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Compact UWB-MIMO antenna with metamaterial FSS decoupling structure

Xiaoming Zhu^{1,2*}, Xiaodong Yang^{2,3}, Qichao Song¹ and Baisen Lui¹

Abstract

In this paper, an UWB-MIMO antenna with frequency selective surface (FSS) decoupling structure is proposed. To realize antenna system miniaturization and integration, silicon material is applied as substrate. The proposed antenna becomes a very compact construction with dimension of $38.2 \times 26.6 \times 0.4 \text{ mm}^3$. The proposed broadband FSS unit consists of four split rectangles and one I-shaped strip. The effective permittivity or effective permeability of FSS unit is negative, so the FSS is a metamaterial structure and has a broadband frequency band gap in the entire UWB range. Six FSS units are positioned in the middle of antenna backside, like band-stop filter to reduce the coupling between the antennas placed side-by-side. Compared to UWB-MIMO antenna without FSS, the proposed array not only keeps each antenna performance but also decreases 7.2 dB coupling. The UWB-MIMO with FSS structure provides an overall isolation of more than 16 dB in the UWB spectrum, so it is suitable for portable UWB-MIMO system applications.

Keywords: UWB-MIMO antenna, FSS, Metamaterial, Decoupling

1 Introduction

The ultra-wideband (UWB) system is a radio engineering technology with frequency from 3.1–10.6 GHz [1], which has several advantages including very large bandwidth, low power consumption, high data rate, high time resolution, resistance to interference, co-existence with narrowband systems, and so on. Such advantages enable UWB technology widely applied in communication, radar, imaging, and positioning [2–5]. To improve transmission rate and communication reliability of UWB system, multiple-input-multiple-output (MIMO) technology can be joined to become UWB-MIMO system. The combinative system needs multiple antennas coexisting in the finite space of transmitters and receivers. The individual antenna not only has broad impedance matching characteristic over the entire spectrum but also has better isolation from adjacent antenna. The coupling influence between antennas is more serious as the increase of the antenna number, so the effective decoupling method is a key technology for UWB-MIMO system. The straightforward decoupling way is to extend

separation distance of antennas, but the size of each component is strictly controlled for miniaturization UWB mobile terminals. The correct scheme is to design special structure to decrease coupling without sacrificing transceiver space. For plane monopole MIMO antennas, the common decoupling structures are parasitic elements and defected grounds. The detailed structures are diversified such as T-shaped element, Y-shaped element, or combination with several long and short strips [6–8]. Another approach for designing UWB-MIMO antennas is to use slot antennas with orthogonal feeding to achieve polarization diversity and pattern diversity [9–12]. These layouts are relatively larger than the above decoupling antenna structures. Frequency selective surface (FSS) is a period electromagnetism material with frequency band gap performance. FSS structures can selectively determine electromagnetic waves to pass or prevent within specified frequency ranges.

In this paper, a UWB-MIMO structure of antenna is presented. The broadband FSS cell is composed of electric resonator and magnetic resonator with the band gap characteristic as same as metamaterial. This UWB-MIMO antenna with FSS structure obtains more than 16 dB isolation between antennas in the UWB frequency band. The rest of this paper is as follows: Section 2

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presents the antenna configuration, Section 3 discusses the performances of metamaterial FSS unit, Section 4 analyzes the results of UWB-MIMO antenna, and finally, the paper is concluded in Section 5.

