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STRUCTURAL COMPOSITES WITH TUNED EM CHIRALITY

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Final Report

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AFOSR FINAL PERFORMANCE REPORT

Grant/Contract Title:

STRUCTURAL COMPOSITES WITH TUNED EM CHIRALITY

Grant No.: FA9550-09-1-0528

Period of Performance: August 1, 2009 – September 20, 2014

PI: Sia Nemat-Nasser, UC San Diego

AFOSR Program Manager: Dr. Charles Lee AFOSR/NA

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Abstract [Status of Effort]

The AFOSR project on structural composites with tunable chiral elements has produced some impressive results in the past few years. These include (1) electronically tunable overall chiral composites, (2) mechanically tunable chiral composites, (3) flat lenses with soft hyperbolic focusing due to indefinite overall permittivity, (4) a tunable flat lens based on chiral elements with adjustable focal spot based on applied mechanical deformation, and (5) a three-phase periodic composite was created that demonstrates positive and negative refraction depending on the input frequency and angle of incidence. A MATLAB code directly computes the group velocity and pass bands for a given set of wave vectors and generates an intuitive plot for quick, but thorough, analysis.

Executive Summary

1. Summary of Significant Work Accomplished

1.1 Three-Phase Composite [April 1, 2014 – September 30, 2014]

Negative index materials have been developed in a variety of ways, including split-ring resonators and wire arrays. We have created a three-phase periodic composite that demonstrates positive and negative refraction depending on the input frequency and angle of incidence. A MATLAB code directly computes the group velocity and pass bands for a given set of wave vectors and generates an intuitive plot for quick, but thorough, analysis. Results for the periodic Rexolite-glass-air composite illustrated in Figure 1 show negative refraction on the second pass band (see Figure 2).

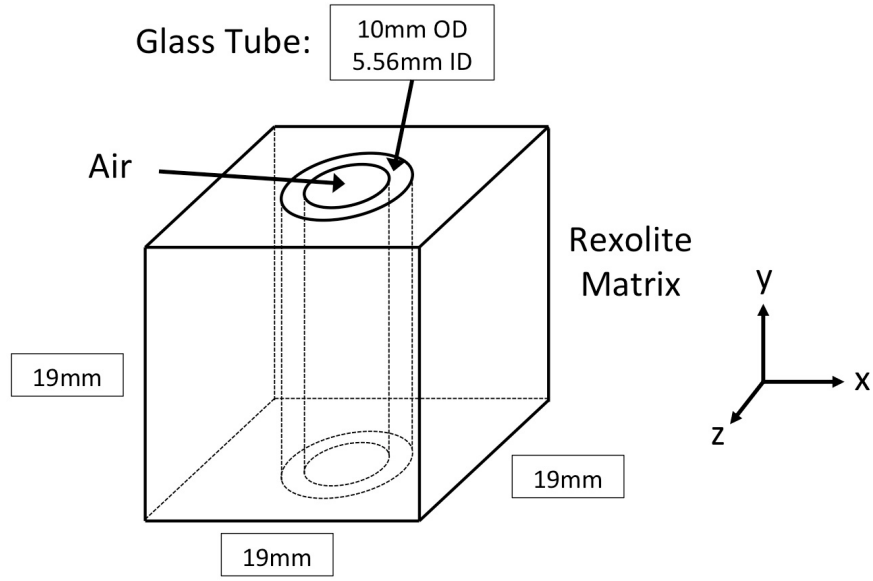


Figure 1: Unit cell for the periodic Rexolite-glass-air composite.

