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Realization of 3D Isotropic Negative Index Materials using Massively Parallel and Manufacturable Microfabrication and Micromachining Technology

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ABSTRACT

In this paper, we present a method to realize a three dimensional (3D) homogeneous and isotropic negative index materials (3D-NIMs) fabricated using a low cost and massively parallel manufacturable microfabrication and microassembly technique. The construction of self-assembled 3D-NIM array was realized through two dimensional (2-D) planar microfabrication techniques exploiting the as-deposited residual stress imbalance between a bi-layer consisting of e-beam evaporated metal (650nm of chromium) and a structural layer of 500nm of low stress silicon nitride deposited by LPCVD on a silicon substrate.

A periodic continuation of a single rectangular unit cell consisting of split-ring resonators (SRR) and wires were fabricated to generate a 3D assembly by orienting them along all three Cartesian axes. The thin chromium and silicon nitride bi-layer is formed as hinges. The strain mismatch between the two layers curls the structural layer (flap) containing the SRR upwards. The self-assembled out-of-plane angular position depends on the thickness and material composing the bi-layer. This built-in stress-actuated assembly method is suitable for applications requiring a thin dielectric layer for the SRR. The split-ring resonators and other structures are created on the membrane which is then assembled into the 3-D configuration.

INTRODUCTION

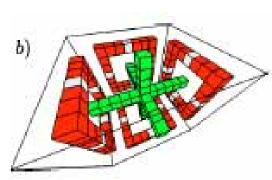
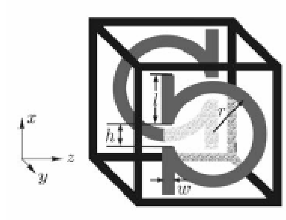
In the past 6 years, interests have grown in the research community on the "discovery" of materials that have been termed Metamaterials (MTM), also known as *Negative Index Material (NIM)*, Double Negative Media (DNM), Left-Handed Media (LHM), Backward Wave Media (BWM), and Negative Refractive Index media (NRI). These metamaterials are new class of artificial electromagnetic materials that exhibit unique properties that are consistent with simultaneous negative permittivity ($\varepsilon < 0$) and negative permeability ($\mu < 0$) as postulated by Veselago [1] some 40 years ago.

The existence of NIM was first experimentally verified by Smith and coworkers [2] from earlier work of Pendry and coworkers [3, 4] who introduced the first design for a negative permittivity, ε and permeability, μ material. Such an unconventional electromagnetic material property provides some unique and exotic application areas in, for example, new design in airborne radar, thin slab of “perfect” lenses where images are no longer subject to the conventional diffraction limits [5, 6], higher resolution magnetic resonance imaging, miniature antenna and high power communication signal modulation. In fact, it has also been shown that suitably arranged negative-only permittivity (ε<0) *and* negative-only permeability (μ<0) material instead of a single metamaterial can lead to some interesting device applications for imaging [7].

The key concept in achieving NIM is to construct a composite periodic array of NIM particles comprising: resonant elements that will couple to the magnetic fields and conducting elements that will couple to the electric fields. The dimensions of these particles should be much smaller than the wavelength of interest, such that, the incident electromagnetic radiation ‘sees’ a homogeneous material. Consequently, geometric consideration is critical for building a working NIM. Microwave realizations of NIM have been successful but once the NIM particle (or inclusion) size begins to decrease as the frequency range is pushed higher to THz, IR and optical frequencies, innovative structures and precision fabrication processes are among the pressing needs. For example, the recent demonstration of 1D-NIM at 200THz (λ=1.5μm) [8], necessitates a physical dimension of 50nm.

In principle, NIM could be one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D), but the choices become more limited as one gets closer to real applications. The realization of the above-mentioned applications of negative refraction, requires the fabrication of three dimensional (3D), homogeneous, isotropic NIM (“3D-NIM”) with simultaneously negative permittivity, ε and magnetic permeability, μ [3]. Despite substantial progress in the theory, numerical analysis and experimental investigation of NIM, no such 3D-NIM exists in nature or has been invented in the laboratory for any frequency range. It remains a technical and engineering challenge since 3D-NIM was first envisioned as the building blocks of many future applications [4, 9-11].

Only recently, possible true isotropic 3D-NIM (both μ < 0 and ε < 0) implementations have been proposed theoretically by C. Soukoulis [11], H.Sailing [12] via integrated SRR-wire arrays and G. Eleftheriades [13], C. Caloz [14] via transmission line *LC* elements as shown in Table 1. Till date, the use of 3D microfabrication method has been shown for a single unit cell of 3D-μ by N. Quack et. al [15].

