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Electromagnetic characterization of 3D printed metamaterial absorber with conductive paint

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Abstract

In this study, electromagnetic characterization of 3D printed metamaterials manufactured by using conductive paint is carried out in terms of their absorption behavior. The samples have been prepared in sizes to fit waveguide setup in the frequency range of 12-18 GHz. 3D printing technique was used to prepare the substrate of the design while conductive paint and copper tape were used for the conductive parts of the structure including the metamaterial resonator and the ground plane. For electromagnetic characterization of the design, different thickness of substrate layers, various raster orientation (0°, ±45° and ±90°), different infill densities have been simulated and experimentally tested in terms of their effects on absorption behavior. In addition, conductivity of the paint was improved by adjusting its formulation and the resulting absorption behaviors have been compared with copper tape using the same metamaterial dimensions. Using 3D printing technology along with conductive paint rather than solid conductors in manufacturing electromagnetic absorbers will provide the possibility of producing flexible and non-planar electromagnetic absorber structures in desired frequency ranges. The design can be easily adopted to different frequencies and this technique can be used to design wideband metamaterial absorbers using 3D layered structures.

Keywords: Additive Manufacturing, 3D Printing, conductive paint, metamaterials, absorber.

1. Introduction

The idea of metamaterials (MTM) goes back to 1968 when a Russian physicist Veselago published a paper presenting the idea of having negative electrical permittivity and magnetic permeability simultaneously [1]. These materials have very unique properties that cannot be readily found in nature such as negative refractive index. However, after the idea of these unusual materials had not gain too much attention for almost thirty years. At around 2000, Pendry and Smith were able to realize these materials for the first time [2-4]. MTMs are composed of wires and/or line combinations arranged in periodic order. After the realization of the first MTMs, the interest on these materials and their application areas increased very rapidly. Their application fields are very wide and continuously expanding with the developing technology. Perfect lenses, perfect absorbers, source imaging, RF filters, polarization rotators, sensors, etc. can be counted as some of the applications studied in the related literature [5-8].

Even though there are several applications of MTM in literature and in the related industry, MTM based microwave absorbers are some of the most studied areas. There are numerous studies in the literature about MTM absorbers in almost the entire electromagnetic spectrum [9, 10]. In particular, the use of paint process in the fabrication of MTM studied by Singh et al. [11]. They proposed a new method for manufacturing MTM with large areas on planar and flexible substrates. They specifically used silver ink and latex paint for fabricating MTM based absorbers operating at 8-12 GHz. They have successfully obtained 95% to 99% absorption in their absorber samples manufactured by using the paint process.

Although several methods have been studied in various studies, the use of 3-D printers on manufacturing MTM absorbers for electromagnetic (EM) applications is a promising research area. Thanks to this new printers, material productions vary widely in the material science field. Just like in Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), PolyJetting and etc., all 3D printer productions rely on additive manufacturing. Parts are designed in computer environment are manufactured through 3D-printers in any desired geometry. For the manufacturing process in this study, PLA+Filament (Polylactic Acid) having high tensile and impact strength was selected. It can be used for fast productions with considerably fine surface quality. Manufacturing MTMs THROUGH 3D-Printers have been an interesting topic in the scientific and engineering community. In a study, Zhou et al., studied the production of EM absorbing MTMs in cross-helix shape using the combination of 3-D printing technology and precursor-derived ceramic [12]. In their study, they have found that ceramic metamaterials can be fabricated using 3D printing technique in order to obtain electromagnetic absorber structure.

In the production of MTMs, printed circuit boards (PCB) are widely used. In this type of production copper is widely selected as the conductive part to build the periodic resonators of MTMs and FR-4 type dielectric material is used commonly as the substrate. In this study, dielectric materials were manufactured using a 3D printer with various configurations and conductive coating (paint) was used for the resonators and ground plane of the MTM structure.