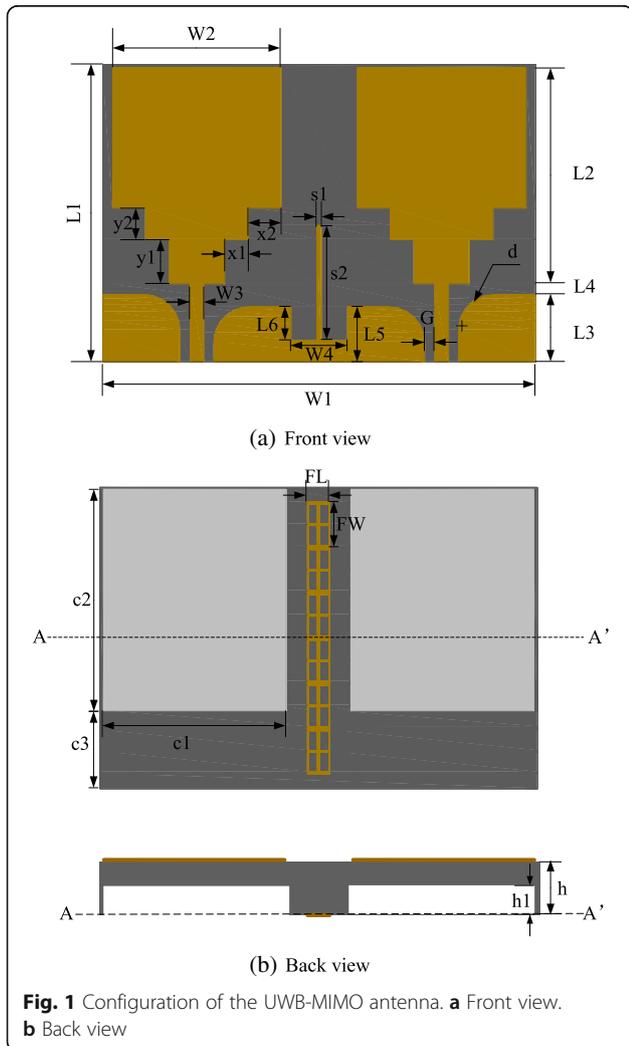
2 Antenna structure design

According to UWB technology in small mobile devices, the antenna is designed on planar microstrip transmission line with coplanar waveguide (CPW) feeder. The 400 μm thickness silicon wafer is chosen as antenna substrate. Because the relative dielectric constant of silicon is 11.9, the size of MIMO antenna can be shrunk. Then, silicon wafer is the material of most of integrated circuits, so antennas with silicon substrate are easily integrated with functional circuits to become a complete on-chip system.

The proposed UWB-MIMO antenna configuration is shown in Fig. 1. Table 1 presents the final dimensions of antenna. There are two same rectangular radiation patches and CPW feeders on the upper side of array. The shape of patches is rectangle initially, but this

Table 1 Dimensions of the UWB-MIMO antenna

Parameter	mm	Parameter	mm
W1	38.2	L1	26.6
W2	14.88	L2	19.36
G	0.9	W3	1.2
W4	5	L3	6.01
L4	0.96	L5	4.91
L6	3	x1	2.1
x2	2.9	y1	3.95
y2	1.81	d	3.18
s1	0.4	s2	10.26
h	0.4	h1	0.2
c1	15.96	c2	19.54
c3	6.88	FW	2
FL	4	f1	0.04
f2	0.04	f3	0.03
f4	0.04	f5	0.06
f6	0.1		

