FSS Sandwiched Reflectarray for Dual–frequency Application

[#]Jianfeng Li[1], Qiang Chen[1], Qiaowei Yuan [2], Kunio Sawaya[1]

[1] Department of Electrical and Communication Engineering, Tohoku University
Aramaki Aza Aoba 6-6-05, Aoba-ku, Sendai, Miyagi 980-8579,Japan, jflee@ecei.tohoku.ac.jp;
chenq@ecei.tohoku.ac.jp; sawaya@ecei.tohoku.ac.jp
[2] Department of General Science, Sendai National College of Technology
4-16-1, Ayashi-chuo, Aoba-ku, Sendai, Miyagi 989-3128, Japan, qwyuan@sendai-nct.ac.jp

1. Introduction

Microstrip reflectarray has attracted significant interest because of its planar structure, surface mountable and low cost. It has been constantly developed for many years and the most recent researches have been focused on dual-band/polarization, beam scanning and so on [2-5]. However, the reflection phase range is the main limitation of reflectarray, especially for dual-frequency system. For a single-layer substrate, the achievable phase range of a traditional reflectarray is approximated to $360° \times (1.0 - kh/\pi)$, where k is a wavenumber in the substrate and h is the substrate thickness [6]. It can be seen that a thinner substrate offers a wider reflection phase range at the cost of high nonlinear. A rapid variation around the patch resonance makes the design difficult due to manufacturing errors. On the other hand, a thicker substrate offers a much smoother phase variation. However, the phase range becomes narrow, which makes practical designs unfeasible. Thus, for a dual-frequency system, a substrate may be too thin to have smooth phase range at lower frequency resulting slope; at the same time, it may be too thick at higher frequency to obtain an enough phase range. Usually, we need a tradeoff between the wide phase range and the smooth linear level.

In this paper, a novel concept is proposed to solve this problem. To simultaneously obtain a smooth reflection phase curve, a larger reflection phase range and dual operating frequency bands, an FSS (Frequency Selective Surface) layer is introduced and sandwiched between the reflectarray element layer (RA layer) and the metal ground plane. The FSS layer can act as an additional reflecting plane for the upper frequency. For lower frequency, the FSS layer is transparent so that the metal ground plane acts as the reflection plane. As a result, a smooth and wide reflection phase range can be achieved at both frequencies. Firstly, a new modified narrow band stop FSS is designed to provide a proper additional reflection plane. Moreover, a dual-band and dual-polarization reflectarray comprised cross-dipole elements and sandwiched FSS layer is designed, fabricated and measured to demonstrate the performance. For normal incidence, a maximum directivity of 18.1 dB (58°scattering angle) and 21.2 dB (29°scattering angle) are obtained at 12GHz and 16GHz, respectively.

2. Design of Modified Narrow Band FSS

The configuration of the FSS sandwiched reflectarray is shown in Figure 1. The distances from FSS layer to metal ground plane and RA layer are h_1 and h_2, respectively. The substrate has a thickness H and a relative permittivity ε_r. To provide an additional reflection plane for upper frequency (16GHz) and transparent plane for lower frequency (12GHz), a suitable FSS is designed.

An FSS is a surface construction designed as a 'filter' for plane waves [7]. A typical band stop FSS comprises loop elements, as depicted in Figure 2 (a). The size of each unit cell resonating at 16GHz is 10mm×10mm ($0.4\lambda \times 0.4\lambda$ at 12GHz, $0.53\lambda \times 0.53\lambda$ at 16GHz). The permittivity of the substrate is selected as 2.5.The equivalent circuit of the loop FSS and other detailed dimensions are

