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IN-SITU LARGE AREA FABRICATION OF METAMATERIALS ON ARBITRARY SUBSTRATES USING PAINT PROCESS

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Abstract—This paper proposes a novel method to make large area metamaterials on arbitrary planar hard or flexible substrates, *in-situ*. The method is based on painting the desired substrate with metallic and dielectric paints through a patterned stencil mask. We demonstrate this painting approach to fabricate ultra-thin electromagnetic absorbers based on metamaterials at X-band frequencies (8–12 GHz) with paper-based stencils, silver ink and latex paint. Measurement results on absorber samples made with this process show absorption of 95%–99% in close agreement with simulation results. The proposed painting approach is a simple low cost additive manufacturing process that can be used to realize metamaterials, frequency selective surfaces, radar absorbers, camouflage screens, electromagnetic sensors and EMI protection devices.

1. INTRODUCTION

Metamaterials are an emerging class of artificial materials that are made bottom-up from individual unit cells consisting of metallic inclusions in dielectric medium, which can show exotic electromagnetic properties in RF, microwave and optical wavelengths. Contrary to naturally occurring materials, metamaterials acquire their exotic electromagnetic properties more from the geometry and shape than the constituent physical properties of the metal and dielectric. Some of the major advances in the area of metamaterials include cloaking of 3-D objects at radio and optical frequencies [1, 2], super-lensing

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for extremely high resolution imaging [3], and active terahertz devices [4, 5]. While the potential applications for metamaterials for electromagnetic and optical devices have been suggested, the complexity and cost of manufacturing have been a hindrance for their practical realization. Conventional methods for their fabrication include chemical vapor deposition and ion sputtering followed by lithography for patterning geometrical metamaterial structures [6]. However, these methods may not be suitable for large area implementation. More recently new manufacturing processes have been suggested in the literature to address large area fabrication. While these methods are developed mainly for electronics application, they can be used for manufacturing metamaterials. One major development is the use of super-fine inkjet printers [7]. The use of various printer technologies in the creation of RF circuits is not new. In the RFID industry, printing of antennas has been demonstrated in commercial settings. In 2005, DuPont suggested the use of screen-printing as another way of generating passive RF devices [8, 9]. Such an additive process allowed a large reduction in cost per device and helped to eliminate potentially dangerous waste products. Such printing technologies have also attracted industry attention because they can be performed at room temperature in roll-to-roll processes that does not require expensive clean-room environmental conditions as needed by photolithography.

The ability to fabricate metamaterials is only one part of the picture. For many applications, including cloaks and radar absorbers, flexibility of the metamaterials and ease with which one can modify the attributes of regular objects with metamaterial features are also important considerations. Several authors have demonstrated the production of metamaterials and RF circuits on flexible substrates such as polyimide [10]. While one could find ways to wrap an object of interest with a flexible metamaterial fabricated using standard lithography or inkjet printing, the available approaches still do not offer the flexibility to implement metamaterials directly on any arbitrary substrate. Ability to design metamaterials on any arbitrary substrate over a large area, *in-situ*, with custom electromagnetic properties will provide groundbreaking opportunities such as cloaks for large objects, absorbers or reflectors for radars and smart windows, reduced electromagnetic interference in microwave circuits, sensors and other emerging applications.

With a goal to demonstrate in-situ fabrication, the authors have developed an additive low cost process for making large area metamaterial based on painting. The basic premise of our approach is that planar and layered metamaterials can be simply painted on any arbitrary substrates through patterned stencils. We demonstrate the proposed approach using low-cost materials for making metamaterials in a challenging microwave frequency spectrum using common latex paint, silver ink, copy paper and mounting spray indicating feasibility for large area application with very low cost materials. We demonstrate the proposed methodology on 2D planar surfaces for three different metamaterial designs. The use of flexible substrates and the ease of painting method suggest that the process could be performed on arbitrary 3D non-planar objects. Such a technology will allow rapid fabrication of metamaterial conformably on any objects, *in-situ* making metamaterial-based practical devices possible.