NIM Method	**NIM Particle**	**Theoretical 3D-NIM [2005] Model**	
Scattering Resonator	SRR and/or Wire array	 Th. Koschny, L. Zhang, & C. M. Soukoulis [11]	 Simovski CR & H. Sailing [12]

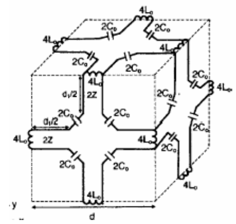
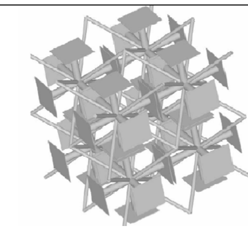
Transmission Line *LC*	*LC* arrays	 A. Grbica & G. V. Eleftheriades [13]	 C. Caloz & T. Itoh [14]

Table 1: Topologies for 3D-NIM implementation

FABRICATION METHOD

In an effort to realize a 3D-NIM topology, we demonstrate a fabrication method using a low cost and massively parallel manufacturable microfabrication and microassembly technique. The construction of self-assembled 3D-NIM array was realized through two dimensional (2-D) planar microfabrication techniques exploiting the as-deposited residual stress imbalance between a bi-layer consisting of e-beam evaporated metal (650nm of chromium) and a structural layer of 500nm of low stress silicon nitride deposited by LPCVD on a silicon substrate.

A periodic continuation of a single rectangular unit cell consisting of split-ring resonators (SRR) and wires were then fabricated to generate a 3D assembly by orienting them along all three Cartesian axes. The thin chromium and silicon nitride bi-layer is formed as hinges which also functioned as the negative permittivity material. The strain mismatch between the two layers curls the structural layer (flap) containing the SRR upwards. The self-assembled out-of-plane angular position depends on the thickness and material composing the bi-layer. This built-in stress-actuated assembly method is suitable for applications requiring a thin dielectric layer for the SRR. The split-ring resonators and other structures are created on the membrane which is then assembled into the 3-D configuration.

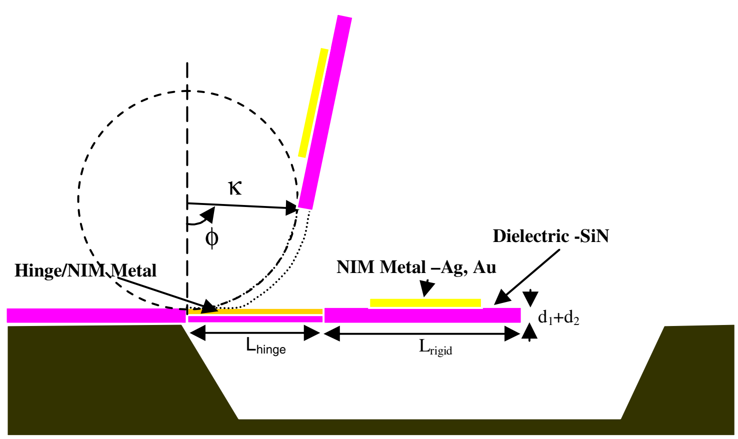


Figure 1. Cross-sectional view of a single flap SRR and hinge with release etch hole. Hinge (ε<0) and SRR (μ<0) on dielectric bi-layer deflection model.

The theoretical relationship for the metal-dielectric layer has been derived in [16, 17] and implemented for single cell portable 3D power source by In et. al [18].

The radius of curvature, R = 1/κ, is given by

$$R = \frac{t_2(1+m)\left[3(1+m)^2 + (1+mn)\left(m^2 + \frac{1}{mn}\right)\right]}{6\varepsilon_0(1+m)^2} \qquad \text{(Eqn 1)}$$

where ε_0 = initial strain, m = (t_1/t_2), n = (E_1/E_2), and t = $t_1 + t_2$. The length of the hinge can then be designed (mask dimensions) by deciding on the required angle that the flap containing the SRR to be set at for obtaining the negative permeability value through the beam-curvature equation, $L_{hinge} = R\theta$. Figure 2 shows a typical plot for the hinge length selection for a fixed value of strain and a flap that is orthogonal to the hinge. For a minimum curvature and hinge length, the minima region of the graph should be desirable i.e with a metal to nitride thickness of $0.54 < t_m/t_f < 0.56$. The hinge size depends also on the requirement for the negative permittivity values [19]. Hence there is a requirement for an optimization procedure between the mechanical design, microfabrication design rules and electromagnetic properties.

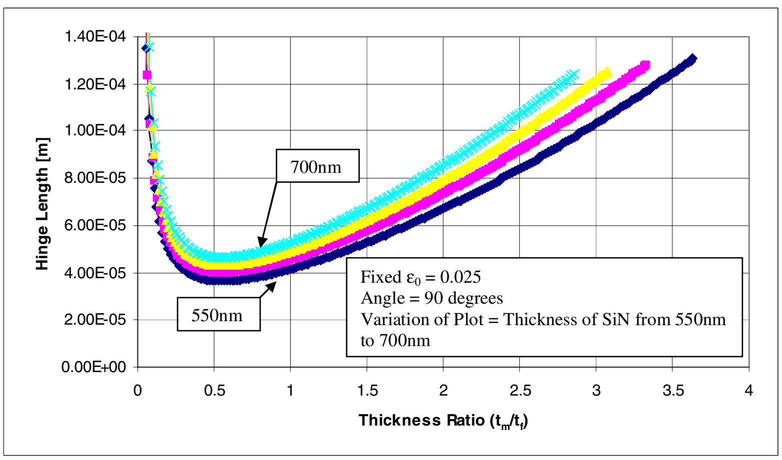


Figure 2. Hinge (ε<0) length for a given angle and metal-to-nitride thickness. The graphs are plotted for varying silicon nitride thickness from 550nm (dark blue) to 700nm (light blue). It is preferable to design in the region where t_m/t_f = 0.54 to 0.56.