also given in this figure. It resonates at $f_r = 1/2\pi\sqrt{LC}$, where L and C are the inductance and capacitance respectively.
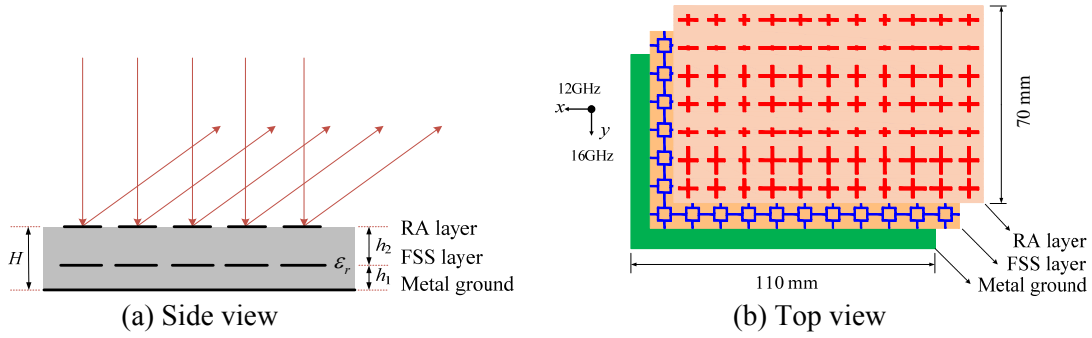

(a) Side view (b) Top view

Figure 1.   Configuration of reflectarray using sandwiched FSS

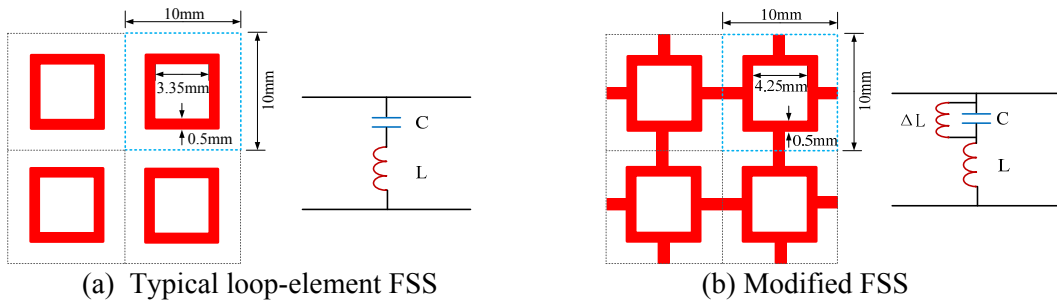
(a) Typical loop-element FSS (b) Modified FSS

Figure 2. Geometry and equivalent circuit of FSS

In Figure 3, the magnitude of the reflection coefficient is about 0 dB and the reflection phase is about -180° at 16 GHz for loop FSS. Thus a PEC-like plane can be realized at the upper operating frequency. However, as observed in Figure 3 (a), the -10 dB S11 band of the loop-element FSS is too wide and the S11 is as high as -3.5 dB at 12 GHz, indicating that about half incidence power will be reflected. In order to achieve a high transparent performance at the lower operating frequency, a modified narrow band stop FSS is designed.
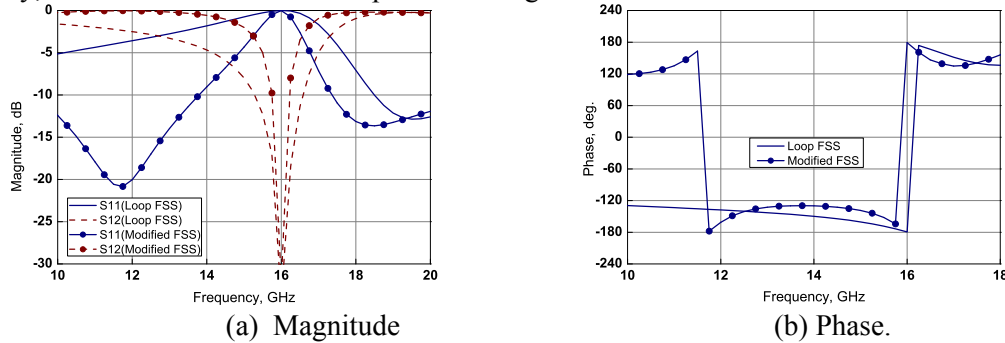

(a) Magnitude (b) Phase.

