Radar Absorbing Applications of Metamaterials

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Abstract **- Radar Absorbing Materials (RAM) is used to camouflage or shield highly reflective surfaces such metallic surfaces from incident electromagnetic (EM) waves. In this paper, we explore the applications of metamaterials as conformal RAM coatings for controlling the reflection of EM waves from metal surfaces. Metamaterials are engineered materials with specially designed metallic resonant structures that are much smaller than the wavelength of incident microwaves (MW) and effectively such materials may negative permittivity and/or permeability. For the first time, we also explore the experimental use of metamaterials as conformal Frequency Selective Surfaces (FSS). Using a specially designed free space focused microwave beam automated scanning system, the reflection reduction properties of metamaterials are demonstrated for oblique angles of incidence and for orthogonal polarizations.**

Index Terms- **Metamaterials, Radar Absorbing Materials (RAM), Frequency Selective Surfaces (FSS), Free Space Measurements**

I. INTRODUCTION

The study of metamaterials with uncommon electromagnetic properties, also called left-handed materials or negative property materials, is a hot research topic in the last 6-8 years (see, e.g., [1] and [2]). One type of the metamaterials takes advantage of the resonance of the embedded metallic structures to have unusual, sometimes negative dielectric and/or magnetic properties at a resonance frequency where the material is highly dispersive. These metamaterials usually have an array of specially designed metallic structures such as - split-ring resonators (SRRs) [3], or a form such as Omegas [4], S-shaped [5], and other exotic shapes [6]. These shape and dimensions of the structures are able to produce a resonant response when excited by an external electromagnetic wave at a certain frequency. As long as the resonance wavelength is much large than the size of the unit cell, the metamaterials can be homogenized as an effective medium with effective dielectric and magnetic properties. They are able to achieve a negative effective permeability in a certain frequency range while the permittivity at those frequencies remains positive or *vice versa* or both can simultaneously become negative. Unlike ordinary materials whose refractive index is just complex with positive real and imaginary parts, for metamaterials, the refractive index can be real positive, real negative or imaginary (evanescent waves and we may say that this band of frequencies is a stop band for the material). A metal wire array, however, has another kind of stop band where effective permittivity is negative and effective permeability positive [7]. Combining ring resonators and continuous wires, the stop bands overlap and result in a pass band with negative refractive index [8].

Metamaterials with planar metallic structures are easy to fabricate on a substrate using inexpensive lithographic techniques. For frequencies up to 10 GHz, ordinary Printed Circuit Board (PCB) fabrication methods are sufficient for feature sizes > 0.2 mm. At higher frequencies, the loss and dispersive properties of PCB substrates such as FR4 are unacceptable. Materials such as Rogers Duroid are less lossy for high frequency applications but conventional liquid etching limits the frequency range. Low Temperature Cofired Ceramics (LTCC) fabrication method is preferred for high frequency applications. This approach is well suited for mass production at low cost and rapid throughput. Two and three-dimensional composite materials can be constructed using such structures. Traditional planar structures are highly anisotropic [9], and an electromagnetic wave traveling along different primitive axes will give rise to different properties. The properties of bi-anisotropic materials have been discussed in some papers (see, e.g., [10]). Bi-anisotropy arises from the coupling of the E- and H- fields in an unsymmetric metamaterial structure. To cancel the bi-anisotropic effect, an edge-coupled SRR has been proposed [11] and similarly paired Omega structures and cubical arrangements of Omega have been proposed [4], to result in symmetric isotropic structures.

In a certain band of frequencies close to the plasmon resonance frequency of the metamaterial, the strongly dispersive permittivity and permeability lead to unexpected minima in the reflected and transmitted waves propagating through a planar slab of such a material. In previous theoretical and experimental papers on metamaterials [11,12], metamaterials were modeled with specific orientations of the metamaterial structure since it was assumed this would result in optimal conditions for a strong plasmonic resonance. For example, the H-field of the propagating electromagnetic wave was always required to be perpendicular to the plane of a split ring oscillator or the electric field was required to be parallel to the wire structure. This imposes many restrictions on practical realizations of metamaterials for realistic applications. The applications we are interested in are many. The reflection and transmission minima in metamaterials can be designed and controlled so that they behave like passband or stopband filters, phase shifters, focusing media for super lenses, substrates for conformal microstrip antennas and as microwave absorbers for shielding and 'stealth' (Radar Absorbing Materials or RAM) applications.