Other design considerations include, for example, the rigidity of the dielectric flap with SRR metal patterned on it and the residual stress from that bilayer as well. Hence it is preferable to choose a metal with high Young's modulus for the hinge and vice versa for the SRR.

FABRICATION PROCESS

The fabrication process is depicted in Figure 3. A low-stress LPCVD nitride is grown on a p-type wafer and (A): patterned to form the SRR by e-beam deposition and lift-off. Next the wafer is re-patterned and the nitride at the opening for the hinge is thinned down by RIE to control the hinge length and the radius of curvature followed by hinge metal deposition, (B): the release etch holes are patterned by nitride RIE etch and the wafer is immersed in 45% KOH at

80°C etch bath for 6 hours. The released device is then rinsed in DI water and blow dried in N_2 carefully.

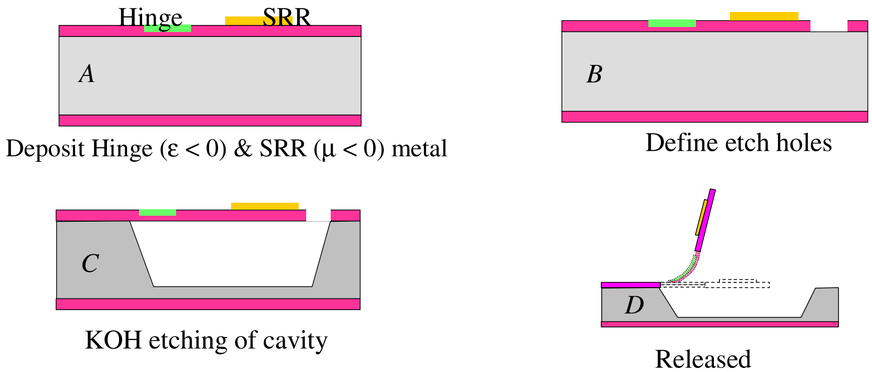


Figure 3. Process flow for the realization of 3D-NIM

CONCLUSIONS

The fabricated devices are shown in Figure 5. We have shown that using a metal-dielectric bilayer stress actuated self-assembly, realizations of 3D-NIM for microwave to optical is practical and mass manufacturable.

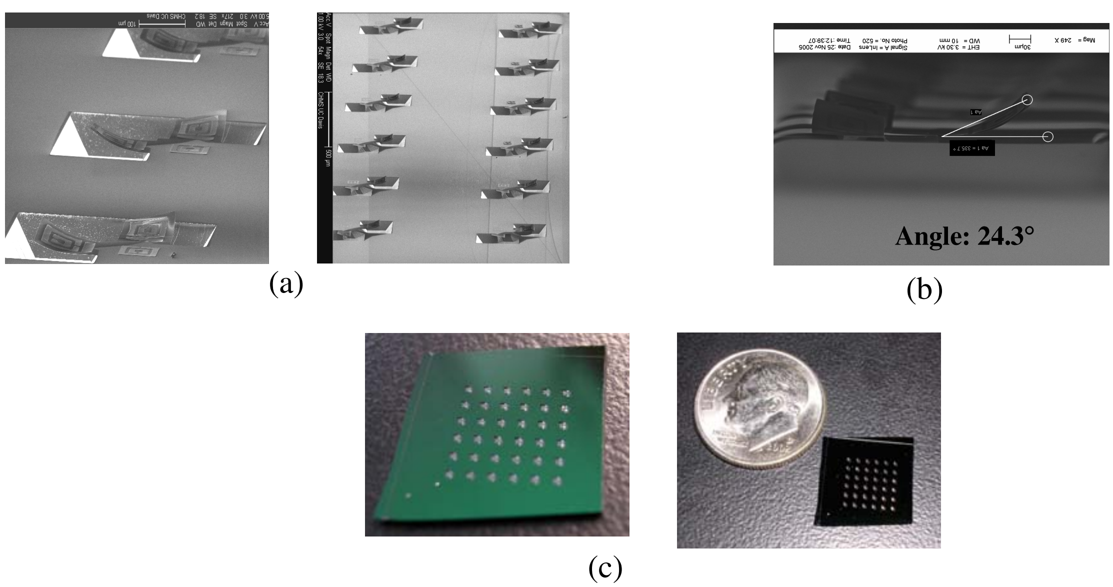


Figure 5. (a) SEM images of the 3D-array, (b) the angle of the flap with respect to the substrate & (c) final device size

Efforts are currently underway to develop a parallel microfabrication and self-assembly process using a thicker released holding plate (~5 to 10 microns) with deformable hinges for the SRR and wires. Unlike the research-based approach of fabricating a single structure for characterizing the unique properties of NIM, our mass-manufacturable process may offer opportunities for reproducible fabrication of 3D-NIM materials with frequencies from microwave to optical domain.

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