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14. ABSTRACT
We have designed, fabricated, and measured low-loss, highly isotropic, sub-wavelength (lambda/radius ~15) single and dual-frequency antennas which operate between 1 and 2 GHz, but can be scaled to operate at higher or lower frequencies. Measurements indicate that we achieved a ~95% radiation efficiency while maintaining ~1dB gain anisotropy in phi for single frequency antennas and for the lower operating frequency of dual-frequency antennas, in agreement with simulations. For dual-frequency antennas, the higher operating frequency exhibits a lower 75-85% efficiency and somewhat higher (~2%) gain anisotropy.

We have optimized the sensitivity of our Varian E-4 X-band EPR spectrometer and used it to measure potentially high Tc superconducting samples at temperatures in the range of 300K down to 4.2K. We also constructed a magnetic field coil to apply DC and modulation magnetic fields parallel to the RF magnetic field to allow us to discriminate between possible superconductivity and any paramagnetic signal which may be present in the sample being measured. Using our EPR spectrometer we have measured

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sub-wavelength microwave antenna, high isotropy antenna, high efficiency antenna, dual-frequency antenna, high temperature superconductor, balanced valence material

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Final Performance Report for AFOSR Contract #: FA9550-07-1-0119

Reporting Period: February 01, 2007 to May 31, 2011 (with 18 month NCE)

Title: **Left Handed Materials Research for Air Force Applications**

Program Manager: Dr. Harold Weinstock

I. Executive Summary

At the beginning of this grant the words “Left Handed Materials” in the Title were one early way of expressing what is now termed “Negative Index (of refraction) Metamaterials” or NIMs. Our research group developed and demonstrated the first proof of the existence of Negative Index of Refraction by designing, numerically simulating, and fabricating metamaterial based samples and then performing confirming experiments at microwave frequencies. In our proposal for this grant we focused on the following goals for design and optimization of a single frequency, nearly isotropic, high efficiency, sub-wavelength antenna:

1. Our first goal, which we completed, was to have several of our single frequency sub-wavelength antennas (both free standing, and a ground plane version) retested in an anechoic chamber at our industrial collaborating company’s (Qualcomm’s) facility. A comparison of the new data with our initial measurements and extensive sets of simulation data determined our specific direction for Goal 2.

2. Based upon the test results for Goal 1, we extended our numerical simulations to further predict modifications to our fabricated sub-wavelength antenna designs that would optimize key figures of merit, including radiated power efficiency, isotropy of the radiation pattern, and increasing the wavelength to cell size ratio. We then fabricated additional antennas in our own laboratory and tested this new group of antennas at Qualcomm’s testing facility. We also briefly studied how the performance of the antennas is altered when the metal film components are replaced by a high Tc superconducting material, such as YBCO, with mixed results.

3. After optimizing the key figures of merit of our single frequency (~3% bandwidth) antennas, we undertook discussions with antenna experts at several companies, as well as with other colleagues such as Dr. Steven Best at MITRE. Based upon these consultations, we determined that there was a need for further experimental and numerical simulation experiments, in particular for the design of a dual frequency band antenna having properties similar to our optimized single frequency band antenna. This dual frequency antenna might be of sufficient interest that it could be introduced to AFOSR, other U.S. government agencies, or possibly commercial companies.

In Section II below we summarize the progress made on our sub-wavelength antennas, which has already been briefly discussed in our previous Annual Progress Reports.

Personnel Involved: Professor Sheldon Schultz (Principal Investigator)

Dr. David C. Vier (Senior Project Scientist)

Mr. Roger Isaacson (Senior Technician)

Mr. Aleksander Simic (Graduate Student)

II. Technical Report

A. Summary of work on sub-wavelength antennas

Our group is experienced in the design of NIM materials at microwave frequencies, i.e., materials having both negative permittivity and negative permeability. We embarked on a novel approach towards using negative permeability design concepts for development of high efficiency, isotropic, sub-wavelength antennas operating in the cellular frequency range. They are of simple construction and are excited by a drive loop which can be directly matched to the typical 50 ohm source without the need for Baluns or matching networks. We believe these antennas can be used for Unmanned Aerial Vehicle (UAV) and other applications of direct interest to the Air Force over a broader range of frequencies, and their further development was the main thrust of this grant.

