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Design and characterization of radar absorbing structure based on gradient-refractive-index metamaterials

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ABSTRACT

A gradient-refractive-index radar absorbing structure(GRINRAS) for stealth aircraft is proposed in this paper. It is a layered shell composed of a gradient-refractive-index (GRIN) refractor, an absorber and a reflector. The GRIN refractor consists of the isotropic non-resonant woodpile metamaterials, which was designed according to the permittivity distribution equation of the electromagnetic(EM) black hole to bend and match the waves from the air to the radar absorbing structure. The absorber dissipates the EM waves and transforms them into the heat energy. The reflector reflects the EM waves to the absorber and prevents them from entering the inner space of the structure. A ring and a board GRINRAS were designed, and then fabricated by the three-dimensional (3D) printing process of stereolithography (SL). Simulation and experimental results show that the GRINRASes can control the wave propagation and their absorption capacity is better than −10 dB in the broadband of 12–18 GHz. The GRIN refractor and the absorber have almost equal contributions to the absorption capability. This is the first radar absorbing composite structure composed of the gradient 3D metamaterials. It demonstrates the feasibility of using the metamaterials and 3D printing technology in the innovative radar absorbing structure (RAS) of the stealth aircraft.

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1. Introduction

With the development of the radar detection technology, the stealth ability of aircraft becomes more and more urgent to keep flight safe and reliable [1–3]. After trials of decades, the most widely used stealth technologies in aircraft are the shapes with low radar cross section (RCS) and the coatings of radar absorbing material (RAM). However, they both have some inherent drawbacks, which hinder the further improvement of the stealth ability. Low RCS shapes work by reflecting radar waves to other directions than the back direction to make it undetectable. They usually sacrifice some good aerodynamic shapes and does not work against bistatic radars [4]. RAM coatings are required to have both abilities of impedance matching to the surrounding environment and a large absorption capability at broadband, which are hard to meet simultaneously. Besides, RAM coatings may add undesirable extra weight and expensive maintenance costs for its flake off at high speed [5–7]. Therefore, stealth technologies that could simultaneously have good aerodynamic properties, good impedance matching, broadband absorption and impact resistance are urgently needed.

Radar absorbing structure (RAS) is a kind of structural stealth technology. Typical RASes, such as cellular cores sandwich structure and foam cores sandwich structure, obtain the broadband absorption through appropriate material composition, distribution, geometry angle and sandwich layer number [8–11]. By adding enhancement layers, the load-bearing capacity of the sandwich structures is increased. So they are both electromagnetic (EM) structure and mechanical structure [12–16]. However, the conventional sandwich RASes can not make an excellent impedance match with the surrounding environment, because the dielectric permittivity of the transparent layer on the surface is not small enough. And some special propagating paths beneficial to a high absorption capability, such as the paths of small incident angles [17], and the capture paths of the electromagnetic (EM) black hole [18] can not be achieved by the sandwich RASes. Indeed, these problems could be solved by the metamaterials.

Metamaterials are artificially EM medium, composed of periodic metallic or/and dielectric structures (named unit cells). By tailoring the geometry parameters of the unit cells, the required refractive

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index, impedance, permittivity, permeability can be achieved [19–21]. Thus, excellent impedance matching could be realized by metamaterials. By layer-wise controlling the geometry parameters of the unit cells, gradient-refractive-index (GRIN) metamaterials can be got. In recent years, some innovative structures of GRIN metamaterials, such as optical lens [22,23], invisible cloaks [24,25], wave absorbers [26,27] have been designed. These researches prove that GRIN metamaterials optionally manipulate the propagation of the EM waves, like blocking, absorbing, capturing or bending, providing the feasibility of using metamaterials to absorb the radar waves. However, to the best of our knowledge, little literature has been reported on the three dimensional (3D) radar absorbing structure composite of metamaterials. There are mainly two reasons. Firstly, radar absorbing structures usually need to be complex 3D structures to acquire good aerodynamic performance, while the majority of the realized metamaterials are two dimensional (2D) meta-surfaces or planar metamaterials, hard to build highly complex 3D shapes [28–31]. Secondly, metamaterials are structures integrated with micro-structure (structures of unit cells) and macro-structure (overall structures), which are difficult to fabricate by the conventional processes such as lithographic techniques. To overcome these difficulties, 3D dielectric metamaterials that provide possibility to construct complex 3D EM structures [32–34], and 3D printing technologies that provide solutions for extremely complex structures are both considered.