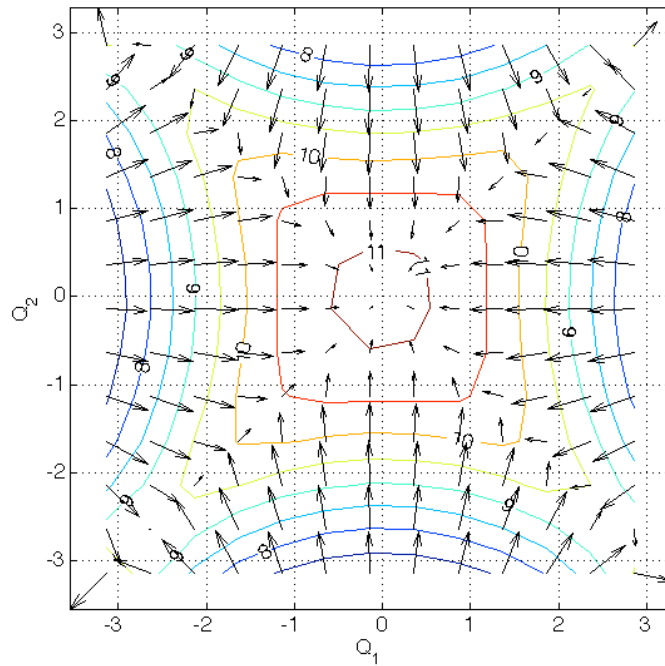


Figure 2: Plot of the second pass band calculated using MATLAB code. Black arrows represent group velocity.

An HFSS simulation models the material using a full-wave adaptive solution for the 1-12GHz frequency band with an incidence angle between 0 and 90deg. Experiments are underway with a 3-layer sample consisting of an array of hollow glass tubes in a Rexolite matrix. Thicker samples may be tested through the addition of extra layers. The sample is

placed in a polycarbonate-Fiberglas test fixture that is adjusted for the desired angles of incidence. A 3D scanning robot scans the desired test volume and the VNA sends and receives the field response in the form of S-parameters for the 7-12GHz frequency band. See Figure 3 for a schematic and a photo of the test setup.

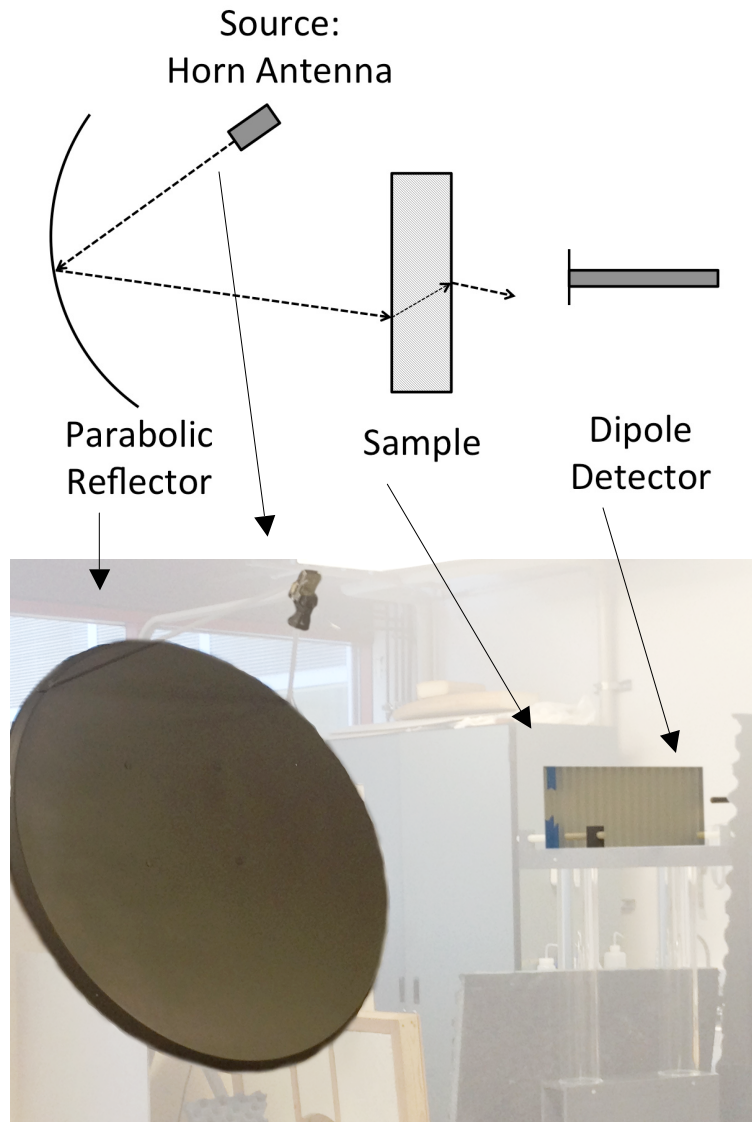


Figure 3: Schematic of the test configuration (top) and actual test setup (bottom).
Note: Schematic not to scale.

