Article

A New Miniaturized Active Frequency Selective Surface with Convoluted Element for UHF Applications

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***Abstract*— This paper presents a study on Active Frenquency Selective Surface (AFSS) for applications in modern wireless communication systems. Initially, an FSS with an element inspired by convoluted metallic lines printed on a dielectric substrate of FR-4 is proposed. The unit cell size is equal to 10.2 % of the wavelength in free space for the frequency of 1.53 GHz. An equivalent circuit model is proposed to better understand the operating principle of the FSS. Four Schottky diodes have been inserted in a symmetrical manner for switching, and three operating states are analyzed (all diodes in off state, all diodes directly polarized and therefore conducting, and two diodes conducting and two diodes off). The reconfiguration allows the frequency response to vary between frequencies from 0.8 GHz to 2.5 GHz. The FSS proved to be stable with respect to the angle of incidence of the plane wave on the circuit surface. The simulated numerical results for the designed prototype was obtained by ANSYS HFSS software. The prototype was built and the experimental characterization of the transmission coefficients, bandwidth and resonance frequency was performed. The values obtained in the experiment were compared and discussed with the simulation results, which showed good agreement.**

***Index Terms*—** Active Frequency Selective Surface, AFSS, equivalent circuit model, Schottky diodes.

I. INTRODUCTION

With the growth in the number of users and the diversification of services, telecommunication systems, especially those for mobile communications, are increasingly dependent on the intensive exploitation of frequency spectrum. The rise of artificial intelligence (AI), cloud computing, the Internet of Things (IoT), big data analytics, cybersecurity, resilience, robotic process automation and the advent of fifth generation (5G) mobile networks are just a few examples of current needs. These demands impose the imperative need for careful management of the radio spectrum, leading to limitations on both the frequency bands available for use and the power levels to be employed [1]-[5]. In response to these constraints, innovative solutions such as reconfigurable antenna systems [6], [7] and buildings equipped with electromagnetic intelligence [8], [9] have emerged to optimize spectrum allocation and minimize potential interference.

When it comes to the application of reconfigurable antennas and also buildings with electromagnetically intelligent characteristics, one of the strategies employed involves the use of frequency selective surfaces (FSS), in its reconfigurable variant, that is, frequency selective surfaces with adaptive capacity (Active Frenquency Selective Surface - AFSS) [6]-[9]. Frequency selective surfaces are spatial filters of electromagnetic waves and, traditionally, are composed of periodic arrangements of elements that can be of the type conductive patches or openings, printed on dielectric substrates [10]-[12]. These structures aim to filter out unwanted frequency components, from the frequencies of interest, in the signals passing through it.

Gomes Neto et al. [13] proposed a reconfigurable frequency selective surface (FSS) using cross dipoles and matryoshka geometries, incorporating active PIN diodes. This arrangement achieves three resonant frequencies: two fixed ones tied to the matryoshka geometry and a switchable frequency linked to the cross dipoles geometry. An inductor is integrated into cross dipoles' horizontal arms for sustained x polarization resonance. A PIN diode in the vertical arms regulates this resonance. Reconfiguration bandwidth spans 0.24 GHz (2.12 GHz to 2.36 GHz), with a minimum 10 dB variation between OFF and ON states.

Liang et al. [14] introduces a flexible, multifunctional active frequency selective surface (AFSS) with miniaturized units. The structure employs PIN diodes for control, allowing flexible manipulation of electromagnetic-wave transmission, reflection functions, and polarization selection within 8–12 GHz. The AFSS comprises two layers of frequency selective surface (FSS) with PIN diodes on top and bottom, separated by a thin, flexible dielectric layer, and connected by vias.

The main objective of this work is to propose a new AFSS structure to operate in the UHV frequency band that can be used for applications that operate in the 0.8 GHz to 2.5 GHz band, such as applications in the GSM-900 bands, GSM-1800, GSM-1900 or ISM bands centered on 900 MHz and 2.4 GHz. The numerical characterizations for the FSS, were obtained with electromagnetic simulation using the commercial software ANSYS HFSS. Structures were analyzed with geometries based on convoluted dipoles. The FSS elements are conductive patch type. The final proposed prototype was built and measured, and its results showed good agreement with the simulated ones.

II. FSS DESIGN

The FSS element analyzed is inspired convoluted geometry printed on a dielectric substrate of FR-4 with relative electrical permittivity equal to 4.4 and loss tangent of 0.02. Fig. 1 (a) and Fig. 1 (b) indicates the geometry used and its associated physical dimensions, a_x and a_y are equal to 20,0 mm, L_x and L_y are 17.15 mm and w and g are 0.5 mm. From 1 to 19 the values are: 2.25 mm,1.5 mm, 1.5 mm, 3.5 mm, 1.5 mm, 5.5 mm, 1.5 mm, 9.5 mm, 3.5 mm, 4.5 mm, 1.5 mm, 2.0 mm, 2.5 mm, 2.5 mm, 3.5 mm, 9.5 mm, 1.5 mm, 7.3 mm e 2.5 mm.