Recently there has been much publicity associated with the so called 'cloaking' properties of metamaterials [13,14]. However, in this paper, we wish to explore RAM applications of metamaterials but also explore unconventional conformal use of metamaterials as frequency selective surfaces and frequency selective RAM coatings. Experimental results are presented for split ring resonator samples and omega samples in both conventional 3D orientations as well as flat conformal coatings in the C-, X-, and Ku- bands. We demonstrate that the plasmon resonance dominates the response of the sample no matter what the orientation of the resonant structure is. We also show that the reflection reduction of conformal metamaterial coatings is satisfactory even for oblique angles of incidence and for parallel and perpendicular polarizations.

II. METAMATERIAL SAMPLES AND MEASUREMENT SYSTEM

The samples used in this study were fabricated on ordinary FR4 (ε=4.4+j0.04) dielectric substrates, 0.7mm thick on which metamaterial structures were printed using lithography. The shapes were placed periodically on the FR4 sheets with vertical and horizontal periodicity of 5mm. Two shapes are considered in this paper, Split Ring Resonators (SRR) and Omega shaped structures. The strips can be placed such that the metamaterial shapes are in the plane of the k-vector of the incident wave or the shapes are perpendicular to the k-vector. In the second case, the sample thickness is only 0.7mm and it can be considered a conformal coating whereas in the first case the sample thickness is 5mm. In Fig.1a, the dimensions of the SRR and Omega shapes are shown. The SRR has a resonance frequency at 10.4 GHz and the Omega has a resonance frequency at 15 GHz. We show the method of mounting the printed FR4 strips in Fig. 1b. so that the H-field of the incident wave is perpendicular to the SRR and Omega planes. This results in a sample of thickness 5 mm, not exactly a conformal coating.

We note that the SRR shapes can be printed in three different ways, as shown in Fig. 1b. In one, the gap of the SRR is parallel to the E-field, as most commonly used [4,7]. We refer to this as SRR3. The SRR can be printed on the FR4 such that the gap is perpendicular to the E-field, this called SRR1, and this is an unsymmetric sample with $S_{11} \neq S_{22}$. The third type of SRR sample is one in which the SRRs are randomly oriented and this referred to as SRR2. The Omega shapes are unsymmetrical and hence $S_{11} \neq S_{22}$. Omega shapes can also be rotated the on the FR4 substrate to make the E-field parallel or perpendicular to the gap. Both SRR and Omegas may be modeled as resonant LC equivalent circuits, with L and C determined by the radius of the ring, width of the metallization and the gap size. Fig. 2 shows photographs of the sample with the strips parallel to the k-vector and flat conformal strips with k-vector perpendicular to them. This is truly a conformal coating

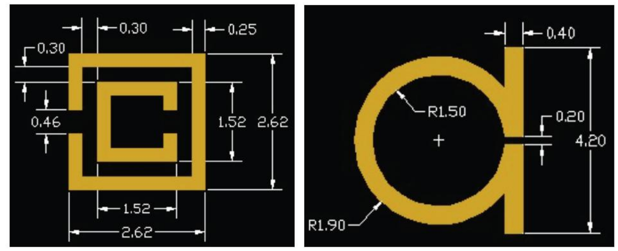

Fig. 1a. Geometry and dimensions of the SRR [8] and Omega [4] shaped metallized patterns printed on FR4 dielectric substrate.

since the thickness is only 0.7 mm.

