise both resonant negative-μ 'particles', which couple to the magnetic fields, and conducting negative-ϵ particles, which couple to the electric fields.[4–6]

The dimensions of the elements should be much smaller than the wavelength of interest, by a factor of 20-100, so that the incident electromagnetic radiation 'sees' a homogeneous material. Microwave realizations of NIM have been successful, but at higher terahertz, IR, and visible frequencies, the required particle size decreases. Therefore, innovative structures and precision fabrication processes are a pressing need.[7]

The large elements that comprise microwave NIMs have been limited in another way as well, because the particles used generate a field in only a single direction. In principle, the electromagnetic response can be extended from one dimension to 2D or 3D by incorporating additional particles with different orientations. Published work to date centers on 1D- and 2D-NIMs, however, because they are relatively easy to make using well-known printed-circuit-board lithography-macroassembly technology[4,8–13] and microlithography-macroassembly techniques.[7,14,15]

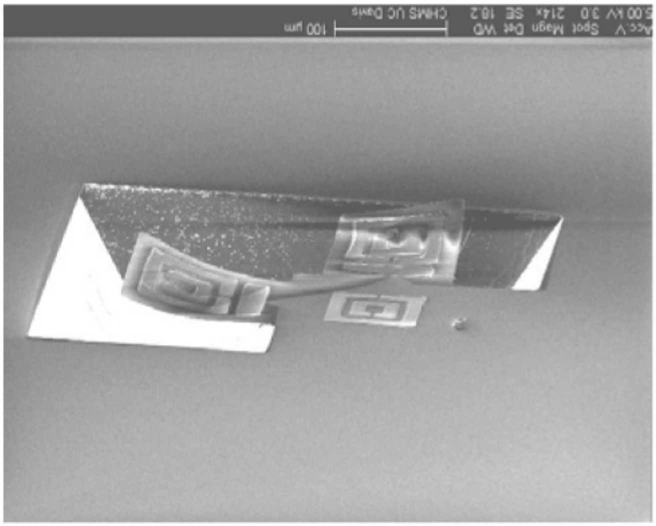

Figure 1. *In the self-assembled element, strain within a patterned bilayer film raises coils off of the substrate in two directions, providing the three axes of electromagnet response needed for a three-dimensional negative-index material (3D-NIM).*

The above-mentioned applications, however, would ideally employ 3D, homogeneous, isotropic NIMs (3D-NIMs).[5] As the size of individual NIM particles shrinks, however, fabrication and assembly grow more complex. Established technologies are not amenable to realizing 3D-NIM and do not support sub-millimeter ($<200\mu$m) feature sizes reliably. Coarse macroassembly of individual NIM particles or 2D substrate-gluing methods will not be advantageous for the high-quality, low-cost 3D-NIM media that are envisioned as building blocks for many future applications.[6,16–18]

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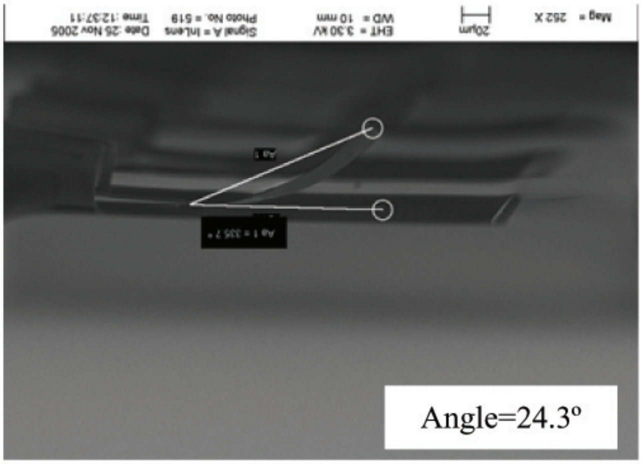

Figure 2. *The angle of curvature for the self-assembled NIM unit cell is about 25°.*