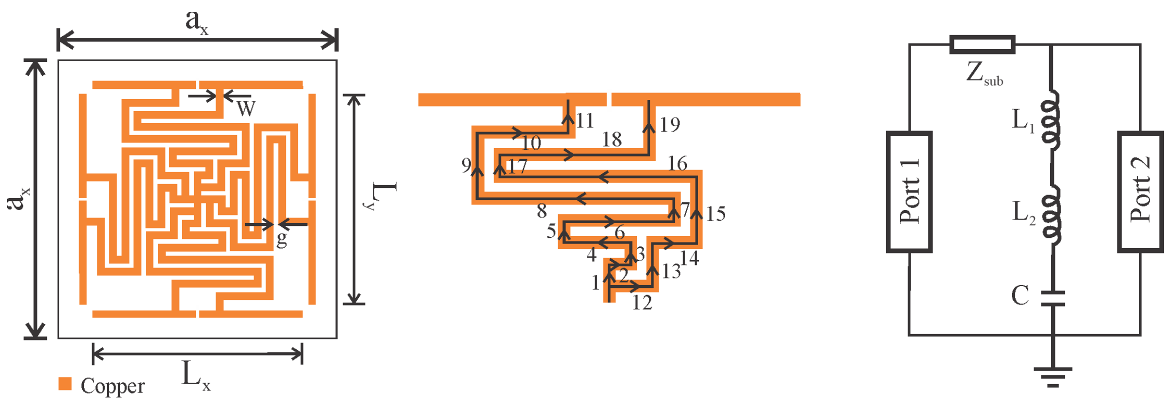


Fig. 1. FSS element design: (a) unit cell; (b) details; and (c) equivalent circuit model.

By evaluating the equivalent circuit of the proposed FSS as shown in Fig. 1 (c), the frequency can be calculated as: $f_0 = 1/2\pi((L_1+L_2) \times C)^{1/2}$. Here, L_1 and L_2 are the effective inductances due to the lengths of the values from 1 to 11 and 12 to 19, respectively, which can be derived as: L_1 = 18.47 nH and L_2 = 18.81 nH using quasi-static analysis of the microstrip line [15]. C = 272.63 fF is the effective capacitance resulting from series and parallel connections. The dielectric substrate used to print the metallic pattern has profound effect on capacitances only. The higher the dielectric constant, the higher the capacitance, which will shift the resonance frequencies to lower ranges, thus resulting in greater miniaturization.

For the reconfiguration, four Schottky Diodes are inserted in the central region of the geometry. It is known that diodes are devices that work as switches, operating as a short circuit (ON state) or as an open circuit (OFF state), depending on the DC polarization applied. Particularly, the change from OFF to ON states, provided by the polarization of the four diodes, causes the appearance of the proposed closely spaced resonances.

Three modes of operation are investigated with this structure, the first (Case 1) is with all diodes polarized and conducting (ON), the second (Case 2) is with all four diodes in OFF state and the third (Case 3) is with two diodes polarized (Diodes 1 and 2) and two diodes in OFF state (Diodes 3 and 4) and. Fig. 2 (a) illustrates the position of the diodes. The three cases are shown in Fig. 2 (b), Fig. 2 (c) and Fig. 2 (d), considering the diode in the ON state as a short circuit and in the OFF state as an open circuit.

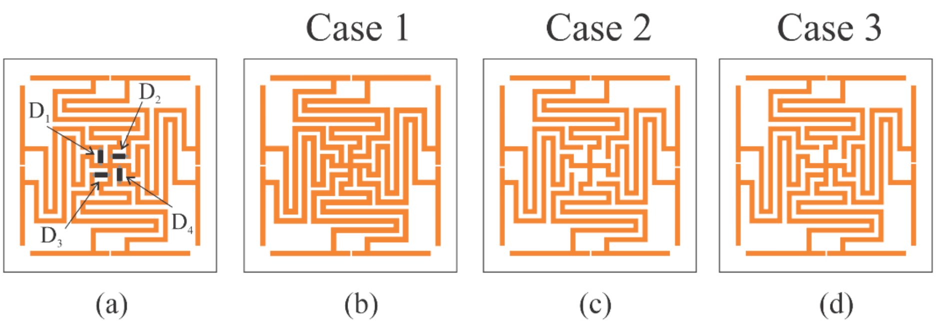


Fig. 2. AFSS configurations: (a) Case 1; (b) Case 2; and (c) Case 3.