Tests of the fixture with and without the sample(s) will be normalized with respect to air. The measured S-parameters will indicate the stop and pass bands in the frequency range and will be correlated with the numerical predictions. Preliminary results are shown in Figure 4. For this plot, the sample data is normalized with respect to the test fixture without the sample. In other words, the data presented represents gain over the test fixture and air.

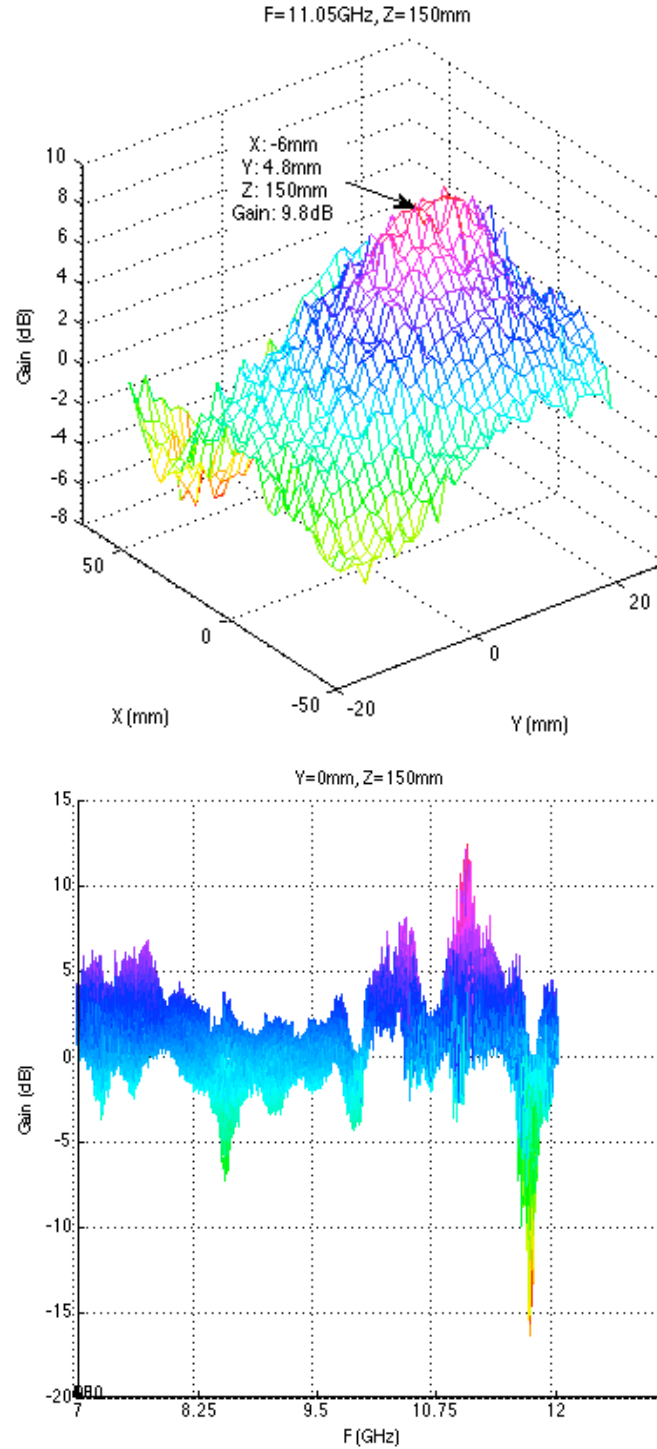


Figure 4: Measured gain over test fixture and background for the XY test area (top) and frequency (bottom) at 150mm from the sample surface.

1.2. Abstract of PhD Dissertation

S. Wheeland “Metamaterial Composites with Tunable Electromagnetic Properties” University of California, San Diego. ProQuest/UMI, February 2013.

A broadening application range has increased demand for advanced RF control. Recent research has identified several metamaterials to provide this control. This work seeks to expand this idea through several novel metamaterials with enhanced electromagnetic properties. First copper wires braided with Kevlar and nylon to form conductive coils are woven among structural fiber to create a fabric. This yielded a composite with all coils possessing the same handedness, producing a chiral material. The measured scattering parameters showed considerable chirality within the 5.5-8GHz frequency band, agreeing with simulation results.

