46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-1234

# MODEL BASED STUDY OF A METAMATERIAL LENS FOR NDE OF COMPOSITES

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## ABSTRACT

*Metamaterials have been increasingly used in the past few decades in the design of novel microwave circuits and sensor systems. Superlens is a lens which utilizes metamaterials to achieve resolution beyond the diffraction limits. The unique properties of metamaterials offer several advantages such as sub-wavelength nature, compact design and super-resolution, that is not found in conventional materials. This contribution focuses on the physical design of the metamaterial lens. The theoretical approach behind such a design, followed by simulation results will be presented to investigate the viability of using the metamaterial lens for NDE of composites.*

Keywords: metamaterials, superlens, composites, sub-wavelength defects

## NOMENCLATURE

| | |
|---|---|
| n | refractive index |
| μ | permeability |
| ε | permittivity |

## 1. INTRODUCTION

Composites have gained large attraction over the past few years and have replaced metals in industries due to its high strength, flexibility and light weight [1]. Hence, there is a need for reliable NDE sensors for composites which can reliably detect crucial anomalies that can affect the performance of these structures such as disbonds, voids and delaminations [2].

Far field microwave sensor systems have advantages of rapid scan time and hence fast detection of large areas of composites. However, the spatial resolution is limited due to the imposition of the diffraction limits [3]. Near field microwave sensor systems have better spatial resolution but the probe stand-off distance is very small leading to high scanning time, which can be an issue for practical implementations [4].

A metamaterial lens, also called a superlens combines the advantages of both near field and far field sensors in the sense that it can work at large scanning distances and provide high resolution. Prior experimental results have demonstrated the ability of such a lens with a relative refractive index of -1, to form images that overcome diffraction limits [5]. Recent work has demonstrated the application of utilizing such a lens to increase the sensitivity for detecting defects [6], in isotropic dielectric materials. The design of the lens has not yet been optimized for NDE and sub-wavelength imaging of composite materials. The motivation of our work is to develop a microwave NDE sensor which will make use of the unique properties of a metamaterial lens for detection of defects in composites.

## 2. METAMATERIAL LENS

Artificially manufactured periodic structures with unique electromagnetic properties which are not readily available in nature are known as metamaterials. The unique electromagnetic properties of metamaterials are attributed primarily to simultaneous negative permittivity ε and permeability μ which results in a negative refractive index at certain frequencies. Equation (1) gives the relationship between refractive index with permittivity and permeability for metamaterials.

$$n = -\sqrt{\mu\varepsilon} \tag{1}$$

Negative refractive index gives rise to unique physical phenomena inside such a material such as reversal of Snell's law, enhancement of evanescent waves, reversal of Doppler effect and reversed Cherenkov radiation [7]. The effect of the reversal

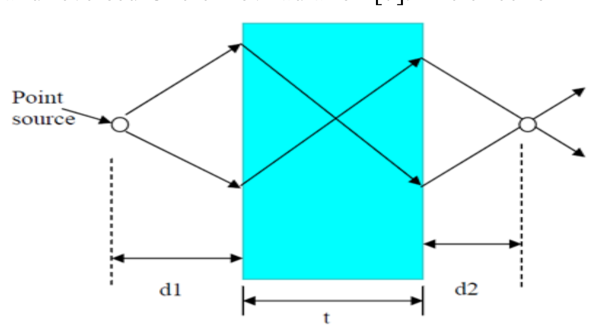


**FIGURE 1:** RAY DIAGRAM OF A SUPERLENS

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of Snell's law can be demonstrated in Figure 1. When a point source is placed in front of a lens of appropriate thickness with refractive index n=-1, the waves are refracted in such a way so that the waves focus once inside the lens and then outside the lens. The relationship between distance of the source from lens d1, focusing distance d2 and thickness of the lens t for the metamaterial lens with refractive index equaling -1 can be expressed as

$$d1 + d2 = t \qquad (2)$$

Additionally, the amplitude of the evanescent wave which contain the high frequency information amplifies inside the metamaterial lens. While they decay exponentially over the direction of propagation and hence not transmitted in a conventional medium, Pendry demonstrated in [8] using strictly causal calculations that these waves are amplified in metamaterials. This phenomena of magnification of evanescent waves along with the perfect focusing nature of the superlens can be taken advantage of in detection of sub-wavelength defects. Figure 2 shows the schematic of the proposed NDE system with the metamaterial lens. Fields transmitted from the source are focused by the lens at the sample. The scattered fields from the defect will be stronger due to the focused fields and amplified evanescent waves in the presence of the lens. The scattered fields can be captured by the receiver array and processed with an imaging algorithm that will provide high resolution information about the sample. Next section discusses the theory governing metamaterials and the unit cell design of a physical lens while section 4 includes some initial results and discussion.