III. RESULTS AND DISCUSSIONS

The commercial software ANSYS HFSS was used for the simulations. The simulations were performed using periodic boundary conditions (floquet ports), and with the electromagnetic waves incident in the z direction. For the ON diodes, lumped elements with a resistance of 20 ohms were inserted and for the OFF diodes, lumped elements with a capacitance of 0.07 pF were inserted. The simulation setup can be seen in Fig. 3.

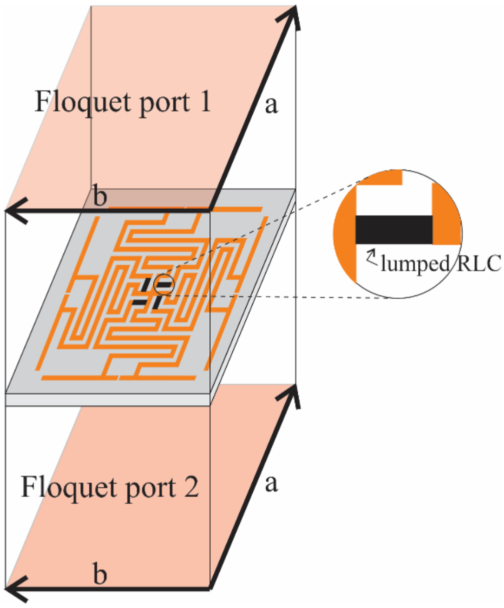


Fig. 3. Simulation setup.

Fig. 4 shows the simulated transmission coefficient for the three configurations of the FSS the frequency range analyzed is UHF. The FSS behaves as a band-reject filter. For the case where the four diodes are conducting (case 1), within the analyzed range the structure presents a resonance frequency at 1.53 GHz with the value -35.86 dB for the transmission coefficient at resonance and 0.53 GHz bandwidth; for the case in which the four diodes are in the OFF state (case 2) the structure presents a dual-band behavior being the resonance frequencies equal to 0.94 and 2.27 GHz with -28.11 and -28.3 dB of transmission coefficients modules and 0.15 GHz and 0.32 GHz of bandwidths. For the case where two diodes are ON and two OFF (case 3) the FSS also presents a dual-band behavior being its resonance frequencies equal to 1.06 and 1.87 GHz with -26.91 and -25.79 dB of transmission coefficient modulus with 0.17 GHz and 0.30 GHz of bandwidths.

