Design of a Flexible and Reconfigurable Frequency Selective Surface

In-Gon Lee, and Ic-Pyo, Hong*

Abstract—In this paper, a flexible and reconfigurable frequency selective surface (FSS) using varactor diodes was designed and fabricated on flexible printed circuit board for curved surface application. We designed the rhombus-type patch and grid array, which is a novel type of unit cell structure, to increase the sensitivity of the capacitance for high-frequency operation. We fabricated the proposed reconfigurable FSS using a flexible printed circuit board and varactor diode using the optimized design parameters from commercial electromagnetic software simulations. To show the validity of simulation results, we measured the transmission characteristics for different bias voltages and curvature radii of the surface using free-space measurement method. The measurement results show that the proposed structure has a wideband operating frequency of 6.05-7.08 GHz for normal incidence and the proposed structure can be applied to curved surfaces like curved radomes.

***Keywords*—**Reconfigurability, frequency selective surface, flexible printed circuit board, varactor diode, rhombus-type patch

I. Introduction

THE frequency selective surface (FSS), which is used as an electromagnetic spatial filter, is an electromagnetic structure with periodic arrays of patches and apertures on a dielectric substrate [1]. The FSSs have found widespread applications in communication, microwave, and radar systems, including radomes, sub-reflectors, circuit analog absorbers, and polarizers. The FSSs, particularly with band-pass characteristics, have been studied in a wide range of applications of fields including stealth radomes and reflect arrays [2][3].

Recently, to improve the characteristics of passive FSSs, which pass only single-frequency band, many studies have been conducted with a focus on active FSSs that allow frequencies to be transformed into active forms, i.e., shifting their resonant frequency through an array of integrated switching devices. The typical method of frequency transformation by a reconfigurable FSS is to use active switching devices such as PIN diodes, varactor diodes, and micro-electromechanical systems (MEMS). When a PIN diode is used for such frequency transformations, the operating frequency can be varied using the on/off state of the diode with bias voltage application. This technique provides a wide variable range of the operating frequency, but allows only two variable operating frequencies [4][5]. The idea behind the use of a varactor diode is to vary the operating frequency by changing the diode capacitance depending on the bias voltage. This method can achieve a wide range of operating frequencies, but has limitations at high-frequency bands because it is very difficult to get the sensitivity of the capacitance in an FSS structure when compared with the small capacitance variation of the varactor. The reconfigurable method using MEMS switch is implemented using mechanical switching and RF MEMS features. It has the advantages of low-cost fabrication, low loss, high isolation, and fast switching, but provides a limited dynamic range of variable capacitance because of the narrow-band characteristics of the achieved operating frequencies and the extremely small size of MEMS devices [6][7].

In this paper, we designed a flexible and reconfigurable FSS using the flexible printed circuit board and varactor diode for C-band applications. As described earlier, the reconfigurable FSS designed with a varactor diode has the low Q value of the capacitor and requires very small capacitance in high-frequency bands, and therefore most of the previous studies had designed such FSSs for operation in low-frequency bands. For high-frequency application and flexibility, we have to implement the unit cell structure, which has small capacitance when compared with the capacitance variations of a varactor diode. We presented the rhombus-type patch array as a unit cell structure on flexible printed circuit board to provide the small capacitance for resonant-frequency reconfigurability in C-band applications because of very small vertex of the rhombus-type patch. The reconfigurable FSS designed in this study, unlike the existing ones designed by the use of a varactor diode, applied rhombus-type patch array and grid arrays for the realization of its operation in high-frequency bands and used a flexible substrate for easy application to curved surfaces like radomes.

II. Design and Measurements

The unit cell geometry of the proposed FSS is illustrated in Fig. 1. Fig. 1 shows the reconfigurable FSS with rhombus-type patch array and ground grids proposed in this study. Typically, FSSs should have small capacitance between patches and ground grids when designed for reconfiguration of operating frequencies in high-frequency bands because the capacitance variation of a varactor diode is very small when compared with

