

Effect of Weaving Direction of Conductive Yarns on Electromagnetic Performance of 3D Integrated Microstrip Antenna

Fujun Xu · Lan Yao · Da Zhao · Muwen Jiang · Yipping Qiu

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Abstract A three-dimensionally integrated microstrip antenna (3DIMA) is a microstrip antenna woven into the three-dimensional woven composite for load bearing while functioning as an antenna. In this study, the effect of weaving direction of conductive yarns on electromagnetic performance of 3DIMAs are investigated by designing, simulating and experimental testing of two microstrip antennas with different weaving directions of conductive yarns: one has the conductive yarns along the antenna feeding direction (3DIMA-Exp1) and the other has the conductive yarns perpendicular the antenna feeding direction (3DIMA-Exp2). The measured voltage standing wave ratio (VSWR) of 3DIMA-Exp1 was 1.4 at the resonant frequencies of 1.39 GHz; while that of 3DIMA-Exp2 was 1.2 at the resonant frequencies of 1.35 GHz. In addition, the measured radiation pattern of the 3DIMA-Exp1 has smaller back lobe and higher gain value than those of the 3DIMA-Exp2. This result indicates that the waving direction of conductive yarns may have a significant impact on electromagnetic performance of textile structural antennas.

Keywords 3-Dimensional reinforcement · Electromagnetic performance · Computational modeling · Microstrip antenna

1 Introduction

Antennas, as devices that can transmit or receive radio frequency signals, are widely used in many occasions such as mobile radio, wireless communication systems and so forth. However, most of the conventional antennas have protruding aerials which may increase aerodynamic drag and thus limited their aerospace applications. Microstrip antennas have the advantages of low profile, conformable to planar and nonplanar surfaces, simple and low

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cost to manufacture, and have been widely used in high-performance aircraft, spacecraft, satellites, and other applications [1, 2].

In this decade, many researchers have focused on embedding the microstrip antennas into a polymer composite multilayer sandwich panel in order to make the antennas with both good radiation performance and mechanical properties. The conformal load-bearing antenna structures (CLAS) [3, 4], surface-antenna-structure (SAS) [5, 6] and composite smart structure (CSS) [7, 8] were developed to realize the integration of structure and antenna. However, the sandwich panel structures were not effectively reinforced in thickness direction and thus delamination dominant failure may develop in those CLAS, SAS and CSS panels when subjected to impact loading [9, 10].

More recently, a three dimensional integrated microstrip antenna (3DIMA) structure was demonstrated by Yao L et al. [11]. As shown in Fig. 1, the fundamental design concept of 3DIMA is an integral composite structure, in which a microstrip antenna is woven into a 3D orthogonal composite and integrated by the yarns in through-thickness direction (Z-yarn). The Z-yarn in 3D orthogonal woven composites binds the preform to hold the in-plane fibers, preventing delamination of the composites [12, 13]. Therefore, compared with the CLAS, CSS and SAS structures, 3DIMA shows superior integrity and delamination resistance.

In the design process of the 3DIMA, to optimize the thickness and maintain its low profile property, the copper yarns with large diameter in the first face and bottom layers were adopt as conductive yarns and those with small diameter in the second face and bottom

