Composites: Part A 80 (2016) 111–117

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Broad bandwidth of thin composite radar absorbing structures embedded with frequency selective surfaces

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A R T I C L E I N F O

Article history:
Received 15 July 2015
Received in revised form 9 October 2015
Accepted 14 October 2015
Available online 19 October 2015

Keywords:
Functional composites
A. Polymer-matrix composites
A. Sandwich structures
B. Magnetic properties

A B S T R A C T

The three-layer ultrathin radar absorbing structure (RAS) involving a frequency selective surface (FSS) exhibiting excellent broad bandwidth properties is designed and fabricated. The EW and flaky carbonyl iron powders were used to produce two kinds of silicone rubber matrix magnetic composites for the top and the bottom layer, respectively. The electromagnetic parameters of the composites were measured in the frequency range of 2–18 GHz. The middle layer is an FSS in the form of double-square loops with four micro-split gaps in the middle of the outer loop. The results show that the proposed RAS can provide a 10 dB absorbing bandwidth of 13.2 GHz from 4.8 to 18 GHz (1.7 mm thickness) and a 10 dB absorbing bandwidth of 14.1 GHz from 3.9 to 18 GHz, covering C-band, X-band and Ku-band (2.0 mm thickness). A good match between simulation and measurement results demonstrates the validity of our design.

1. Introduction

Radar absorbing structure (RAS) is currently viewed as a kind of functional composite that can absorb electromagnetic wave effectively and convert electromagnetic energy into heat or make electromagnetic wave disappear by interference, which is widely applied in military applications and all areas of modern life. The frequency interval of 2–18 GHz is of particularly importance, in which many communication and information-transmission systems operate. The traditional dielectric and magnetic RASs yet exist some shortcomings. The typical light dielectric absorbers, achieving the broadband absorption properties, require large matching thicknesses [1,2] or obtain relatively narrow absorbing bandwidth [3]. Meanwhile, pute magnetic absorbers employing metallic or ferrimagnetic micron-sized materials suffer from heavy weight and poor characteristics in frequency ranges higher than gigahertz due to the Snoek limit [4]. Compared to traditional radar absorption materials, metamaterials are attractive not only for their exotic physical effects, but also for their free design and wide range of applications, including electromagnetic wave absorber [5–7]. The standard objective of the radar absorber designing is to obtain the RAS with the least thickness and the lowest possible reflectance within the widest operating bandwidth by applying composite absorbers [8,9] or multilayer structures [10,11] instead of only including one kind of absorber or single layer ones, respectively [12]. However, the microwave absorbing property about the frequency bandwidth fails to be greatly improved or wideband absorption characteristics can be obtained still at the sacrifice of the total thickness and weight of RAS, resulting in the limitations to the applications of RAS. Thus, the design of thin and simultaneously broadband RASs is a hot topic without increasing the original total thickness basically. Kazantsev et al. [13] and Cheng et al. [14] have attempted to achieve this goal most applying the magnetic media as a substrate in the design of the magnetic materials, the bandwidth could be extended in some degree with a relative thinner material thickness, which give some new ideas to design ultrathin RAS by combining the traditional absorption materials with Frequency selective surface (FSS). Based on the above consideration, people began to research the combination of FSS and RAM in order to develop composite radar absorption materials with great absorptive performance, thinness, light weight, and broad band at the same time. Much design about composite FSS-embedded RASs showed that FSS is embedded in nonmagnetic materials. Conductive FSS layer loaded with lumped resistors [15] and the FSS with split-ring resonator (SRR) unit cell [16,17] can be used for synthesizing thin and wideband RASs. The effect of FSSs on the reflection characteristics of RASs is based on lossy

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http://dx.doi.org/10.1016/j.compositesa.2015.10.019
1359-835X/

dielectrics [18–21]. Calculations about RAS embedded with FSS of special structures have shown FSS plays an important role in improving absorbing characteristics of composite RASs [13,22–24]. The light nonmagnetic RAS with FSS in the reports above can't obtain broadband absorption and ultrathin properties. There are other reports about the magnetic composite RAS embedded with FSS, which concentrates on the low frequency region [25] and broadening the frequency bandwidth [11,21,26,27]. But the composite RASs do not have a particularly wide bandwidth or have wide bandwidth with the thickness of more than 2 mm.

This work deals with the experimental studies on the composite three-layer sandwich RASs for 2–18 GHz. EW (a type of iron carbonyl powder produced by BASF chemical company) sheet is used as the top layer mainly for impedance matching and the flaky carbonyl iron is used as the bottom layer mainly for absorption. The middle layer is an FSS in the form of double-square loops marked as the FSS without a split and double-square loops with four micro-split gaps marked as the FSS with splits. The fabrication and the measurements of the composite RASs containing these fillers were conducted. The proposed composite RASs can obtain excellent absorption properties, especially for the bandwidth of exceeding 10-dB in the thickness of 1.7 mm and 2.0 mm. The measured reflection characteristics are validated by simulation calculations of reflection loss (RL), based on a unit cell model of RAS backed by a perfect conductor by the high frequency structure simulator (HFSS).

