AFRL-AFOSR-UK-TR-2012-0001

Fundamentals of Metamaterials for High-power RF Applications

Rebecca Seviour

Lancaster University
Department of Physics
Lancaster, United Kingdom LA1 4YB

EOARD GRANT 10-3082

Report Date: February 2012

Final Report for 21 June 2010 to 21 June 2011

Distribution Statement A: Approved for public release distribution is unlimited.

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***
08-02-2012

2. REPORT TYPE
Final Report

3. DATES COVERED *(From – To)*
21 June 2010 – 21 June 2011

4. TITLE AND SUBTITLE
Fundamentals of Metamaterials for High-power RF Applications

5a. CONTRACT NUMBER
FA8655-10-1-3082

5b. GRANT NUMBER
Grant 10-3082

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Rebecca Seviour

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lancaster University
Department of Physics
Lancaster, United Kingdom LA1 4YB

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
EOARD
Unit 4515 BOX 14
APO AE 09421

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR/RSW (EOARD)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-UK-TR-2012-0001

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited. (approval given by local Public Affairs Office)

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Microwave metamaterials have shown promise in numerous low power applications, ranging from strip lines to antennas. In general, metamaterials allow microwave designers to obtain electromagnetic characteristics not typically available in nature, leading to new behavior as well as reductions in the size of typical devices. High Power Microwave (HPM) sources have in the past drawn inspiration from work done in the conventional microwave source community. This programme of research focused on several key elements critical for the development of metamaterials for future HPM devices; the effects of disorder in metamaterials, the effect of high power on the material, and a comparative analysis of different realizations of metamaterial "atoms".

This work has been carried out by Prof. Rebecca Seviour, Dr. Elena Luchinski and Dr. Yap Soon Tan, at the University of Lancaster (UK), in collaboration with Dr. Don Shiffler, Erin Stranford, Wilkin Tang , and David French, of the Air Force Research Laboratory/ Directed Energy Directorate, Kirtland AFB, NM.

15. SUBJECT TERMS
EOARD, high power microwave, RF Application

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18, NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			SCOTT DUDLEY, Lt Col, USAF
UNCLAS	UNCLAS	UNCLAS	SAR	11	19b. TELEPHONE NUMBER *(Include area code)* +44 (0)1895 616162

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

EOARD Grant 103082 - final report

Author/Grant holder: Prof. Rebecca Seviour

Abstract

Microwave metamaterials have shown promise in numerous low power applications, ranging from strip lines to antennas. In general, metamaterials allow microwave designers to obtain electromagnetic characteristics not typically available in nature, leading to new behavior as well as reductions in the size of typical devices. High Power Microwave (HPM) sources have in the past drawn inspiration from work done in the conventional microwave source community. This programme of research focused on several key elements critical for the development of metamaterials for future HPM devices; the effects of disorder in metamaterials, the effect of high power on the material, and a comparative analysis of different realizations of metamaterial "atoms".

This work has been carried out by Prof. Rebecca Seviour, Dr Elena Luchinski and Dr Yap Soon Tan, at the University of Lancaster (UK), in collaboration with Dr Don Shiffler, Erin Stranford, Wilkin Tang, and David French, of the Air Force Research Laboratory/ Directed Energy Directorate Kirtland AFB.

Introduction

Recent years have seen a burgeoning interest in the physics and applications of metamaterials. Briefly, metamaterials consist of a periodic array of sub-wavelength structures that produce an electromagnetic response not typically available in nature. Such structures, in the form of wire arrays or conducting spheres, received attention in the 1940s and 1950s as "artificial dielectrics". However, after fundamental work by Pendry, Smith, and colleagues, the area gained new impetus, particularly with applications in the infrared to optical regime. Modern computer simulation techniques have added greatly to the advances in this field. Notably, composites of these structures in general exhibit both frequency and spatial dispersion, leading to a rich variety of physical phenomena, such as backward wave propagation and a negative refractive index.

