Journal of Electrical Engineering & Technology (2019) 14:331–337
https://doi.org/10.1007/s42835-018-00034-4

ORIGINAL ARTICLE

Design of a Multi-Layered Reconfigurable Frequency Selective Surface Using Water Channels

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Received: 20 July 2018 / Revised: 30 August 2018 / Accepted: 14 September 2018 / Published online: 4 January 2019

Abstract

In this study, we propose a multi-layered reconfigurable frequency selective surface (FSS) using water channels, which can be switched between the bandpass and bandstop states. Variation ratio in transmission between the bandpass and bandstop states is drastically improved by multi-layer dielectric slabs with water channels. We then fabricate the design, and the measured results in the X-band shows a good agreement with the simulation. The variation in transmission coefficients between the two states increases from 0.34 to 0.71 using the 5-layered dielectric slabs with water channels, which verifies the reconfigurability of the proposed FSS.

Keywords Frequency selective surface · Water channels

1 Introduction

A frequency selective surface (FSS) is a periodic structure that transmits or reflects electromagnetic waves at a specific frequency. The typical FSS consists of passive elements and operates in a single, unchanged state at a fixed frequency band. The FSS can be used within radomes to obtain stealth functions [1, 2]. Recently, there have been many studies on the reconfigurable FSS to overcome the drawbacks of the FSS. For example, a reconfigurable FSS using various active elements, such as PIN diodes, varactor diodes, and micro-electro-mechanical systems (MEMS) to control the impedance of unit cells, has been extensively studied. The reconfigurable FSS with PIN diodes can change the transmission frequency to either on or off state depending on the bias voltage, but only two transmission frequency variations according to the states are possible [3–6]. The FSS using varactor diodes can change various transmission frequencies by changing the bias voltage, but it is difficult to apply to a high frequency band and require a high fabricating cost [7–11]. The FSS using MEMS is able to change the transmission frequency with a low cost, low loss, high isolation, and fast switching, but it has a disadvantage of a narrow-bandwidth and small variation of the transmission frequency [12–14]. We proposed a reconfigurable FSS using a single dielectric slab with water channels [15] and demonstrated that using the fully filled or unfilled state (i.e., bandpass or bandstop state) of the fluid channels can control the transmission characteristics by changing the effective dielectric constants of the dielectric slabs. We have also shown that

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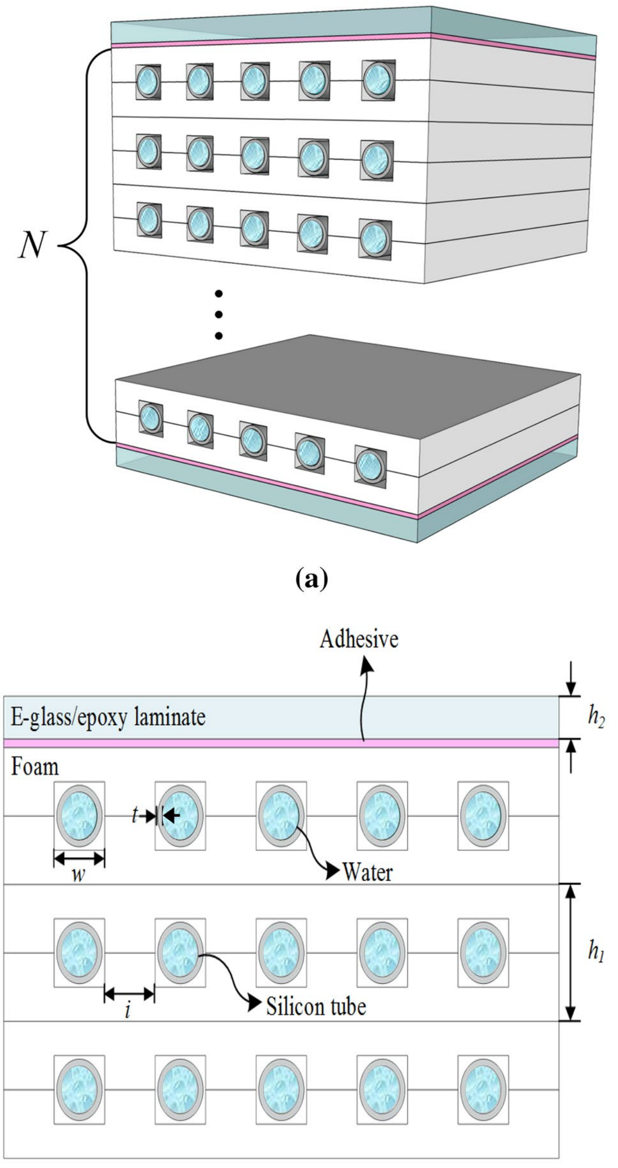


