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High-gain microstrip patch antenna with conformal metamaterials based on topological transformation

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Abstract: Microstrip patch antennas are widely used in various communication, telemetry and detection systems because of small size, light weight, low profile, simple fabrication, low cost and easy integration. However, microstrip patch antennas suffer from the disadvantage of low directive gain. In this paper, a high gain microstrip patch antenna with loading conformal metamaterials has been presented. A square split-ring resonator (SRR) is topologically transformed into a topological SRR which conforms to the cylindrical substrate and gives the metamaterials effect to suppress surface wave of the antenna. The conventional circular microstrip patch antenna resonates at 10 GHz, and the gain is 6.12 dBi. The near-field parameters of the antenna with loading 10 topological SRR unit cells keep good, and the gain is 7.88 dBi which is an increase of nearly 2 dBi compared to the conventional one.

Key words: microstrip patch antenna; split-ring resonator (SRR); conformal metamaterials; topological transformation; gain

0 Introduction

Microstrip patch antennas are widely used in various communication, telemetry and detection systems because of small size, light weight, low profile, simple fabrication, low cost and easy integration. However, they suffer from the disadvantage of low directive gain[1-2].

The development of metamaterials opened a new possibility for designers to enhance has the performance of microstrip patch antenna[3-4]. The split-ring resonator (SRR) structure was proposed by Pendry et al. in 1999[5]. This small and light artificial electromagnetic structure could produce magnetic resonance in a specific frequency band by setting its size to obtain negative permeability. This structure also helped Shelby et al. successfully design left-handed metamaterials (LHM) in 2001[6], in combination with metal wires, which confirmed the conception which was first proposed by Veselago et al. in 1968[7]. Over the next decade, LHM, single-negative metamaterials (SNM) and zero index metamaterials (ZIM) were collectively referred to as metamaterials. In the meantime, the effects of metamaterials on various antennas were studied, and a series of exciting results were obtained[8-12].

Cai et al. proposed ZIM as the coverage of microstrip antenna, which can effectively improve the directivity[13]. Li et al. adopted the three-layer ZIM method to significantly improve the antenna gain[14]. Liu et al. embedded a compact nested three-dimensional SRR in a low-temperature co-fired ceramic (LTCC) substrate. Compared with the traditional microstrip antenna, the gain of the microstrip antenna is increased by 1.5 dB, and the beam width of E-plane is reduced by 14°[15]. Gao et al. proposed a permeability negative metamaterial (MTM) cells consisting of dual-layer symmetry single ring resonator pair (D-SSRRP) and embedded on both sides of the dielectric layer, which made the antenna gain increase at least 2.2 dB and the half-power beam width (HPBW) decrease around 20°[16]. Valayil et al. proposed a method to increase the gain of slot array antenna by using metamaterials. The results are verified by manufacturing and measuring on the antenna array containing metamaterials. The increase of directivity also leads to the increase of efficiency and sidelobe depth, but does not reduce the

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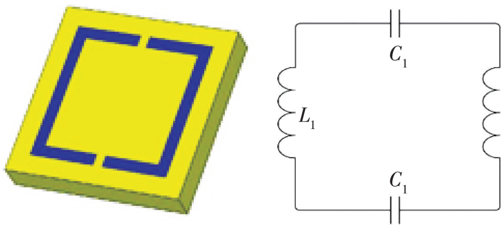
return loss. The measurement results show that compared with the control antenna without metamaterials, the maximum gain of the antenna with metamaterials is increased by 58%[17]. Hui et al. designed a microstrip patch antenna (MPA) loaded with linear negative permittivity metamaterials (NPMMS). From the simulation and measurement results, it is concluded that the linear metamaterials loaded on map substrate can well suppress surface waves and increase forward radiation[18]. In conclusion, the use of metamaterials has achieved good results in improving the performance of microstrip antenna.

In some special cases, the cross-section shape of the dielectric substrate should be conformal with the placement space (e. g. circle), so as to obtain better survivability in the harsh mechanical environment. In our study, the regular SRR is topologically transformed into a topological SRR which conforms to the cylindrical substrate and gives the metamaterials effect to suppress surface wave of the antenna.