3D printing technologies allow to fabricating structures directly from digital models without moulds, thus gaining increasing popularity in manufacturing components with high geometrical complexity. For instance, stereolithography(SL) was used to fabricate gradient structures as artificial electromagnetic medium [35]. Selective laser melting (SLM) and electron beam melting (EBM) were used to fabricate custom implants [36]. Inkjet printing technology was used to fabricate sine wave and trapezoidal sandwich structures [37]. Selective laser sintering (SLS) and fused deposition modeling(FDM) were used to fabricate the net-like structure [38] and hybrid patterned dielectric structures [39] respectively. Actually, these years, 3D printing techniques have already been tried in aerospace industry, especially SLS, EBM, friction stir additive manufacturing (FSAM), wire and arc additive manufacturing(WAAM), which can produce extremely dense structures without post-processing [40–43]. Further more, with the combination of 3D printing techniques and smart materials, the technology known as 4D printing, can produce structures reacting and changing dynamically to the surrounding environment [44–46]. The fabricated structures are expected to act as automating actuation and camouflage devices, which are very useful for avoiding radar detection.

In this paper, a kind of metamaterial gradient-refractive-index radar absorbing structure (GRINRAS) was proposed. It is a layered shell surrounding the fuselage of aircraft. It consists of a GRIN refractor, an absorber and a reflector. The GRIN refractor has a strong capability to bend and capture the EM waves. The absorber dissipates the EM waves and transforms them into heat energy. The reflector reflects the EM waves to the absorber and prevents them from entering the inner space it surroundings. A ring and a board GRINRAS were both designed. The overall structures come from basic shapes of aircraft. The GRIN refractor are woodpile metamaterials whose EM parameter follows the permittivity distribution equation of the EM black hole. The two GRINRASes were fabricated by a 3D printing process and assembled. By simulations and experiments, the absorptance and bandwidth were measured. The absorption mechanism of the GRINRAS was discussed. Two features make this structure quite different from traditional RAS. One is that this proposed composite structure is the first RAS composed of the gradient 3D dielectric metamaterials. Another is that it uses the method of gradually bending and trapping the waves inward the structure to reduce the wave reflection. It is expected to enrich the variety of RASes and promote the applications of metamaterials in stealth aircraft.

2. Design and fabrication of GRINRAS

2.1. Design of overall structures

A ring GRINRAS and a board GRINRAS are designed and fabricated in this paper. Though aircraft shapes differ from each other, their forms are similar. They usually consist of a spherical head, a cylindrical fuselage and two board wings. The rings constitute the cross sections of the head and fuselage, while the boards constitute the wings. To some extent, aircraft are composed of numerous rings and boards. Therefore, ring and board were chosen as the overall shapes of the GRINRASes. To show the line of thinking clearly, some 3D models were built in the software of CATIA as shown in Fig. 1 (a),(b),(c),(e),(f). Photographs of fabricated structures are shown in Fig. 1 (d), (g). By analysing aircraft shapes, a simplified aircraft model was got. It is composed of cylinders, spheres, boards as shown in Fig. 1(a). There are two lines of pictures. The pictures on the top line show the design procedure of ring GRINRAS structure. The cylinder in Fig. 1(b) was simplified from fuselage. Then a thin cylinder GRINRAS, namely a ring GRINRAS was designed. Its 3D model was built as shown in Fig. 1(c) and then it was fabricated as shown in Fig. 1(d). The pictures on the bottom line show the design procedure of the board GRINRAS. The board in Fig. 1(e) was simplified from aircraft wings. Then a small square board GRINRAS was designed, and ts 3D model was built as shown in Fig. 1(f). The photography of the fabricated board is shown in Fig. 1(g).

To meet the requirements of the subsequent experimental measurements, there are some constrains to the dimension of the GRINRASes. The two dimensional (2D) electric field (E-field) intensity distribution measurement can be used to test the wave path in the ring GRINRAS. In this measurement, the thickness of the test sample is required to be 10–15 mm and it dimension should be smaller than 360 mm by 400 mm to ensure samples can be suitably put in the test area. Here the thickness of the ring GRINRAS ring is set as 10 mm, and the external diameter is set smaller than 360 mm. The far-field reflectance measurement can be used to test the reflectance of board GRINRAS. In this measurement, the dimension of test board should be as large as 300 mm by 300 mm to receive enough EM waves from the horn antennas. Here the side length of the board GRINRAS is set as 300 mm.

2.2. Design of the GRIN refractor

2.2.1. Ring GRINRAS

The permittivity of the GRIN refractor follows the permittivity distribution equation of the EM black hole (1) [47]. Thus, the GRIN refractor obtains the ability of capturing waves which is beneficial to the wave absorption.

$$\varepsilon(r) = \begin{cases} \varepsilon_b & r \geq R \\ \varepsilon_b \left(\dfrac{R}{r}\right)^n & R_C < r < R \\ \varepsilon_c + i\gamma & r \geq R_C \end{cases} \tag{1}$$

In the theory of black holes, EM black holes consist of a capture shell ($Rc \leq r \leq R$) and a lossy core($r < Rc$). The GRIN refractor of the GRINRAS was designed to mimic the capture shell. So the external radius of the GRIN refractor equals to R, and the internal radius of the GRIN refractor equals to Rc. The GRINRAS works in air, so the

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