Varactor-tunable frequency selective surface with an embedded bias network*

Lin Bao-Qin(林宝勤)[a)†], Qu Shao-Bo(屈绍波)[b)], Tong Chuang-Ming(童创明)[b)], Zhou Hang(周 航)[b)], Zhang Heng-Yang(张衡阳)[a)], and Li Wei(李 伟)[a)]

[a)] *Institute of Information and Navigation, Air Force Engineering University, Xi'an* 710077, *China*
[b)] *Institute of Science, Air Force Engineering University, Xi'an* 710051, *China*

(Received 1 September 2012; revised manuscript received 7 November 2012)

A new technique for designing a varactor-tunable frequency selective surface (FSS) with an embedded bias network is proposed and experimentally verified. The proposed FSS is based on a square-ring slot FSS. The frequency tuning is achieved by inserting varactor diodes between the square mesh and each unattached square patch. The square mesh is divided into two parts for biasing the varactor diodes. Full-wave numerical simulations show that a wide tuning range can be achieved by changing the capacitances of these loaded varactors. Two homo-type samples using fixed lumped capacitors are fabricated and measured using a standard waveguide measurement setup. Excellent agreement between the measured and simulated results is demonstrated.

Keywords: frequency selective surface, varactor diodes, embedded bias network

PACS: 41.20.Jb, 78.20.Ci, 84.40.Az **DOI:** 10.1088/1674-1056/22/9/094103

1. Introduction

Frequency selective surfaces (FSSs) have been intensively studied for several decades[1–14] and widely used in a number of applications in telecommunications, antenna design, and electromagnetic compatibility. A typical FSS is constructed by periodically arranging elements of resonant type on a given surface. Over the years, many element geometries, such as patch,[2] dipole,[3] loop,[4,5] and one of their complementary structures, have been introduced for a band-stop or band-pass FSS.

The traditional FSS structures are only passive printed conductors on a dielectric substrate. The frequency behavior of an FSS is mainly determined by the geometry of its unit cell, and it cannot be changed once designed and manufactured. Recently, the active FSS has been studied. A well-established method of tuning the FSS is to incorporate electronically tunable components into its unit cell. A limited number of electronically tunable FSSs have been designed by embedding solid-state varactor diodes[10–13] and MEMS switches[14] in the traditional FSSs. For biasing the active components, these tunable FSSs require a separate circuitry. Because of the effect of the bias network on the FSS frequency response, biasing the active components properly is a major difficulty in designing a tunable FSS.

In this paper, we propose a novel varactor-tunable, band-pass FSS with an embedded bias network. The frequency tuning capability of the proposed FSS is demonstrated through numerical simulations using Ansys HFSS software. To verify the simulations, two homo-typical samples using fixed lumped capacitors with different capacitances are fabricated and measured using a standard waveguide measurement setup. Excellent agreement between the measured and simulated results is demonstrated.

2. Designing process

The proposed FSS is based on a square ring slot FSS. One unit cell of the primary FSS is composed of a square mesh surrounding an unattached square patch mounted on a dielectric substrate. The FSS has a band-pass performance, and its resonant frequency can be effectively lowered when the lumped capacitive components are loaded in the square ring slot, as shown in Fig. 1(a). The resonant behavior of the FSS can be illuminated effectively according to the equivalent circuit of one cell, which is indicated in Fig. 1(b). The equivalent circuit is a parallel LC circuit shunted across a transmission line of impedance Z_0, the inductance L is derived from the square mesh, and the capacitance C is the total capacitance beside one patch, which comprises the slot capacitance C_g, the lumped capacitance C_{Lu}, as well as the equivalent inductance L of the square patch. The capacitance C can be expressed as

$$C = \frac{(C_g + C_{Lu})}{2 - \omega^2 L(C_g + C_{Lu})}. \quad (1)$$

Based on the above primary FSS, a novel varactor-tunable FSS structure is proposed. One unit cell of the proposed FSS is shown in Fig. 1(c), and it approximates a combination of four unit cells of the primary one, and the loaded capacitive

*Project supported by the National Natural Science Foundation of China (Grant Nos. 60901029, 61172148, and 60925005) and the Natural Science Foundation of Shaanxi Province, China (Grant No. 2011JQ8040).