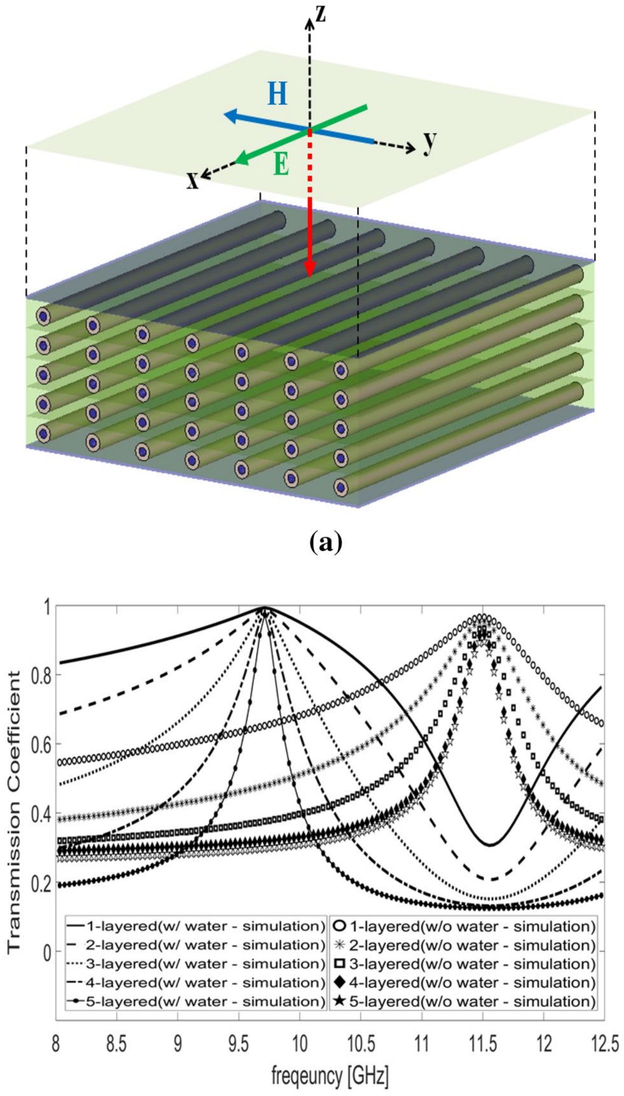
(a)

(b)

Fig. 1 Geometry of the multi-layered reconfigurable FSS. **a** Perspective view; **b** front view

Table 1 Optimized design parameters of the multi-layered reconfigurable FSS

S: Slab surface dimensions (mm^2)	100 × 100
h_1: Foam height (mm)/ε_1	6.4/1.093
h_2: Composite height (mm)/ε_2	0.6/4.35
w: Tube diameter (mm)	4
t: Tube wall thickness (mm)/ε_3	0.5/11.9
i: Interval of tubes (mm)	10
N: Number of layers	From 1 to 5



(a)