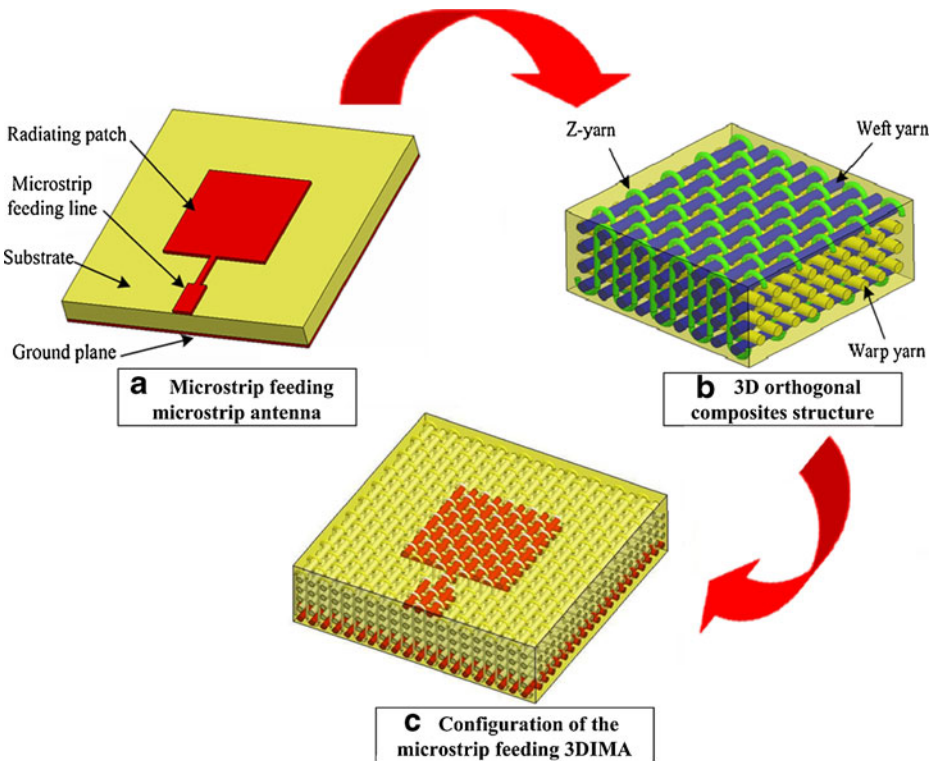


Fig. 1 Basic concept of the microstrip feeding 3DIMA structure

layers were adopted as connective yarns. The conductive yarns and connective yarns connect with each other and formed the radiating patch, feeding line and ground plane. For some textile structural antennas, the conductive yarns or conductive threads may need to be tailored for special structure or special radiation properties [14, 15]. The researches show that the conductive element materials and conductive fabric pattern have significant impacts on the radiation property of the textile structural antennas [16, 17]. However, the weaving direction of conductive yarns of 3DIMA may influence its electromagnetic performance of 3DIMAs, which has never investigated before.

In this study, two types of the 3DIMAs with conductive yarns in different weaving directions were designed, simulated and measured experimentally. Both simulated and measured results show that the 3DIMA with the conductive yarns along the antenna feeding direction has better resonant frequency, radiation pattern and gain properties than those of the 3DIMA with the conductive yarns perpendicular the antenna feeding direction.

2 Design of 3DIMAs

2.1 Material Selection

In this study, copper yarns supplied by Shanghai Jingzu Copper Material Factory (Shanghai, China) were adopted to weave the radiating patch, the microstrip feeding line and the ground plane of the 3DIMAs. E-glass yarns, EDR24-800-386 and EDR14-300-778 were provided by JUSHI Group Company (Zhejiang, China). E-glass yarns with the linear density of 800 tex were adopted as the warp and the weft yarns to weave the substrate structure; E-glass yarns with the linear density of 300 tex were used as the Z-yarn. Vinyl ester resin (901-VP) was used as the resin system and the curing agent (methyl ethyl ketone) was supplied by Shanghai Fucheng Chemical Company.

The dielectric constant of the substrate of 3DIMA can be calculated by the following equation [18].

$$\varepsilon_r = v_f \varepsilon_f + \varepsilon_m (1 - v_f) \quad (1)$$

ε_r , ε_f , ε_m are the dielectric constants of composites, glass fiber and vinyl resin respectively, v_f is the volume fraction of glass fiber. Preliminary results showed that the volume fraction of glass yarns in 3D orthogonal composites was about 50 %. As shown in Table 1, the ε_f , ε_m of E-glass fiber and resin are 6 and 3 respectively. After substituting the ε_f , ε_m , v_f into Eq. (1), ε_r of the 3DIMA was calculated as 4.5.

The microstrip feeding 3DIMA was designed to operate at radar L-band with the resonant frequency of 1.5 GHz. The substrate of the 3DIMA is a 3D E-glass/vinyl ester resin composite with a dielectric constant of 4.5 and a dielectric loss tangent of 0.02. The structure parameters of microstrip feeding antenna were calculated using documented design equations in [19, 20]. Then, the patch was designed to be fed by a 50 Ω microstrip transmission line, with a quarter-wave microstrip transformer inserted to match the antenna impedance to 50 Ω .