†Corresponding author. E-mail: aflbq@sina.com

© 2013 Chinese Physical Society and IOP Publishing Ltd

components are selected as a kind of varactor diode with capacitance $C_{\rm Var}$. To bias the varactor diodes properly, one simple and effective method is proposed. We regard the square mesh as a combiner of a pair of similar ones with double periods. The pair of square meshes are staggered with half the period both in x and y axes, and they are mounted on the same surface and overlapped at each intersection. To keep the pair of square meshes electrically unattached, we make one square mesh stride over the other at each intersection using additional strips as shown in Fig. 1(c). Now the primary square mesh is divided into two parts, and each square patch is surrounded by them. According to the resistive-lumped-element biasing grid in Refs. [10] and [11], a kind of surface mount resistor with proper resistance R is loaded between each mesh and patch as shown in Fig. 1(c), a common direct-current (DC) voltage $V/2$ can be introduced to bias each varactor diode in parallel when a DC voltage V is introduced between two square meshes. For the equivalent circuit of the tunable FSS, because the pair of square meshes are mounted on the same surface, their equivalent inductances are shunted across the transmission line of impedance Z_0 in parallel. Combined with the capacitance C beside each patch, the equivalent circuit is shown in Fig. 1(d), its total admittance G is

$$G = \frac{1}{\mathrm{j}\omega 2L} + \left(\mathrm{j}\omega 2C + \frac{1}{\mathrm{j}\omega L}\right)/2 = \mathrm{j}\omega C + \frac{1}{\mathrm{j}\omega L}. \qquad (2)$$

It is educed that the equivalent circuit is entirely equivalent to that of the primary FSS, and the resonant behaviors of the tunable FSS can be kept the same as those of the primary FSS. Now with the augment of the varactor capacitance $C_{\rm Var}$, the capacitance C is increased, the resonant frequency of the FSS can be lowered effectively. In this way, a novel varactor-tunable FSS with an embedded bias network is proposed.

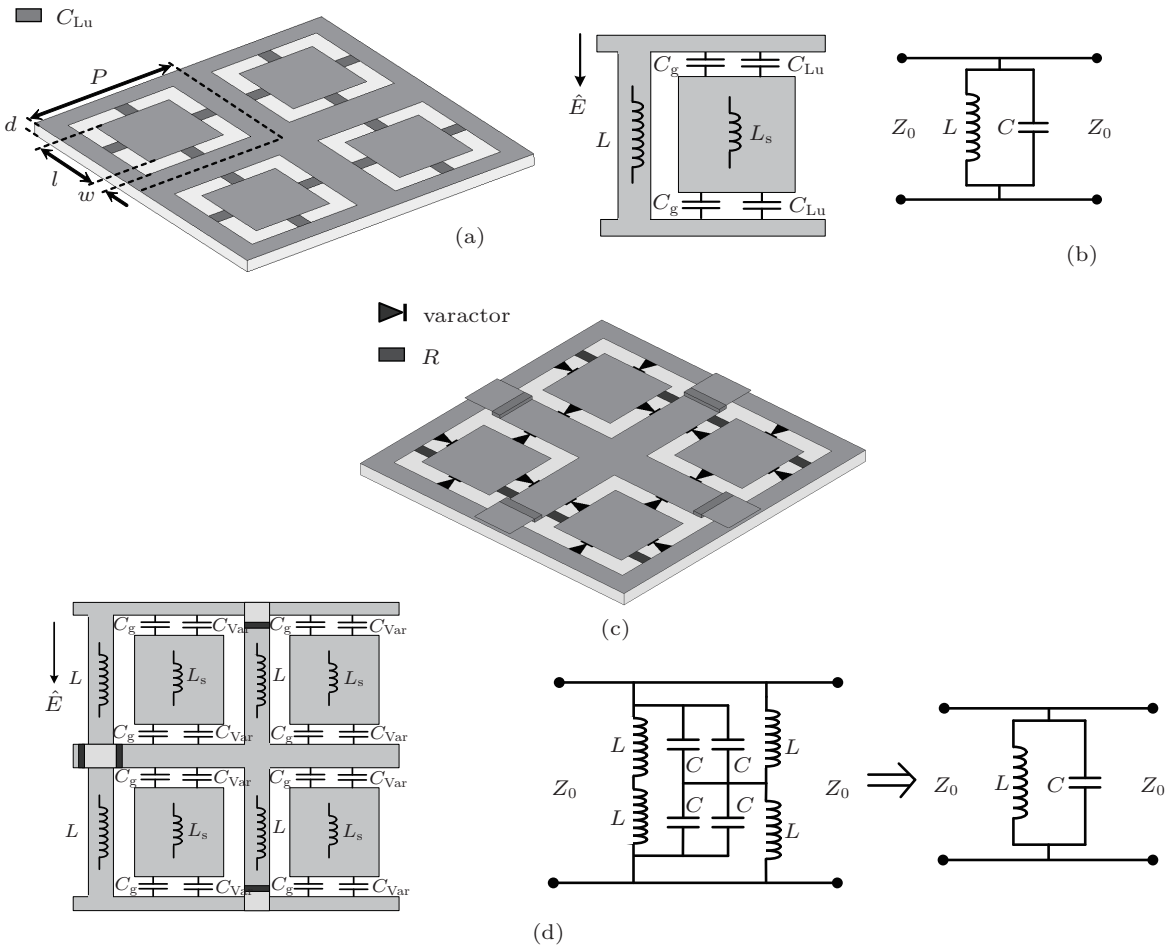


Fig. 1. FSS structures and equivalent circuits: (a) structure and (b) equivalent circuit of the primary FSS, (c) structure and (d) equivalent circuit of the proposed FSS.