Metamaterials have received little attention in the HPM area, with the exception of work considering the use of a wire array as an artificial dielectric for a Cerenkov maser as well as novel research investigating the use of a metamaterial in a serpentine waveguide traveling wave tube (TWT). In the case of the Cerenkov maser, the metamaterials act to produce, within a given frequency band, nearly the same characteristics as a conventional dielectric, but with an all-metallic structure. In the case of the TWT, the metamaterial introduces new regimes of operation unavailable with standard slow wave structures. In contrast to electron beams numerous authors have considered the interaction of single charges with metamaterials. A vast literature exists concerning Cerenkov radiation in a metamaterial, a topic of some interest due to the backward wave nature of the interaction. Authors have examined the passage of single electrons through a bulk metamaterial, in direct correspondence with Cerenkov radiation in double positive materials. The principal difference lies in the excitation of backward waves by the moving charge. This phenomenon attracted the attention of the accelerator community due to the backward wave nature and the reduction of wakefields in accelerator structures.

Importantly, metamaterials offer two key advantages for HPM source design. First, they offer the possibility of exploiting new forms of interaction previously unavailable for microwave source design. Additionally, they offer a path to reduce the dimensions of standard HPM sources and components, gaining significant size advantages for the source designer. Both issues, however, hinge on the ability to find sub-wavelength, resonant structures in configurations that can withstand the harsh operating environment of an HPM device.

Effects of disorder in metamaterials: (*Paper submitted to IEEE Science of Plasmas*) In this activity we considered a configuration in which an array of split-ring resonators, forming a “mu-negative” structure, allows transmission of power in a waveguide well below the cut-off frequency. This configuration would not be used in an actual HPM device, but explores the methods and considerations that might be required for developing a metamaterial structure for either making HPM sources more compact or developing new types of interaction at these high powers. For any HPM application, a microwave structure must be able to sustain high electric and magnetic fields, as well as high peak and possibly average power. The challenge for metamaterials consists of devising the sub-wavelength structures (a defining characteristic of metamaterials) that can sustain such fields. In particular, one must understand the sensitivity of any metamaterial system to changes in the individual elements, which in the case of high power pertains mainly to the loss of an individual resonator element. As such a sample system, we explored the physical operating characteristics of the waveguide system loaded with an array of split ring resonators (SRR) with particular emphasis upon the role of defects on its properties. Such defects would form an important feature in any high power application in which sub-wavelength structures can be damaged by high field stresses. We examined the physics of microwave propagation below cut-off using a split-ring resonator array, via both numerical models and experiments.

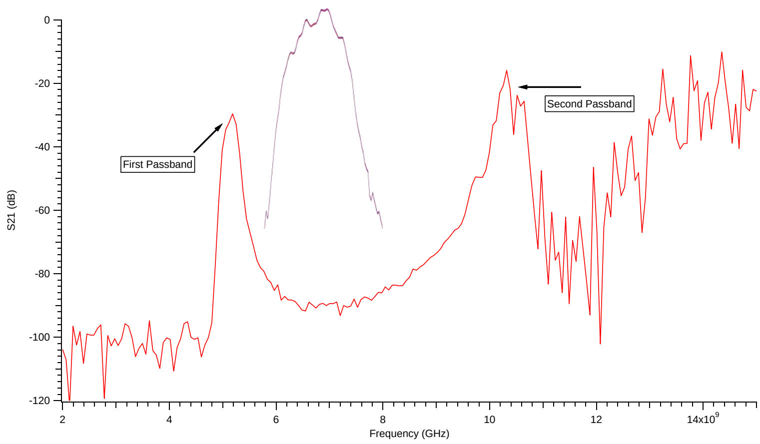

Figure 1:

Figure 1 above shows the experimental passband measurement of the waveguide with loading by the SRR array. Note first that passbands now appear *below* the 25 GHz cut-off frequency of the waveguide. The inset of Figure 4 shows a magnified version of this feature, showing the existence of four peaks, a manifestation of the five eigenmodes supported by the SRR array. The second feature, centered at about 10 GHz, also shows five eigenmodes. An eigenmode analysis of the geometry with no defects, performed using HFSS to search, demonstrates that these peaks coincide with the resonate eigenmode of the structure. Thus this finite element array thus acts more as a system of coupled harmonic oscillators than an effective medium. This fact plays an important role in the application of metamaterials to a high power device. If one element plays a critical role in the electromagnetic characteristics of a metamaterial structure, loss of a single element due to heating or breakdown might well prove critical.