Figure 3. Frequency characteristics of reflection coefficient on reflectarray

A new modified FSS element geometry is sketched in Figure 2 (b). To obtain a narrow band stop performance, the adjacent loop elements are connected by a strip line which is equivalent to shunt an inductor as depicted in the equivalent circuit in Figure 2 (b). The unit cell still keeps the size of 10mm×10mm. The width of the loop element and the strip line are both 0.5 mm. The inner length of the loop is tuned to 4.25 mm and the length of the strip line is the distance between the adjacent loop elements, which is optimized as 4.75mm for resonating at 16 GHz.

The bandwidth of a band stop filter is related to $\sqrt{L/C}$, which depends on the dimension of unit cells [7]. By adding a strip line with the loop element, the inductance is changed into $L' = L/(1+(L/\Delta L))$, which is smaller than that of the loop-element FSS. To keep the resonant frequency, when the inductance becomes smaller, a bigger capacitance C' is required. The value of $\sqrt{L'/C'}$ is obviously smaller than $\sqrt{L/C}$, thus a narrow band stop FSS is obtained.

As shown in Figure 3, the -10 dB S11 band is reduced to 3.2 GHz and the reflecting amplitude is degreased to -20 dB at 12 GHz for modified FSS. The reflection amplitude is about 0 dB and the reflection phase is about $180°$ at 16 GHz. Excellent transparent and reflection performances are obtained at lower and upper frequencies, respectively.

3. Design of Dual-frequency Reflectarray

To meet the dual-frequency and dual-polarization requirements, cross-dipole elements of variable sizes are used. For each cross-dipole element, the horizontal dipole (*x*-direction) is designed to obtain the required phase correction for the horizontally polarized incident wave at 12 GHz; the vertical dipole (*y*-direction) deals with the vertically polarized incident wave at 16 GHz. The configuration of the FSS sandwiched reflectarray is shown in Fig.1. The reflectarray element layer is composed of 7×11 elements with a size of 70 mm $\times$ 110 mm. The distances from FSS layer to metal ground plane and RA layer are $h_1 = 0.8mm$ and $h_2 = 1.6mm$, respectively. The permittivity of the substrate is selected as 2.5.

An infinite periodic model was used to analyze the reflection phase characteristics of the unit cell using HFSS with normal incidence. For 12GHz, as can be seen in Figure 4 (a), when there is a metal ground plane at a distance of *H*=1.6mm from the RA layer(without FSS layer), the curve of the reflection phase shows a rapid variation around the resonance and slow variation off resonance. When the metal ground is set at the distance of *H*=2.4mm, a smoother phase range can be obtained. However, the distance of *H*=2.4mm is too thick for 16 GHz. As depicted in Figure 4 (b), for the case of *H*=2.4mm without FSS, the phase variation is smooth but phase range is limited to less than $300°$.

When the modified FSS is inserted between the RA layer and the metal ground plane, the reflectarray has a frequency-dependent reflection plane. Thus for 12GHz, the FSS is invisible and the reflection plane is the real metal ground. For 16GHz, the FSS is a PEC-like layer, from which the incidence field is directly reflected. As shown in Figure 4, smooth phase ranges are obtained at both lower and upper frequencies. At 12GHz, the reflectarray element has similar reflection phase with or without FSS (*H*=2.4mm), i.e., the FSS is invisible. At 16GHz, the reflectarray element with FSS has a wider phase range than that without FSS. For the case of *H*=1.6mm, when the metal ground plane is replaced by FSS, similar phase response can be obtained, i.e., the FSS is PEC-like. However, for the actual case (*H*=2.4), FSS and the ground plane comprise a whole reflection structure. Due to the interaction between them, the FSS design should be properly tuned to optimize the phase behavior of the complete backing structure. Fortunately, by utilizing the interaction properly, a more linear performance is obtained with FSS at the higher operating frequency as can be seen in Figure 4 (b). The final optimized inner loop length is 3mm.
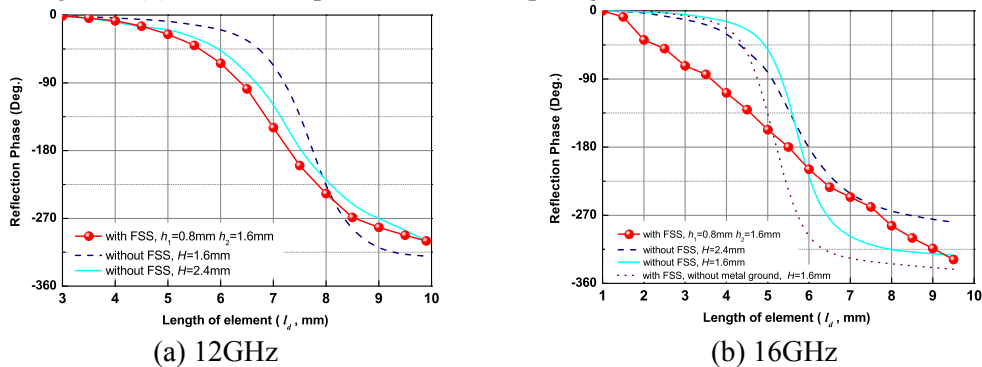