1 Topological transformation of regular SRR

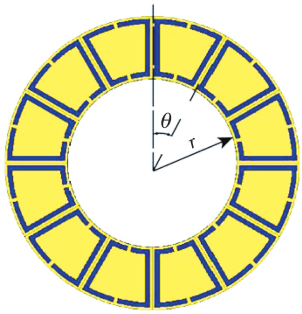
In order to conform to the cylindrical substrate of the antenna, the regular square SRR unit cell shown in Fig. 1 is topologically transformed (i. e. stretching, twisting and compressing) into a topological SRR unit cell shown in Fig. 2. Each topological SRR unit cell can be tightly attached to the cylindrical substrate, and the antenna can be wrapped well by using multiple unit cells (Fig. 2(a)).



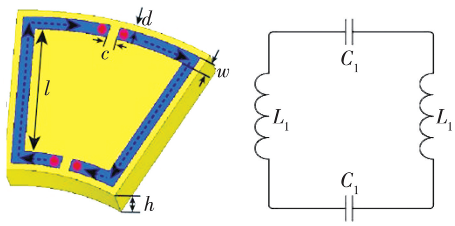
(a) 3D (b) Equivalent circuit

Fig. 1 Regular SRR

We observe that the unit cell after topological transformation has the same equivalent circuit as the regular one, as shown in Fig. 1(b) and Fig. 2(c). When the magnetic field direction of the incident electromagnetic wave is perpendicular to the plane of the metal ring, a loop current is generated on the surface of the SRR. The part of conduction current can be equivalent to inductance, and there is displacement current in the split gap of metal ring, which is represented by equivalent capacitance. Therefore, the topological SRR has magnetic response under the excitation of the incident electromagnetic wave, and this resonator is an electrically small LC resonator with a high quality factor. When the direction of the magnetic field excited by the loop current on the SRR is opposite to that of the incident electromagnetic wave and the amplitude exceeds the latter, the total magnetic flux on the SRR is less than zero, and the equivalent permeability is negative.



(a) Multiple unit cells



(b) 3D (c) Equivlent circuit

Fig. 2 Topological SRR

By changing the size and geometric parameters of the topological SRR, the resonant frequency can be easily tuned to the desired value. The topological SRR unit cell has width of the ring $w=0.3$ mm, split gap $c=0.3$ mm, and length without split gap $l=4$ mm. Spacing between ring edge and substrate edge $d=0.2$ mm and 12 unit cells form a circle (i. e. $\theta=30°$). The minimum radius of the unit cell is 7 mm (r). The effective permeability is calculated by[19]

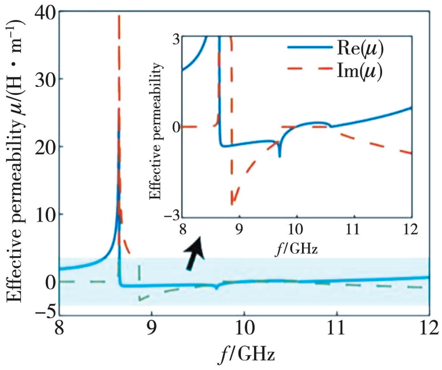
$$n=\frac{1}{kd}\cos^{-1}\left[\frac{1}{2S_{21}}(1-S_{11}^2+S_{21}^2)\right], \tag{1}$$

$$z=\sqrt{\frac{(1+S_{11})^2-S_{21}^2}{(1-S_{11})^2-S_{21}^2}}, \tag{2}$$

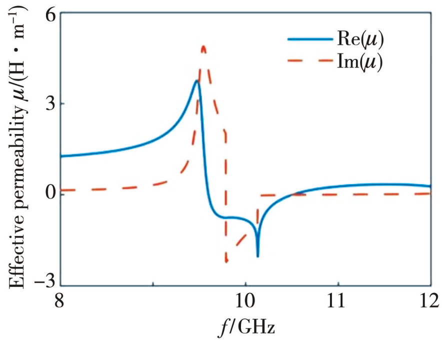
$$\mu=nz, \tag{3}$$

where n and z are the refractive index and the wave impedance, respectively.

The effective premeability comparison of regular SRR and topological SRR is shown in Fig. 3.