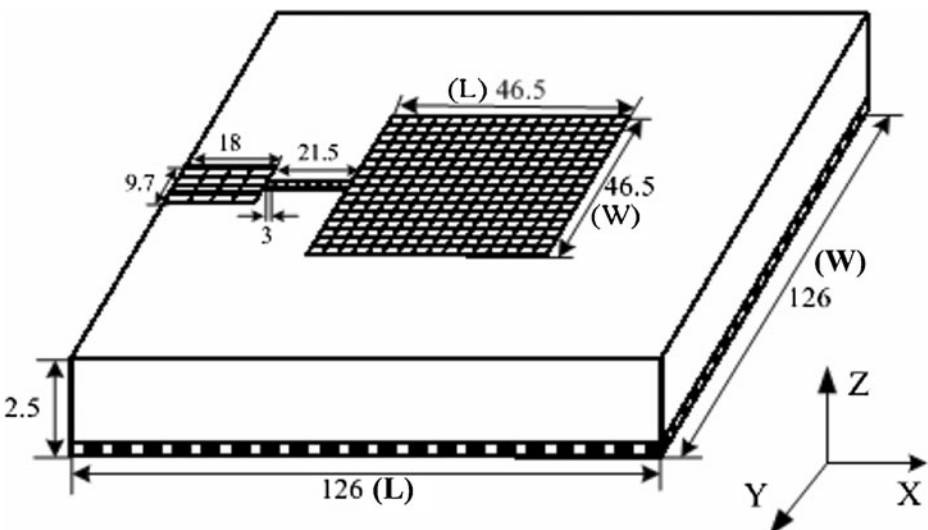
As shown in Fig. 2, the patch is in a square shape with a length of 46.5 mm for both its length and width. The ground conductor was also designed to be in a square shape with the same length for both sides. To ensure a good performance of the 3DIMA, the area of the ground conductor was designed to be at least three times large as the patch [21].

Table 1 Material properties of the microstrip feeding 3DIMA

Material	Properties
E-glass yarn	Linear density: 800 Tex
	Density: 2.55 g/cm ³
	Diameter: 24 μm
	Tensile strength: 1.87 GPa
	Tensile modulus: 61.3 GPa
	Tensile strain to fracture: 3.05 %
Copper yarns	Dielectric constant: 6
	Dielectric loss: 0.002
	Density: 8.9 g/cm ³
	Diameter 0.8 mm
	Tensile strength: 194 MPa
	Tensile modulus: 911 MPa
Vinyl ester resin (901-VP)	Tensile strength: 207 MPa
	Tensile modulus: 896 MPa
	Tensile strain to fracture: 23 %
	Density: 1.1 g/cm ³
	Dielectric constant: 3
	Dielectric loss: 0.02

3 Simulation Procedure

Unlike conventional microstrip antenna, the radiating patch, microstrip feeding line and the ground plane of the 3DIMA are woven by conductive yarns and connective yarns while not

**Fig. 2** Dimensions of the 1.5 GHz microstrip feeding antenna (in mm)

made of solid copper foils. For investigating the effect of weaving direction of conductive yarns to the 3DIMA, High Frequency Structural Simulator (HFSS) software provided by Ansoft Corporation was used to simulate VSWR properties and radiation patterns of the 3DIMAs.

To simplify the simulated models, substrates of the 3DIMAs were simulated as uniform cuboids with dielectric constants of 4.5 and dielectric losses tangent of 0.02; the conductive yarns and connective yarns were simulated as conductive sheets with the widths of 3.5 mm and 1.2 mm respectively.

As shown in Fig. 3, the traditional microstrip antenna as a control antenna and two types of the 3DIMAs with different weaving direction of conductive sheets were built. The 3DIMA-1 has 3.5 mm wide conductive sheets along the feeding direction and 1.2 mm wide conductive sheets perpendicular the feeding direction; while the 3DIMA-2 has 1.2 mm wide conductive sheet along the feeding direction and 3.5 mm wide conductive sheet perpendicular the feeding direction. Antenna feeding direction is along the direction of the microstrip feeding line shown in Fig. 3. The simulated VSWR curves and radiation patterns of the three types of the antennas are shown in Fig. 4. According to Fig. 4(a), all of the VSWR values are much lower than 1.5, which means all three antennas have good impedance matching between their radiating patches and feeder lines. The simulated resonant frequency result of the 3DIMA-1 is close to the designed resonant frequency of 1.5 GHz; while that of the 3DIMA-2 decreases to 1.4 GHz. According to Fig. 4(b), the simulated radiation pattern results shown the 3DIMA-2 has smaller main lobe and gain value than those of 3DIMA-1. In addition, both of the 3DIMA-1 and 3DIMA-2 have larger back lobe than that of the control antenna.

