A Novel Dual-Band Ultrathin FSS With Closely Settled Frequency Response

Sibel Ünaldı, Sibel Çimen, *Member, IEEE*, Gonca Çakır, *Member, IEEE*, and Umut E. Ayten

***Abstract*—This study presents a novel ultrathin dual-band frequency selective surface (FSS) for X-band applications. The proposed single-layer FSS operates as a band reject filter at 8.47 and 10.45 GHz. The ratio of these two operating bands has small value such as 1.23, and it points out that the proposed FSS has closely spaced characteristic. In addition, the designed dual-band single-layer FSS has an ultrathin thickness of 0.021$*\lambda_l$, where λ_l is the wavelength of the lower operational frequency. The stable frequency responses are sufficiently achieved for the transverse electric and transverse magnetic polarizations by using the proposed FSS. The validity of FSS is obtained by comparing measurements and simulations.**

***Index Terms*—Dual-band filters, frequency selective surfaces (FSSs).**

I. Introduction

FREQUENCY selective surfaces (FSSs) that work as a filter are periodic arrays including different types of resonance elements (metallic patterns printed on dielectric substrate) [1], [2]. Researchers have been intensely attracted by the topic of FSS since the 1960s with its widespread application in microwave and millimeter-wave such as radar cross-section controlling, radomes, absorbers, polarizers, subreflectors, and reduced interference in indoor wireless environments [1], [3], [4].

As the improvement of electronic and wireless communication devices, the multifrequency system designs are becoming very important. For the applications, the FSSs with multiple bands are used where multiple independent transmission bands are especially required [5]. Different techniques and approaches to design multiband FSSs are in the literature. In [2], dual-band FSS that has large band separation response and stable performance is investigated. Dual wideband FSSs for different incident angles are studied in [6]. Multiple resonant elements [7], single-layered FSS that consists of various elements [8], [9], and fractal structures [10] are some designs that are reported in the literature. Among them, the fractal structures are also applied as FSSs [11], [12].

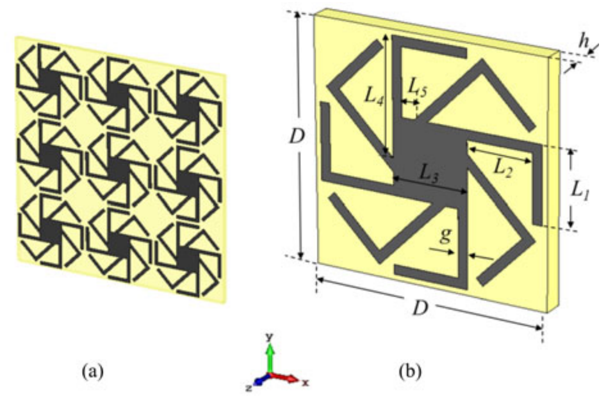

Fig. 1. Geometry of the (a) presented FSS and (b) its unit cell.

One of the considerable features in FSS design is the frequency response sensitivity to the various incident angles. In view of most of the proposed FSSs, the low unit cell size or controlling the interelement spacing makes the structure more sensitive to the different incident angles of the electromagnetic wave in the transmission and reflection characteristics. The miniaturized dual-band FSSs that have stable frequency characteristics are studied in [13] and [14].

In the multiband FSS designs, the closely spaced band separation is an important specification. In [15] and [16], they proposed dual-band closely spaced FSS structures. In this letter, a new closely spaced, angular-independent FSS is proposed. We achieved the ratio of dual resonating bands by only 1.23. Also, the structure of presented FSS has an ultrathin overall thickness of $0.021\lambda_l$. Thus, the proposed FSS has an ultrathin profile, and it can be readily fabricated. For the validity of proposed FSS, a prototype was fabricated, measured, and discussed with simulation results.

II. Geometry of the Unit Cell

The geometry and the dimensions of the designed FSS are illustrated in Fig. 1, where the conductive surface is represented by the gray region while the other region indicates dielectric substrate. The FSS structure is designed on a substrate Arlon Di 880 with a thickness $h = 0.762$ mm, a relative permittivity $\varepsilon_r = 2.2$, and a loss tangent $\tan\delta = 0.0009$. Additionally, in terms of

Manuscript received June 15, 2016; revised September 2, 2016 and November 7, 2016; accepted December 2, 2016. Date of publication December 12, 2016; date of current version May 22, 2017.