We will present experimental data and simulations of antenna performance at cell communication frequencies. Our simulations use Ansoft HFSS version 10.1 to calculate S11 and make infinite sphere far-field calculations to determine the radiation isotropy and efficiency of the simulated antenna design. We considered only non-ground plane antennas, which we designed for high radiated power efficiency with matched coupling (S11(min) < -20db) to a 50 ohm source impedance. All of our sub-wavelength antennas have a robust manufacturable design with the ability, at manufacture, to tune them to the desired operating frequency.

Initial measurements of the antenna operating frequency, bandwidth, and coupling (S11) are made in our lab using an Agilent Model 8722ES network analyzer. Measurements of the radiated power efficiency and angular gain isotropy are made in an anechoic chamber at Qualcomm using a French Satimo SR32 data acquisition system.

Single layer, 2-layer, and 4-layer sub-wavelength (lambda/radius ~15) antennas were designed to maximize their radiation efficiency and isotropy. At 1.2 GHz the 2-layer designs were found to be optimal and were scaled to cover the frequency range from 25 MHz to 4 GHz with comparable figures of merit. The antenna designs are made with Cu Split Ring Resonators (SRRs) and Rexolite material (to minimize losses) and they have simple low cost fabrication and low mass making them suitable for UAVs. All our designs have high radiation efficiency (90% or greater), ~3% bandwidth, and are easily designed to couple to match (S11<-20db) for typical source impedances (i.e., 50 ohm). The designs have low gain anisotropy; at theta=90 degrees the measured phi angle anisotropy can be as low as 0.5 db. This is contrary to a standard dipole antenna which has a large degree of anisotropy. As shown in Figure 1, the key to the low anisotropy in our antenna design is the use of a single SRR in each layer, rather than the dual SRR typically used in NIMs.

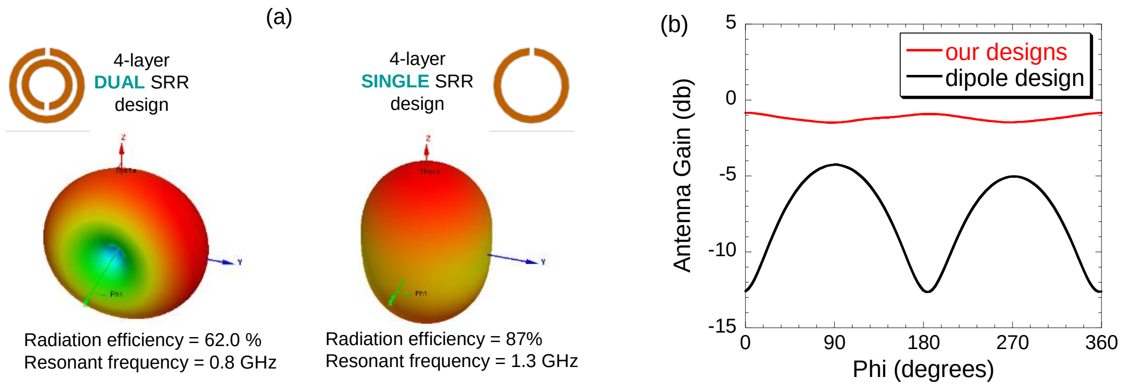

Figure 1. Comparison of the antenna gain for a standard dipole design and for our low anisotropy, high efficiency, sub-wavelength antenna design. (a) Typical 3D radiation plots comparing dual (dipole) and single SRR antenna designs, and (b) comparison of the energy radiated at theta = 90 degrees for the same two antenna designs.

