Research Article

Scalable Frequency Selective Surface with Stable Angles of Incidence on a Thin Flexible Substrate

In-Gon Lee and Ic-Pyo Hong

Department of Information and Communication Engineering, Kongju National University, 1223-24 Cheonan-daero, Cheonan City 31080, Republic of Korea

Correspondence should be addressed to Ic-Pyo Hong; iphong@kongju.ac.kr

Received 26 June 2016; Accepted 9 August 2016

Academic Editor: Rodolfo Araneo

Copyright © 2016 I.-G. Lee and I.-P. Hong. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

A band-stop scalable frequency selective surface (FSS) structure that provides stability for an angle of incidence and polarization is designed using the repetitive arrangement of a unit structure miniaturized on a thin dielectric substrate. The designed miniaturized FSS has a hexagonal unit cell of a minimum size of 0.081λ at 2.5 GHz in which a triangular loop is repeated. In addition to the frequency stability, the proposed structure reduces the design complexity that is the biggest shortcoming of the miniaturization techniques studied previously. A scalable FSS structure possessing stable frequency response characteristics over a wide band ranging from 2 to 8 GHz, which is achieved by the control of a single design variable, can be designed. For verification of the proposed structure, FSS structures that operate in the bands of 2.5 GHz, 5 GHz, and 8.2 GHz have been designed and fabricated on a very thin substrate. It has been confirmed that the results of the measurement and simulation correspond well with each other. The designed structures also demonstrate high stability for both the polarized wave and the incidence angle of the incident wave.

1. Introduction

Frequency selective surface (FSS) is a periodic structure, where a single structure is arranged infinitely with the same interval and has the characteristic of passing or reflecting specific frequency bands of incident electromagnetic waves based on the geometry of the unit structure, arrangement period, placement, and so forth [1]. FSSs possessing this electrical characteristic of passing or reflecting specific frequency bands are used in diverse applications such as microwave absorbers [2], antenna gain enhancement [3], interference-signal control technology [4], RFI shielding [5] or EMI shielding technology [6], and defense-related stealth technology [7]. To apply the FSS structure in an actual environment as a spatial filter, the propagation characteristics of the radio wave that is propagated via diverse mechanisms such as reflection, refraction, scattering, and diffusion should be taken into consideration. Such an environment requires the FSS structure to have adequate attenuation performance, frequency bandwidth, band isolation, and incidence angle stability. Several shapes for the unit structures have been

proposed recently for stable frequency response characteristics. The traditional FSS structure is organized in a single plane, where a conductive pattern is arranged on a dielectric; the typical shapes of patterns include N-pole types such as crossed-dipole and Jerusalem-crossed type and loop types such as square-loop, four-legged loaded-element loop, and circular ring [8]. While the performance of an FSS structure is highly sensitive to the number of arranged unit structures [9], an infinite arrangement of the unit structures is assumed when designing an FSS structure in most cases; the unit structures should be finitely arranged in a limited space for application in an actual environment. The traditional FSS structure has several limitations—it is difficult to achieve stable performance because of the issues related to the size of the unit structure, which is determined by the wavelength. It is also difficult to apply this structure to certain forms such as curved surfaces because of the low frequency response stability of both the polarized wave and the incidence angle of the incident wave [9–11]. Therefore, to improve these limitations of the existing structure, studies are being conducted using a miniaturized FSS structure to obtain stable frequency

response characteristics by reducing the pattern size of the unit structure. The typical miniaturization techniques for FSS unit structures can be classified into the methods that use a lumped element and those that use a complicated organized pattern that facilitates efficient area utilization. In the miniaturization technique using a lumped element, a unit structure of a considerably small size can be designed. This can be achieved by directly influencing the equivalent impedance of the unit structure, using a lumped element such as an inductor or capacitor, to reduce its electrical length. However, an increase in the production cost is inevitable as a large number of elements are required. This technique also has the disadvantage that it is difficult to be applied to high-frequency bands as the stabilities of both the polarized wave and the incidence angle of the incident wave are lower compared to those of other miniaturization techniques. Moreover, the loss is high due to the resistance component of the lumped element [12–14]. The miniaturization technique using a complicated organized pattern usually has an expanded and applied geometric structure of a meander and fractal element. This method utilizes the space of the unit cell to the maximum, by increasing the density of the conductive pattern in a limited area. The required stability for both the polarized wave and the incidence angle of the incident wave can be achieved, and the structure can be designed with a relatively small unit cell size using the equivalent reactance component in a wide range. However, a large number of design variables should be taken into account because of the complicated pattern. This leads to high complexity in design and redesigning for different frequencies will be difficult [4, 15, 16]. To solve this problem, a miniaturization technique using stacking based on a relatively simple structure has been proposed; however, it leads to problems in the narrowband characteristics in low-frequency bands and in the frequency characteristics sensitive to the permittivity or thickness of the dielectric [17, 18]. In this paper, to solve such issues, we have designed a miniaturized FSS structure with band-stop characteristics and a stable frequency response using a hexagonal pattern organized by repeating a loop-type structure. The proposed structure arranged on the surface of a thin dielectric has overcome the disadvantage of high design complexity in the existing miniaturization techniques. Moreover, we have proposed a method for designing a scalable FSS structure that operates in a desired band through the adjustment of a simple design variable; stable frequency response characteristics are guaranteed for this structure. We designed and fabricated FSS structures that operate in the different bands of 2.5 GHz, 5 GHz, and 8.5 GHz and performed measurements to verify the operation of the proposed structure.