2. METAMATERIAL ABSORBERS

We present the proposed painting approach for fabricating metamaterials for microwave absorbers. Microwave absorbers are used to reduce radar cross-section and in microwave circuits to reduce electromagnetic interference. Metamaterial-based absorbers can be designed for perfect absorption and have been recently proposed at different frequencies ranging from gigahertz to terahertz including IR and visible region [11–16]. A planar metamaterial absorber consists of a periodic patterned layer of resonators on the front-side and another patterned or continuous metal on the backside separated by a dielectric spacer. The incident electromagnetic wave interacts with the top resonator layer resulting in localization of the incident electromagnetic energy in the resonator and the underlying dielectric material at the resonant modes. The incident wave at other frequencies is either reflected back or transmitted through, depending on the presence or absence of the backside metal layer. By carefully choosing the resonator pattern and its size, and thickness of the dielectric spacer, one can design metamaterial-based absorbers with controllable response in the frequency range from RF to the optical. We show one design of an absorber based on metamaterials at microwave frequencies in Fig. 1. The top layer is periodic distribution of metallic split ring resonators (SRRs) unit cells patterned on a dielectric spacer substrate. Electromagnetic wave incident on metamaterial surface with right electric field polarization, which in this case is along the gap of the SRRs, interacts strongly with these resonators at resonance frequencies and none at other frequencies. At resonance frequency, simultaneous interaction of electric field (at SRR gap) and magnetic field (between SRR and back metal) results in perfect absorption of the wave [11]. Such approaches utilizing metamaterials have resulted in ultrathin geometries not possible with conventional methods [11].

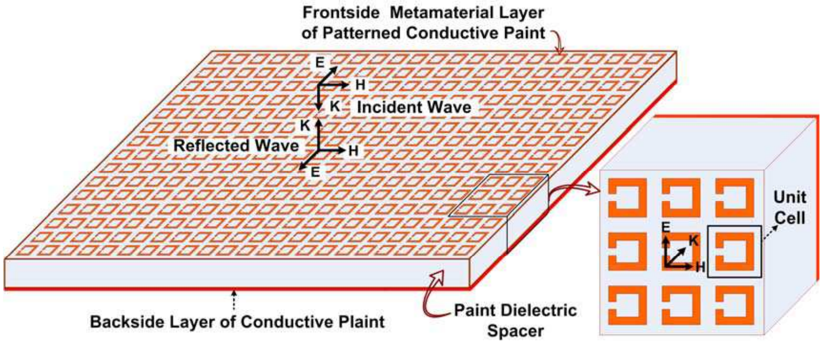


Figure 1. Conceptual planar metamaterial absorber: the incident electromagnetic wave is absorbed at metamaterial resonance frequency and reflected back at other frequencies. There is no transmitted wave due to backside metal layer.

3. FABRICATION PROCESS

Fabrication of these absorbers is generally performed using optical photolithography or even electron-beam-lithography for operation in the IR and visible spectrum. These fabrication processes are only suitable for fabrication of devices on specific substrates (e.g., glass, silicon etc.). Moreover high cost of fabrication limits the overall dimensions of these devices by wafer size. It would be desirable to make absorbers on any arbitrary substrates over large area to realize a full range of applications. The proposed painting approach makes this feasible. Fabrication of metamaterial absorbers shown in Fig. 1 requires three layers, a metamaterial pattern of conductive layer on front side, a continuous conducting layer on backside and the dielectric spacer between the two layers. In the proposed painting process, the dielectric spacer is realized by a uniform and repeated application of a suitable non-conducting paint with desirable dielectric properties. Paint is also used to create a continuous uniform metal layer using conductive ink. The conducting metamaterial patterns on the front side are created by painting conductive ink through patterned stencils. Since the process depends on conformal application of paint for all the layers, it can be used on any arbitrary substrates. The complete fabrication process of paint-based metamaterial absorber is presented in Fig. 2. A PET sheet is used as an example of starting base material (substrate). The conducting back layer of the metamaterial absorber is painted using a small-applicator brush to a 15×15 cm square sample area of PET film. A liquid silver paint available for scanning electron