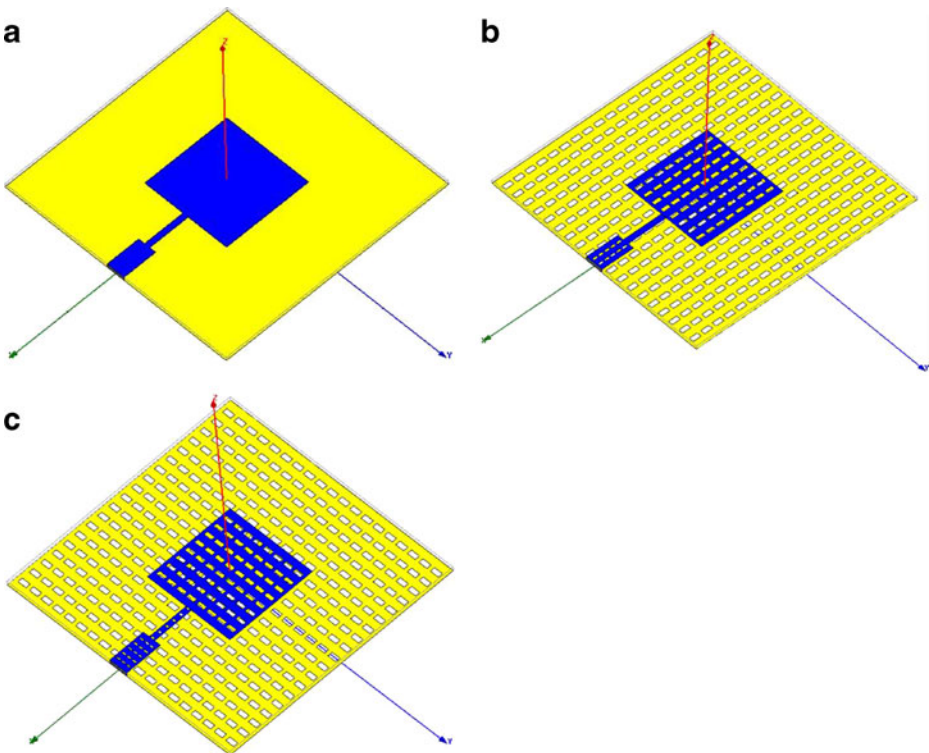


Fig. 3 Simulated models of the microstrip antennas with conductive sheets in different directions. **a** Control antenna, **b** 3DIMA-1 antenna, **c** 3DIMA-2 antenna

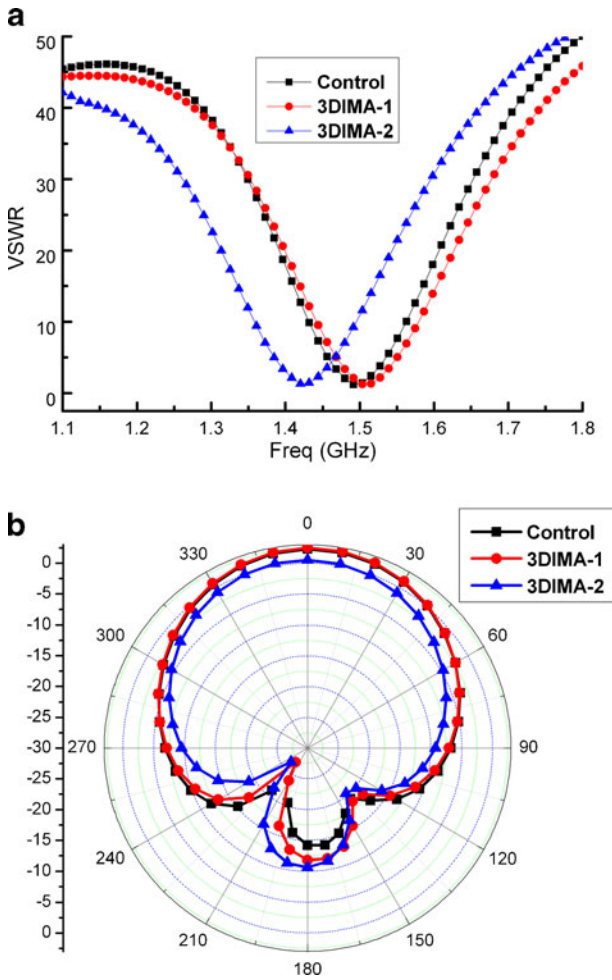


Fig. 4 Simulation results of the microstrip antennas with conductive sheets in different directions. **a** Simulated VSWR results, **b** Simulated radiation pattern results

From the simulated results a conclusion can be drawn that the 3DIMA with the wider conductive sheets in its feeding direction has better simulated resonant frequency, radiation pattern and gain property than those of the 3DIMA which has wider conductive sheets perpendicular the feeding direction.