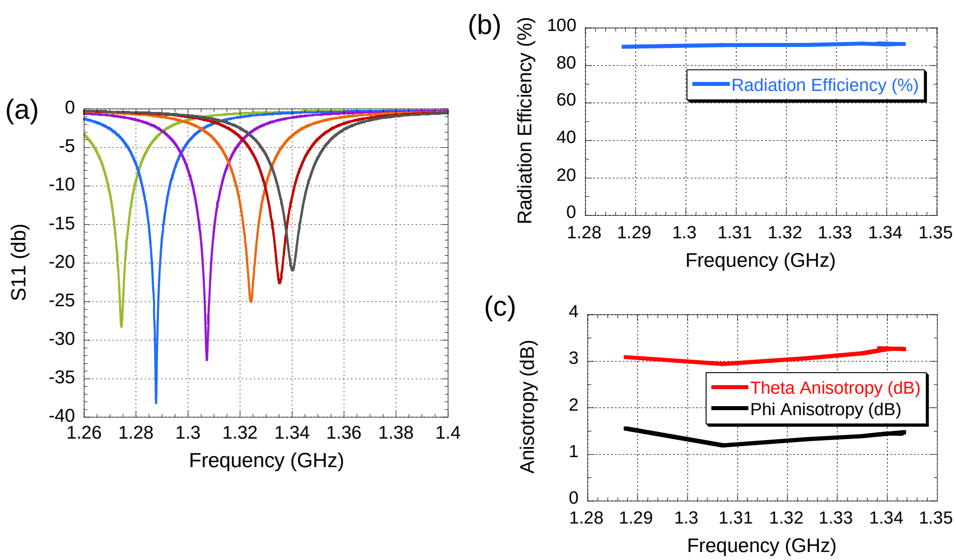

Figure 2. Simulations of the effects of adjusting the tuning wire of our single frequency antenna. (a) Change in the peak operating frequency (S11 minimum) of our antenna with tuning, (b) constancy of the antenna's radiation efficiency with tuning, and (c) slight variation of power anisotropy with tuning.

We have devised a simple means for adjusting the manufactured antenna's peak operating frequency to that of the desired operating frequency using a Cu tuning wire. As seen in Figure 2, the operating frequency of the antenna can be tuned over an approximate 10% range while maintaining a coupling of better than -20 dB, with little to no change in the anisotropy or radiation efficiency of the antenna.

We have also optimized a "pancake" type of geometry operating at a frequency of 25 MHz where we designed a diameter-to-thickness ratio antenna of 30:1. Utilizing the advantage of its low gain anisotropy, large thin outdoor antennas could be designed to rotate with the power source and built to act as a windsock to reduce wind forces.

As a result of discussions with various commercial companies regarding our single frequency antenna, we designed, fabricated, measured, and optimized sub-wavelength (λ/r ~15) dual frequency antennas which operate between 1 and 2 GHz, but can be scaled to operate at higher or lower frequencies. The frequency separation between the two operating frequencies can be adjusted over a significant range. The dual frequency antenna, shown in Figure 3, is quite similar to the single frequency 2-layer antenna described above, but each of the two layers has a different size SRR which gives rise to the dual frequency property of the antenna. A tuning wire in each layer allows control over tuning each individual frequency independently to the correct designed target frequency, to compensate for manufacturing variations. Both operating frequencies exhibit relatively low anisotropy over all angles.

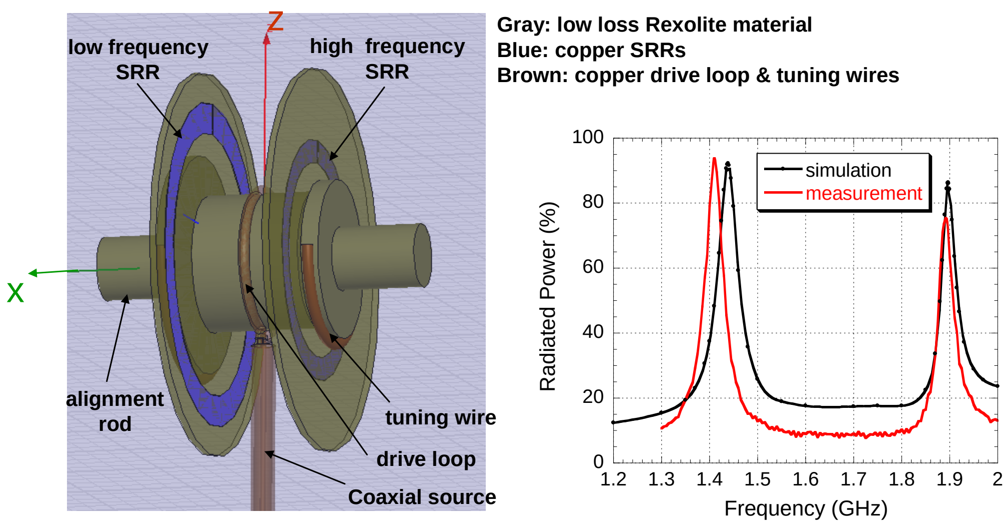

Figure 2. (**left**) A schematic of our dual frequency antenna designed for high radiation efficiency with low anisotropy. Note that the blue SRR on the right is smaller than the one on the left. This difference gives rise to the dual operating frequencies of the antenna. (**right**) Radiated power vs. frequency for the antenna shown. The radiation anisotropy is low for both operating frequencies of the antenna.