3. Numerical simulations

To validate the properties of the proposed tunable FSS, numerical simulations are carried out at first. The primary FSS in the design is constructed on a $d = 1.5$ mm thick dielectric substrate with relative permittivity $\varepsilon_{\rm r} = 9.6$, and the dimensions of each cell are as follows: $P = 13.65$ mm, $l = 7.0$ mm, and $w = 1.5$ mm. To realize the proposed tunable FSS, the additional strips with width 3.65 mm and length 5.65 mm are introduced and mounted on a 0.2 mm thick dielectric film ($\varepsilon_{\rm r} = 2.2$). The resistances of the loaded resistors are all cho-

sen to be $R = 1.0$ MΩ.

Firstly, to study the effect of the embedded bias network on the FSS frequency response, the proposed tunable FSS, together with a primary one loaded with lumped capacitors, is simulated using HFSS software. The capacitances $C_{\rm Var}$ and $C_{\rm Lu}$ of their loaded capacitive components are both assumed to be 0.5 pF. The simulated results of their transmission coefficients at normal incidence are shown in Fig. 2. It is shown that the bias network does not affect the FSS frequency response much, their transmission coefficients are basically uniform, except that there is an undesirable resonance at the frequency 3.23 GHz, which may be attributed to the coupling capacitance between the two parts of the divided square mesh.

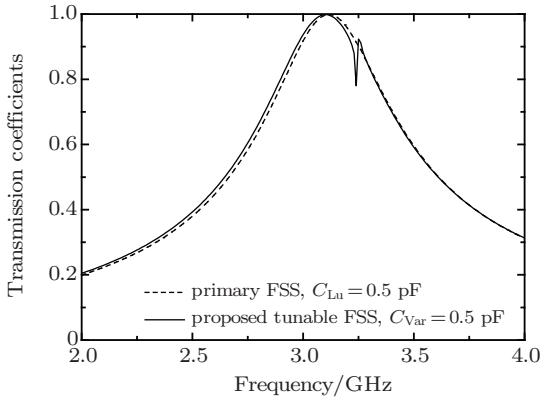


Fig. 2. Transmission responses of the proposed and the primary FSSs to frequency.

When the capacitances $C_{\rm Var}$ of these loaded varactors are assumed to be different, the proposed FSS is simulated to prove its frequency tuning capability. The simulated results in Fig. 3 show that the resonant frequency of the FSS is tuned from 3.86 GHz to 1.80 GHz when the capacitance $C_{\rm Var}$ is changed from 0.2 pF to 2.0 pF, and the transmission coefficients are close to 1.0 at the resonant frequency at all time.

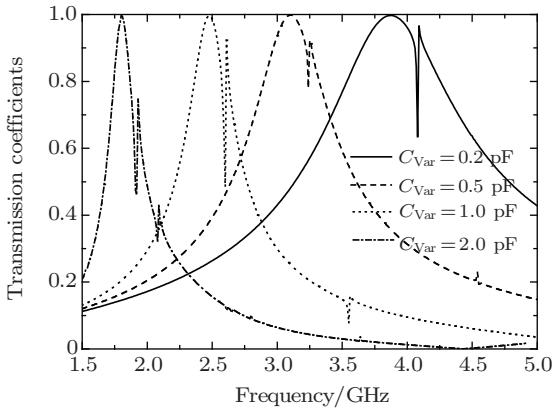


Fig. 3. Transmission responses of the tunable FSS to frequency for some different values of varactor capacitance.

4. Experimental validation

To verify the above simulations, an experiment is carried out in a rectangular waveguide simulator. The cross-sectional area of the waveguide used in the convenient experimental setup is approximately $a \times b = 109.2$ mm $\times$ 54.6 mm. The dimensions of the fabricated FSS are close to those of the waveguide cross section as shown in Fig. 4, which consists of a 2×4 array of unit cells with a period of $P = 27.3$ mm.

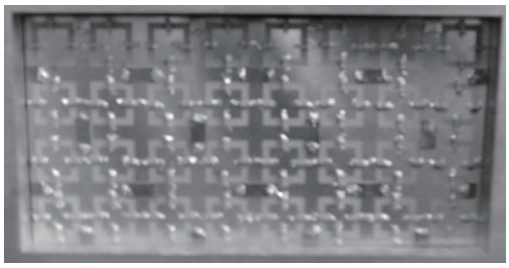


Fig. 4. Prototype of the fabricated FSS in the experimental setup.