Electronic chirality tuning is investigated by integrating varactor diodes into an array of helical elements on a printed circuit board. Applying a varied reverse bias voltage across the sample effectively tunes the chiral behavior of the material. The measurements demonstrate the feasibility of creating a rigid helix composite with tuned chirality in the 5.5-12.4GHz frequency band.

Chirality can be further tuned mechanically through the deformation of an array of conductive coils. Parallel, metallic helices embedded in a polyurethane matrix are subjected to mechanical stretching for pitch adjustment. This change in pitch directly affects the overall chirality of the composite. Repeatable elastic deformation is achieved up to 50% axial strain. Over the 5.5-12.5GHz frequency range, an increase of 30% axial strain yields an ~18% change in axial chirality.

Hyperbolic microwave focusing is explored through an indefinite medium with anisotropic permittivity. An array of 12-gauge brass wires is embedded in Styrofoam and scanned over the 7-9GHz frequency band to establish focusing patterns. A soft-focusing spot is observed at 7.6GHz with a relative gain of ~7dB over averaged background.

Applying an axial refractive gradient to a coil composite creates a lens capable of fine adjustment in the microwave range. The gradient required to achieve sharp focusing, and the extent of this effect, is calculated through an anisotropic ray-tracing analysis. A composite is created using coils of opposite handedness to minimize chiral effects. Through extension of these coils, the refractive index can effectively be fine-tuned to achieve the desired result. Measurements and full-wave simulations confirm a gain of 6-8dB over averaged background at the predicted focal frequencies.

1.3. Abstracts of Archival Papers

C. J. Schuil, A.V. Amirkhizi, F. Bayatpur and S. Nemat-Nasser, “Composites with Mechanically Tunable Plasmon Frequency,” *J. Smart Materials and Structures*, Vol. 20 (2011) 115012 [5pp]

This paper summarizes our efforts to create a composite material with a mechanically tunable plasmon frequency at the microwave band. The permittivity of the composite changes sign at the plasmon frequency. Such composites, therefore, can be used as electromagnetic filters. Theoretically, an array of non-magnetic, metallic wire coils has been shown to have a plasmon behavior that is dependent on the wire thickness, coil inner diameter, pitch and coil spacing. Here, a material is made out of an array of coils placed within a non-metallic frame, and the material plasmon frequency is tuned through altering the pitch. The coils are arranged with alternating handedness to create an effective, non-chiral medium. A transmit/receive setup is used to characterize the electromagnetic behavior of the composite. The setup consists of a vector network analyzer and two horn antennas, which are used to measure the scattering parameters of the material. These parameters are then used to calculate the permittivity. The results show an increase in the plasmon frequency with increase in the pitch. Increasing the pitch 30%, from 3 to 3.9 mm, results in a corresponding increase from 6.3 to 7.5 GHz in the frequency.

F. Bayatpur, A. V. Amirkhizi, S. Nemat-Nasser, “Experimental Characterization of Chiral Uniaxial Bianisotropic Composites at Microwave Frequencies,” *IEEE Trans. Microwave Theory and Techniques*, Vol. 60, No. 4 (2012) 1126-1135

This paper presents an experimental procedure for retrieving the effective constitutive parameters of chiral materials. Unlike past research that primarily deals with isotropic materials, this study considers a glossy uniaxial bianisotropic slab with a nonzero chirality along its axial direction. First, plane-wave scattering off the uniaxial slab in a free-space environment is studied analytically. This forward analysis gives insight into the problem and the choice of proper independent measurements required for the inverse process, i.e., retrieving the slab constitutive parameters from its $\mathbf{S}$ -parameters. Based on this analysis, three sets of co-polarized and cross-polarized $\mathbf{S}$ -parameters are required, including both the transmission and reflection coefficients of the slab. Given the measured scattering data, the complex permittivity, permeability, and chirality tensors are determined numerically using the results of the analytic study. To test the performance of the new retrieval method, an array of 256 long, metallic helices is designed and fabricated for operation at $\mathbf{S}$ -band. Having the same handedness, the helices are closely spaced and held in parallel to each other in a wooden frame in order to create an effective uniaxial chiral medium. A conventional transmission/reflection setup measures the array scattering parameters, which are fed into the retrieval process to obtain the effective parameters. The measured parameters well model the array scattering response, exhibiting a significant averaged chirality of 0.4 over 5.5–8.7 GHz and a plasmonic behavior at 7.1GHz.