S. Ünaldı is with the Department of Electrical and Electronics Engineering, Bilecik Şeyh Edebali University, Bilecik 11210, Turkey, and also with the Department of Electrical and Electronics Engineering, Sakarya University, Sakarya 54187, Turkey (e-mail: sibel.unaldi@bilecik.edu.tr).

S. Çimen and G. Çakır are with the Department of Electronics and Communication Engineering, Kocaeli University, Kocaeli 41000, Turkey (e-mail: sibelgunduz@kocaeli.edu.tr; gonca@kocaeli.edu.tr).

U. E. Ayten is with the Department of Electronics and Communication Engineering, Yıldız Technical University, İstanbul 34220, Turkey (e-mail: ayten@yildiz.edu.tr).

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Digital Object Identifier 10.1109/LAWP.2016.2637080

TABLE I
DIMENSION OF THE PROPOSED STRUCTURE

D	L_1	L_2	L_3	L_4	L_5	g
8.8 mm	2.8 mm	2.45 mm	2.8 mm	4.28 mm	0.47 mm	0.35 mm

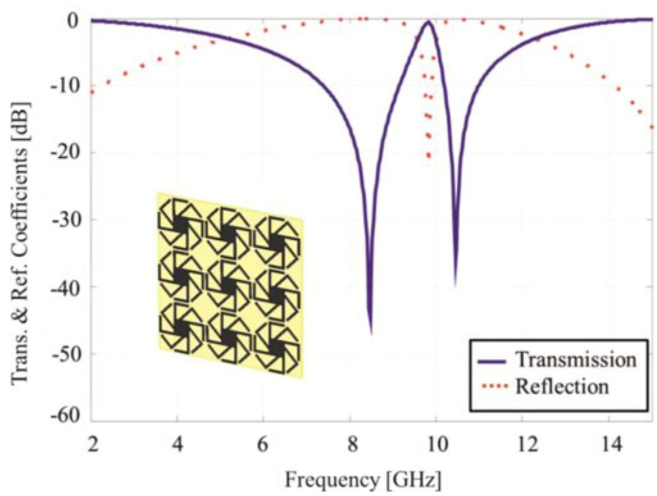

Fig. 2. Transmission coefficient (S_{21}) and reflection coefficient (S_{11}) simulation results at normal incidence angle.

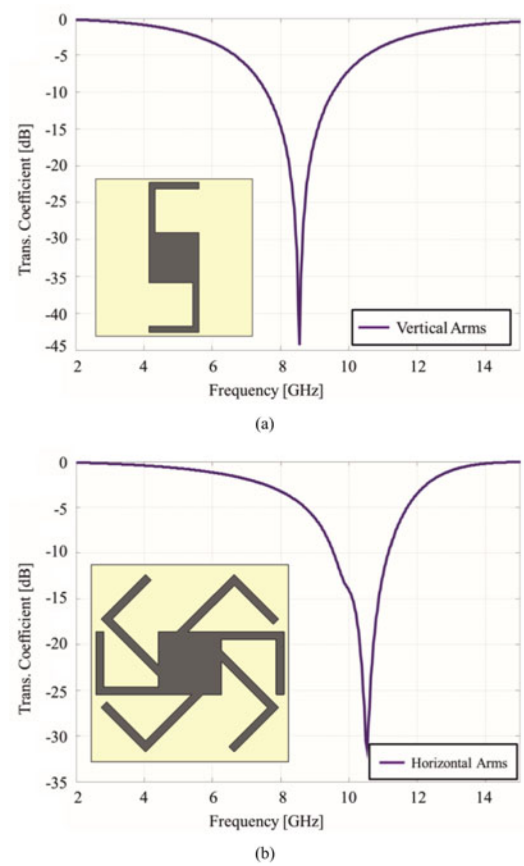

Fig. 3. Simulation results of transmission coefficient (S_{21}) for (a) vertical and (b) horizontal arms.

x- and y-directions, the unit cell lengths are 8.80×8.80 mm^2. The dimensions of the designed unit cell are shown in Fig. 1(b). Also, design parameters are given in Table I.

III. DESIGNS AND SIMULATION RESULTS

Numerical analysis of proposed FSS is performed by using CST Microwave Studio. Although the FSSs have finite dimensions in practical realizations, their simulations are done by the assumption that they were infinite. Therefore, the boundary conditions of the unit cell are used to provide periodicity along x- and y-directions in FSS simulation. The plane wave is used as an excitation with different incident angles. In Table I, the optimized parameters are given.