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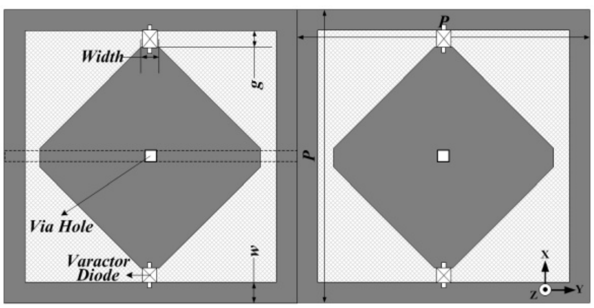
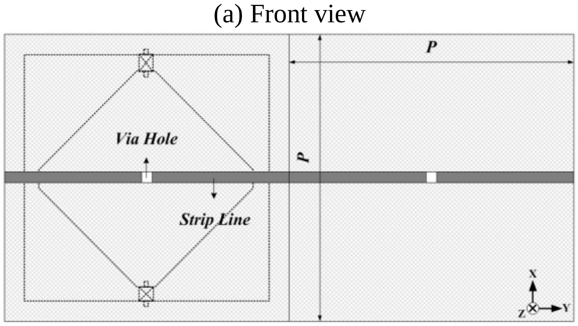
the capacitance of the structure itself. This makes it difficult for a commercial variable capacitor to achieve frequency reconfigurability at high-frequency bands. Therefore, the use of a rhombus-shaped patch as shown in Fig. 1 is proposed. The proposed rhombus structure could increase capacitance between ground grids and the FSS. The implemented capacitance by the varactor diode can be used for providing the reconfigurability at high frequencies by the addition of the capacitance of a rhombus-type patch array. We designed a reconfigurable FSS with a wide dynamic range of capacitance for application of commercial varactor diodes by adjusting the capacitance of the proposed reconfigurable FSS via the design parameter width, as shown in Fig. 1(a). The proposed structure has the FSS in a rhombus-shaped patch form located in the ground grid on the top of the dielectric as shown in Fig. 1(a) and has a strip line for bias application of the varactor diode at the bottom as shown in Fig. 1(b). As a result, unit cell of the proposed FSS is connected with the patch via holes, as shown in Fig. 1(c).



(a) Front view



(b) Back view

(c) Side view

Fig. 1. Designed unit cell of the reconfigurable FSS

In this study, as shown in Fig. 1(a), the FSS was designed to allow capacitance variation using a commercial varactor diode (SMV2019-079LF, Skyworks) between the ground grid and the rhombus-shaped patch. Further, the proposed reconfigurable FSS was designed to operate in the C-band centered at about 7 GHz and used a flexible dielectric, 1-mil-thick polyimide, for application to curved shapes. To obtain the optimal electromagnetic performance of the proposed reconfigurable FSS, the simulation is done using Ansoft HFSS commercial electromagnetic software, which utilizes finite element method to test the design results and determine the electromagnetic behavior of the structure. Floquet ports are used to determine the reflection and transmission coefficients of the proposed FSS

Table 1. Design parameters

Designed parameters	Value[mm]
P	45.0
Width	1.50
g	1.00
w	2.88
Strip Line	1.5x45

unit cell. In Table 1, the optimized design parameters are listed for simulation and fabrication.

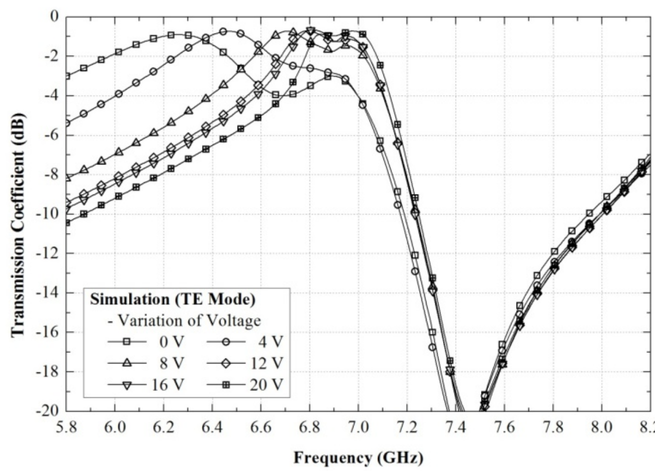
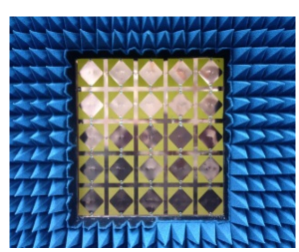
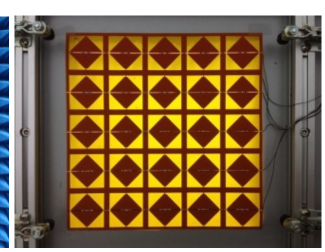


Fig. 2. Simulated transmission results of the proposed reconfigurable FSS for different bias voltages : TE mode,

The transmission characteristics of the proposed reconfigurable FSSs were simulated with the variable capacitance values changed to 0.30 pF (20 V), 0.32 pF (16 V), 0.35 pF (12 V), 0.44 pF (8 V), 0.81 pF (4 V), and 2.22 pF (0 V), respectively. In Fig. 2, the transmission characteristics for different bias voltages applied to the varactor diode are presented for TE mode. The simulation shows that the FSS has the expected band-pass characteristic centered at 7 GHz. It is observed that the design provides band-pass characteristics for a broad band of 720 MHz with its start and stop band frequencies lying at 6.27 GHz (0 V) and 6.98 GHz (20 V), respectively, for the transmitted peak frequency.