S. Wheeland, F. Bayatpur, A. V. Amirkhizi, and S. Nemat-Nasser, “Elastomeric Composites with Tuned Electromagnetic Characteristics,” *Smart Mater. Struct.* Vol. 22 (2013) 015006 (6pp)

This paper presents a novel elastomeric composite that exhibits a deformation-induced change in chirality. Previous efforts primarily dealt with a coil array in air without chiral tuning. Here, a composite is created that consists of an array of parallel, metallic helices of the same handedness embedded in a polymer matrix. The chiral response of the composite depends on pitch, coil diameter, wire thickness and coil spacing; however, pitch has the greatest effect on electromagnetic performance. The present study explores this effect by using helical elements to construct a chiral medium that can be mechanically stretched to adjust pitch. This adjustment directly affects the overall chirality of the composite. A prototype sample of the composite, fabricated for operation between 5.5–12.5 GHz, demonstrates repeatable elastic deformation. Using a transmit/receive measurement setup, the composite scattering response is measured over the frequency interval. The results indicate substantial tuning of chirality through deformation. An increase in axial strain of up to 30% yields a ~18% change in axial chirality.

F. Bayatpur, S. Wheeland, A. Amirkhizi and S. Nemat-Nasser, “ A Varactor-Tuned Helix-Based Chiral Layer” *J. IEEE Microwave and Wireless Components Letters*, Vol. 23, No. 5 (2013) 246-248

Tuning performance of a chiral layer using varactor diodes is presented here. The chiral structure consists of an array of metallic long helices fabricated in parallel on a PCB. The helices have the same handedness, sub-wavelength diameter, pitch, and spacing in the array. Varactor diodes are incorporated into the array to tune array cross-polarized transmission response, a qualitative measure of the effective tuned chirality. Each helix is connected to one of its neighboring helices through a set of varactors placed between them. Array has one varactor per one helix pitch. The tuning performance of the chiral array transmissivity is measured over frequency band of 5.5–12 GHz with the bias voltage sweeping from 1 to 15 V. Voltage tuning changes each varactor capacitance from 0.9 to 0.13 pF. This results in ~50% increase in the cross-polarization peak frequency, changing it from 6 to 9 GHz, for a linear polarization incidence perpendicular to the helices. Tuning rotates the transmitted wave polarization ellipse by ~15%.

2. Scientific Personnel

Dr. Alireza V. Amirkhizi (9/09 to 1/31/14) – Assistant Research Scientist – research focused on experimental and analytical methods for design and characterization of electromagnetic and mechanical properties of novel tunable chiral and bianisotropic composites.

Dr. Farhad Bayatpur (9/09 to 9/11)- Postdoctoral Research Employee – research focused on developing chiral and bianisotropic composite structures with enhanced mechanically and electronically tunable attributes, in addition to developing a characterization method.

Dr. Yuanyuan Chen (9/13 – 9/14) – Visiting Scholar - research focused on metamaterial and

computations of electromagnetic characteristics in 2D photonic crystals.

Tammuz Dubnov (7/14 – 9/14) – Laboratory Assistant - assisted in the testing of the material as well as optimization of the analytical code

Dr. Sara (Marshall) Wheeland (9/09 – 9/14) – Graduate Student Researcher – research focused on full-wave finite element simulation and experimental characterization, including sample/test frame design and testing, of microwave metamaterials. Ph.D. conferred 2/2013. Staff Research Associate 5/2014 – 9/30/2014.