In Fig. 2, the simulation results of frequency response belonging to the designed FSS are illustrated. According to the observed frequency response, the designed structure is operating as a band-stop filter in two frequencies. The lower operating frequency is at $f_l = 8.47$ GHz, and the higher operating frequency is at $f_h = 10.45$ GHz. The fractional bandwidths of FSS for the lower and higher resonant frequencies are 47.6% and 20.52%, respectively.

The proposed FSS is composed from the centered square patch and L-shaped arms. The arms are connected to the central square with 45° as demonstrated in Fig. 1. The dual-band characteristic is obtained from the L-shaped arms. As seen from Fig. 3, the vertical arms are controlling the first resonance frequency while the horizontal arms are controlling the second resonance frequency. Thereby, the designed FSS structure has the advantage of freedom for controlling the resonant frequencies individually.

The results in Fig. 3 can be explained by the induced current distributions depicted in Fig. 4. The current distributions are performed at lower and upper frequencies for transverse electric (TE) polarization. As seen from Fig. 4(a), at the first resonant frequency, the current path is along the vertical arm while the current is flowing along the horizontal arm at the second resonant frequency.

The designed FSS provides stable frequency response at various oblique incident angles in view of the rotational arms at its geometry (in Fig. 1). The conductors shaped as arms are connected to a central square conductor with 45° as shown in Fig. 1. To present the resonant stability of designed FSS, the transmission coefficients both for the TE and the transverse magnetic (TM) polarizations are simulated. For this purpose, FSS is considered to be obliquely excited by plane wave with different incidence angles. The simulation results of the transmission characteristics under the oblique incidence angles for TE and TM polarizations are shown in Figs. 5 and 6, respectively. Therefore, the stable resonance responses for various incident angles θ ($\theta = 0°$, 30°, and 60°) that are between the normal plane and incident wave are observed clearly by the help of Figs. 5 and 6.

IV. MEASUREMENT RESULTS

To verify the simulation results, the proposed FSS structure is fabricated and tested. For the periodic structures like FSSs, the waveguide transmission lines can be used for the measure-

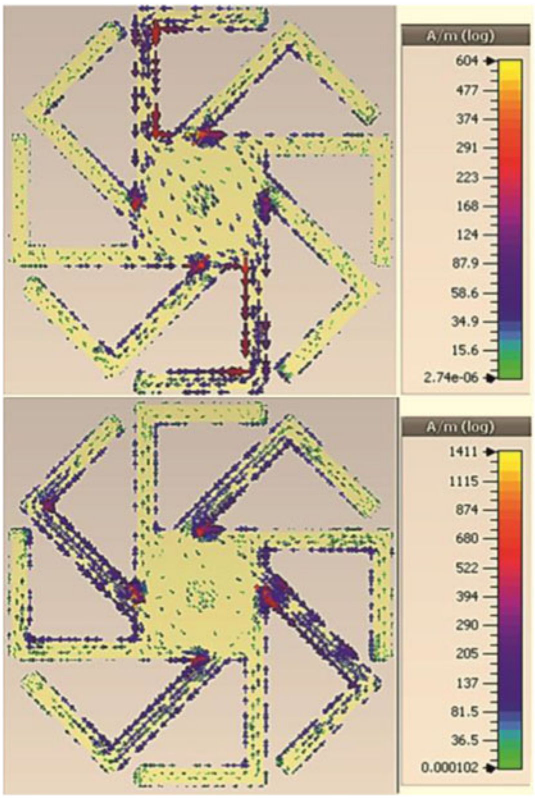

Fig. 4. Current distributions on the proposed FSS for TE polarization: (a) $f = 8.47$ GHz, (b) $f = 10.45$ GHz.