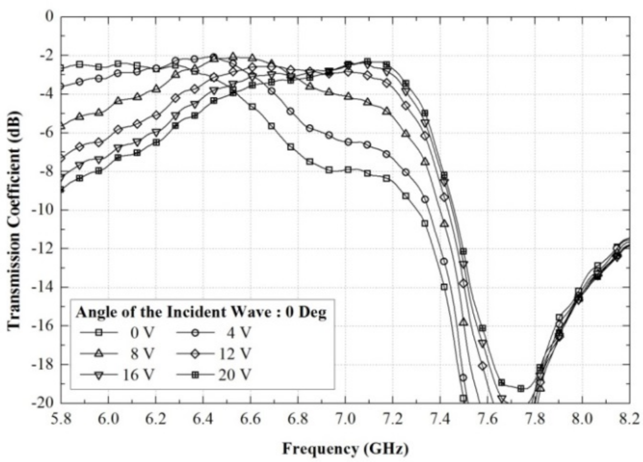
(a) front view



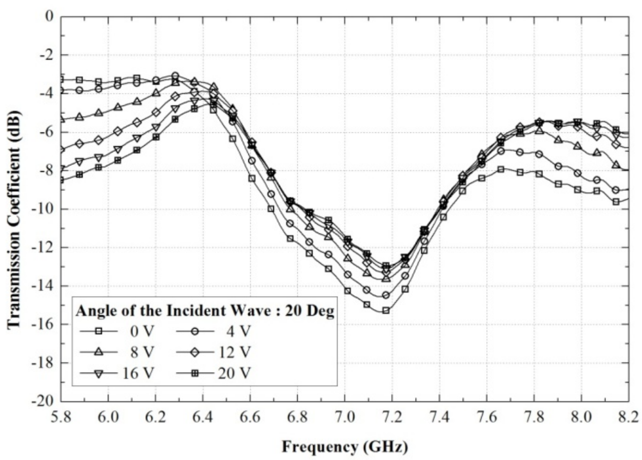
(b) back view

Fig. 3. Fabricated reconfigurable FSS :,

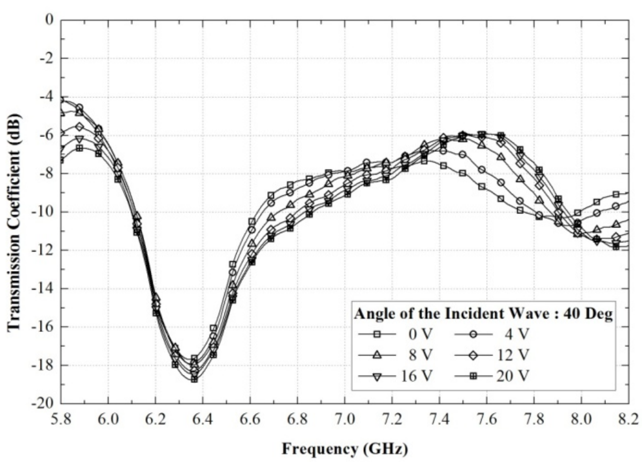
Based on the simulation results, we fabricated a reconfigurable FSS of 225 mm x 225 mm with 5 x 5 unit cells for measurement; the front and back views of the fabricated FSS installed on the measurement equipment are shown in Fig. 3(a) and (b), respectively. The proposed FSS are designed and fabricated with unit cells arranged on polyimide which have $\varepsilon_r = 3.5$, $\tan\delta = 0.008$, and 1 mil as the substrate dielectric thickness.



(a) Normal incidence



(b) 20^o incidence



(c) 40^o incidence

Fig. 4. Measured TE mode transmission characteristics of the proposed planar reconfigurable FSS for different bias voltages and incident angles

The proposed FSS's reflection characteristics were measured by a free-space measurement technique and using a bias voltage at intervals of 4 V between 0 and 20 V. Fig. 4(a), (b), and (c) show the measured TE mode transmission characteristics for normal incidence, 20^o incidence, and 40^o incidence, respectively. For normal incidence, the reconfigurable frequency range of peak transmission is from 6.05 GHz to 7.08 GHz, which are of 1.03 GHz bandwidth. The measured transmission characteristics were almost consistent with the simulation results. The reconfigurable frequency range for 20^o incident wave is 0.34 GHz and there is little frequency change for 40^o incidence. We concluded that this is due to the large unit cell structure, when compared with the operating wavelength.

Because of its flexibility, we can apply this proposed FSS to a curved surface as shown in Fig. 5. In Fig. 5, we presented the fabricated FSS on the curved surface for the measurement of curvature effect in transmission characteristics. To eliminate the dielectric loading effect of curved surface, we used the foam which has $\varepsilon_r = 1.03$.