2. Design of Miniaturized FSS Structure

The unit structure of the proposed FSS is a hexagonal fractal structure in which triangular loops are repeated. Triangles at the innermost side (L_{in}) and the triangles at the enclosing side (L_{out}) are arranged in circular patterns at intervals of 60° . The sides L_{in} and L_{out} are in the relation shown in (1), and the length of the entire unit structure shape is determined based on L_{out} . The inner diameter (R_1) and the outer diameter

FIGURE 1: Unit cell structure of the proposed FSS.

(R_2) of the hexagonal-form circular arrangement are in the relations given by (2) and (3), and L_{in} and R_1 are variables dependent on L_{out} , where G is $G = G_{triangle} = G_{neck} = G_{element}$ in Figure 1:

$$L_{in} = L_{out} - 2\sqrt{3}(W + G), \quad (1)$$

$$R_1 = \frac{3G}{2} + \left(\frac{\sqrt{3}}{2}\right)L_{out}, \quad (2)$$

$$R_2 = G - W + 0.5(6W + \sqrt{3}G). \quad (3)$$

The stability of the two different polarized waves, TE and TM, which intersect each other perpendicularly, can be secured through the symmetric arrangement of the hexagonal forms. The stable performance of the incidence angle of the incident wave has been secured by the miniaturized unit structure using repeated fractal shapes. For the proposed structure, the frequency response depending on the change in the design variable L_{out} has been verified using the EM simulation of Ansoft HFSS. The simulation assumes the variable L_{out} , which determines the size of the entire shape of the unit structure, as the main design parameter that determines the electrical length of the structure, that is to say, the resonance frequency. The main design variables and the appearance of the unit structure are shown in Figure 1. The transmission characteristics at the polarized waves of incident wave, TE and TM, and at the incidence angles of 0° , 30° , and 60° are observed. The following assumptions were made for the observation: the line width of the conductive pattern $W = 0.15$ mm, the distance between the lines and between the unit structures $G = 0.25$ mm, the permittivity of the dielectric $\epsilon_r = 4.4$, and $\tan \delta = 0.02$. To confirm the stable frequency response performance of the designed miniaturized FSS, an analysis of the structure has been carried out. The characteristics of the polarized wave and the incidence angle of the incident wave, depending on the change in the bandwidth and the changes in each design variable, are shown in Figure 2. From the analysis results, it can be confirmed that the resonance frequency varies in the range of 1.9 to 8.3 GHz for TE (0°) as the variable L_{out} varies in the range of 2.25 to 6.75 mm.

In Figure 2, we also presented the resonant frequency difference between TE mode and TM mode, $f_{r,TE} - f_{r,TM}$, for

FIGURE 2: Resonant frequency, FBW, and frequency offset for L_{out} variation.

incidence angles of 0° , 30° , and 60° . It can be observed that the proposed FSS has stable frequency response characteristics against changes in the polarized wave and incidence angle. From the analysis result, a trend can be confirmed in which the resonance frequency moves to a high-frequency band and the bandwidth increases as the design variable L_{out} becomes smaller.