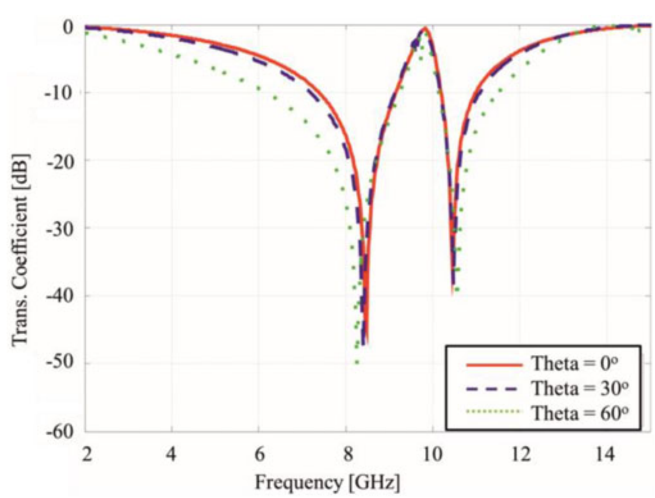

Fig. 5. Simulation results of transmission coefficient (S_{21}) for TE polarization at different incidence angles.

ment [17]. A waveguide measurement setup is employed for investigating the experimental transmission property of FSS structure. The fabricated prototype is fitted properly within the waveguide flanges to obtain the actual periodic FSS structure in the experiment. As seen from Fig. 7, the Rohde & Schwarz ZVB20 vector network analyzer and Flann 16441 waveguide are used in a measurement system. The measured and simulated transmission coefficients for TE polarization are shown in

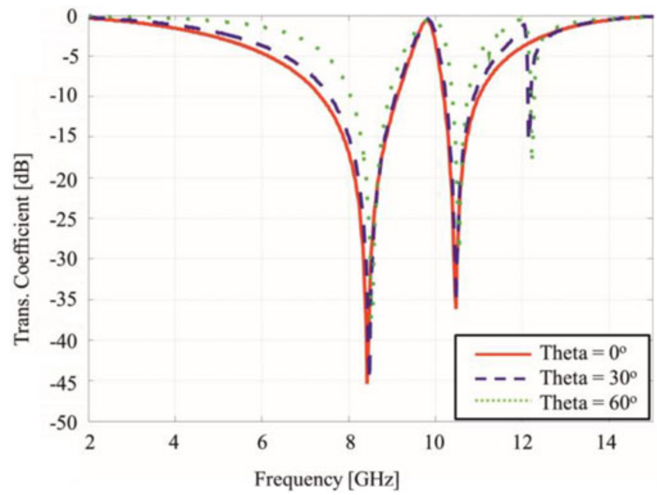

Fig. 6. Simulation results of transmission coefficient (S_{21}) for TM polarization at different incidence angles.

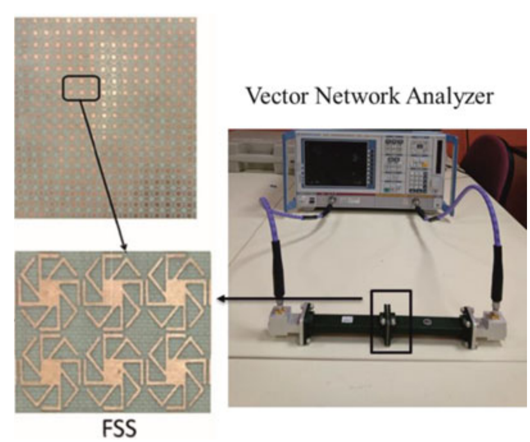

Fig. 7. Measurement setup and fabricated FSS.

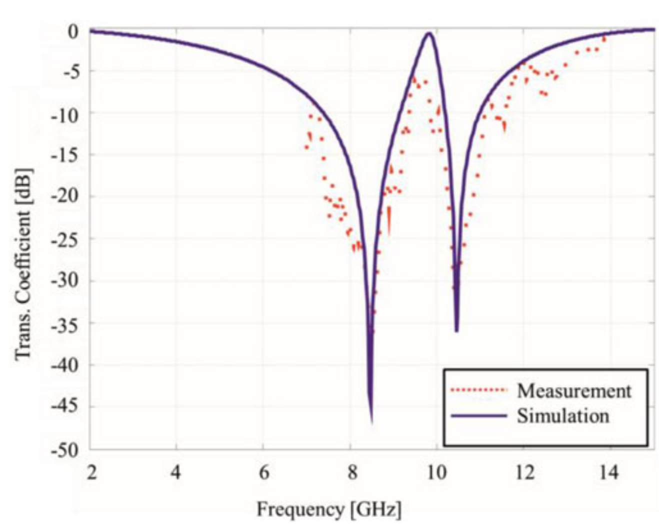

Fig. 8. Measurement and simulation results of transmission coefficients.

Fig. 8. As observed, the measured and simulated results show good agreement and confirm the proposed FSS.