To overcome the biasing problems in the waveguide simulator, the varactor diodes are replaced with lumped capacitors with different capacitances. As the operating frequency of the TE_{10} mode in the used waveguide is in the range of 1.72 GHz–2.61 GHz, according to the simulated results in Fig. 3, we fabricate two homo-typical samples in which the values of capacitance $C_{\rm Lu}$ are chosen to be 1.0 pF and 1.8 pF, respectively. In addition, the resistors have not been loaded for convenience because of the limited sizes of these unit cells.

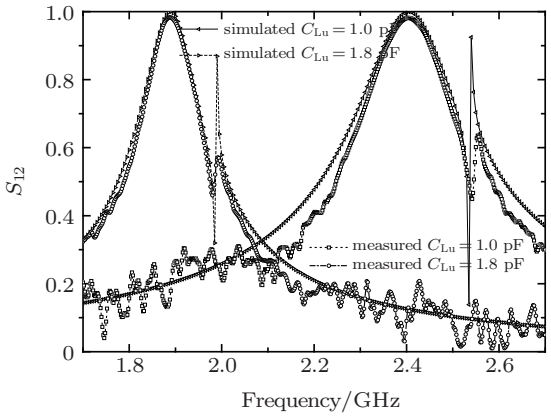


Fig. 5. Comparisons between experimental results and simulated ones.

The guided wave of the TE_{10} mode in the rectangular waveguide can be seen as a TE oblique incident wave. The comparison between the measured data and the simulated results at TE incidence with proper incident angle θ is shown in Fig. 5. The incident angle is determined by the formula $\theta = \arcsin(c_0/2af)$, where $a = 0.1092$ m is the width of the used waveguide, and f is the resonant frequency of the FSS, which is adopted to be 2.42 GHz or 1.89 GHz when the capacitance $C_{\rm Lu}$ is chosen to be 1.0 pF or 1.8 pF. Figure 5 shows that the experimental results are in good agreement with the numerical predication, except that there is a little difference between simulation and experiment at the frequency deviating

from the resonant frequency, which may be attributed to the change of the incident angle θ with frequency f in the waveguide or due to the accuracy of measurement.

5. Conclusion

In this paper, a novel varactor-tunable FSS is proposed and experimentally verified. The proposed FSS structure has an embedded bias network, which has little effect on the frequency response of the FSS. The frequency tuning capability of the proposed FSS is demonstrated through numerical simulations. A wide tuning range from 1.80 GHz to 3.86 GHz is achieved by changing the capacitance of the varactor diode from 2.0 pF to 0.2 pF. Two homo-typical samples using fixed lumped capacitors with different capacitances are fabricated and measured using a standard waveguide measurement setup. Good agreement between the simulation and experimental results is observed.

References

[1] Munk B A 2000 *Frequency Selective Surfaces: Theory and Design* (New York: Wiley)
[2] Chen C C 1970 *IEEE Trans. Antennas Propag.* **18** 660
[3] Munk B A, Kouyoumjian R G and Peters L 1971 *IEEE Trans. Antennas Propag.* **19** 612
[4] Huang J, Wu T K and Lee S W 1994 *IEEE Trans. Antennas Propag.* **42** 166
[5] Wu T K and Lee S W 1994 *IEEE Trans. Antennas Propag.* **42** 1484
[6] Jia H Y, Feng X G and Sheng C X 2012 *Chin. Phys. B* **21** 054102
[7] Sun L K, Cheng H F, Zhou Y J and Wang J 2012 *Chin. Phys. B* **21** 055201
[8] Zhou H, Qu S B, Peng W D, Lin B Q, Wang J F, Ma H, Zhang J Q, Bai P, Wang X H and Xu Z 2012 *Chin. Phys. B* **21** 054101
[9] Zhou H, Qu S B, Peng W D, Wang J F, Ma H, Zhang J Q, Bai P and Xu Z 2012 *Chin. Phys. B* **21** 030301
[10] Mias C 2005 *IEEE Microw.Wireless Compon. Lett.* **15** 570
[11] Mias C 2004 *Microw. Opt. Technol. Lett.* **43** 508
[12] Bayatpur F and Sarabandi K 2009 *IEEE Trans. Antennas Propag.* **57** 590
[13] Bayatpur F and Sarabandi K 2009 *IEEE Trans. Microw. Theory Tech.* **57** 1433
[14] Schoenlinner B A, Abbaspour T A, Kempel L C and Rebeiz G M 2004 *IEEE Trans. Microw. Theory Tech.* **52** 2474