4 Experimental Procedure

4.1 Fabrication

The 3DIMA preform was manufactured on a 3D orthogonal weaving machine. Because both the diameter of copper yarns and the thickness of the antenna were at millimeter level, the copper yarns with different diameters were adopted to control the thickness of the 3DIMAs.

The 0.8 mm diameter copper yarns were adopted as conductive yarns weaved in the first face and bottom layer; while the 0.3 mm diameter copper yarns were adopted as connective yarns weaved in the second face and bottom layer. The conductive yarns and connective yarns connect with each other and formed the conductive grid structure of radiating patch, feeding line and ground plane. In this study, two types of 3DIMAs with different weaving direction of conductive yarns were fabricated. One has the conductive yarns weaved along the antenna feeding direction (3DIMA-Exp1) and the other has the conductive yarns weaved

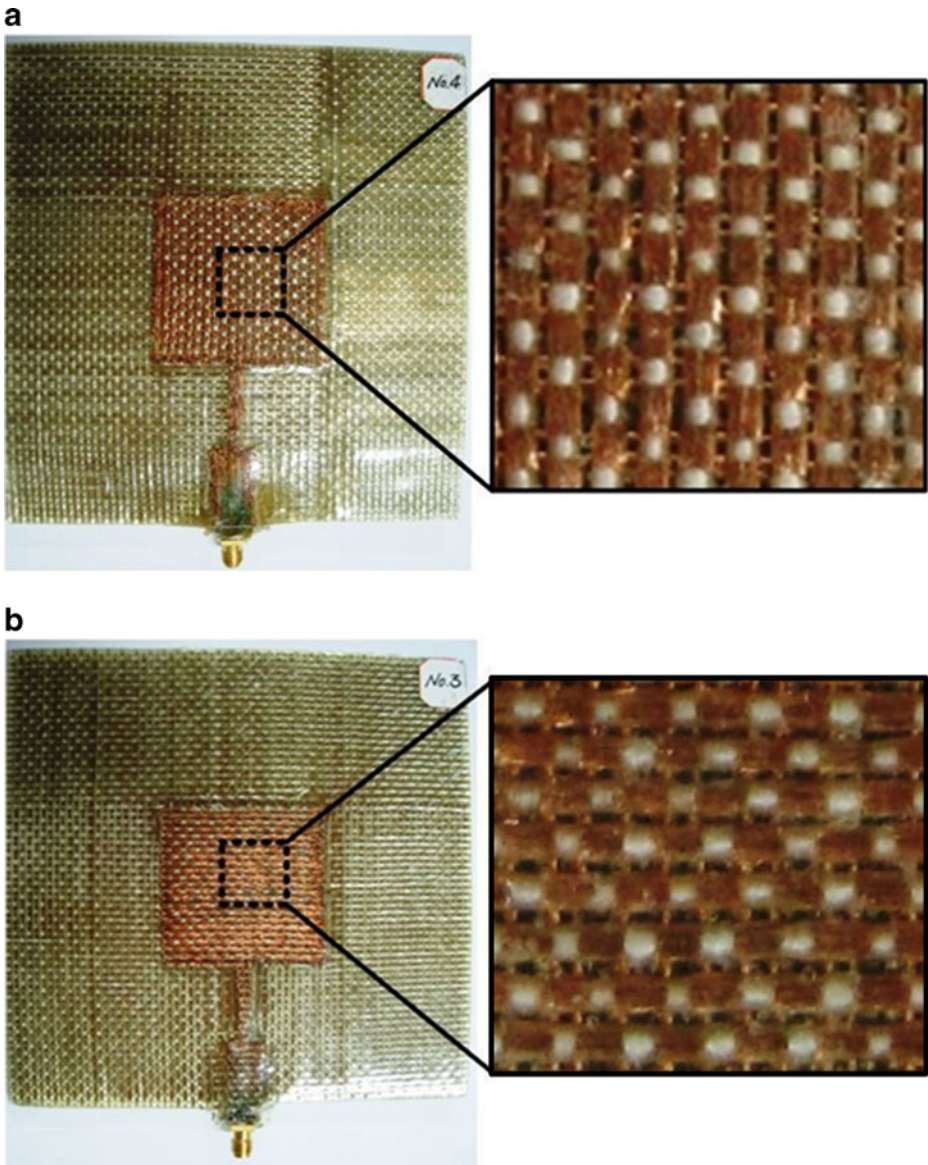


Fig. 5 Pictures of the 3DIMAs with conductive yarns in different weaving directions. **a** 3DIMA-Exp1, **b** 3DIMA-Exp2