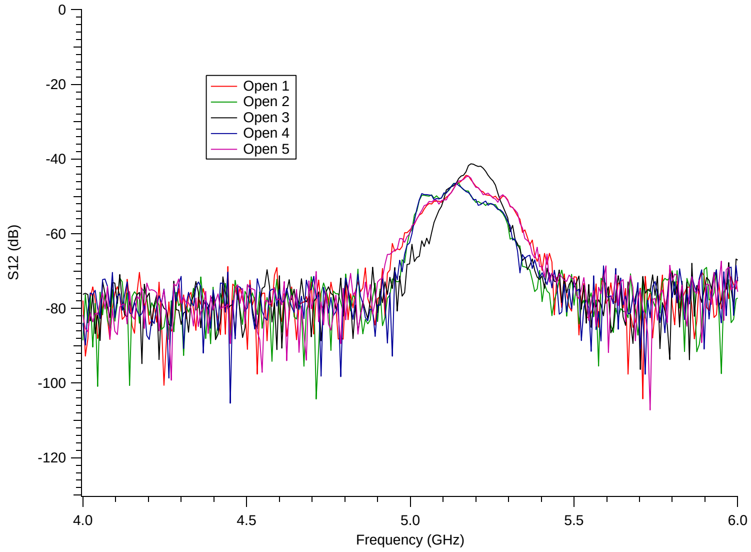

Figure 2:

To further consider the applicability of the SRR structure for high power, we experimented with the effects of either shorting or opening single elements in the array. Clearly, operation at high power levels can prove damaging to any small structure. To achieve the open, we merely etch away the trace. We then consider the cases in which one element is replaced by a defect, leaving all the others unchanged. Figure 2 shows the effects on the lowest passband for open individual elements. In these traces, note that S12 for the case with elements 1 and 5 open are nearly identical, as is the case for elements 2 and 4. The case with element 3 open is unique, given that element three is on the axis of symmetry for the array. The opening of an element has four effects. First, the overall amplitude of the signal decreases. Secondly, one of the eigenmodes clearly vanishes from the transmission peak. Third, the peak center shifts slightly, and finally, the overall bandwidth decreases. Qualitatively, one expects these characteristics if the structure couples power like a system of coupled oscillators.

While metamaterials offer the promise of reducing the size of microwave components and sources, as well as permitting new regimes of operation, the application of such sub-wavelength structures to HPM sources and components remains to be demonstrated. High field strengths and high peak and average power present severe challenges for the HPM environment. Therefore, given the importance of field strengths, we examined the type of defects that might be introduced under high power operation. Notably, loss of an element of the array, whether due to a short or an open, reduces the transmitted power and bandwidth, while keeping the center frequency unchanged. Regardless of these two problems for the SRR array, other resonator and thus metamaterials designs might exist. A careful understanding of the physics of operation for such a system may well lead other researchers to consider such structures. In this sense, the research presented here represents merely the first step in the use of metamaterials to produce compact microwave and HPM sources.

Comparative analysis of SRRs and CSRRs: (*paper in preparation for APL*) To advance our work on the HPM field we have studied two systems, the system of SRRs and their dual counterparts – complementary split ring resonators (CSRRs). In this work a numerical and experimental study of microwave propagation in a square metallic waveguide loaded with the SRRs and CSRRs below cut-off frequency is presented. The transmission and reflection coefficients for both systems are obtained using the commercial software package Ansoft HFSS. The effective medium characteristics such as magnetic permeability, electric permittivity, and propagation constant are compared and discussed.