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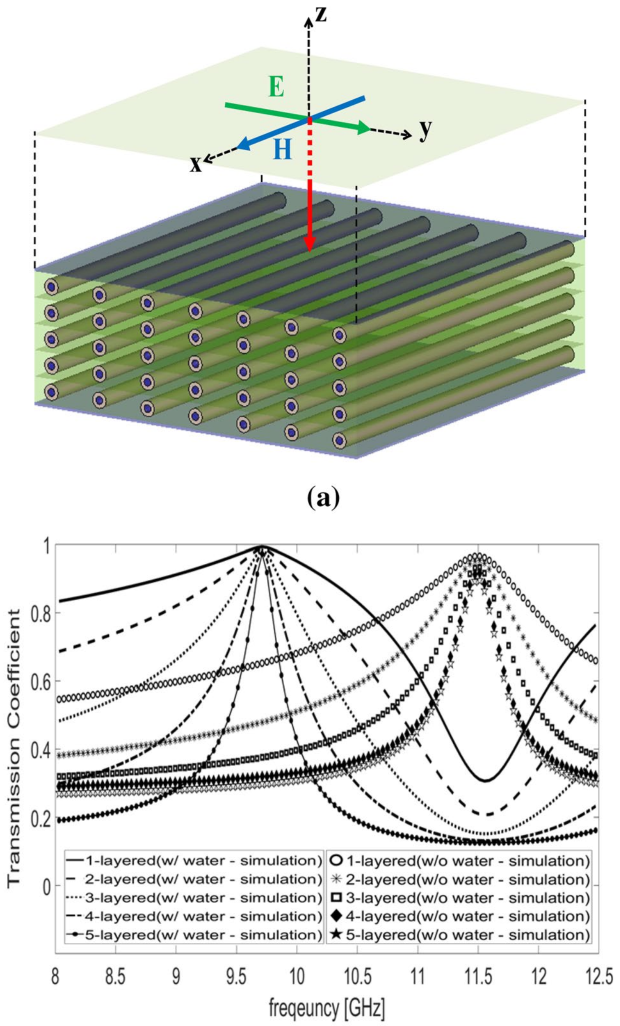
Fig. 2 3-D model and the simulated results of the multi-layered reconfigurable FSS. **a** Simulation geometry (E-field: x-pol); **b** simulation results

water ($\varepsilon_r = 66–57\text{-}j(26–33)$) can be used as the fluid in channels, and the transmission characteristics are controlled by the diameter, spacing, and presence of the fluid in the channels. However, the single-layered reconfigurable FSS using fluidic channels could not make an appreciable variation in transmission coefficients between the two states (i.e., frequency selectivity) at the target frequency.

In this study, we propose a multi-layered reconfigurable FSS using the water channels, which can be switched between the bandpass and bandstop states according to the filled or unfilled of the water channels. Variation ratio in transmission between the bandpass and bandstop states is drastically improved by stacking the dielectric slab with



(a)

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Fig. 3 3-D model and the simulated results of the multi-layered reconfigurable FSS. **a** Simulation geometry (E-field: y-pol); **b** simulation results

water channels in parallel as the number of layers increases. We then fabricate the design, and the measured results in the X-band show a good agreement with the simulation. The variation in transmission coefficients between the two states increases from 0.34 to 0.71 using the 5-layered dielectric slabs with water channels, which verifies the reconfigurability of the proposed FSS.

2 Design and Fabrication

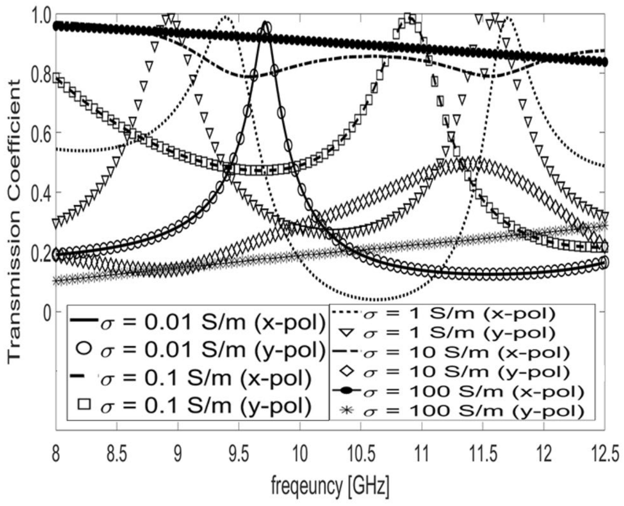
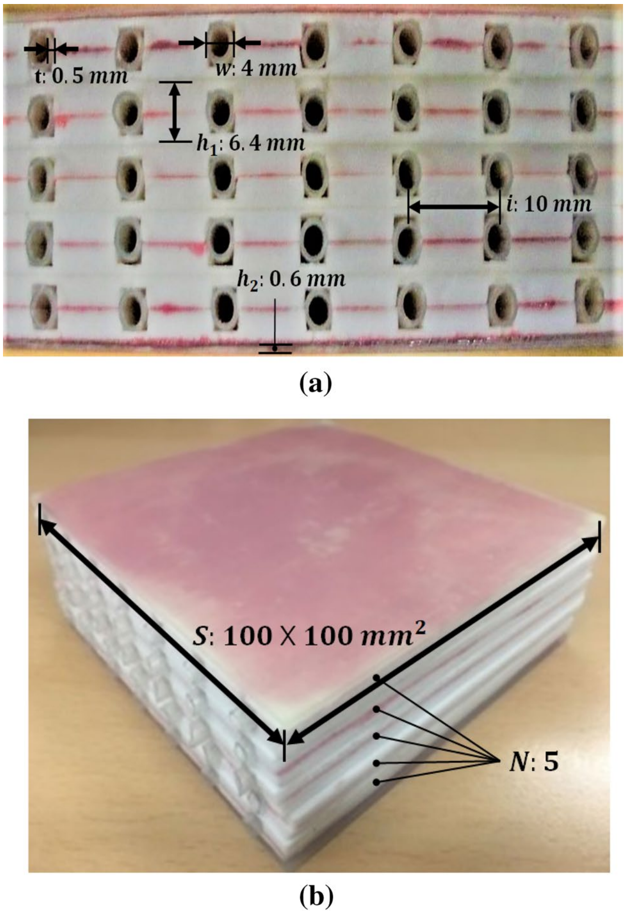