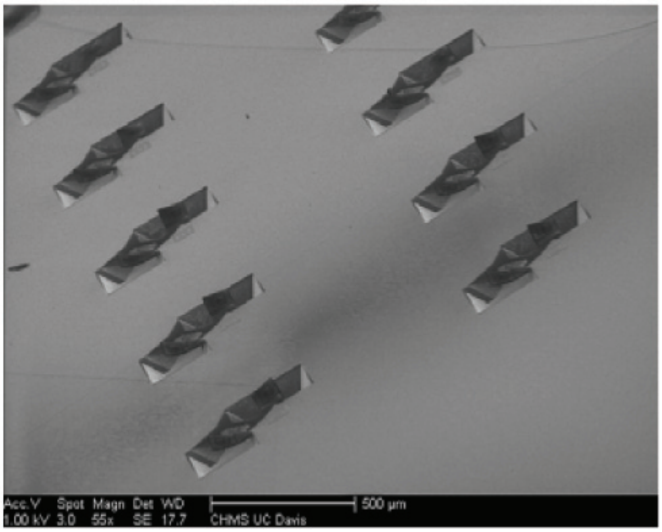

Figure 3. *Standard lithography yields an array of virtually identical self-assembled nonplanar elements suitable for 3D-NIM.*

Recently, true isotropic 3D-NIM implementations have been proposed theoretically by Costas Soukoulis[18] and He Sailing[19] via integrated split-ring-array-wire arrays and by George Eleftheriades[20] and Christophe Caloz[21] via transmission-line inductor-capacitor (LC) elements. To date, however, 3D microfabrication has only been demonstrated for a single unit cell of 3D-μ by Niels Quack et. al.[22]

To enable 3D-NIM topology, we developed a fabrication method using a low-cost and massively parallel microfabrication and self-assembly technique.[23] First, an array of elements was created through planar microfabrication techniques. The construction exploits the as-deposited residual stress imbalance in a bi-layer consisting an electron-beam-evaporated chromium metal layer and a structural layer of low-stress silicon nitride deposited on a silicon substrate. The thin chromium-and-silicon-nitride bi-layer is formed as hinges, and functions as the negative-ϵ material. The strain mismatch between the two layers curls the structural layer (a flap) containing the split-ring resonators (SRR) upwards. The self-assembled out-of-plane angular position depends on the thickness and materials comprising the bi-layer.

A periodic continuation of a single, rectangular unit cell consisting of SRRs and wires were then fabricated. The individual unit cells can be designed to be isotropic and arrays of the unit cells can be stacked to achieve larger 3D structures.

This built-in stress-actuated assembly method is suitable for applications requiring a thin dielectric layer for the SRR. The SRR and other structures are created on the membrane, which then self-assembles into the nonplanar configuration required for 3D electromagnetic response. The theoretical relationship for the metal-dielectric bi-layer has been derived[24,25] and successfully implemented for a single-cell portable 3D power source, nanophotonics, and 3D photonic crystals.[26]

Since the bi-layer hinge acts as the negative-ϵ element and the SRR acts as the negative-μ element, the SRR metal must be judiciously chosen to have a small interaction with the dielectric layer to avoid introducing secondary beam curvature. We used gold for the SRR particle and chromium for the hinge particle. The hinge length is chosen through the beam-curvature equation[24] so that the angle of the flap containing the SRR results in a negative μ. The hinge size depends also on the requirement for the negative ϵ values.[14] Hence the mechanical design, microfabrication design rules and electromagnetic properties must be optimized together.

Figure 1 shows a scanning-electron micrograph of a unit cell of the fabricated SRR and hinge. The self-assembled angle is $\sim 25^\circ$, as shown in Figure 2. Overall, the feasibility of the configuration is supported by the array that faithfully reproduces the unit cell, shown in Figure 3.

Our preliminary results have shown that mass manufacture of 3D-NIMs is feasible using a metal-dielectric-bilayer stress-actuated self-assembly. This fabrication method is scalable from microwave (10GHz) to optical frequencies (300THz) by appropriate choice of material, thickness, and release-etching chemistry. Efforts are currently underway to develop a parallel microfabrication and self-assembly process using a thicker released holding plate ($\sim$5 to 10 microns) with deformable hinges for the SRR and wires. Unlike the research-based approach of fabricat-

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ing a single structure for characterizing the unique properties of NIMs, our mass-manufacturable process may offer opportunities for reproducible fabrication of 3D-NIM materials with frequencies from the microwave to optical domain.

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