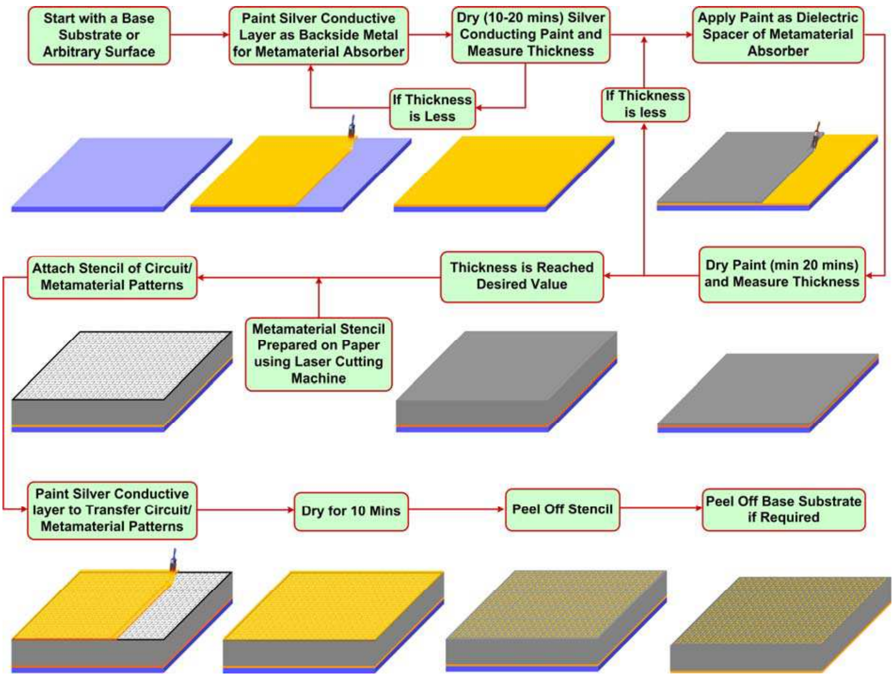


Figure 2. Process flow of paint process for the *in-situ* large area fabrication of planar metamaterials.

microscope (SEM) sample preparation is used as the conducting layer. Liquid silver paint contains silver flakes with grain sizes $< 1\,\mu\text{m}$ which can offer low sheet resistance of 0.02 Ohms-per-square for thickness of 1 mil. After application of conducting layer, it is dried for a time period of 10 to 20 minutes. The average thickness of conducting layer after one paint application was $20\,\mu\text{m}$ and can be adjusted by changing the concentration and viscosity of the paint. Materials other than silver ink (such as nickel, copper and gold dispersions) can also be used as conducting paint. To achieve additional thickness, repeated application of the paints can be done.

To fabricate dielectric spacer layer of an absorber a non-conducting paint is applied with a hand brush on the painted conductive backside. Latex (acrylic) paint is used as non-conducting material for the dielectric spacer. This paint is water based and can be diluted using water if required. Drying of this paint is fast; it also becomes water resistant after drying. Paint is dried for more than 20 minutes between applications. Thickness of the layer is measured using a micrometer at different positions over the sample. Single layer thickness of dielectric paint is around 80 μm. We use repeated application of paint to reach the desired value of 1 mm, as needed for present design of metamaterial absorbers at X-band frequencies (8 ∼ 12 GHz). Once thickness of dielectric spacer is reached, the process is advanced to next step of metamaterial patterning.

Stencil based process is used to transfer metamaterial patterns on the top of dried dielectric layer. The metamaterial patterns are first developed on paper as stencil mask using laser cutter machine (Versa laser VLS 3.5). This stencil is then attached on the paint substrate by spraying on a temporary adhesive (Scotch $^{(R)}$ spray mount 3 M). The conductive silver paint layer is then painted using hand brush through this stencil. A professional spray-painting apparatus may also be used. After finishing application of conductive paint, it is allowed to dry for 10 minutes. The stencil is then peeled off from the substrate leaving behind the desired pattern for metamaterial on the dielectric substrate. Detached stencils are reusable in this process. This metamaterial absorber fabrication is complete after this stage. The supporting PET sheet can also be peeled off if needed resulting in a freestanding absorber samples.