Conductive coatings are preferred in various application areas including static discharge, electromagnetic shielding, antistatic coating and numerous electrical applications. With conductive paint, it is possible to obtain any desired conductivity values on any surface and to stabilize this conductivity. In essence, a linear conductivity can be obtained with the addition of dielectric materials such as nickel, silver, copper and graphene. For these reason, conductive paint was used in this study to design the MTM and compared with the one designed using copper. Three methods are widely preferred to design conductive paints which include utilizing conductive polymers as the continuous matrix, using conductive pigments and the combination of these two. In order to simulate conductive paint, it is necessary to determine the conductivity and thickness. Although the thickness is known, its conductivity could not exactly be determined. In a study conducted by Andriambeloson et al., graphite was used in order to predict the effect of conductive paint [15]. In this study, they have successfully analyzed a conical antenna using 3D printing technique and graphite as the conductive layer. For this reason and to enlarge the resistivity range, graphite was used since it is readily available in CST Microwave studio. Using graphite as pigment is advantageous because of high conductivity for low surface area.

2. Material and methods

The MTM structure is composed of a conductive material and a dielectric substrate. 3-D printed samples were used as the dielectric substrate for the design. For this purpose, four different configurations have been manufactured in the sizes that can fit into the sample holder of a waveguide measurement system. The produced samples are shown below.

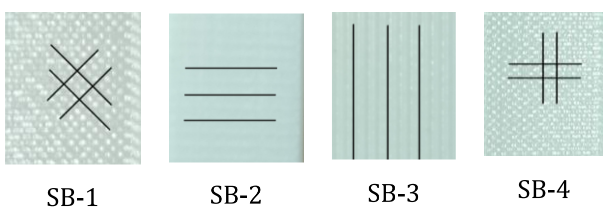

Fig 1. Manufactured 3-D substrate samples with different configurations.

As seen in the figure, each 3-D sample has different configurations and the details of these samples are tabulated below (Table-1). All samples have 60°C plate temperature, 0.2 mm first layer height and 0.8 mm top/bottom thickness values.

Table 1. Properties of the 3-D substrate samples.

No	Filling Shape	Filler Dens.	Print. Temp. (°C)	Printing Speed (mm/s)	Wall Thick. (mm)	Layer Height (mm)
SB-1	Grid 45°	30%	200	50.0	0.8	0.15
SB-2	H. Lines	30%	200	50.0	0.8	0.15
SB-3	V. Lines	30%	200	50.0	0.8	0.15
SB-4	Grid VH	30%	200	50.0	0.8	0.15

After manufacturing the samples, waveguide measurement system was used to obtain the electromagnetic properties of the samples. This measurement system consists of a network analyzer, two waveguides and a sample holder as shown in the figure below (Fig. 2).

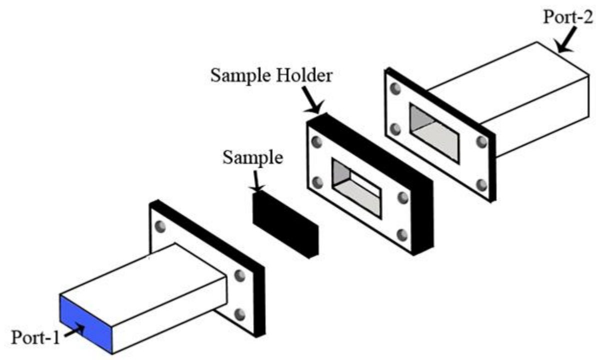

Fig 2. Waveguide measurement system for Electromagnetic characterization of materials.

In order to clarify the electromagnetic characterization, it is necessary to mention about scattering parameters, shortly known as S-parameters. In a two port system (Figure 3), there are four different scattering parameters which refers to the signal reflected back to the port it was sent and the signal transmitted from one port to the other.

