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Cylindrical conformal single-patch microstrip antennas based on three dimensional woven glass fiber/epoxy resin composites

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ABSTRACT

Three dimensional integrated microstrip antenna (3DIMA) can carry the designed load while functioning as an antenna. In this study, the cylindrical conformal single-patch 3DIMAs with various curvatures were designed, simulated, fabricated and tested experimentally using a 3D orthogonal woven glass preform/epoxy resin composite system. The electromagnetic performances of the cylindrical microstrip antennas were analyzed. The simulated and tested results matched well and the return losses of the cylindrical conformal 3DIMAs with radii of curvatures of 60, 45 and 25 mm were less than −10 dB while resonant frequencies and their gain values were significantly influenced by the radius of curvature and the feeding direction. The 3DIMAs with the curvature perpendicular to the feeding directions showed more stable resonant frequencies and larger gain values than those of 3DIMAs with the curvature along their feeding directions.

1. Introduction

An antenna is an electronic device that radiates or receives electromagnetic waves, playing an essential role in wireless communications and aircraft navigation. However, the conventional antennas have protruding structures and thus the increased aerodynamic drag resulting in structural instability [1,2]. In 1980s, the concept of conformal antennas were proposed to be integrated with the outer metallic layers of aircrafts to reduce the aerodynamic drag, improving aircraft speed, fuel consumption, and gas emissions [3,4].

In 1990s, new conformal antenna structures called CLAS (conformal load-bearing antenna structures) have been developed to realize the integration of structures and antennas [5–9]. The CLAS and surface-antenna-structure (SAS) or composite smart structure (CSS) is a buildup of structurally effective layers. The basic structure of CSS or SAS is a sandwich construction which was proved to be weight efficient. However, the face sheets of CLAS panels were pulled off when the structures were subsequently subjected to F-18 class air vehicle loads. Similar results were also found in the CSS and SAS structure, finally leading to malfunction of the antennas [10,11].

Studies of conformal microstrip antennas have been reported in literature [12–16]. A conformal low-profile e-shaped patch antenna with unequal thickness substrate was proposed and the performance of antenna was greatly impacted by the curvature of the ground [12]. The effects of curvature radius on radiation patterns in multibeam conformal antennas were comprehensively investigated by Wincza and Gruszczynski, showing that radiation patterns of conformal antennas deteriorate gradually with the decrease of the radius of curvature [13]. Giang and Dreher [15] proposed a generalized analysis method of microstrip antennas on hemispherical multilayer structures and reported that the resonant frequency was shifted with decreasing radius of curvature from 100 to 30 mm. In addition, the studies on textiles structural microstrip antennas in bent or crumpled conditions showed that the antenna performance was influenced by the curvatures [17–20].

More recently, a three dimensional integrated microstrip antenna (3DIMA) structure was demonstrated [21–24]. The fundamental design concept of 3DIMA is an integral composite structure, in which a microstrip antenna is woven into 3D orthogonal composites and integrated by the yarns in through-thickness direction (Z-yarn). Due to the existence of through-thickness reinforcements, the 3DIMA can effectively prevent delamination problem [25–27]. Compared to the CSS and the SAS structures, the 3DIMA shows

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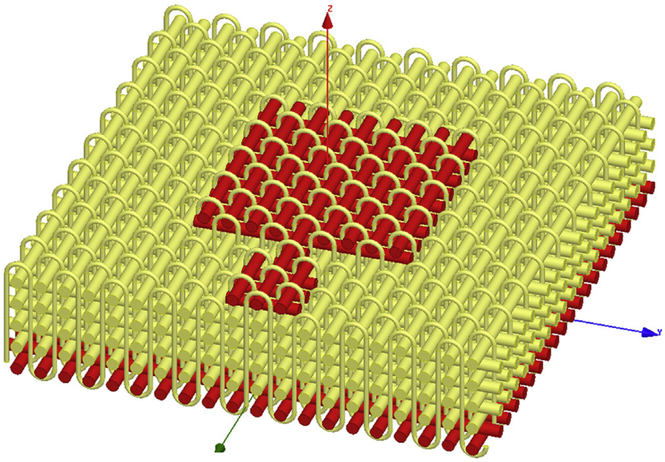

Fig. 1. Structure of the microstrip feeding 3DIMA.