The images of the samples at various stages of fabrication process are shown in Fig. 3. Fig. 3(d) shows final sample photograph of

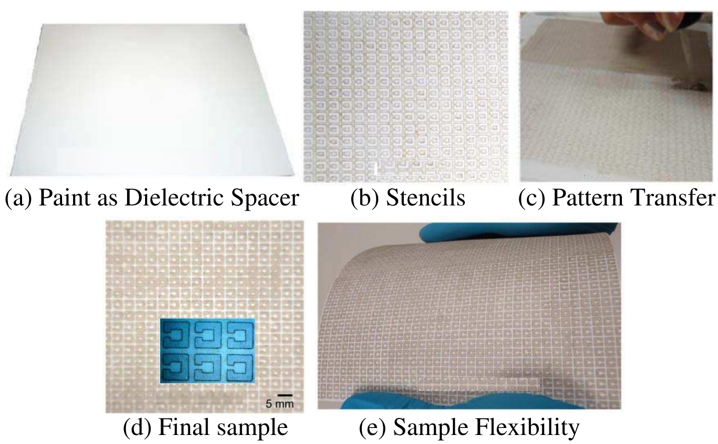


Figure 3. Optical photographs of the sample at different stages during the metamaterial absorber fabrication using paint process. (a) Dielectric paint spacer (1 mm thick) with back side metal layer, (b) metamaterial patterned stencils on paper prepared by laser cutting machine, (c) process of metamaterial pattern transfer on paint spacer layer through stencils, (d) metamaterial patterns on sample after stencil is peeled off, and (e) showing flexibility of samples made.

the metamaterial absorber (magnified optical microscope image is shown in the inset). Paint metamaterial absorber samples presented in this paper are flexible as shown in Fig. 3(e). Thickness profiles of the metamaterial structures are measured using Dektak profilometer. Measured root mean square (rms) roughness of the dielectric substrate surface is 0.69 μm, and after the transfer of metamaterial patterns the rms roughness of the conductive region is 1.89 μm. Measured minimum thicknesses of the metal is above the expected value of 20 μm. Thickness profile of the metal shows peaks at edges of stencil patterns where ink particulates are expected to agglomerate. However, this will not degrade performance of the metamaterial absorbers. The measured width of metal strip is 1.05 mm closer to the target value of 1.10 mm resulting in very accurate pattern transfer using this approach. Thickness of dielectric spacer is also important in realization of the metamaterial based absorbers. The average measured thickness of paint spacer is 1.04 mm (target value 1.00 mm) with standard deviation of 0.08 mm over sample area of 15×15 cm square.

4. RESULTS AND DISCUSSION

In this section we present simulation and measurement results on different absorbers made using the paint approach.

4.1. Material Parameters

The choice of materials for use as paint for both dielectric and metal depends on their dielectric constants and conductivity values. Dielectric constant of paint substrate is extracted from measurement of S-parameters using vector network analyzer in the waveguide mode. A process described in [17] is used to find the relative permittivity and loss tangent of various paints. Latex is tested and chosen for its durability, flexibility, quick drying times, and achievable thickness after single application. Paint, rubber, resin, and conformal sprays were also considered for the dielectric layer. The test process for latex paint involved applying several layers of paint to a Teflon plate, peeling off these layers, and folding them onto each other using additional paint as glue. This method provided the chance to quickly build samples with thicknesses required for accurate testing in a waveguide. Reflection and transmission measurements are taken and the dielectric properties are extracted. Results of the material characterization are summarized in Table 1.

The extracted complex relative permittivity of paint dielectric material used in design of metamaterial absorber is $6.62 - 0.63j$,

Table 1. Measured material parameters.

Materials	Properties	Values	Units
Paint Substrate	Relative permittivity	$6.62 - 0.60j$	$\sim$
	Loss tangent	0.09	$\sim$
Conductive Silver Paint	Conductivity	5.6×10^5	S/m

indicating loss tangent value of 0.09 at X-band frequencies. The conductivity of the metal layer painted on the surface of paint substrate is determined from four-point probe measurement. An average value for conductivity of the silver conductive paint measured on 20-micron thick layer is 5.6×10^5 S/m. The thickness of the metal layer is chosen to be higher than skin depth [18] of the metal (6.7 μm) at 10 GHz. These material properties were used in the design and simulation of the absorbers.