In order to investigate the utility of metamaterials to reduce the size of typical HPM structures, we studied a configuration initially developed by Marquez and its counterpart where SRRs are replaced with a copper sheet with CSRRs cut in it. To investigate the SRR numerically we used the commercial simulation software HFSS. HFSS utilizes a 3-D full-wave frequency domain electromagnetic field solver, using the finite element method to discretize the domain, and solving Maxwell’s equations in integral form along each element.

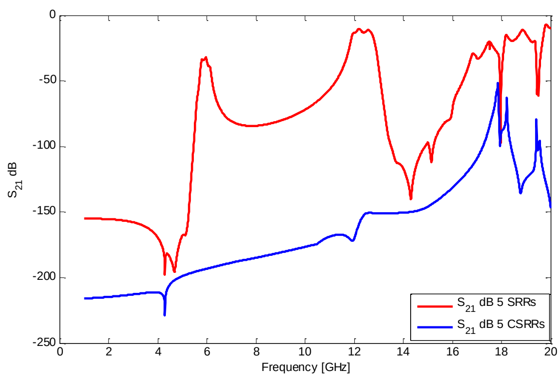

Fig. 3 presents the numerically obtained S_{21} (magnitude and phase) vs. frequency for both systems. As we can see, the system of 5 SRRs shows three peaks in S_{21} at the central frequencies of 6GHz, 12.5GHz and 18GHz respectively. At the same time the CSRR system shows only one peak in S_{21} at the higher frequency of 18 GHz. The passband is broader in the case of CSRR than the first passband in the SRR structure, however, the magnitude of S_{21} in the case of CSRR is lower than in the SRR system. Both the experimental and numerical results for S_{21} for conventional SRRs demonstrate substructure at the peaks of S_{21}. An eigenmode analysis performed using HFSS to search demonstrates that these peaks coincide with the resonant eigenmode of the structure. The analogous substructure in the peak of S_{21} can be seen and in the case of CSRRs (see Fig. 2). The eigenmodes analysis shows that the peak in S_{21} corresponds to the third mode; the first two modes do not propagate in the structure.

To extract the electromagnetic parameters of the systems we used the approach developed by Smith, which utilizes the transmission and reflection coefficients. These coefficients are inverted to calculate the refractive index n and impedance z of the system, which then can be used to determine permeability and permittivity. In both systems the electric permittivity has a first minimum at about 4.3 GHz. This corresponds with the increase in phase for both systems. At 7.5 GHz there is a resonant peak in magnetic permeability followed by the resonant peak in electric permittivity at 13.5 GHz and a small peak in permeability at 18GHz. In both cases the peaks in the permittivity and permeability occur at the same similar frequencies; however, the magnitude of both permittivity and permeability is higher in the case of CSRRs. In the case of SRRs the small regions where both the permittivity and permeability are negative are observed between 12.3-13GHz. Both systems demonstrate that the change in μ in the first instance occurs at frequency slightly higher than the system resonant frequency which lies around 6 GHz (SRR) and 7 GHz(CSRR), however, both the magnitude and phase of S_{21} are changing smoothly.

In this work we have examined the physics of microwave propagation in a rectangular waveguide below the cut-off frequency using a split ring and complementary split-ring resonator arrays. The properties of both systems were studied and compared. While both systems demonstrate duality in terms of their eigenmodes and field distribution patterns, the transmission properties of the systems are rather different.

The CSRR system supports electromagnetic wave propagation at a higher frequency than an array of SRRs does with reduced transmitted power. The application of CSRRs to high power sources may have advantages, therefore a careful understanding of the physics of operation for such a system may well lead to the development of such applications.