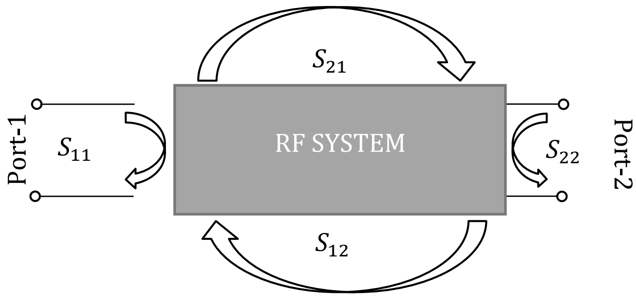

Fig 3. Scattering parameters in a two-port system.

When a two-port system (Fig. 3) is considered, there are four S-parameters including S_{11}, S_{22}, S_{12} and S_{21}. At this

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point, S_{11} represents the signal reflected back from Port-1, S_{22} refers to the signal reflected back from Port-2, S_{12} and S_{21} is the transmitted signals between Port-1 and Port-2.

Before starting the measurement, the system is calibrated using a metal plate for full reflection and empty space for full transmission. As known, the system provides the scattering parameters (S-parameters) which are used to obtain electrical permittivity and magnetic permeability via Nicolson Ross Weir (NRW) method. This method was originally developed by scientists Nicholson and Ross and Weir [13, 14].

In the NRW method, the permittivity and permeability values are calculated by using the obtained reflection and transmission coefficients.

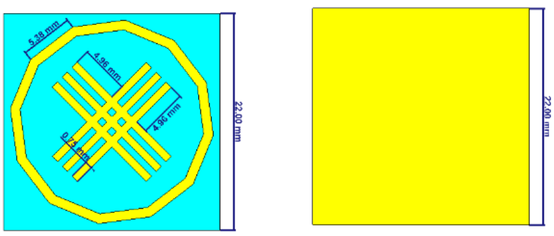
$$\mu_r^* = \frac{2\pi}{\Lambda\sqrt{k_0^2-k_c^2}}\left(\frac{1+\Gamma}{1-\Gamma}\right) \text{ and } \varepsilon_r^* = \frac{1}{\mu_r^* k_0^2}\left(\frac{4\pi^2}{\Lambda^2}+k_c^2\right) \quad (1)$$

Here, the parameters used in the equations above can be found by the following equations.

$$\Gamma = X \pm \sqrt{X^2-1}\,,\; X = \frac{S_{11}^2-S_{21}^2+1}{2S_{11}} \quad (2)$$

$$T = \frac{S_{11}+S_{21}-\Gamma}{1-(S_{11}+S_{21})\Gamma}\,,\; \frac{1}{\Lambda^2} = -\left[\frac{1}{2\pi L}\ln(T)\right]^2 \quad (3)$$

After obtaining the electromagnetic permittivity and permeability values from scattering parameters, the data were transferred into the CST Microwave Studio for further analysis. The designed metamaterial absorber structure using the 3D samples whose electromagnetic properties were obtained is given below in details (Fig. 4). In this figure yellow parts represent the conductive layer which is copper and graphite in each cases while turquoise color refers to the 3D printed substrate.



(a) (b)

Fig 4. Metamaterial Absorber Structure (Front side (a) and back side (b)).

As seen in the MTM structure given in Figure 4, the absorber is composed of three cross lines surrounded by closed line with twelve segments. As known, the backside of the shape is composed of a metal ground plane to eliminate any transmitting signal. The structure provides absorption at around $f = 3.5\ GHz$ with various magnitudes depending on the configuration of the substrates. The substrates were selected as the 3D printed samples and the conductive lines were investigated for two cases, copper and graphite.

3. Results and discussion

The results will be discussed for two main cases. First case includes copper as the metamaterial and ground plane part of the structure while graphite was used for the second case. 3D printed samples were used and compared for both cases in order to achieve maximum absorption response.

As known, absorption ($A(w)$) depends on the reflection ($R(w)$) and transmission ($T(w)$) as;

$$A(w) = 1 - R(w) - T(w) \quad (4)$$

where $R(w) = |S_{11}|^2$ and $T(w) = |S_{21}|^2$.