V. Conclusion

In this study, a novel closely spaced band-stop FSS is introduced. The proposed FSS is resonating at 8.47 and 10.45 GHz. The advantages of the proposed FSS are simple geometry and low ratio of two closely spaced resonance frequencies with 1.23 s. In addition to these advantages, the designed structure has dual-band reject filter characteristic, which provides a stable transmission performance at oblique incidence angle. The proposed design is validated through simulated results and measured results of the fabricated prototype. The measurement and simulation results are in good agreement. Considering these properties as providing two closely spaced resonance frequencies, the designed FSS can be used in dual-frequency applications at X-band.

References

[1] S. Çimen, "A novel closely-spaced planar dual-band frequency selective surface," *Microw., Antennas Propag.*, vol. 7, no. 11, pp. 894–899, Aug. 2013.

[2] Z. Hang *et al.*, "Dual-band frequency selective surface with large band separation and stable performance," *Chin. Phys. B*, vol. 21, no. 5, 2012, Art. no. 054101.

[3] S. N. Azemi, K. Ghorbani, and W. S. T. Rowe, "Angularly stable frequency selective surface with miniaturized unit cell," *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 7, pp. 454–456, Jul. 2015.

[4] F. C. Huang, C. N. Chiu, T. L. Wu, and Y. P. Chiou, "Very closely located dual-band frequency selective surfaces via identical resonant elements," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 414–417, 2015.

[5] G. H. Schennum, "Frequency-selective surfaces for multiple frequency antennas," *Microw. J.*, vol. 16, pp. 55–57, May 1973.

[6] P. Samaddar, S. De, S. Sarkar, S. Biswas, D. C. Sarkar, and P. P. Sarkar, "Study on dual wide band frequency selective surface for different incident angles," *Int. J. Soft Comput. Eng.*, vol. 2, no. 6, pp. 340–342, Jan. 2013.

[7] E. A. Parker and J. C. Vardaxoglou, "Plane-wave illumination of concentric ring frequency-selective surfaces," *Proc. IEE, Microw., Antennas Propag.*, vol. 132, no. 3, pp. 176–180, Jun. 1985.

[8] L. Mingyun, H. Minjie, and W. Zhe, "Design of multi-band frequency selective surfaces using multi-periodicity combined elements," *J. Syst. Eng. Electron.*, vol. 20, no. 4, pp. 675–680, Aug. 2009.

[9] A. D. Chuprin, E. A. Parker, and J. C. Batchelor, "Convoluted double square: Single layer FSS with close band spacings," *Electron. Lett.*, vol. 36, no. 22, pp. 1830–1831, Oct. 2000.

[10] S.-S. Wang, J.-S. Gao, X.-G. Feng, and J.-L. Zhao, "Design methods of Y apertures fractal FSS," *Opt. Precis. Eng.*, vol. 19, no. 5, pp. 959–966, May 2011.

[11] J. Romeu and Y. Rahmat-Samii, "Fractal FSS: A novel dual-band frequency selective surface," *IEEE Trans. Antennas Propag.*, vol. 48, no. 7, pp. 1097–1105, Jul. 2000.

[12] D. H. Werner and D. Lee, "Design of dual-polarised multiband frequency selective surfaces using fractal elements," *Electron. Lett.*, vol. 36, no. 6, pp. 487–488, Mar. 2000.

[13] A. Ebrahimi, W. Withayachumnankul, S. Al-Sarawi, and D. Abbott, "Design of dual-band frequency selective surface with miniaturized elements," in *Proc. IEEE Int. Workshop Antenna Technol.*, 2014, pp. 206–209.

[14] Y. Mingbao *et al.*, "A miniaturized dual-band FSS with stable resonance frequencies of 2.4 GHz/5 GHz for WLAN applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 895–898, 2014.

[15] R. Sivasamy and M. Kanagasabai, "A novel dual-band angular independent FSS with closely spaced frequency response," *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 5, pp. 298–300, May 2015.

[16] C.-N. Chiu and W.-Y. Wang, "A dual-frequency miniaturized element FSS with closely located resonance," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 163–165, 2013.

[17] F. Bayatpur and K. Sarabandi, "Tuning performance of metamaterial-based frequency selective surfaces," *IEEE Trans. Antennas Propag.*, vol. 57, no. 2, pp. 590–592, Feb. 2009.