To get a clear understanding on how well these values for permittivity, loss tangent and conductivity of the paints are suited for microwave applications, one can perform a simple theoretical study of standard microstrip line using these parameters. A 50 Ohm microstrip line (width 1.3 mm) on latex paint as substrate (1 mm thick) and silver paint (20 μm thick) as conducting strip and ground layer, will exhibit a loss of 0.52 dB/cm at 2.5 GHz, and 1.9 dB/cm at 10 GHz. Comparing these values to a loss-free substrate for a microstrip line which is 0.11 dB/cm at 2.5 GHz and 0.20 dB/cm at 10 GHz, it indicates that the loss tangent of the substrate is more critical than increasing the conductivity of the conductive paint for realization of low loss microwave circuits. However, for realizing absorbers, one takes advantage of the high loss tangent of the substrate, as is shown experimentally to work in this paper. However this may not be desirable for some microwave circuits. One can envision a hybrid approach that combines the paint process with prefabricated substrate materials that are low loss at microwave frequencies.

4.2. Modeling and Simulations

Design and numerical simulation of metamaterial absorbers is carried out using commercially available software, CST microwave studio (version 2011) using the parameters for materials obtained from physical measurements discussed above. Periodic boundary condition is used with single unit cell to capture the overall response of a 2-

D metamaterial built with these cells. Waveguide ports are used for excitation and reception. Simulated S-parameter for metamaterial absorbers is presented in Fig. 4(a). The power reflection coefficient (R) can be calculated from the S-parameter as $R = |S_{11}|^2$. Since transmitted power is negligible due to presence of the back metal layer, the power absorption coefficient can be calculated as $A = 1 - R$. It can be seen from Fig. 4(a) that at resonance frequency (LC resonance) for parallel polarization, the reflected power is reduced which means power is absorbed. The LC resonance is related to the equivalent inductance (L) and capacitance (C) of the SRR. Wave incidence with perpendicular polarization is reflected at LC resonance frequency and a second low reflection appears at a higher frequency. Both electric and magnetic fields of the incidence wave couple to the metamaterial unit cell. Coupling of the electric field manifests itself as high concentration of electric field concentration in the gap of the SRR (Fig. 4(b)). Similarly coupling to magnetic field happens between the resonator and backside conductive plane, which manifests itself, as antiparallel

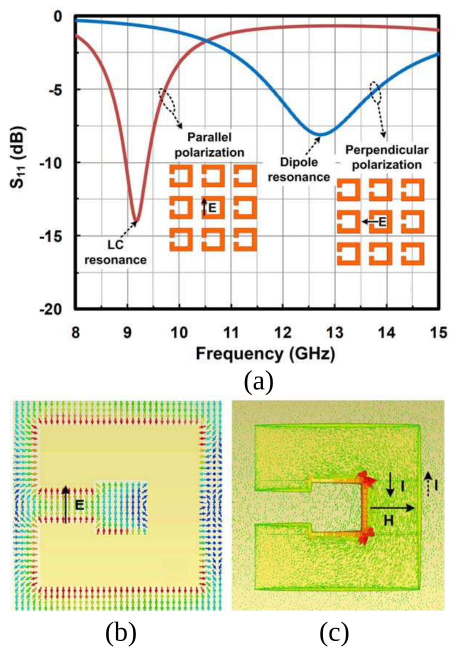
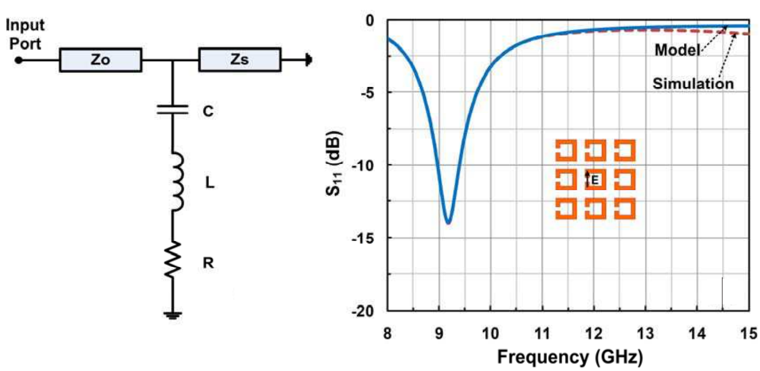


Figure 4. (a) Simulated response of C-shaped metamaterial absorber for the parallel and perpendicular polarizations, (b) induced electric field, and (c) induced surface current due to magnetic field.

surface currents as shown in the Fig. 4(c). This indicates that the metamaterial exhibits both an effective permittivity ε and an effective permeability μ, under an effective medium theory of metamaterials. Perfect absorption will exist if the characteristic impedance of the metamaterial given by $\eta = E/H = \sqrt{(\mu/\varepsilon)}$ matches that of free space [11].