Metamaterial High Power Interactions: (*Paper in preparation for Journal of Applied Physic*) This activity explored the ability of different realizations of metamaterial unit cells to with stand and respond to high power microwave operation. This work involved examining the interactions of the EM field with the metamaterial and the resulting losses and heating, the resulting deformation that arose from the heating and the effect this had on the operational parameters of the metamaterial unit cell. The thermal and mechanical forces the metamaterial experiences arise due to the interaction between the macroscopic structure of the unit cell and the applied EM wave. To enable the thermal and stress analysis we must first determine the force the EM wave applies to the whole structure. The energy released into the structure by the EM wave is determined by calculating the time averaged loss density (r_v) in the structure:

$\rho_v(r)=$ 12Re$\left(\mathbf{E}(r)\circ\mathbf{J}(r)+(-$Ñ´$\mathbf{E}(r))\circ\mathbf{H}(r)\right)$

where **E** and **H** are the averaged electric field, and magnetic field, *r* is the spatial coordinate of a given point in the structure, **J** is the current density. The loss density (r_v) gives the amount of energy converted to heat at any point in the structure. The loss density is then used as a discrete volume heat source for the Thermal and Stress Analysis.

The loss density is determined using the commercial software package HFSS. HFSS is a 3D full-wave electromagnetic field solver, utilizing the FEM, with adaptive meshing, approach to solve the EM wave- structure interaction. To enable the thermal and stress analysis it is only necessary to simulate a single unit cell of the metamaterial. For the simulation the unit cell was discretized into 30K elements, the steady-state loss density was calculated at each element, with a 10W EM plane wave at 10 GHz incident upon the structure.

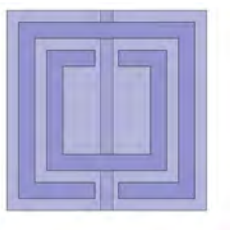

Figure 4:

The most common form of Metamaterial unit cell is formed through a SRR on standard PCB, with a single strip line on the reverse side of the PCB (PCB grade FR4), shown in figure 4.

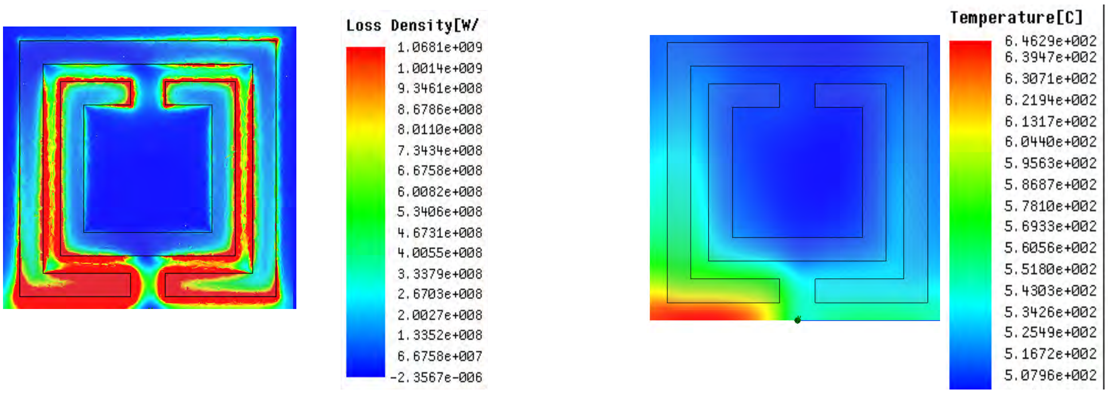

Figure 5:

The Loss density simulation results for the standard SRR exposed to 1W of RF power at 10GHz are shown in figure 5. The linking package e- physics was used to export the 30k data points from HFSS to the thermal and stress analysis software. The temperature profile for the standard SRR is also shown in figure 5. As seen the peak temperature is predicted to exceed 600 Celcius, which is the combustion point of the FR4 PCB. To confirm this result and validate the numerical model an experiment was conducted using SRR's fabricated to the exact specifications of the SRR used in the above model. The SRR was loaded into section of X-band waveguide and exposed to 1W RF at 10GHz for 15 seconds. The waveguide was loaded 9 strips of metamaterial where each strip consisted of 4 unit-cells (SRRs). Figure 6 shows the experimental results and the SRR before exposure to 1W and after in the waveguide, and the effects of heating on a single SRR. As seen the distribution of the combustion pattern from the experimental results on a single SRR is in very good agreement with the combustion patterns predicted by the numerical model, results shown in figure 5. Both the simulation and experimental results demonstrate that the conventional metamaterial realization is not suitable for HPM applications.