Fig. 4 Transmission coefficient according to conductivity

Figure 1 shows the multi-layered reconfigurable FSS, which consists of foams (Rohacell HF-71), composites (E-glass/epoxy laminate), adhesives, and circular silicon tubes that can be filled with water. The effective permittivity of the structure can be optimized by varying the sizes and spacing of the tubes to achieve the reconfigurability of transmission coefficients in the X-band. Note that the impact of the water channels in the single layer on the permittivity and loss tangent of the FSS is not sufficient to obtain the applicable variation ratio in transmission between the bandpass and bandstop states. Therefore, a multi-layered configuration for FSS is employed by stacking the single dielectric slab with water channels in parallel. We have optimized the design parameters of the proposed FSS, such as the diameter and spacing of the water channels, slab thickness, and number of layers, using a full-wave solver (CST MICROWAVE STUDIO (MWS) [16]). The detailed design parameters are listed in Table 1. Figure 2a shows the simulation geometry and conditions, such as mode of the incident wave, polarization of incident wave, and direction of E-field. The incident wave is a plane wave with linearly polarization in the x-direction. In Fig. 2b, the transmission coefficients between two states at a target frequency of 9.7 GHz are observed as the number of layers increases to examine the reconfigurability of the FSS. Even if the direction of E-field is rotated by 90°, the result is the same as that before the situation (see Fig. 3). To verify our results, we have conducted the simulations while increasing the conductivity of the water. When the conductivity is lower than 1 S/m, the transmission characteristic does not change depending on the direction of the E-field. However, if it is higher than 1 S/m, the transmission characteristics change by the direction of the E-field. The conductivity of the fresh water is 0.01 S/m. Therefore, we obtained the same result even though the direction of the E-field is changed to the y-direction since the effective permittivity of the structure is not changed and the conductivity of the water is too small to have an influence on the transmission characteristic (see Fig. 4). Based on the optimized



(a)

(b)

Fig. 5 Fabricated 5-layered reconfigurable FSS. **a** Perspective view; **b** front view

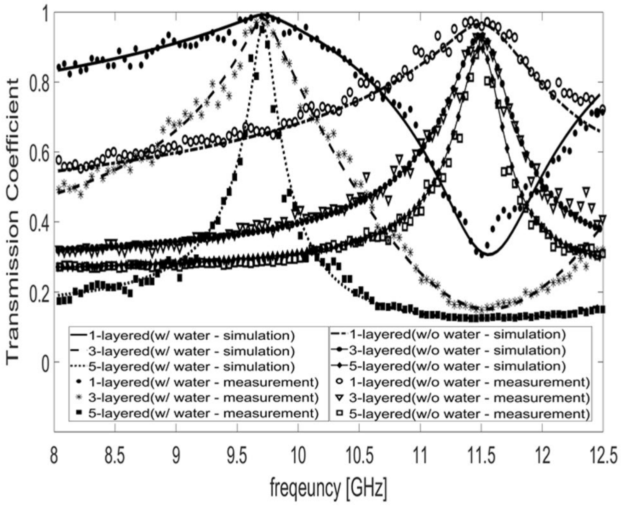


Fig. 7 Transmission coefficient of the multi-layered reconfigurable FSS (comparison of simulation and measurement)

results, we fabricate the 5-layered FSS as shown in Fig. 5. The Styrofoam is carved to obtain the dielectric slabs with designed dimensions, and the square holes having a uniform spacing are extracted from the slabs. The channel made of silicon is then inserted in the square holes, which can be filled or unfilled with water. After the adhesive is applied to the styrofoam slabs, it is laminated with five layers. Finally, the composites are attached on the top and bottom of the laminated layers to achieve mechanical strength, harness, and stability.