3. Fabrication and Measurement

As a result of the frequency response stability analysis performed, it has been confirmed that the proposed structure has stable frequency response characteristics over the entire band. Hence, it is possible to design a miniaturized FSS that has stable frequency characteristics in the desired frequency band (1.89 to 8.27 GHz). Based on this, structures have been designed using FR4 ($\epsilon_r = 4.4$, and $\tan \delta = 0.02$) substrates with the goal of operating them in the three bands, 2.5 GHz (Model 1, $L_{out} = 5.2$ mm and $t = 0.4$ mm), 5 GHz (Model 2, $L_{out} = 3.1$ mm and $t = 0.2$ mm), and 8.2 GHz (Model 3, $L_{out} = 2.25$ mm and $t = 0.2$ mm), to carry out the measurement tests for verification. The transmission-loss characteristics, for polarized waves of the incident wave, TE and TM, and the incidence angles of 0° , 30° , and 60° , were analyzed based on the designed structures, and the results are shown in Figures 3(a), 3(b), and 3(c). Figure 3(a) shows the calculated transmission-loss characteristics for the incidence angle of 0° for the TE mode and TM mode. The frequency response characteristics have been confirmed as follows: the resonance frequency is 2.52 GHz and the -10 dB bandwidth (FBW) is 0.79 GHz (31.3%) in the case of Model 1 structure, the resonance frequency is 4.99 GHz and the bandwidth is 1.51 GHz (30.2%) in the case of Model 2 structure, and the resonance frequency is 8.25 GHz and the bandwidth is 2.76 GHz (33.5%) in the case of Model 3 structure for an

incidence angle of 0° . It has been confirmed from the analysis results that the structures have stable characteristics for both the polarized wave and the incidence angle of the incident wave. This confirmation is based on the fact that the offset of the resonance frequency, which varies depending on the polarized wave and the incidence angle of the incident wave, has shown maximum values of 0.025 GHz (0.9%), 0.018 GHz (0.36%), and 0.024 GHz (0.29%), respectively.

Based on the simulation results, an FSS structure with an actual size of 700 mm $\times$ 700 mm was fabricated. To measure the transmission-loss characteristics of the fabricated miniaturized FSS structure, a test was conducted using the free-space measurement method as shown in Figure 4—a method of measuring the transmission characteristics of FSS using the ratio of the transmitted/received electric power from two independent wideband horn antennas. On the contrary to the simulation results as shown in Figure 3, the measurements were performed only at the incidence angles of 0° and 30° . That is because it is very difficult to get the confident and stable measurement results due to the multipath signals because of the height of the electromagnetic absorber which are used in measurement setup as shown in Figure 4.

The appearances of the miniaturized FSS structures produced for the three bands are shown in Figure 5, and the measured transmission-loss characteristics depending on the change in the polarized wave and the incidence angle are shown in Figures 6(a) and 6(b). It has been confirmed from the measurement results that the resonance frequency is 2.5 GHz and the bandwidth is 0.74 GHz (29.6%) in the case of Model 1 structure, the resonance frequency is 5.29 GHz and the bandwidth is 1.57 GHz (29.7%) in the case of Model 2 structure, and the resonance frequency is 8.63 GHz and the bandwidth is 2.84 GHz (32.9%) in the case of Model 3 structure for the TE mode with an incidence angle of 0° . It has been confirmed that the results correspond well with the

FIGURE 3: Simulated transmission characteristics of the proposed FSSs: (a) normal incidence, 0° , (b) 30° angle of incidence, and (c) 60° angle of incidence.

FIGURE 4: Free space measurement setup for the proposed FSSs.

FIGURE 5: Fabrication of the proposed FSSs.

FIGURE 6: Measured transmission characteristics of the proposed FSSs: (a) normal incidence, 0° ; (b) 30° angle of incidence.

calculated results and that the structure has stable frequency response characteristics.

4. Conclusion

In this paper, we designed a band-stop operation FSS structure on a thin dielectric that has stable frequency characteristics for both polarized waves (TE and TM) and incidence angles (0° and 30°) of the incident wave. The structure was designed based on the repetitive arrangement of a miniaturized hexagonal pattern on a very thin planar substrate. The structure proposed in this paper has the advantages that the design complexity, which is the biggest shortcoming of the existing miniaturized FSS structures, is reduced and the structure can be easily designed in the desired band (1.9 to 8.3 GHz) by adjusting L_{out} (the main design variable that determines the resonance frequency). To verify the proposed structure, FSS structures that operate in three different bands, 2.5 GHz, 5 GHz, and 8.2 GHz, were designed, manufactured, and measured. This shows that the results of calculation and measurement correspond well with each other and that the structure has stable frequency response characteristics. The proposed structure has the advantages that it has stable

frequency response characteristics for the incident waves and that it can be easily designed in the desired band. Hence, it can be applied in diverse fields that require stability of incidence angle and polarized wave, such as the control of interference from indoor adjacent signals or frequency reuse for improvements in the communication environment inside buildings.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF-2015RIA2A2A01003380) and the Functional Districts of the Science Belt Support Program (2015K000281), Ministry of Science, ICT and Future Planning.