(a) 12GHz   (b) 16GHz

Figure 4. Reflection phase versus the dipole length

By using the reflection phase response with the elements size depicted in Figure 4, a 7×11 elements reflectarray is designed and fabricated to validate the performance. The geometry of the designed reflectarray is shown Figure 1. Since the main beam is scanned only in the *xoz*-plane (for 12GHz)/*yoz*-plane (for 16GHz), the dimensions of the cross dipole length in *x*/*y* direction are the same within each column/row.
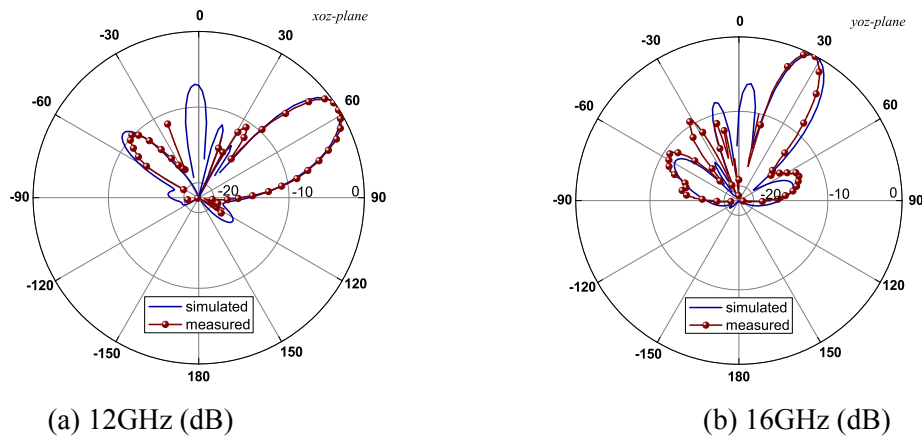
(a) 12GHz (dB) (b) 16GHz (dB)

Figure 5. Scattering pattern of 7×11 elements reflectarray

The simulated and measured scattering patterns of the proposed reflectarray are depicted in Figure 5. During the measurement, the transmitting and receiving horn antennas overlap at rang of -15~15°. Thus the measured data in this range is not considered. For normal incidence, the direction of the maximum directivity points at 58° at 12 GHz and 29°at 16 GHz, which shows a small shift from the desired angle (60°and 30°). This angle shift attributes to both simulation errors and mutual coupling. The maximum directivities are 18.1 dB and 21.2 dB at 12 GHz (*xoz*-plane) and 16 GHz (*yoz*-plane), respectively.

4. Conclusion

This paper presented a new concept for dual-frequency reflectarray design by sandwiching a narrow band FSS, which exhibits wide smooth phase bands at both lower and upper operating frequencies. A 7×11 elements reflectarray is designed and fabricated. Maximum directivities of 18.1 dB at 58° scattering angle and 21.2 dB at 29° scattering angle are obtained at 12 GHz and 16 GHz, respectively. The proposed reflectarray can be used to eliminate the blind spots of base station antennas in high-building district and other applications.

Acknowledgments

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