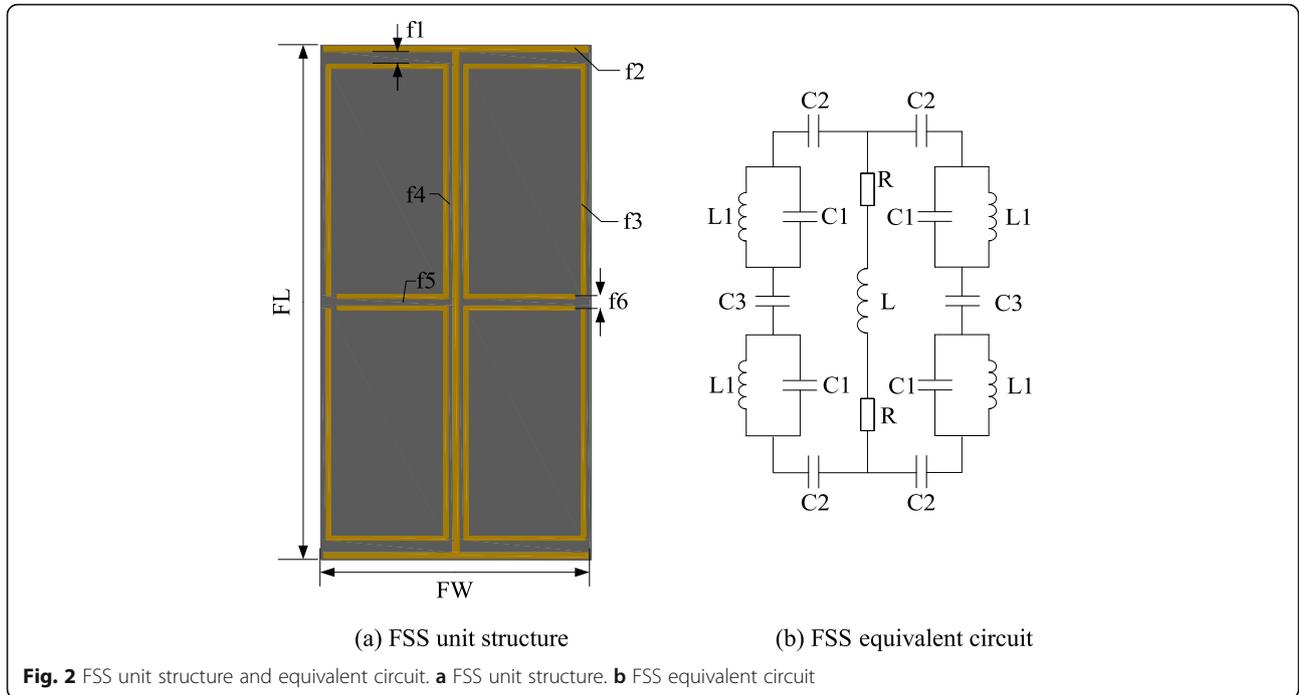


construction cannot cover the whole UWB frequency band. Therefore, transforming the bottom profile of patches is the simple method to increase bandwidth because the current is concentrated in the bottom edge of the antenna. The rectangle patch area is changed to staircase profile, in order to increase current path. If the antenna feeder is microstrip structure, the radiation patch and ground are on the different sides of substrate. But the proposed antenna uses CPW feeder because patch and ground are on the same plane. The coplanar characteristic makes antenna easy to manufacture with low radiation loss and dispersion. To solve current losses of right-angled grounds, arc processing is utilized for grounds next to the feeder, which can improve impedance matching and extend frequency bandwidth.

There are two rectangular cavities and decoupling FSS structure on the rear side of the proposed antenna. High-permittivity substrate can reduce antenna size, but surface waves losses influence the antenna performance seriously. To restrain surface wave appearance, two vertical cavities are etched underneath the patches on the back of substrate. If the antenna substrate is formed by silicon and air cavity, the effective dielectric constant of mixture substrate can be calculated as,

$$\epsilon_e = \frac{\epsilon_0 \epsilon_r}{\epsilon_0 + (\epsilon_r - \epsilon_0) h_1 / h} \tag{1}$$

where ϵ_0 is the permittivity of vacuum, ϵ_r is relative permittivity of silicon, h_1 is the height of air cavity and h is



the thickness of silicon wafer. The vertical air cavities enable to decrease relative dielectric constant, solve surface wave problem, and improve MIMO antenna performances.