Fig. 6 Measurement setup

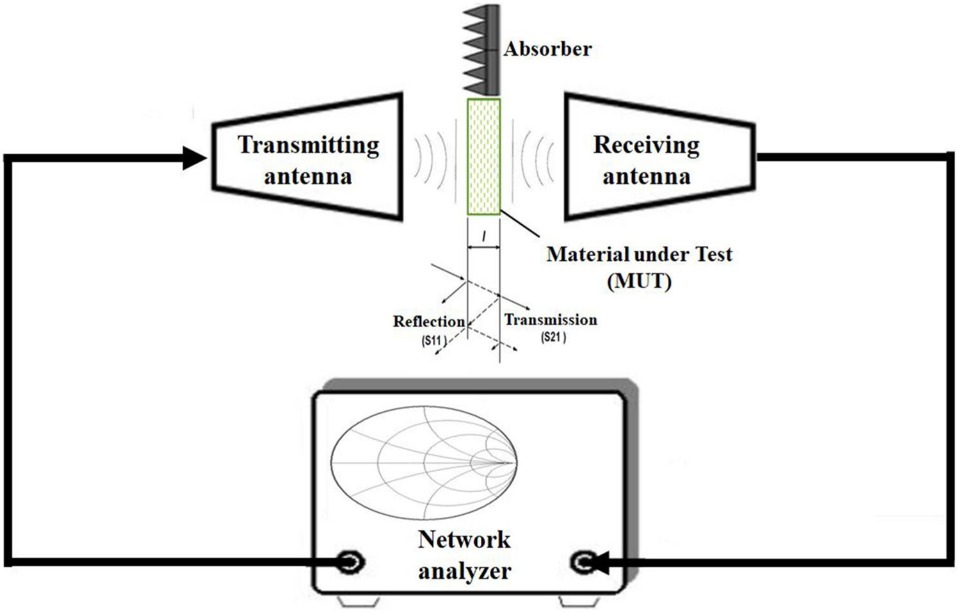


Table 2 Optimized design parameters of the multi-layered reconfigurable FSS

N: Number of layers	Variation in transmission coefficients
1	0.34
2	0.51
3	0.61
4	0.67
5	0.71

3 Measurement

In order to verify the transmission characteristics of the fabricated structure, the free space measurement method is used as illustrated in Fig. 6. The measurement system consists of two horn antennas (ANT-SGH-90, gain: 22 dB, frequency: 8.2–12.4 GHz). One serves as a transmitting antenna and the other as a receiving antenna, and pyramidal absorbers are placed outside the FSS to minimize interference due to the diffraction at the edge of the FSS, a zig, a stand, and a measuring equipment. The phase and amplitude of the transmittance and reflectivity can be measured according to the geometry and material properties of the material under test (MUT) [17]. The distance between the X-band horn aperture and FSS surface is more than 1.8 m. This is because the far-field region for a radiator is defined as the region whose smallest radial distance is about larger than $2D^2/\lambda$ [18] ($D = 0.2$ m, $\lambda = 3$ cm, at 10 GHz). In order to obtain accurate transmission characteristics through calibration, the network analyzer was capable of removing (= gating out) unwanted signals, such as diffractions or reflections, using the time-domain-gating. This requires the frequency response to be transformed from the frequency domain to the time domain. In the time domain, undesired signals can be separated by their different delays, and hence be removed. The response is then transformed back to the frequency domain. This calibration process ensures accurate results.

Figure 7 shows the measured and simulated results of the proposed FSS, and the measurement agree well with the simulations. The variation in transmission coefficients between the water filled and unfilled states significantly increases from 0.34 to 0.71 as number of layers increases from 1 to 5 as listed in Table 2. The rate of variation in transmission coefficients drastically improves as the number of layers increases, but it is saturated at about $N = 5$. Therefore, it is confirmed that the use of the multi-layered FSS with water channels can achieve the improved frequency selectivity.