Since absorbers interact with electromagnetic waves in free space, their design are carried out using electromagnetic simulation, however, equivalent circuit models present a better understanding of its behavior [19, 20]. The combination of LCR (inductor, capacitor, resistor) resonant circuit and transmission line model can be used to model the absorber response for each resonant mode. Such a model for the designed absorber is presented in Fig. 5(a) where free space path is modeled as a transmission line with its characteristic impedance, Z_o and substrate as a transmission line with its characteristic impedance, Z_s which are determined by their dielectric properties. Metamaterial resonator is modeled as LCR circuit where L and C determine resonant frequency and R captures overall loss in the absorber. Results from both circuit model and electromagnetic simulation are shown to match well over the entire absorption band. The mismatch between them becomes more obvious at higher frequencies above 12 GHz, since the model ignores higher order resonances. The equivalent circuit values of the model that provided the best fit to the simulation results are; $L = 2.47\,\text{nH}$, $C = 0.08\,\text{pF}$, and $R = 23.28\,\text{Ohm}$. Transmission line characteristics impedances are $Z_o = 377\,\text{Ohm}$ and $Z_s = 146\,\text{Ohm}$.

Figure 6 shows three different geometries for metamaterials for



(a) (b)

Figure 5. (a) Circuit based model of paint metamaterial absorber made of C-shaped split ring resonator (SRR) unit cells, (b) model and simulation S-parameter at the input port.

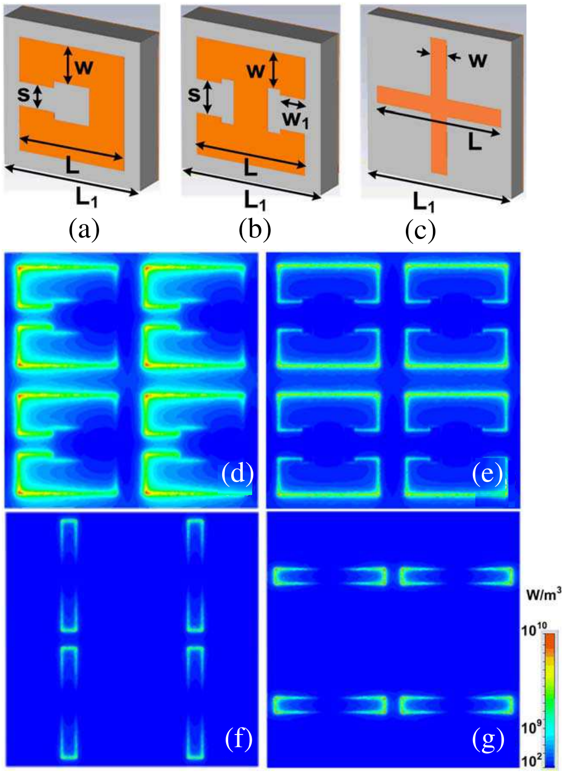


Figure 6. Unit cells of three different absorber designs. (a) C-shaped split ring resonator (SRR), (b) C-shaped dual-SRR (d-SRR), (c) cross dipole and (d)–(g) simulated power loss density in four unit cells at absorption frequencies for parallel polarizations in (d) C-shaped SRR, (e) d-SSR, and dipole metamaterial for (f) parallel and (g) perpendicular polarizations.

realization of three different absorbers. Figs. 6(a) and 6(b) utilize C-shaped SRRs as metamaterial unit cell and absorb wave energy only for single polarization of the electric field, which is parallel to the gap of SRR. Structure of Fig. 6(c) is called the cross dipole resonator and works as absorber for both parallel and perpendicular polarizations and hence is not polarization sensitive [21]. The size of unit cells in Figs. 6(a) and (b) are smaller than the one in Fig. 6(c). The power loss density of these absorbers are simulated at absorption frequencies and shown in Figs. 6(d)–(g) and reveals that most of the absorbed power is dissipated at edges and underneath metal layer of the resonators in the dielectric substrate. These three designs are simulated for absorption at three different frequencies in the X-band. The power absorption level of three designs is also varied in simulation for the comparison with measurement. Dimensional parameters of three designs are summarized in Table 2. The dielectric substrate thickness is kept constant (1 mm) in all three designs.