3 Decoupling structure design

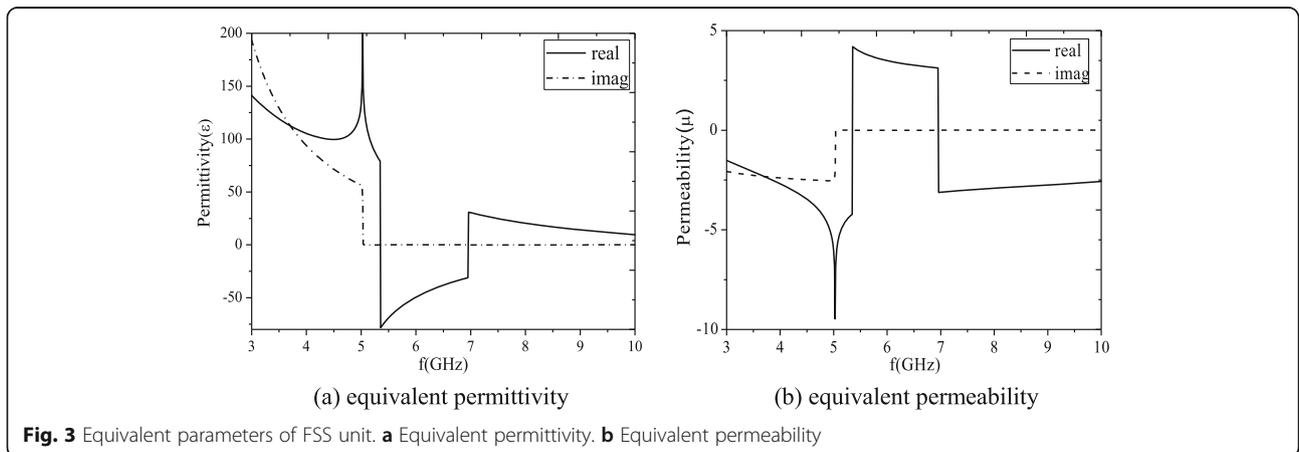
Metamaterial is an artificial composite material with negative refractive index, negative permittivity, or negative permeability. Metamaterial belongs to sub-wavelength structure, which unit size is much less than working wavelength. The equivalent permittivity and equivalent permeability can be applied to analyze the physical property of metamaterial. The ϵ and μ indicate the interaction of electric field and magnetic field, and

the propagation constant k of electromagnetic waves can be described as,

$$k = w\sqrt{\mu\epsilon} \tag{2}$$

When k is a real number, electromagnetic waves can be propagated in the medium. While ϵ or μ is a negative value, the propagation constant k becomes an imaginary number. In this condition, electromagnetic waves cannot be propagated and the band gap appears. Therefore, when electromagnetic waves are incident on the surface of metamaterials, total reflection phenomenon will occur.

The UWB-MIMO antenna is proposed with novel decoupling structures, which are the front defected ground



structure and the rear FSS structure. Because of the CPW feeder of antenna, the middle grounds are connected together with mutual effect in high-frequency band of UWB. The defected ground transformation reduces coupling of connected ground, and the center short-circuited strip plays a role of reflector between two antennas. Broadband FSS structure is positioned in the middle of cavities. As compact antenna dimension, FSS should be placed on the back side to lower the direct impact on the front radiation patches.

The designed FSS unit consists of four split rectangles and one I-shaped strip, which pattern is made of metal material printed on the 400 μm silicon substrate. The FSS structure and equivalent circuit are shown in Fig. 2. L and R are the equivalent inductance and equivalent resistance of I-shaped strip. L1 and C1 are the equivalent inductance and equivalent capacitance of the split rectangle. C2 is the equivalent capacitance between the I-shaped strip and split rectangle. C3 is the equivalent capacitance between the two split rectangles. The split rectangle structure is equivalent to LC resonance circuit and belongs to a magnetic metamaterial, which can generate strong magnetic response with negative equivalent permeability. The I-shaped structure is also equivalent to LC resonance circuit and belongs to an electrical metamaterial, which can produce huge induced electric field to form electric resonance with negative permittivity. In fact, the proposed FSS cell is the combinative element with electrical and magnetic metamaterials. The equivalent permittivity and permeability curves of FSS cell are in Fig. 3. In frequency band of 5.36–6.96 GHz, FSS appears electric resonance phenomenon with negative equivalent permittivity and positive equivalent permeability. And in the other frequency bands, FSS has magnetic resonance characteristic with opposite parameter performance. The S parameters of FSS unit are presented in Fig. 4, where S11 is the reflection coefficient