## 3. THEORY AND UNIT CELL DESIGN

### 3.1 Metamaterial Theory

The dielectric permittivity ε of a metamaterial as a function of frequency is given by [9],

$$\varepsilon(\omega) = 1 - \frac{\omega_P{}^2}{\omega(\omega+i\gamma)} \qquad (3)$$

where, $\omega_p$ is the plasma frequency and γ is the damping factor for dissipation. Equation 3 indicates that ε(ω) is essentially negative below plasma frequency. An array of thin metallic wires can be utilized in order to achieve negative


**FIGURE 2:** PROPOSED MICROWAVE NDE SYSTEM USING A METAMATERIAL LENS

permittivity at microwave frequencies [9]. The magnetic permeability μ of a metamaterial as a function of frequency is given by [8],

$$\mu(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_o{}^2 + i\gamma\omega} \qquad (4)$$

, where $\omega_o$ is the resonant frequency and F is the fractional volume of. Equation 4 indicates that propagating modes exist till $\omega_o$ and then after $\omega = \omega_o/\sqrt{1\text{-}F}$. The stopband exists due permeability being negative over the region. In [10], it was proposed that an array of conducting loops can be utilized in order to achieve negative permeability at microwave frequencies.

### 2.2 Unit cell design

Combining both wire and ring structures in a periodic manner gives rise to materials having a unique property of simultaneously negative permittivity and permeability (double negative medium). The dimensions of the unit cell representing the metamaterial periodic array structure must be much smaller than the operating wavelength to act as an effective medium. This is a required condition for the EM waves to physically interact with the lens as a homogenous medium with distinct macroscopic properties of effective permittivity and effective permeability. Figure 3 shows the unit cell design of the metamaterial lens comprising of thin wires and split ring resonators (SRRs). The splits in the rings are introduced to make the rings resonant at wavelengths much larger than the diameters of the rings. We have used a 1.6 mm thickness FR4 as the substrate. The unit cell is designed to operate at 3.5 GHz range. The dimensions of the unit cells are as follows; a=9.3mm, r=2.5mm, t=w=0.9mm, g=c=0.2mm.

## 4. RESULTS AND DISCUSSION

Initial simulation studies using Ansys HFSS demonstrate the left handed behavior of the lens using periodic SRRs and wires. The electric field was polarized parallel to the wires (x direction) while the magnetic field was polarized parallel to the surface of the unit cell (y direction). We have followed the method of extraction of electromagnetic parameters for homogenous methods to determine the refractive index of our metamaterial design [11]. As seen from figure 4, the refractive index of our simulated unit cell model using periodic boundary conditions is equal to -1 at 3.46 GHz.

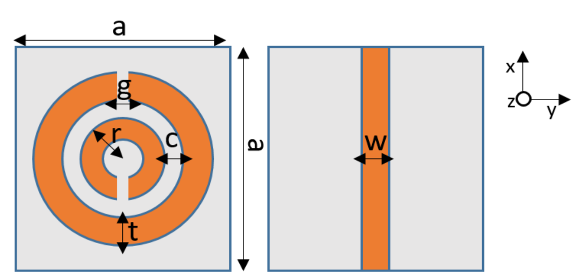


**FIGURE 3:** UNIT CELL DESIGN

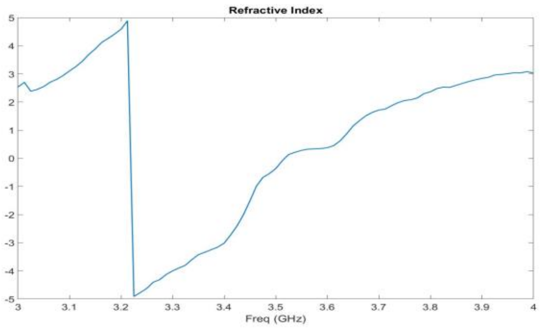


**FIGURE 4:** REFRACTIVE INDEX OF UNIT CELL

Finally, we studied the transmission characteristics of the metamaterial lens using 10x10 unit cells along x and y directions and 4 such layers along direction of propagation (z direction). As can be seen from Figure 5, a left handed transmission peak is obtained at 3.7 GHz as expected. The transmission characteristics is consistent with that reported in literature for a metamaterial lens [12].

The authors of the paper have already demonstrated the idea of sub-wavelength imaging with time reversal using a super lens in [13]. The concept was studied using electromagnetic numerical simulations considering a homogenized double negative layer as the metamaterial lens. This result shows the promise of using periodic, discrete components for the physical design of the lens in order to achieve the required homogenized negative refractive index property.

## 4. CONCLUSION

This work discusses the physical design of a metamaterial lens for NDE of composites. Initial modelling describing the unit cell as well the whole structure of the superlens is performed. Simulation studies show the left handed nature of the lens design which is the basis of our proposed work. While, prior research on numerical modelling of the NDE system comprising a source, receiver and composite sample along with the lens was studied to determine its feasibility, this research focuses on the design of the discrete, periodic structures describing the physical metamaterial lens. Future work will be focused on fabrication of the lens, experimental validation and imaging experiments in order to detect sub-wavelength defects in composite materials, thus transcending the diffraction theory limits in conventional systems.

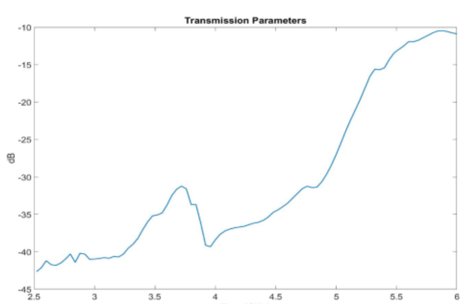


**FIGURE 5:** LEFT HANDED TRANSMISSION PEAK OF METAMATERIAL LENS


## ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation through Manufacturing USA program, award number 1762331.


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