Table 2. Simulated (and measured average) dimensions of three different absorber samples shown in Fig. 4.

Parameters	**C-shaped SRR**	**d-SRR**	**Cross Dipole**
L (mm)	3.3 (3.29)	3.5 (3.53)	6.2 (6.22)
W (mm)	1.1 (1.08)	1.1 (1.12)	0.8 (0.81)
S (mm)	0.7 (0.68)	1 (0.98)	$\sim$
L_1 (mm)	4.3 (4.3)	4.5 (4.5)	7.2 (7.2)
W_1 (mm)	$\sim$	0.7 (0.8)	$\sim$

4.3. Measurement Results

Fabricated samples are measured using vector network analyzer (VNA-HP 8510C). The setup consists of VNA with X-band waveguides connected to flexible cables using coaxial-to-waveguide adapters. In case of free space measurements, the horn antenna is used to transmit and receive microwaves. The frequency range for the measurement in X-band waveguide mode is 8.2–12.4 GHz. Setup is calibrated with open, short and through measurements. Metal plate is used as short and reference for the reflection measurement. Measured S-parameter of C-shaped metamaterial absorber is shown in Fig. 7(a). Measured results are also compared with simulated results. Frequency for minimum reflection is 9.20 GHz in simulation, and 9.25 GHz in measurement, showing a frequency shift of 0.05 GHz. This frequency shift could be associated with various factors such as difference between dimensions of fabricated and simulated structures and dielectric constant of the substrate. Power absorption coefficient determined from S-parameter is presented in Fig. 7(b). The measured maximum absorption for this sample is 95.67% in comparison to simulated value of 96.05%. Since this sample is polarization sensitive, the wave is reflected back when sample is rotated by 90 degrees. To understand the effect of backside metal the S-parameter is also measured at backside of the sample. Wave is reflected back which indicates that backside metal works as an excellent reflector at these frequencies.

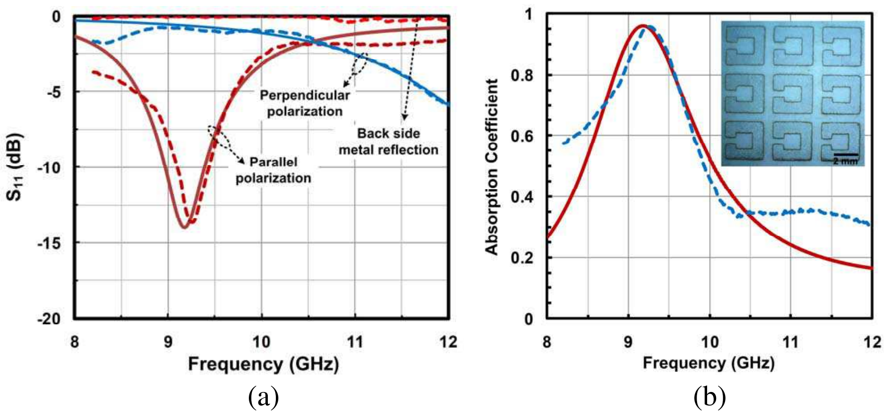


Figure 7. Measured (dashed lines) and simulated (continuous lines) results of C-shaped metamaterial absorber, (a) S-parameters and (b) absorption coefficients, inset showing microphotograph of the sample.