(a) Regular SRR



(b) Topological SRR

Fig. 3 Retrieved effective permeability from S-parameters

2 Conventional antenna configuration

Simulation tests are based on the circular microstrip patch antenna. FR-4 is used as dielectric with dielectric constant of 4.3 and thickness of 1 mm (h). A 50 Ω coaxial probe is feeding the circular patch. The position of feeding varies, so as to match the input impedance and the characteristic impedance. As the frequency range of the magnetic negative region of the topological SRR is near 9.5 GHz—10.5 GHz, the conventional circular patch antenna is designed at 10 GHz in order to compare the effect of topological SRR on antenna. The radius of circular patch[20] is calculated by

$$a=\frac{F}{\sqrt{1+\frac{2h}{\varepsilon_r\pi F}\left(\ln\frac{\pi F}{2h}+1.7726\right)}},\tag{4}$$

$$F=\frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}},\tag{5}$$

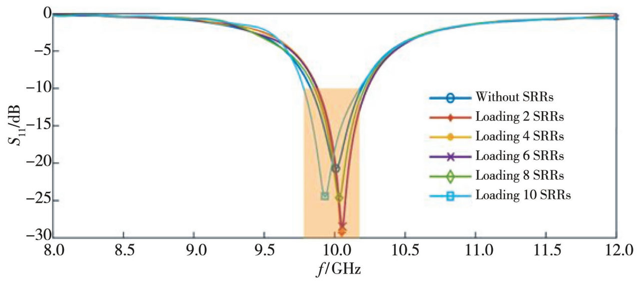
where ε_r is relative dielectric constant of dielectric substrate, and f_r is resonating frequency.

The calculated radius of the conventional circular patch is 3.78 mm and the dielectric substrate dimension is 7 mm (r). The distance between the feeding point and the center of the circular patch is 1.15 mm.

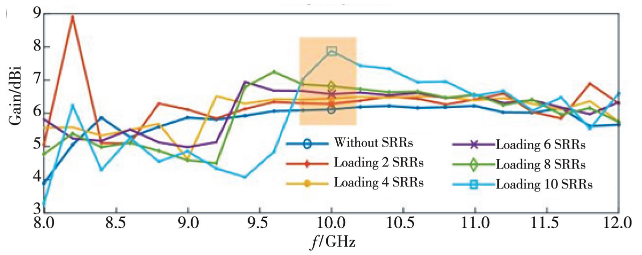
3 Results and discussion

We have simulated microstrip patch antenna without and with multiple topological SRR unit cells in CST Microwave Studio. But first of all, the structure of topological SRR is simulated in CST. Response confirming the behavior of metamaterial is achieved when negative permeability is obtained at the frequency of interest, which is obtained from parameter retrieval process through software. Effective permeability is retrieved from S-parameters using Eqs. (1)—(3) for unit cell SRR, revealing the presence of magnetic resonances nearly 9.5 GHz—10.5 GHz, as shown in Fig. 3(b).

We have carried out a study of loading different number of topological SRR unit cells to observe the change of resonant frequency, impedance matching and far-field gain of antenna with them. Figs. 4(a) and (b) shows the return loss (S_{11}) and the gain of antenna without and with loading 2, 4, 6, 8, 10 topological SRR unit cells, respectively.



(a) Return loss



(b) Gain

Fig. 4 Near-field and far-field parameters of antenna without and with topological SRR unit cells

From Fig. 4(a), we observe that the resonant center frequency of the conventional antenna (without SRR) is 10 GHz, the return loss is near −20 dB at this frequency. The resonant center frequency shift is less than ±0.1 GHz, and the impedance bandwidth is consistent with conventional state, and the impedance matching keeps good, when the antenna loads 2, 4, 6, 8, 10 topological SRR unit cells. We can also observe that in the impedance matching frequency band (⩽−10 dB in Fig. 4(a)), the gain of the antenna is improved when loading the topological SRR unit cells shown in Fig. 4(b). When 10 unit cells are loaded, the gain of the antenna is increased by nearly 2 dBi at 10 GHz compared to that of the conventional circular patch antenna, as also shown in Fig. 5.