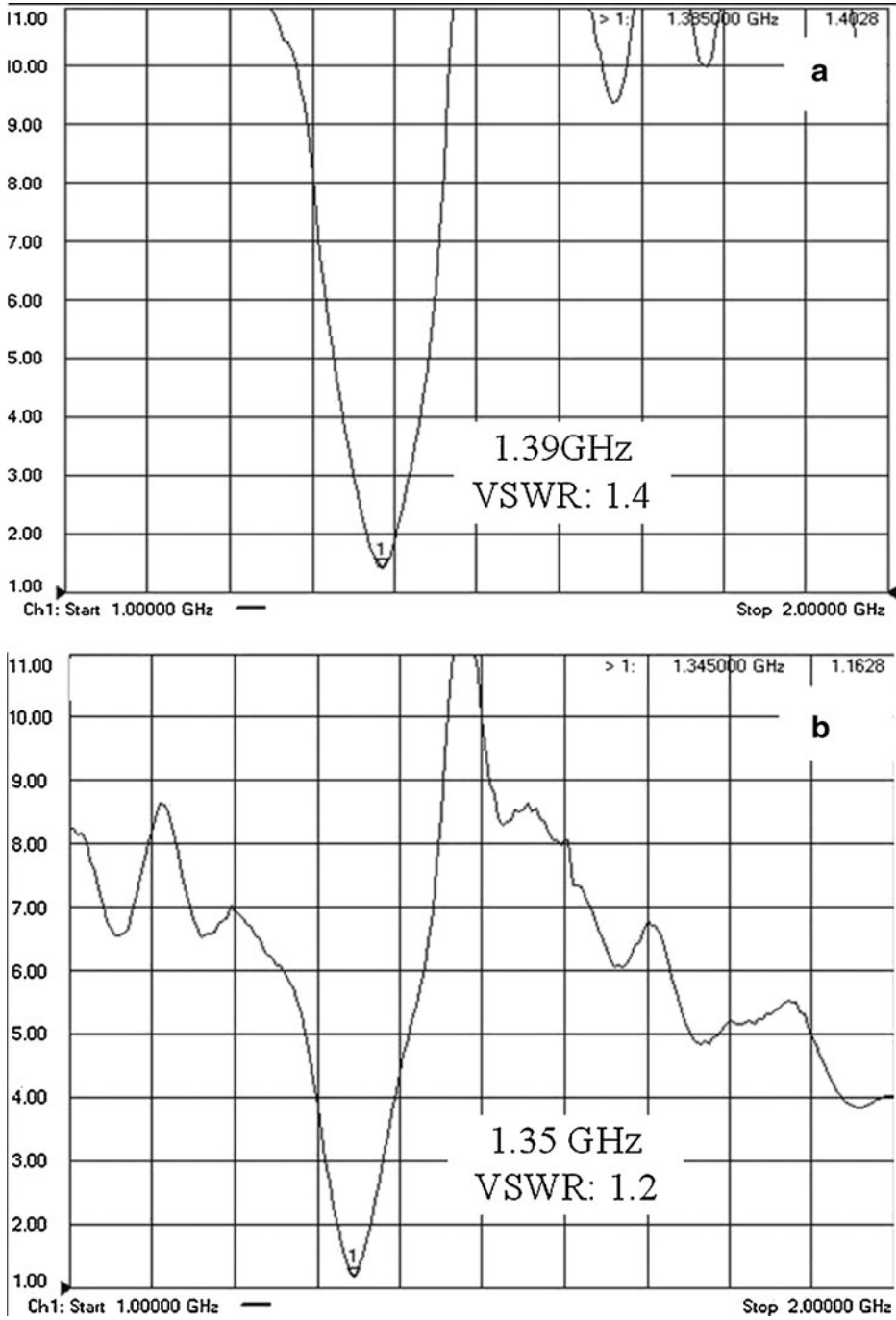


Fig. 6 Measured VSWR results of two 3DIMAs. **a** 3DIMA-Exp1, **b** 3DIMA-Exp2

perpendicular the antenna feeding direction (3DIMA-Exp2). The substrates of two 3DIMAs were woven with five layers of glass yarns with a thickness of 2.5 mm. The whole assembly