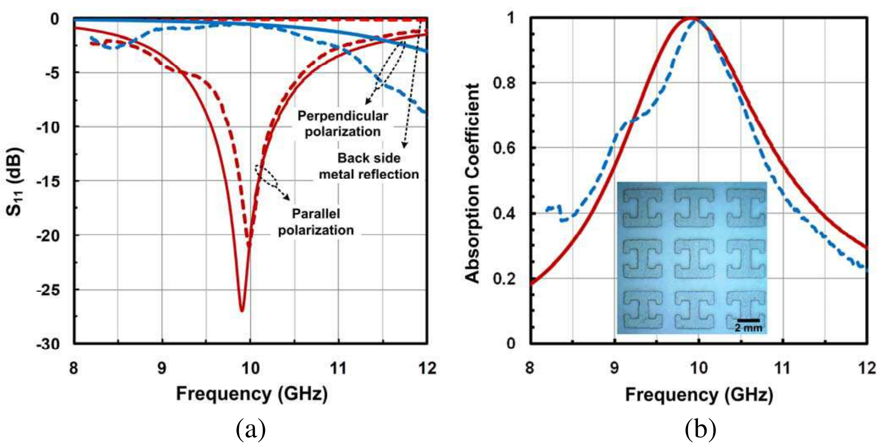
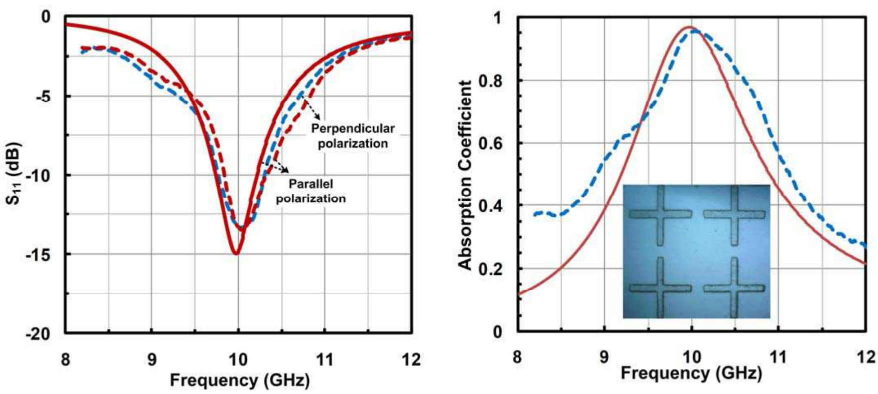


Figure 8. Measured (dashed lines) and simulated (continuous lines) results of C-shaped dual-SRR metamaterial absorber, (a) S-parameters and (b) absorption coefficients.

Measurement on second absorber sample consisting C-shaped dual-SRR metamaterials shows minimum reflection at frequency of 10 GHz and 0.1 GHz frequency shift compared to simulated result as presented in Fig. 8(a). This sample is designed with higher peak absorption level than other sample in order to compare simulated and measured absorption values. As shown in Fig. 8(b), measurement result shows 99.22% absorption in comparison to 99.88% achieved in the simulation. The frequency bandwidth for maximum absorption is lower in measurement than simulation. This discrepancy between simulation and measurement could be attributed to the fact that the parameters used in simulation vary slightly from real values.

Measurement on the third metamaterial absorber sample, which is based on cross dipole resonator, is presented in Fig. 9. This absorber absorbs energy for both polarizations of the wave electric field and thus it is polarization insensitive absorber. Maximum absorption level in measurement for this sample is 95.54% at 10.05 GHz. The simulated maximum absorption level is 96.80% at 9.98 GHz.



(a) (b)

Figure 9. Measured (dashed lines) and simulated (continuous lines) results of cross dipole metamaterial absorber, (a) S-parameters and (b) absorption coefficients.

5. CONCLUSIONS

Paint process is suitable for fabrication of metamaterials and microwave circuit on the arbitrary substrates, *in-situ* using very low cost materials and for large area format. Paint base for both dielectric and conducting metal layer is used to fabricate metamaterial absorber at X-band frequencies. Fabricated absorber samples show absorption level of 95% to 99% in close agreement with simulation. Both absorption level and frequency response can be tailored by design. The metamaterial-based absorbers are ultra-thin in comparison to conventional absorbers [22, 23] making them suitable for many flexible and conformal applications. Metamaterial absorbers have been demonstrated to work over wide incidence angle up to 60 degrees without significant change in the response [24], however tests on flexible application still needs to be done. The paint process is suitable for the fabrication of absorbers on arbitrary surfaces and over a large area making it a suitable candidate for use in radar or radomes absorbers [25, 26]. Paint metamaterial can also be used to reduce scattering or interference in automotive radars and decrease electromagnetic interference (EMI) in microwave circuits. Paint-based metamaterial can provide simple and low cost process to make cloaks and other exotic devices [27]. One can also extend this approach for the fabrication of conventional microwave circuits such as RFID antenna [8, 9].

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