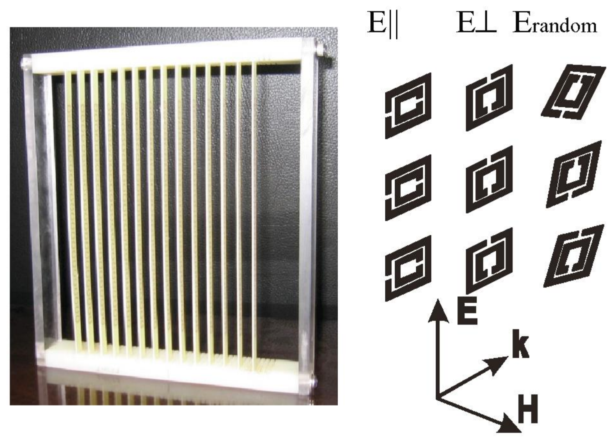

Fig. 1b. Split Ring Resonator (SRR) samples used in experimental studies with three different orientations of the gaps *w.r.t.* the E field, parallel, perpendicular and randomly oriented gaps.

Fig. 2. Conformal metamaterial coating, FR4 dielectric sheet, 0.7 mm thick, on which a periodic, metallized patterns of mixed SRR shapes are printed.

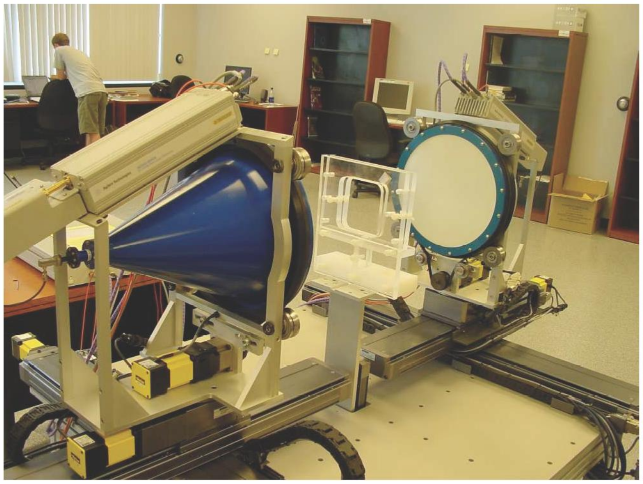

Fig. 3. Automated Focused Beam Free Space Microwave Scanning System for characterization and imaging in the 5-110 GHz range.

A free space measurement system is use to study the radar absorbing properties of metamaterials as shown in Fig. 3. It consists of two horn antennas connected to an Agilent mm wave PNA via high precision circular to rectangualr waveguide transitions, waveguide to co-ax transitions and 1.8 mm coaxial cables. The horn antennas are spwecially designed with two plano-convex dielectric lenses that result in a focused 'plane wave beam' with a very accurately defined phase front. TRL (Thru, Reflect and Line) calibration is implemented to obtain an accurate reference for both the amplitude and phase of the signal at a reference plane that is taken to be the front surface of the planar sample. This surface may also be considered as the input port in a 2-port transmission line model of the experimental set-up. The required sample, either strips mounted as shown in Fig. 1b or the flat conformal sample as shown in Fig. 2 is mounted in the picture frame sample holder seen in Fig. 3. The sample holder is placed at the common focal plane of the two antennas and the complex S-parameters, S11 and S21 are measured [12, 15].

We mention in concluding this section that this measurement method is a non-contact and non-destructive method and mimics a compact range at a much lower cost. The incident beam is focused plane wave with a focal diameter equal to one wavelength at mid-band. If the sample dimensions are greater than 3 wavelengths, the measured S-parameters are the same as that of an infinite sample. For laboratory studies, small samples can be prepared and measured without any loss of accuracy by measureing the amplitude and phase of the reflected and transmitted signals.