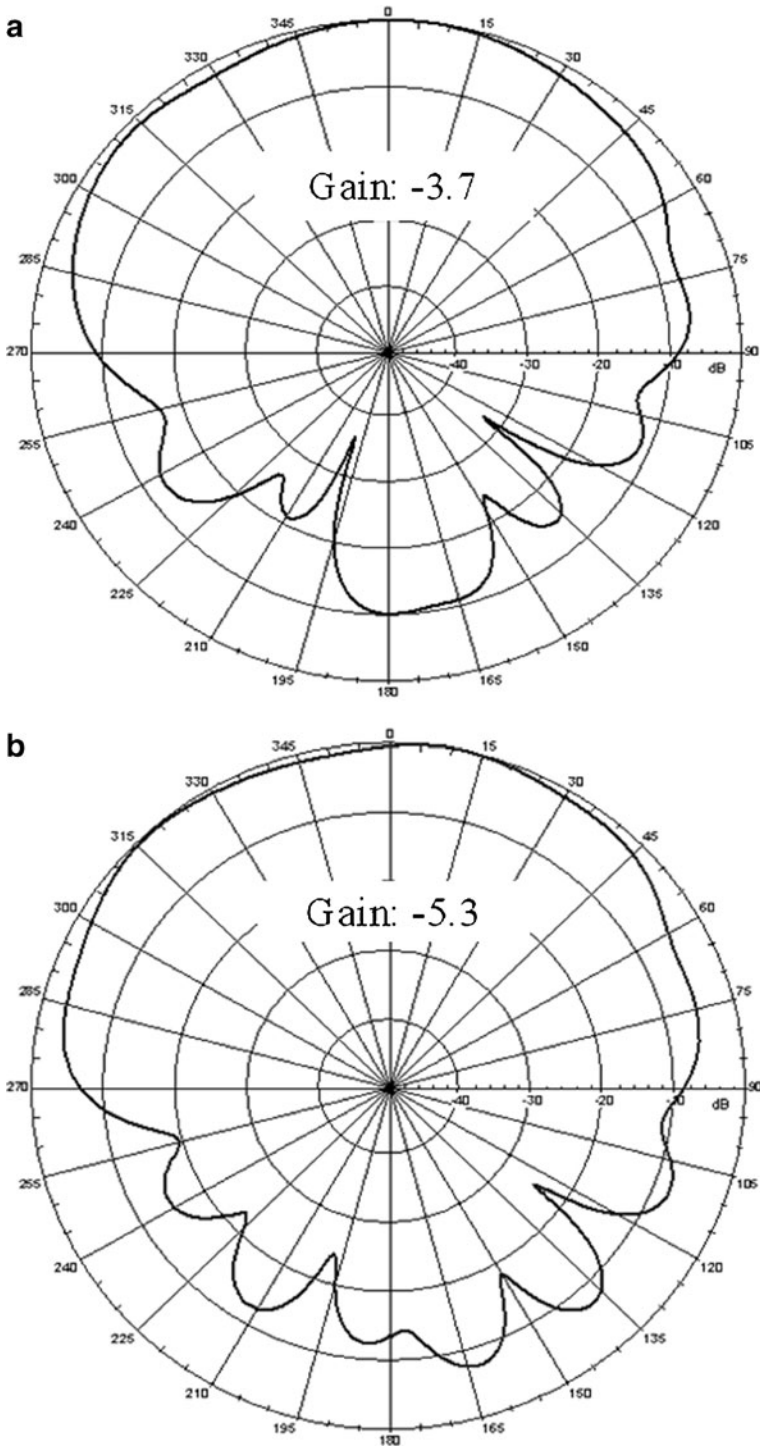


Fig. 7 Measured radiation patterns of two 3DMIAs. a 3DIMA-Exp1, b 3DIMA-Exp2

was then impregnated in a vinyl resin through vacuum assisted resin infusion technique at ambient temperature. The pictures of two 3DIMAs with conductive yarns in different weaving directions were shown in Fig. 5.

4.2 Antenna Performance Tests

To determine the electromagnetic performance, VSWR was measured using an AV3618 Integration Microwave Network Analyzer. The radiation pattern and Gain were measured in the anechoic chamber using HP 8510C Antenna Test System. The signal of the vertical polarization was transmitted to the antenna, which was fixed with a termination of section port. The radiation pattern was obtained from the signal received by rotating the antenna 360° . The gain was calculated by comparing field values of a Reference-Gain Horn Antenna.