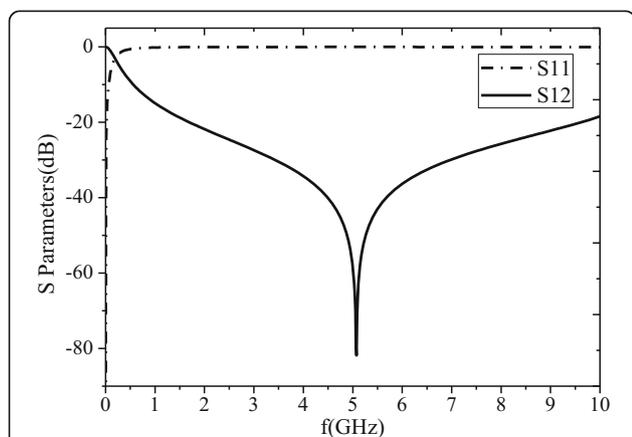


Fig. 4 Reflection coefficient and transmission coefficient of FSS unit

and S12 is the transmission coefficient. In Fig. 4, S12 values are all less than -20 dB in the whole UWB bandwidth, so the FSS unit can generate a wide band gap to restrain the electromagnetic waves propagation like a band-stop filter. Therefore, the metamaterial FSS unit is suitable for UWB-MIMO antenna decoupling.

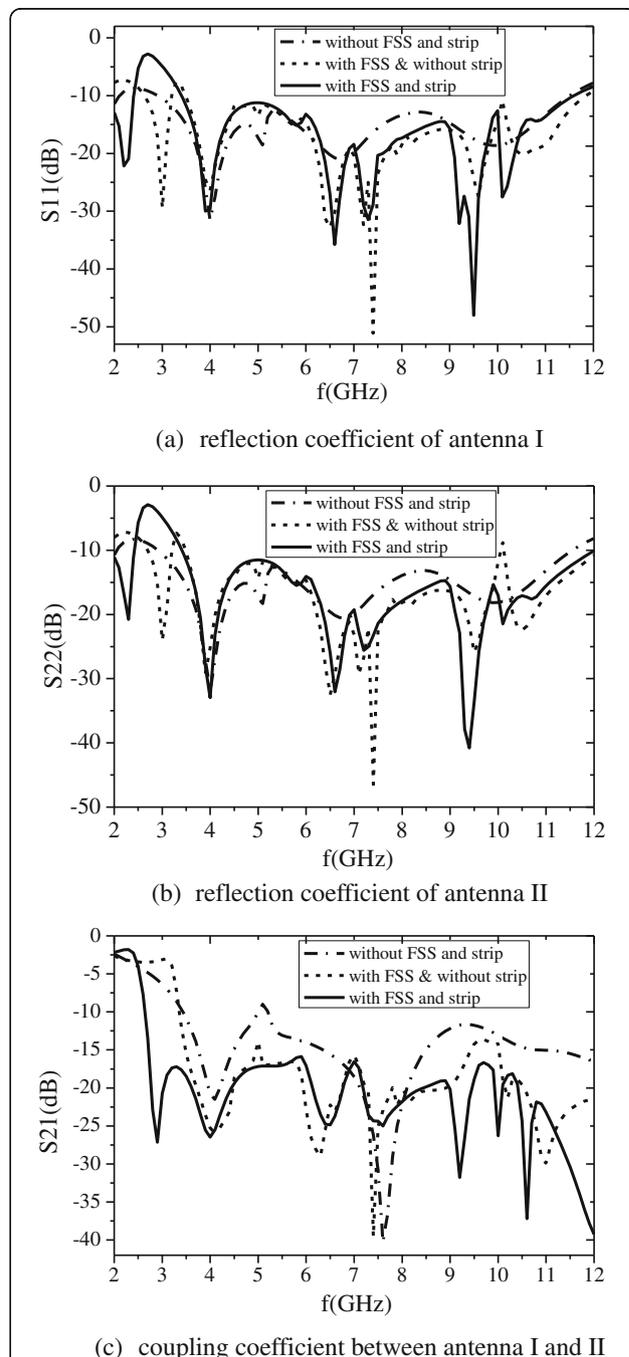


Fig. 5 Return loss and isolation of the UWB-MIMO antenna. a Reflection coefficient of antenna I. b Reflection coefficient of antenna II. c Coupling coefficient between antenna I and II