4 Conclusion

In this study, we have designed, fabricated, and measured the multi-layered reconfigurable FSS using water channels at X-band. It has been demonstrated that the frequency selectivity of the multi-layered structure is drastically improved with increasing number of layers. We then fabricate the optimized design, and the variation in transmission coefficients between the two states increases from 0.34 to 0.71 using the 5-layered dielectric slabs with water channels. The results verify the reconfigurability of the proposed FSS, which can be used in practical applications for reconfigurable FSS radomes.

Acknowledgements This work was supported by the Low Observable Technology Research Center program of Defense Acquisition Program Administration and Agency for Defense Development, and was also supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (No. 2017R1A2B4001903) and the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. 2015R1A6A1A03031833).

References

1. Kim JH, Chun HJ, Hong IP, Kim YJ, Park YB (2014) Analysis of FSS radomes based on physical optics method and ray tracing technique. IEEE Antennas Wirel Propag Lett 13:868–871
2. Kim JH, Song SC, Shin H, Park YB (2018) Radiation from a millimeter-wave rectangular waveguide slot array antenna enclosed by a von karman radome. J Electromagn Eng Sci 18(3):154–159
3. Peroulis D, Sarabandi K, Katehi LPB (2005) Design of reconfigurable slot antennas. IEEE Trans Antennas Propag 53(2):645–654
4. Kiani GI, Esselle KP, Weily AR, Ford KL (2007) Active frequency selective surface using pin diodes. IEEE Antennas Propag Soc Int Symp, Honolulu
5. Kiani GI, Ford KL, Olsson LG, Esselle KP, Panagamuwa CJ (2010) Switchable frequency selective surface for reconfigurable electromagnetic architecture of buildings. IEEE Trans Antennas Propag 58(2):581–584
6. Cho SS, Hong IP (2016) Design of a paper-based reconfigurable frequency selective surface structure. IEICE Electron Express 13(16):20160656
7. Mendoza-Rosales DT, Martynyuk AE, Martinez-Lopez JI, Rodriguez-Cuevas J (2012) Frequency selective surfaces based on ring slots loaded with monolithically integrated capacitors. IET Microw Antennas Propag 6(3):245–250
8. Boukarkar A, Lin XQ, Jiang Y (2015) A dual-band frequency tunable magnetic dipole antenna for WiMAX/WLAN applications. IEEE Antennas Wirel Propag Lett 15:492–495
9. Wang Y, Yoon K-C, Lee J-C (2016) A frequency tunable double band-stop resonator with voltage controller by varactor diodes. J. Electromagn Eng Sci 16(3):159–163
10. Cao X, Tang Z, Wang F, Yang K (2015) A tunable dual-band bandpass filter using asymmetrical varactor-loaded HWRs and defected ground structure. IEICE Electron Express 12(13):20150482
11. Kim DS, Kim DH, Yun SW (2017) Design of an active tunable bandpass filter for spectrum sensing application in the TVWS band. J Electromagn Eng Sci 17(1):34–38

12. Schoenlinner B, Abbaspour-Tamijani A, Kempel LC, Rebeiz GM (2004) Switchable low-loss RF MEMS Ka-band frequency selective surface. IEEE Trans Microw Theory Tech 52(11):2474–2481
13. Zendejas JM, Gianvittorio JP, Rahmat-Samii Y, Judy JW (2006) Magnetic MEMS reconfigurable frequency-selective surfaces. J Microelectromech Syst 15(3):613–623
14. Ho KMJ, Rebeiz GM (2014) A 0.9-1.5 GHz microstrip antenna with full polarization diversity and frequency agility. IEEE Trans Antennas Propag 62(5):2398–2406
15. Son DC, Shin H, Kim YJ, Hong IP, Chun HJ, Park YB (2017) Design and Fabrication of a reconfigurable frequency selective surface using fluidic channels. J Elect Eng Technol 12(6):2342–2347
16. CST Microwave Studio, CST GmbH (2014). Available at: http://www.cst.com
17. Musil J, Žáček F (1986) Microwave measurements of complex permittivity by free space methods and their applications. Elsevier, Amsterdam
18. Balanis CA (2012) Advanced engineering electromagnetics. Wiley, New York, pp 283–284

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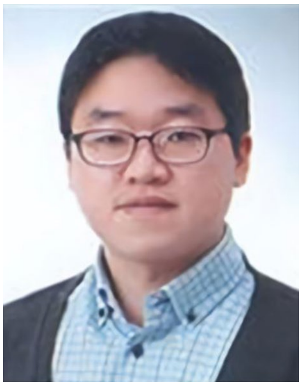

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