References

- [1] B. A. Munk, *Frequency Selective Surface: Theory and Design*, John Wiley & Sons, New York, NY, USA, 2005.

- [2] L. K. Sun, H. F. Cheng, Y. J. Zhou, and J. Wang, "Broadband metamaterial absorber based on coupling resistive frequency selective surface," *Optics Express*, vol. 20, no. 4, pp. 4675–4680, 2012.
- [3] H. Vettikalladi, B. Aqlan, and M. A. S. Alkanhal, "Frequency selective surface superstate antenna for 79-GHz automotive applications," in *Proceedings of the Radio and Antenna Days of the Indian Ocean (RADIO '15)*, pp. 1–2, Belle Mare, Mauritius, September 2015.
- [4] M. Yan, S. Qu, J. Wang et al., "A miniaturized dual-band FSS with stable resonance frequencies of 2.4 GHz/5 GHz for WLAN applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 895–898, 2014.
- [5] P. Wu, F. Bai, Q. Xue, X. Liu, and S. Y. R. Hui, "Use of frequency-selective surface for suppressing radio-frequency interference from wireless charging pads," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 8, pp. 3969–3977, 2014.
- [6] F.-C. Huang, C.-N. Chiu, T.-L. Wu, and Y.-P. Chiou, "A circular-ring miniaturized-element metasurface with many good features for frequency selective shielding applications," *IEEE Transactions on Electromagnetic Compatibility*, vol. 57, no. 3, pp. 365–374, 2015.
- [7] F. Costa and A. Monorchio, "A frequency selective radome with wideband absorbing properties," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 6, pp. 2740–2747, 2012.
- [8] T. K. Wu, *Frequency Selective Surface and Grid Array*, John Wiley & Sons, 1995.
- [9] Z. Sipus, M. Bosiljevac, and S. Skokic, "Analysis of curved frequency selective surfaces," in *Proceedings of the 2nd European Conference on Antennas and Propagation (EuCAP '07)*, pp. 1–5, IEEE, Edinburgh, Scotland, November 2007.
- [10] S. B. Savia and E. A. Parker, "Current distribution across curved ring element FSS," in *Proceedings of the IEE National Conference on Antennas and Propagation*, pp. 332–335, York, UK, April 1999.
- [11] A. Dalkilic, L. Alatan, and C. B. Top, "Analysis of conformal frequency selective surface radome," in *Proceedings of the 8th European Conference on Antennas and Propagation (EuCAP '14)*, pp. 469–472, The Hague, Netherlands, April 2014.
- [12] F. Bayatpur and K. Sarabandi, "Single-layer high-order miniaturized-element frequency-selective surfaces," *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 4, pp. 774–781, 2008.
- [13] H. L. Liu, K. L. Ford, and R. J. Langley, "Design methodology for a miniaturized frequency selective surface using lumped reactive components," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 9, pp. 2732–2738, 2009.
- [14] R.-R. Xu, Z.-Y. Zong, and W. Wu, "Low-frequency miniaturized dual-band frequency selective surfaces with close band spacing," *Microwave and Optical Technology Letters*, vol. 51, no. 5, pp. 1238–1240, 2009.
- [15] B. Sanz-Izquierdo, E. A. Ted Parker, J.-B. Robertson, and J. C. Batchelor, "Singly and dual polarized convoluted frequency selective structures," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 3, pp. 690–696, 2010.
- [16] D. Feng and X. Wu, "A novel miniaturized frequency selective surface," in *Proceedings of the 10th International Symposium on Antennas, Propagation and EM Theory (ISAPE '12)*, pp. 377–380, IEEE, Xi'an, China, October 2012.
- [17] F. Deng, X. Yi, and W. Wu, "Design and performance of a double-layer miniaturized-element frequency selective surface," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 721–724, 2013.
- [18] S. N. Azemi, K. Ghorbani, and W. S. T. Rowe, "Angularly stable frequency selective surface with miniaturized unit cell," *IEEE Microwave and Wireless Components Letters*, vol. 25, no. 7, pp. 454–456, 2015.