It should also be noted that all these functions are frequency (w) dependent. Since the structure has metallic back plane, the transmission will be eliminated, i.e. $T(w) = 0$. For this reason, the absorption behavior can be analyzed by simple examining the reflection behavior corresponding to S_{11}. The obtained results for the first case are given in the following figure (Fig. 5). As seen in the figure, using 3D printed samples as the substrate, we have successfully obtained metamaterial absorber with various magnitudes. The sample SB-2 provides the best absorption behavior compared to the other substrates when copper is used as the metamaterial structures and the ground plane.

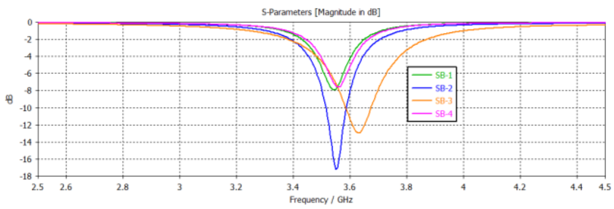


Fig 5. Reflection of the designed metamaterial structure for copper.

When copper is replaced with graphite, the following reflection (return loss) response has been obtained for the same substrate types printed with various configurations. As seen in the figure, the best substrate candidates are SB-3 and SB-4 for the graphite application since they both have lower reflection behaviors resulting in higher absorptions. Substrate made of the sample SB-2 did not provide the best absorption behavior in this case.

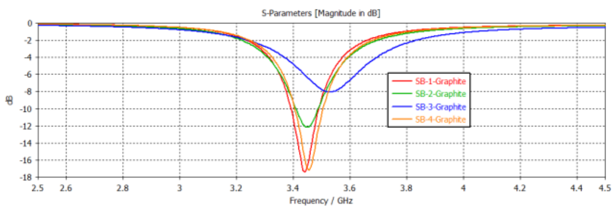


Fig 6. Reflection of the designed metamaterial structure for graphite.

When the absorption behavior is drawn for both cases in terms of the wavelength, the following figures (Figure 7-8) were obtained. As in the return loss graph, absorption graphs also shown that SB-1 and SB-4 samples provided higher absorption for graphite case while SB-2 gave the highest absorption value for the copper case. For both cases, more than 98% absorptions have been obtained.

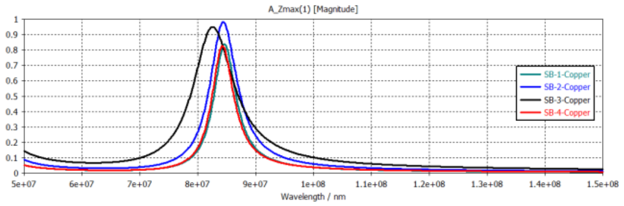


Fig 7. Absorption of the designed metamaterial structure for copper.

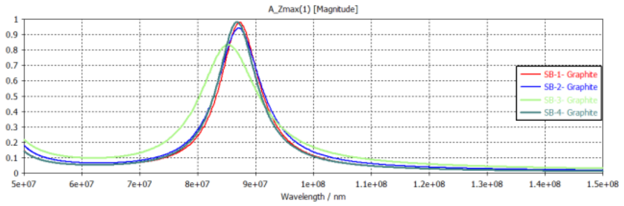


Fig 8. Absorption of the designed metamaterial structure for graphite.

4. Conclusions

In conclusion, we have successfully designed a metamaterial absorber using 3D printed materials as the substrate. In order to estimate the absorption behavior of a conductive paint, graphite was used as the conductive part of the metamaterial cell structure since graphite is an essential part of the conductive paint.

It was determined that Grid 45° and Grid VH samples provided the best absorption behavior for graphite while the sample with horizontal lines gave the highest absorption behavior for the copper case. It should also be noted that more than 98% absorption behaviors have been obtained for both cases.

In the future works, carbon black and graphite will be mixed at different ratios, their mixture will be used as the conductive part of absorber structures, and their effects will be determined both theoretically and experimentally.

Author's statement

Conflict of interest: The authors are associated with TUSAŞ, Ankara, Turkiye. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: n/a.

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