IV. RESULTS AND DISCUSSION

Results are presented for three types of samples, conformal samples with different orientations of SRR on FR4 substrate, conformal samples with different orientations of Omega shapes and frame samples as shown in Fig. 1b, of metamaterial FR4 strips mounted vertically such that the metamaterial shapes are in the plane of incidence unlike the conformal coatings that lie perpendicular to the plane of incidence. In each case, the amplitude and phase of the reflected signal S11 is presented as a function of frequency. X-band (8.4 -12 GHz) results are presented for the SRR samples since the plasmon frequency for these samples is at 104 GHz and for the Omega samples X-band and Ku-band data is presented and the plasmon frequency is at about 15 GHz.

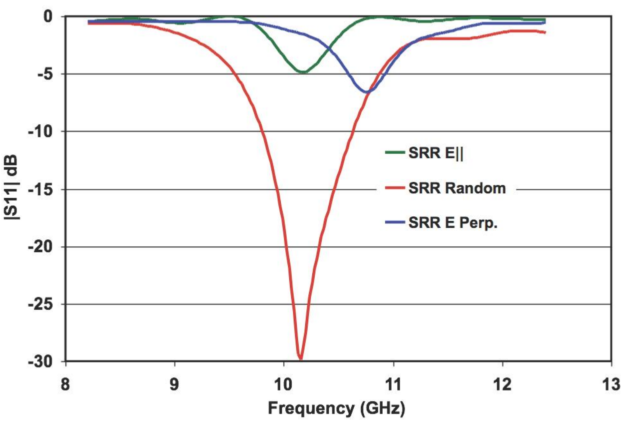

Fig. 4. Reflection from metal backed samples with FR4 strips printed with SRRs of various orientations when strips are perpendicular to metal backing.

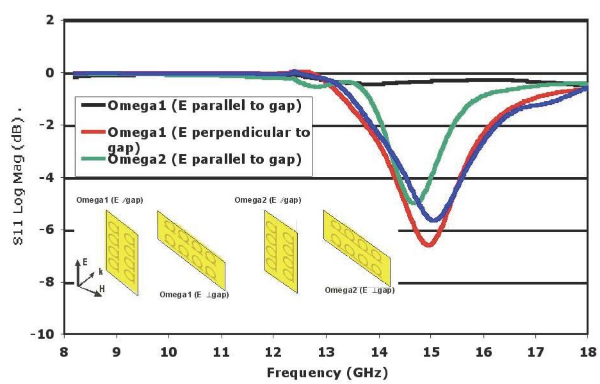

Fig. 5. Reflection from metal backed conformal FR4 samples printed with Omega shapes of various orientations for normal incidence.

In Figs. 4, the dB magnitude of the reflected wave is plotted for the SRR sample when the E-field of the incident wave is parallel or perpendicular to the gap in the SRR shape. Both show a minimum at the plasmon resonance frequency, but the minimum is more pronounced when the E-field is perpendicular to the gap. But the deepest minimum is for he sample with random orientations of the SRR shapes. In fig. 5, we compare the reflection coefficent of various orientations of Omega samples. Here also we observe that the reflection minimum is deeper for when the gap of the Omega is perpenDicular to the E-field. Results for random orientations of Omega shapes are also being measured.

We may conclude that no matter what the orientation of the metamaterial sahpe with respect to the incident E- and H-fields, metal backed samples always show a minimum in the vicinity of the plasmon resonance frequency. Away from resonance, the metal backed samples behave just like a plain sheet of FR4 backed by metal resulting almost 100% reflection. Thus the Ram application of metamwterials can be realized only at the plamon resonance frequency. But by appropriate design and distribution of the metamaterial sahpes, we can realize a broad minimum. We conclude that random orientations give the deepest reflection minima with a high bandwidth (a wider band of frequencies for which the reflection coefficient is less than -10 dB). Results are also needed for oblique angles of incidence and for diverse polarizations of the incident wave. This work is in progress. One drawback of samples with a single resonance frequency is that RAM applications are relaized only in the vicinity of the resonance. To overcome this, we are developing materials with multiple plasminc frequencies at well spaced intervals.

Metamaterials present an attractive conformal approach for the development of RAM coatings of very low thickness. They are lightweight compared to conventional ferrite based RAM coatings.

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