We reduced the losses of our initial dual frequency antenna designs by ~10% by removing Rexolite material from the high-field gap region of the SRRs. Measurements of our improved designs indicate that we achieved a ~95% radiation efficiency while maintaining ~1dB gain anisotropy in phi for the lower operating frequency, in agreement with simulations. At the higher operating frequency, simulations predict a ~85% radiation efficiency; however, measurements indicate a ~75% radiation efficiency with ~2dB gain anisotropy in phi.

Our single and dual sub-wavelength antenna designs could be used for a variety of applications, such as low loss antennas for UAV flying time extension, local range communication for mini-satellite clusters, or autonomous robot sensing and communications.

B. Measurements of novel high temperature superconductors with no-cost extension

The discovery of new classes of superconductors is of great scientific and technical interest. With the renewed interest by AFOSR in searching for new high temperature superconductors, we were granted a no-cost extension to measure potential high Tc superconducting samples provided by AFOSR collaborating research groups. We modified a Varian E-4 X-band EPR spectrometer for this purpose. Using lock-in amplification, our microwave spectrometer has the potential to detect superconducting grains of YBCO weighing as little as 1 microgram, or nanometer thickness YBCO superconducting films with mass as low as 10 nanograms. We designed and built our system to operate at temperatures between 4K and 400K. A long Rexolite tube was designed to hold as many as 4 samples, which at any given temperature could all be checked for superconductivity within minutes.

In collaboration with Ivan Schuller's group here at UCSD, we utilized Nb film samples with volumes as low as 10^{-11} cm^3 to verify and optimize the sensitivity of our system at low temperatures. We also tested our system using various YBCO samples provided by various research collaborators (Schuller, Maple, and Barnes groups). In particular, we tested numerous samples containing various percentages of YBCO provided by the Barnes group.

We constructed an additional magnetic field coil which applies DC and modulation magnetic fields parallel to the RF magnetic field, instead of perpendicular to the RF field. This non-conventional field direction is not normally available in commercial spectrometers. It allows us to discriminate between possible superconductivity and any paramagnetic signal which may be present in the sample being measured.

Using our modified spectrometer we have measured exciting new balanced valence materials provided by Dr. Paul Barnes' AFRL group at Wright-Patterson AFB. The best known high Tc superconductor materials are the Cu-oxides, where the active elements are Cu^{+2} and O^{-2}, and the Fe-As pnictides, with Fe^{+3} and As^{-3}. Their focus area in the search for new superconductors is the study of new balanced valence compounds with active valence states of either ±4 or ±1. Many of these compounds fabricated by the Barnes group were sent to us for microwave measurement and analysis.

Figure 4 shows results for two of their more promising balanced valence compound samples. The zero-field cooled and field-cooled DC magnetization measurements (made at AFRL with a

Quantum Design vibrating sample magnetometer) and our microwave spectrometer measurements both show likely superconductivity at an onset temperature of about 17K for each of these two samples.

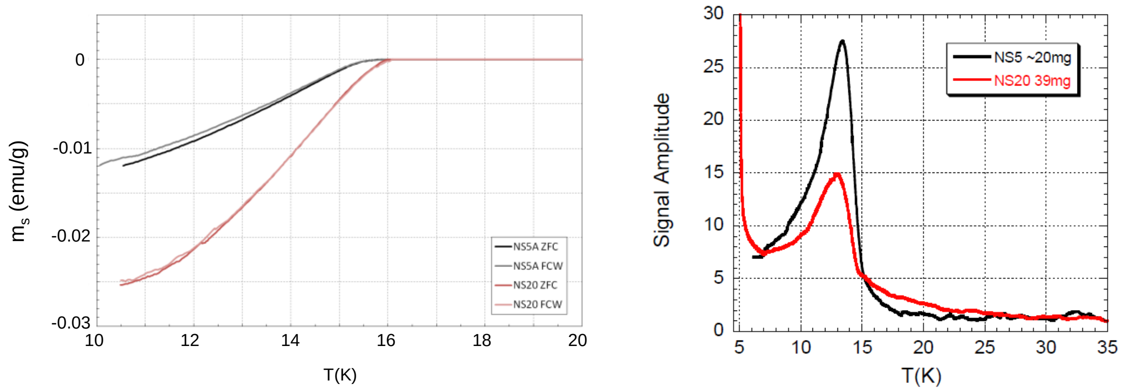

Figure 4. **(left)** Zero-field cooled (ZFC) and field-cooled (FC) measurements of NS5 and NS20 samples, in H = 10 Oe background field. **(right)** microwave magnetic field modulation measurements of the same samples performed at UCSD.