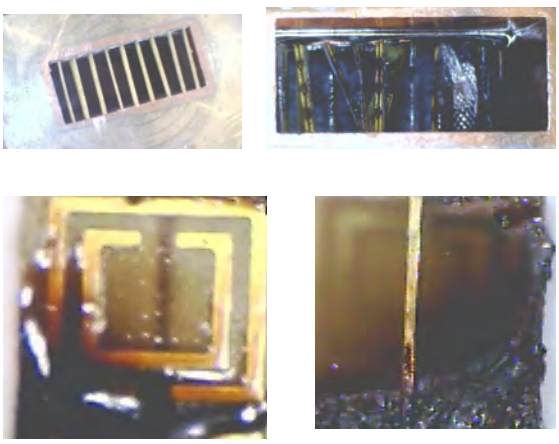

Figure 6:

To further study this effect the FR4 substrate of the Metamaterial was replaced with Quartz. Quartz has a microwave absorption coefficient 1/10 of the absorption coefficient of FR4 and a melting point of over 1700 degrees Celsius.   Simulations for this new metamaterial unit-cell are shown in figure 7 for 15W RF at 10 GHz, where we see the temperature profile across a single unit cell and the resulting deformation that occurs due to heating of the substrate.

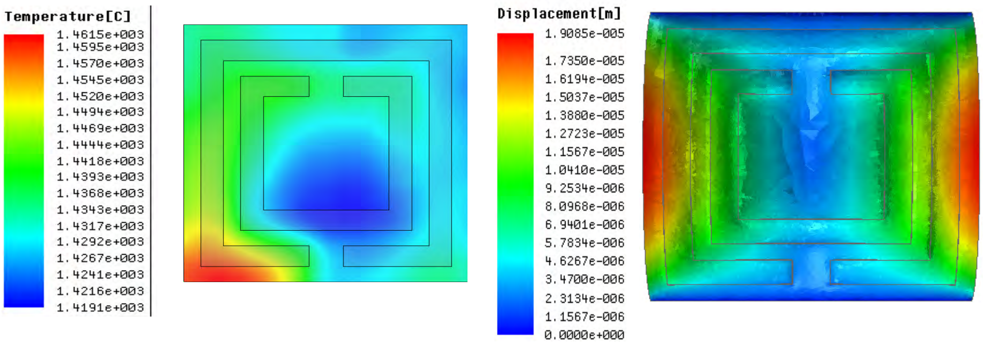

Figure 7:

As seen from figure 7 the maximum temperature reached is below the melt point of the Quartz, with a maximum displacement of 20 microns. This distorted geometry of course responds to the incident EM wave differently to the altering the electromagnetic properties of the SRR. Infact simulations show that the absorption coefficient in the distorted SRR is increased by over two orders of magnitude, this increased absorption results in a localized heating capable in time of exceeding the melt point of Quartz. This is caused by the distorted SRR acting as a high Q resonator with a fundamental mode equal to the 10GHz of the incident wave. Again meaning such realizations of metamaterials are not suitable for high power operation.

Further metamaterial unit-cell structures at frequencies between 10 – 20 GHz were evaluated using the above approach, such as Electromagnetically Induced Transparent materials (EIT’s), SRR’s, ect. All these structures were found to heat/distort to such a degree as to render high-power operation of these metamaterials impossible. The final structure consider was the complementary split ring resonators (CSRRs). We considered a realization of this unit-cell which utilized no substrate. Consisting of just the metallic inverse of the SRR. Evaluation of this structure proved that CSRR unit cells can retain there original EM properties at powers exceeding 100’s of KWs sustain operation without melting or loss of novel properties.