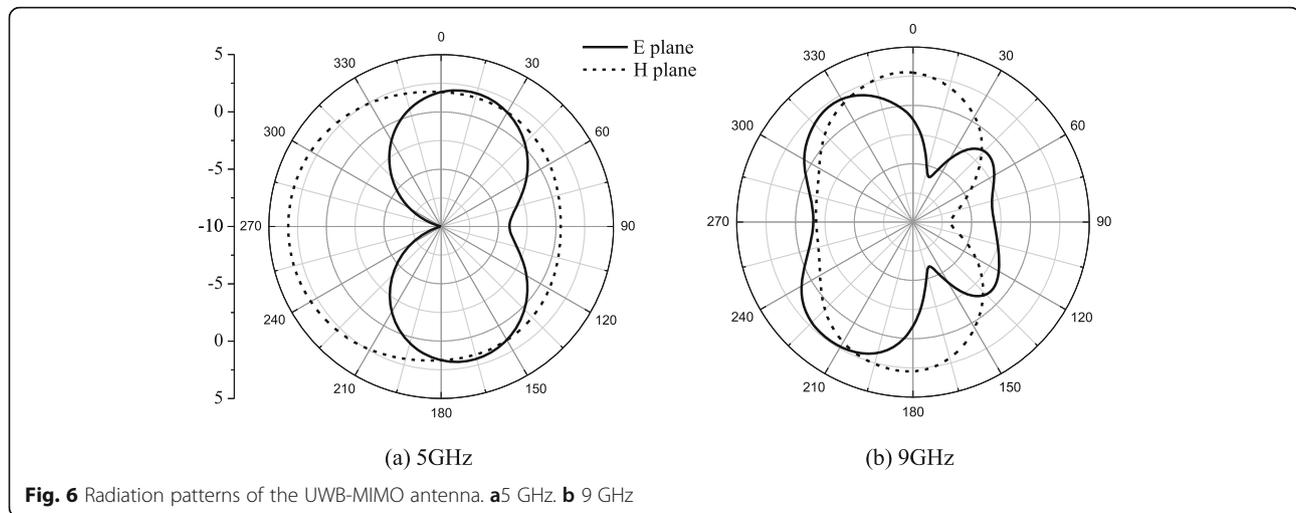


Fig. 6 Radiation patterns of the UWB-MIMO antenna. **a** 5 GHz. **b** 9 GHz

4 Results and discussions

Firstly, the left antenna unit is regarded as antenna I and the other unit is antenna II in Fig. 1. S_{11} and S_{22} are respectively reflection coefficients of antennas I and II. S_{12} and S_{21} are equivalent because of symmetrical structure, and both represent coupling coefficient between two antennas. To analyze the decoupling performance, the proposed UWB-MIMO antenna is simulated with and without the decoupling structures. The reflection coefficients and coupling coefficient of the MIMO antenna are shown in Fig. 5. The S_{11} and S_{22} are less than -10 dB in UWB frequency range, so each independent antenna has better impedance matching performance. The antenna array without decoupling structure has worse isolation especially around 5 and 9 GHz. After adding six metamaterial FSS units on the rear of MIMO antenna, S_{21} decreases over the entire UWB range, but coupling coefficient is still above -15 dB between 9.42 GHz and 10 GHz. The center short-circuited strip of defected ground is applied to solve coupling problem around 9.7 GHz. Finally, S_{21} is all below -16 dB from 2.72 GHz to 12 GHz, and the minimum value is up to -37.2 dB. It is demonstrated that the decoupling structure keeps good impedance matching performance and improves isolation of antennas I and II. The E-plane and H-plane patterns of the proposed antenna are obtained at frequencies 5 GHz and 9 GHz in Fig. 6. The radiation pattern is nearly omni-directional at 5 GHz. But at frequency of 9 GHz, certain distortion appears in the pattern within the tolerable limit. The reason is working wavelengths become tiny close to the size of the proposed antenna at higher frequencies.

5 Conclusions

This paper proposes a novel MIMO antenna based on silicon substrate for UWB communication systems. To achieve high isolation between antennas, six metamaterial

FSS units are employed in the middle of array. Finally, the isolation performance is less than -16 dB over the entire UWB frequency band. More importantly, the designed MIMO antenna becomes a very compact construction especially suitable for mobile terminals, like notebook computer or mobile, where antennas need to satisfy the demands of low profile, small dimensions, and integration with other components.

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Authors' contributions

XZ proposed the main idea and completed the antenna construction design. XY assisted the theory research. QS and BL assisted the simulation and analysis. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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