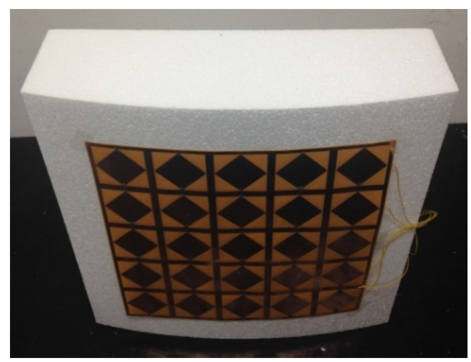
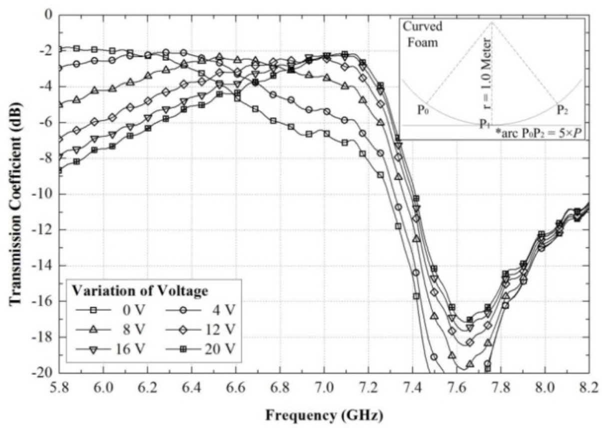
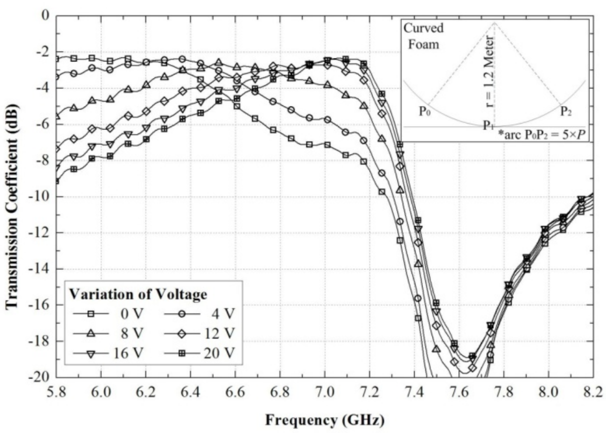


Fig. 5. Curved reconfigurable FSS

We also measured the frequency transmission characteristics in Fig. 6(a) and (b) for curvature radii *r*=1 m and 1.2 m, respectively. The operating frequency at each measured voltage was found to have the same variable range of 5.84-7.07 GHz (approx. 1.23 GHz) for each curvature radius. The operating frequency range for each curvature is extended compared to the planar structure. It is observed that there is no difference in transmission characteristics between *r*=1 m and 1.2 m. We thought this is because the fabricated finite reconfigurable FSS is small compared to the surface area of curvature radii *r*=1 m and 1.2 m.



(a) r =1 m



(b) r =1.2 m.

Fig. 6. Measured TE mode transmission characteristics of the proposed reconfigurable FSS for different bias voltages and curvature radii r

III. Conclusion

In this paper, we designed and fabricated a reconfigurable FSS, which allows the operating frequency characteristics to be varied in an active manner depending on the bias voltage in the C-band. A flexible dielectric polyimide and FPCB were used for the design of the reconfigurable FSS. The rhombus-shaped patch and ground grid were applied for creation of the reconfigurable surface at high frequencies, and a varactor diode was used for fabrication of the proposed FSS. The planar reconfigurable FSS was measured to have a variable operating-frequency range from 6.05 GHz to 7.03 GHz for normal incidence, and broadband characteristics were found from the measurement by a free-space measurement technique. Also, we measured the transmission characteristics of the curved reconfigurable FSS with curvature radii r=1 m and 1.2 m, and it is observed that the operating frequency range of the curved structure is extended to 5.84-7.07 GHz. The proposed FSS can be applied to structures such as curved surfaces, which are used in aircrafts or warships, because it is flexible and hence bendable. Future studies need to examine the characteristics of frequency response to curvature, with a focus on the incident-angle stability and flexibility of the proposed reconfigurable FSS.

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The second paragraph uses the pronoun of the person (he or she) and not the author’s last name. It lists military and work experience, including summer and fellowship jobs. Job titles are capitalized. The current job must have a location; previous positions may be listed without one. Information concerning previous publications may be included. Try not to list more than three books or published articles. The format for listing publishers of a book within the biography is: title of book (city, state: publisher name, year) similar to a reference. Current and previous research interests ends the paragraph.

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