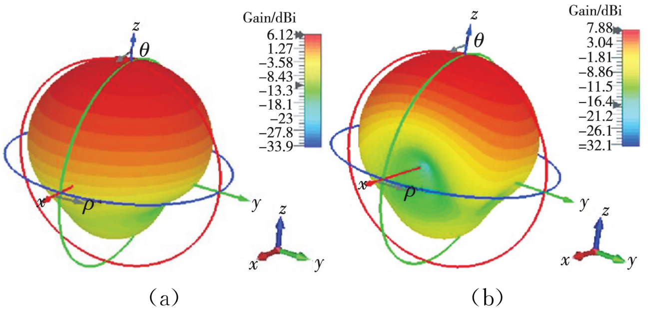


Fig. 5 Simulated 3D gain pattern of (a) patch antenna without SRR (b) patch antenna with 10 topological SRR unit cells

Fig. 6 shows the distribution of the electric field amplitude on the circular patch antenna with loading 2, 4, 6, 8, 10 topological SRR unit cells at 10 GHz. The topological SRR unit cells are resonating at this frequency which makes the internal magnetic flux of the metal ring negative and show negative permeability. We can also observe that with the increase of the number of topological SRR unit cells, the resonance effect becomes stronger, and the one closer to the vertical axis (x in Fig. 6) becomes stronger, which is due to the high amplitude of the incident magnetic field near that area. On the other hand, when the amplitude of incident electric field is high, the topological SRR has a weak resonance, which means that the topological SRR is magnetic resonance metamaterials, as the same as the regular structure.

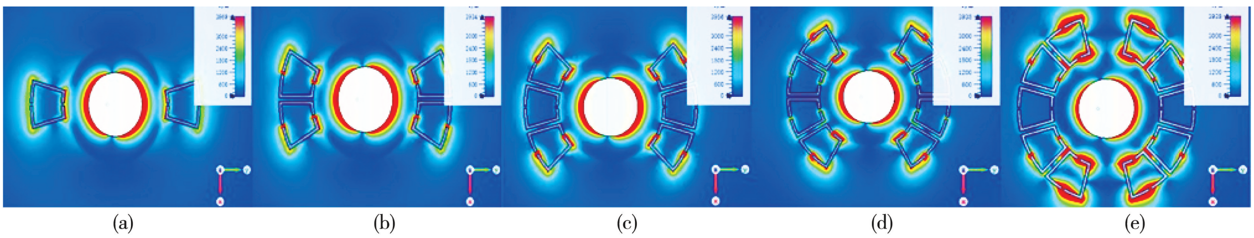


Fig. 6 Distribution of electric field amplitude on circular patch antenna with loading (a) 2 (b) 4 (c) 6 (d) 8 (e) 10 topological SRR unit cells at 10 GHz

4 Conclusions

In order to conform to the cylindrical substrate of the microstrip patch antenna, the regular SRR is topologically transformed into a topological SRR which gives the metamaterials effect to suppress surface wave of antenna. We have carried out a study of loading different number of topological SRR unit cells to observe the change of antenna near-field and far-field parameters. The gain of the antenna with loading 10 topological SRR unit cells is increased by nearly 2 dBi, and the near-field parameters keep good compared to those of the conventional circular patch antenna. It illustrates that the gain of the antenna is greatly improved with loading topological SRR on the premise of achieving good conformal antenna structure. The topological transformation idea can be applied to other metamaterials structures which need conformal design.

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基于拓扑变换的共形超材料高增益微带贴片天线

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摘　要： 微带贴片天线具有体积小、重量轻、剖面低、成本低、易于集成等优点，因而被广泛应用各种通信、遥测和探测系统中。但是，微带贴片天线也存在定向增益低的缺点。为此，提出了一种加载共形超材料的高增益微带贴片天线。将方形开环谐振器(Split-ring resonator，SRR)拓扑变换为符合圆形衬底的 SRR 单元，SRR 赋予抑制天线表面波的超材料效应。仿真结果表明，初始的圆形微带贴片天线的谐振频率为 10 GHz，增益为 6.12 dBi。加载 10 个拓扑 SRR 单元的天线的近场参数保持良好，远场增益为 7.88 dBi，比初始天线增加了近 2 dBi。

关键词： 微带贴片天线；开环谐振器；共形超材料；拓扑变换；增益

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