3. Archival Publications/Conference Proceedings/Dissertation

1. Schuil, C.J., A.V. Amirkhizi, F. Bayatpur and S. Nemat-Nasser, “Composites with Mechanically Tunable Plasmon Frequency,” *J. Smart Materials and Structures*, Vol. 20 (2011) 115012 (5pp).
2. Bayatpur, F., A. V. Amirkhizi and S. Nemat-Nasser, “Experimental Characterization of Chiral Uniaxial Bianisotropic Composites at Microwave Frequencies,” *IEEE Trans. Microwave Theory and Techniques*, Vol. 60, No. 4 (2012) 1126-1135.
3. Wheeland, S., F. Bayatpur, A. V. Amirkhizi and S. Nemat-Nasser, “Elastomeric Composites with Tuned Electromagnetic Characteristics,” *Smart Mater. Struct.*, Vol. 22 (2013) 015006 (6pp).
4. Wheeland, S., F. Bayatpur, A. V. Amirkhizi and S. Nemat-Nasser, “Chiral Braided and Woven Composites: Design, Fabrication, and Electromagnetic Characterization,” *Proceedings of Behavior and Mechanics of Multifunctional Materials and Composites, SPIE Annual International Conference on Smart Structures/NDE*, Vol. 7978 797812-1 (2011).
5. Bayatpur, F., S. Wheeland, A. Amirkhizi and S. Nemat-Nasser, “A Varactor-Tuned Helix-Based Chiral Layer” *J. IEEE Microwave and Wireless Components Letters*, Vol. 23, No. 5 (2013) 246-248.
6. Wheeland, S, “Metamaterial Composites with Tunable Electromagnetic Properties,” PhD Dissertation, University of California, San Diego. ProQuest/UMI, February 2013.

4. Conferences/Symposia Presentations

“Design and Characterization of a Mechanically Tunable Gradient Index Lens,” S. Wheeland, A. Amirkhizi and S. Nemat-Nasser, Symp. Multi-Field Studies in Heterogeneous Materials: Experimental, Theoretical and Numerical Approaches, ASME 2013 International Mechanical Engineering Conference and Expo, San Diego, CA, Nov. 15-21, 2013. [Poster Presentation]

“Microwave gradient index lens design with mechanically tunable permittivity,” A. V.

Amirkhizi, ASME 2012 International Mechanical Engineering Conference and Expo, Houston, TX, Nov. 9-15, 2012.

“Structural Composites with Tuned Electromagnetic Chirality,” A. V. Amirkhizi [Poster presented by Sara Wheeland], AFOSR TriService Meta Review, Virginia Beach, VA, May 2012.

“Structures and Composites with Mechanically Tunable Electromagnetic Properties,” A. Amirkhizi, C. Schuil, S. Wheeland and F. Bayatpur, Symposium on Multiscale Mechanics of Composites with Coupled Mechanical and Nonmechanical Behaviors, ASME 2011 International Mechanical Engineering Conference and Expo, Denver, CO, Nov. 14-17, 2011.

“A Method for Retrieving the Constitutive Parameters of Chiral Uniaxial Bianisotropic Media,” F. Bayatpur 2011 IEEE International Symposium on Antennas and Propagation, Spokane WA, July 3-8, 2011.

“Chiral Braided and Woven Composites: Design, Fabrication, and Electromagnetic Characterization,” S. Wheeland, 2011 SPIE Annual International Conference on Smart Structures/NDE, Symposium on Behavior and Mechanics of Multifunctional Materials and Composites, March 6-10, 2011 San Diego, CA

“Stress-Wave with Anti-parallel Phase and Group Velocities in Structural Composites,” S. Nemat-Nasser, UC San Diego Physics Symposium, November 4, 2010.

“Mechanically-Tunable composite filter at low frequencies,” S. Wheeland, A. Amirkhizi and S. Nemat-Nasser, SPIE 2010 Conference – Behavior and Mechanics of Multifunctional and Composite Materials, San Diego, CA, March 7-11, 2010.

“Mechanically tunable Plasmon frequency using a spring array,” C. Schuil, A. Amirkhizi, J. Isaacs and S. Nemat-Nasser, SPIE 2010 Conference - Behavior and Mechanics of Multifunctional and Composite Materials, San Diego, CA, March 7-11, 2010.

“Mechanical tuning of electromagnetic constitutive parameters in composites,” A.V. Amirkhizi, C. Schuil, S. Marshall, and S. Nemat-Nasser, ASME 2009 International Mechanical Engineering Conference and Expo, Florida, November 13-19, 2009.

5. New Discoveries, Inventions, or patents. None