5 Results and Discussion

The VSWR of antenna is one of the most essential parameters in the antenna design and application. When a transmitter is connected to an antenna by a feeding line, VSWR must low enough to transfer maximum energy from the feeding line to the antenna. For a traditionally designed microstrip antenna, VSWR is usually required to be less than 1.5 for a relatively low energy loss. The radiation pattern is a graphical representation of the far-field radiation properties of an antenna. A good radiation pattern of the microstrip antenna should have a dominant main lobe in designed direction and very small back and side lobes in other directions.

The tested VSWR results of the 3DIMA- Exp1 and 3DIMA- Exp2 are shown in Fig. 6. The VSWR values of both 3DIMAs are lower than 1.5, which indicates that the weaving direction of conductive yarns has slight effect to the VSWR property. The tested resonant frequencies of the 3DIMA- Exp1 and 3DIMA- Exp2 are 1.39 GHz and 1.35 GHz independently, both of which are lower than designed resonant frequency of 1.5 GHz. The deviation of resonant frequencies can be caused by many reasons. The deviation of the radiating patch dimension and the dielectric properties of substrate may lead to the change of resonant frequency. In this study, the resonant frequency of 3DIMA- Exp2 has more deviation than that of the 3DIMA- Exp1, which may be caused by the different weaving direction of the conductive yarns.

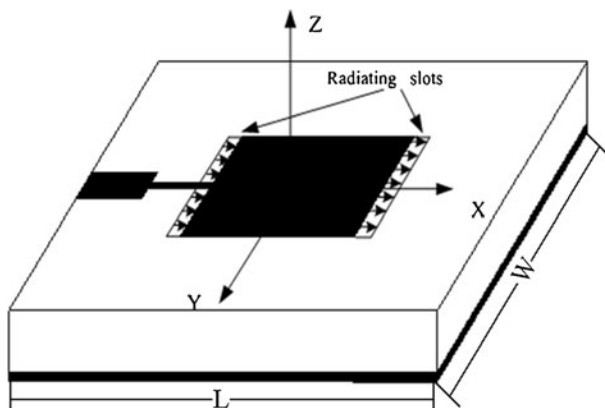


Fig. 8 Microstrip antenna represented as two radiating slots

The tested radiation patterns of two 3DIMAs are shown in Fig. 7. Both the magnitudes of the main lobes of their radiation patterns have their maximum near 0° and some side lobes in other directions. It means both 3DIMAs have relative proper radiation pattern, which is result from the good conductivity of the grid pattern patch composed by copper yarns. However, as shown Fig. 7, the 3DIMA-Exp1 has gain value of -3.7 dB, 1.6 dB higher than that of the 3DIMA-Exp2 which is -5.3 dB. Moreover, 3DIMA-Exp2 has a larger back lobe and side lobes than those of the 3DIMA-Exp1. These suggest that the weaving direction of conductive yarns perpendicular the antenna feeding direction may cause the decrease of the gain and radiation pattern property. The reasons that both gain values of the two 3DIMAs are negative may be caused by the deviation of expected dielectric constant and dielectric loss tangent of the substrate. Additionally, the resin layer cover on the 3DIMAs may also affect the antenna gain property [22, 23].

According to the transmission line model [19], the microstrip radiator element can be treated as a line resonator with no transverse field variations. The radiation occurs mainly from the fringing fields at the open-circuited ends. The radiator may be represented as two radiating slots in the length direction as shown in Fig. 8. The conductivity and continuity of the antenna in its feeding direction are very important for the radiating slots and thus for the antenna properties. That may be the main reason accounting for why the weaving direction of conductive yarns of the 3DIMA in antenna feeding direction has better electromagnetic performance.

6 Conclusions

In this paper, two types of 3DIMAs were designed, fabricated, simulated and experimentally tested. The tested results showed that VSWR values of both antennas were lower than 1.5. The resonant frequency of the 3DIMA with the conductive yarns weaved along the antenna feeding direction was 1.39 GHz, while that of the 3DIMA with the conductive yarns weaved perpendicular the antenna feeding direction was 1.35 GHz. Both simulated and measured results showed that due to the different weaving direction of the conductive yarns, the radiation pattern of the 3DIMA with the conductive yarns perpendicular the antenna feeding direction had a larger back lobe, side lobes and lower gain value than those of the 3DIMA with the conductive yarns along the antenna feeding direction. This study proved that waving direction of conductive yarns of a textile structural microstrip antenna should be along the antenna feeding direction to optimize the electromagnetic properties of the antenna.

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