2. Design

The research focus about broadband and strong absorption is the design of the multilayer polymer-matrix composite RASs. Considering the total thickness of the composite RASs, we decide to start the design with two layers. The structure diagram of the RAS is shown in Fig. 1(a). The EW magnetic sheet has good absorption characteristics because of the good impedance matching, due to the EW powders are coated by SiO_2 and the SiO_2 coated on the outside can improve the impendence matching characteristic of the absorbers [28]. Therefore it is chosen as the top layer, so called the matching layer. In addition, the matching layer also plays the role in consuming the diffraction microwave energy, which consists of 70 wt% EW, 29.6 wt% silicone rubber and a little vulcanizing agent. The other magnetic sheet mainly containing flaky carbonyl iron and the flaky powders can make the magnetic sheet achieve a better electromagnetic properties with a higher dielectric loss and magnetic loss [29,30], which is used as the bottom layer, so called the absorbing layer. The bottom layer has the following compositions: 63 wt% flaky carbonyl iron, 36.4 wt% silicone rubber and a little vulcanizing agent. The manufacturing operation of the magnetic sheets will be demonstrated in Section 3.

To further improve the absorption properties without increasing the total thickness nearly, an FSS was introduced to be embedded into the proposed two-layer composite RASs. The composite structure of FSS-embedded RASs with two variables t_1 and t_2 is shown in Fig. 1(a). The structures of the FSS without a split containing six variable parameters including a_1, w_1, a_2, w_2 and p are shown in Fig. 1(b). Fig. 1(c) shows that the adjusted FSS with splits exists another parameter of g in addition to the above variable parameters.

3. Fabrication of composites and measurement of electromagnetic characteristics

3.1. Fabrication of composites

Flaky carbonyl iron powders are prepared by ball-milling the raw carbonyl iron with the stirring speed of 400 rpm for 12 h by the ball-to-powder mass ratio of 10:1. Anhydrous alcohol mixed with a few drops of oleic acid was used as process controlling agent to avoid the aggregation and oxidization of particles in the period of ball-milling, ensuring the accuracy of the experiment. The raw carbonyl iron was purchased from Jiangxi Yuean Superfine Metal Co., Ltd. The EW is a type of carbonyl iron powder purchased from BASF chemical company. The low average particle size of 3.5 μm covers the microwave skin depth of 1–2 μm, which makes EW an economic choice. The EW powders had spherical particles between 1–8 μm and their surfaces were coated by SiO_2.

The fabrication process diagram of magnetic sheet and the coaxial test samples were shown below: the flaky carbonyl iron and EW are mixed with silicone rubber and a small amount of additives respectively, which were processed into different mixed uniformly semi-finished product by double roll rubber mixing mill. And then they were vulcanized and molded through plate vulcanizing machine at 170 °C for 8 min, processed into magnetic sheet with $180 * 180\ mm^2$, which were tested for reflectivity loss. On the other hand, the magnetic sheets were sequentially fabricated into the coaxial test samples with outer diameter of 7.0 mm and inner diameter of 3.04 mm.

3.2. Measurement of electromagnetic characteristics

The coaxial test system include coaxial fixture, coaxial-cable and network analyzer (8720B).The coaxial test samples used for measuring the electromagnetic parameters are processed into toroidal-shape specimens with outer diameter of 7.0 mm and inner diameter of 3.04 mm. The reflectivity loss of the sample is measured by arch testing method system. The basic structure of the bow method measuring system is shown below:

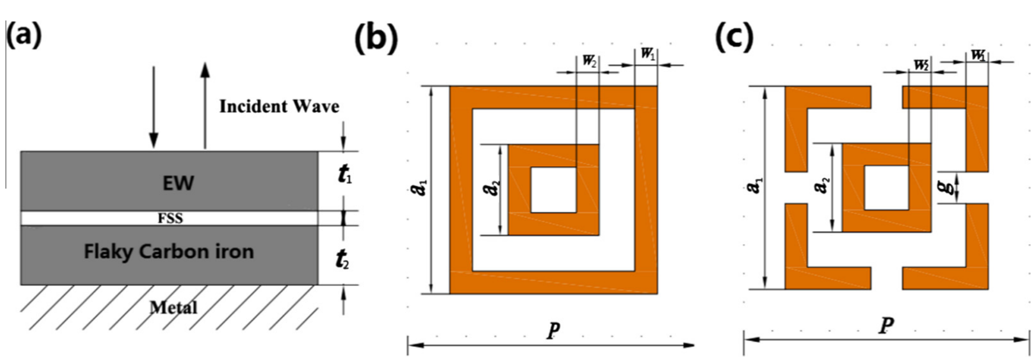

Fig. 1. (a) The cross section of three-layer structure diagram of the composite RASs, the unit cell of the FSS structure (b), the unit cell of the FSS structure with micro-split gaps (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)