Approximately 50 different balanced valence samples provided by the Barnes group have been measured by us. Some of these samples also show strong signs of superconductivity near 17K, similar to the two samples shown in Fig. 4. For a few balanced valence samples our microwave measurements also hint at possible superconductivity occurring at temperatures near 50K in small regions within the sample. This can be seen in Figure 5 for three samples. Sample NS16C, which shows no signs of a superconducting signal, is also shown in the plot for comparison.

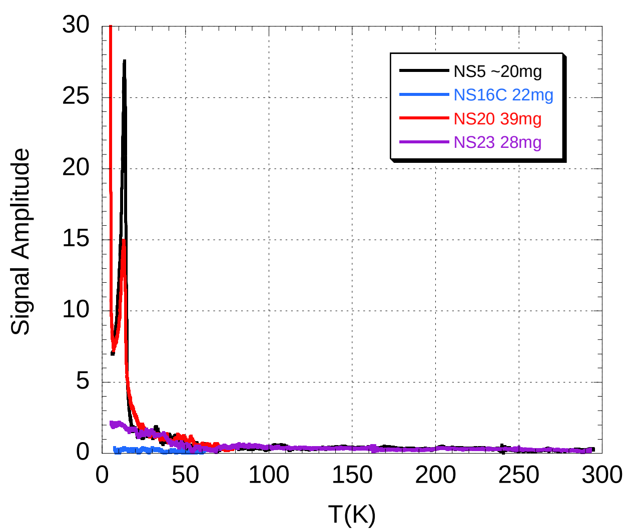

Figure 5. Measurements from 4.5K to room temperature for 4 mixed valence samples. Sample NS16C shows no signs of superconductivity, whereas the other 3 samples all show weak signs of a superconducting signal occurring at temperatures below about 50K.

Note that sample NS23, which exhibits a weak onset signal near 50K, shows no strong superconducting signal at lower temperatures.

In Figure 6 we summarize the positive results obtained for many of the measured samples. Again the null result for sample NS16C is shown for comparison. Strong signal onsets are observed in a number of samples near 17K and/or near 8K, with very weak onsets near 50K also observed in many cases.

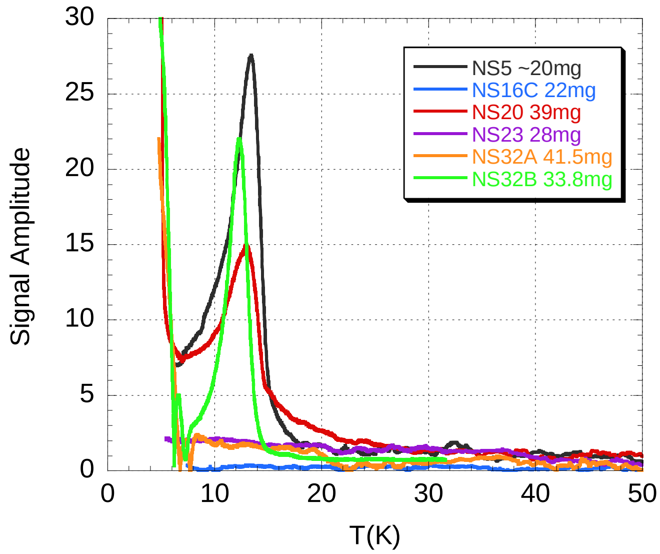

Figure 6. Measurement summary for many mixed valence samples showing the variety of signals observed.

Another focus area for the Barnes group is the growth of carbon thin films doped to increase the charge carrier density and induce superconductivity. Superconductivity has been observed in carbon materials doped with elements including B,Y, Li, S, and Cs. However, by the end of this grant period we had not detected any superconductivity (above 4.5K) from any of the carbon thin films provided to us.