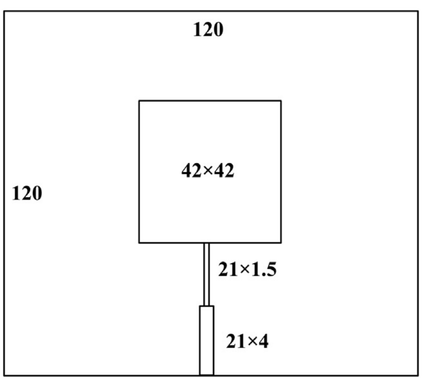

Fig. 2. Structural parameters of the single-patch 3DIMAs (mm).

superior integrity and could be a better candidate for CLAS structures. However, all the reported 3DIMA structures are planar structure and little has been reported on the effects of the curvature structure on the electromagnetic performance of the 3DIMA [21–24].

In this study, the cylindrical conformal single-patch 3DIMAs with various curvatures were designed, simulated, fabricated and tested experimentally using a 3D orthogonal woven glass preform/epoxy composite system. The effects of the curvatures on their electromagnetic performances were analyzed.

2. Design of 3DMIAs

The 3DIMA takes the both advantages of 3D composites and microstrip antenna and has a promising capability on excellent mechanical and electrical properties. There are two feed methods to fabricate microstrip antenna, coaxial-feeding and microstrip feeding. In most cases, microstrip feeding antenna is more suitable for the conformal structure and thus is adopted in this study as shown in Fig. 1. The copper yarns supplied by Shanghai Jingzu Copper Material Factory (Shanghai, China) were used to weave the radiating patch, the microstrip feeding line and the ground plane. The dielectric properties, such as dielectric constant and dielectric loss, significantly impact the antenna performance. In this paper, the E-glass fiber with relative low dielectric constant (6) and dielectric loss (0.001) were adopted. E-glass yarns provided by Jushi Group Company (Zhejiang, China) with a linear density of 1200 tex were adopted as the warp and the weft yarns to weave the substrate structure and E-glass yarns with the linear density of 370 tex were used as the Z-yarn. The resin system was the epoxy resin (JL-235) and the curing agent (JH-242) supplied by Jiafa Chemical Company, China.

The microstrip feeding single-patch 3DIMAs were designed to operate at radar L-band with the resonant frequency of 1.5 GHz. The substrate of the 3DIMAs is a 3D E-glass fiber/epoxy resin composite with a dielectric constant of 5.25 and a dielectric loss tangent of 0.01. In the design procedure, the structural parameters for the 3DIMAs can be calculated as described elsewhere [28,29]. The width of the patch can be calculated as follows:

$$W = \frac{c}{2f_r}\left(\frac{\varepsilon_r + 1}{2}\right)^{1/2} \quad (1)$$

where c is the velocity of light, f_r is the resonant frequency of the antenna, ε_r is the dielectric constant of the substrate. The length of the patch is

$$L = \frac{c}{2f_r\sqrt{\varepsilon_e}} - 2\Delta l \quad (2)$$

where ε_e is the effective dielectric constant and Δl is the length extension. The patch was designed to be fed by 50 Ω microstrip transmission lines, with a quarter-wave microstrip transformer inserted to match the antenna impedance to 50 Ω. The structural parameters of the single-patch 3DIMAs was shown in Fig. 2.

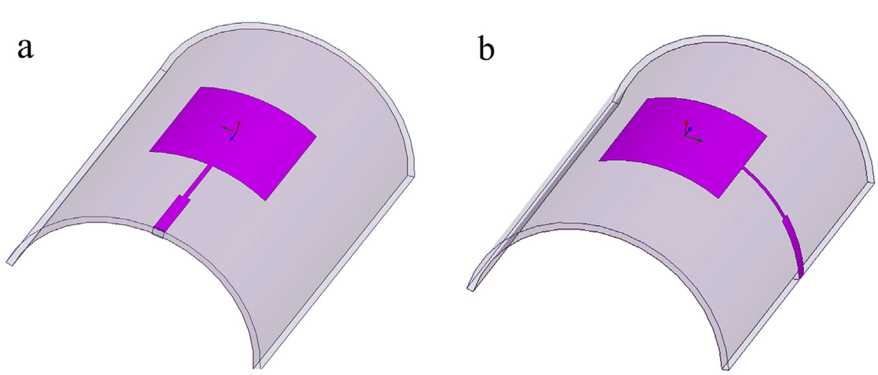

Fig. 3. Simulated models of the cylindrical single-patch (a) 3DIMAs-AFd and (b) 3DIMAs-PFd.