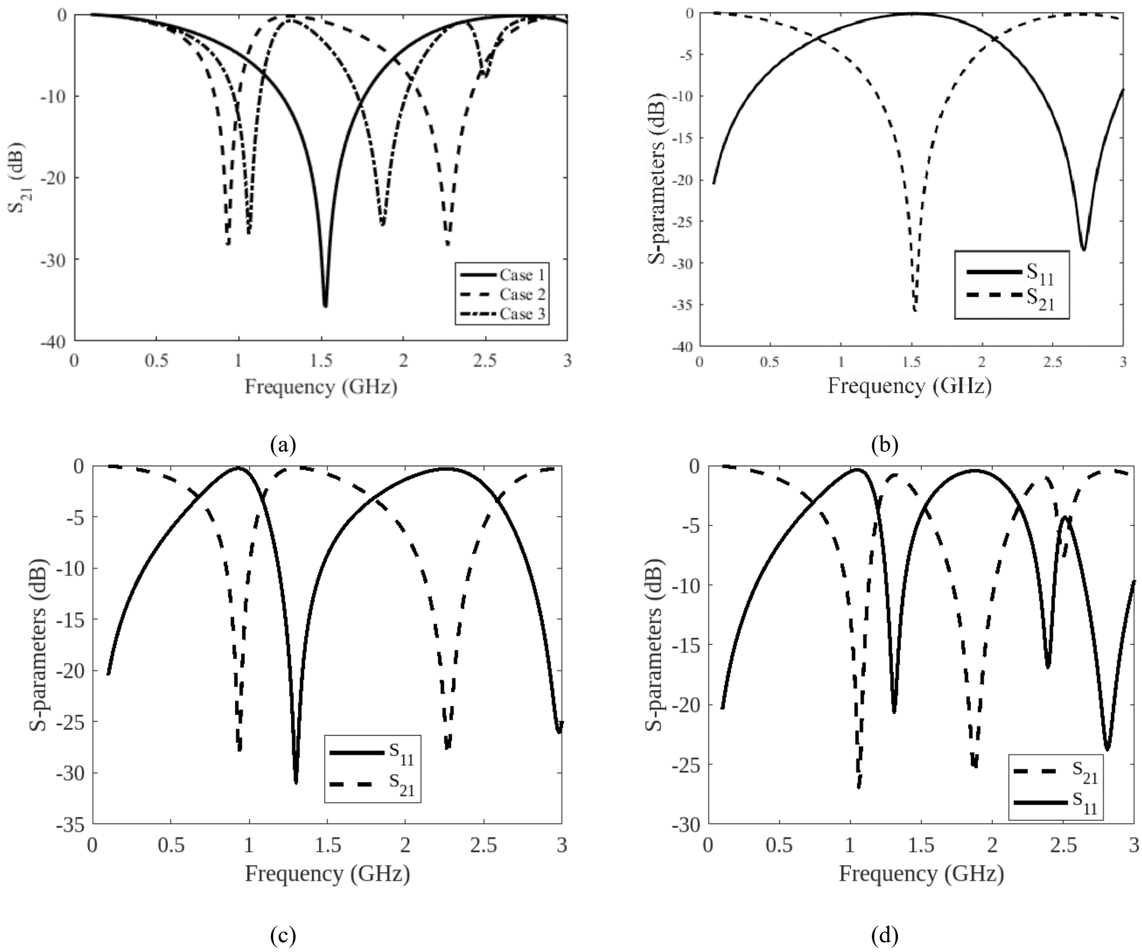


Fig. 4. Transmission and reflection coefficients for all AFSS operating modes: (a) three cases; (b) Case 1; (c) Case 2; and (d) Case 3.

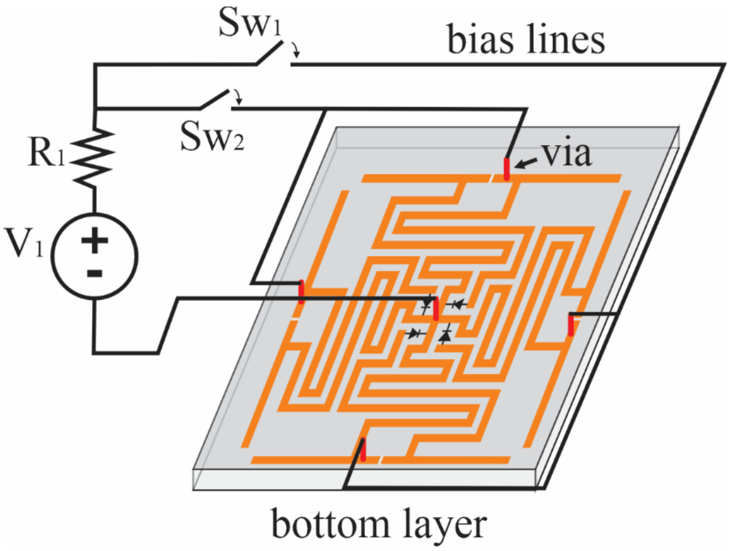
Fig. 4 (a) shows that the structure presents an excellent reconfiguration capability, since in each operating mode the frequency response changes, covering the range from 0.8 GHz to 2.5 GHz. The transmission and reflection coefficient curves for each case are shown in Fig. 4 (b), Fig 4 (c) and Fig. 4 (d).

To set up the AFSS measurement, a DC power supply was used to guarantee the polarization of the diodes, as well as DC filters to avoid interference in the propagation of the RF signal. Paths were also inserted in the structure for the polarization of the diodes to be through the lower layer of the FSS. Measurements were performed for the AFSS with all diodes in the OFF or ON state. To perform the reconfigurable AFSS experiment with Schottky diodes, an electrical circuit was developed, as illustrated in Fig. 5 (a). This circuit was used for DC bias in the diodes. The SW_1 and SW_2 switches were used to perform the two AFSS configurations.

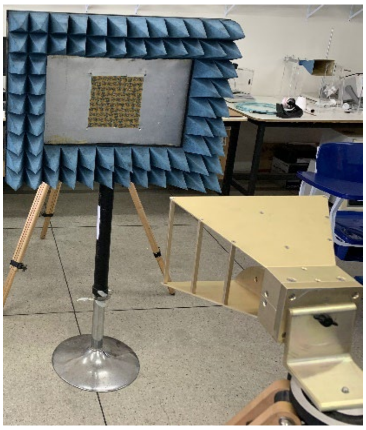
To verify the performance of the designed FSS, a prototype was fabricated and measured. The structure was built using the same substrate considered in the simulations, FR4, with overall dimensions of 200 mm x 200 mm, containing a 20 x 20 element arrangement as is illustrated in Fig. 5 (c). After an investigation into various Schottky diode parameters, the Schottky diodes utilized were the SMS7630-

079LF model SC-79 from the manufacturer Skyworks Solutions, Inc. This diode model presented the most suitable specifications for use in this project. Some criteria assumed for the proper specification of the diodes were, cost, operating frequency bandwidth and size. For the polarization of the diodes, vias were inserted, these vias were interconnected and a DC power supply was used to ensure the polarization of the diodes as well as DC filters to avoid interference in the RF signal propagation.

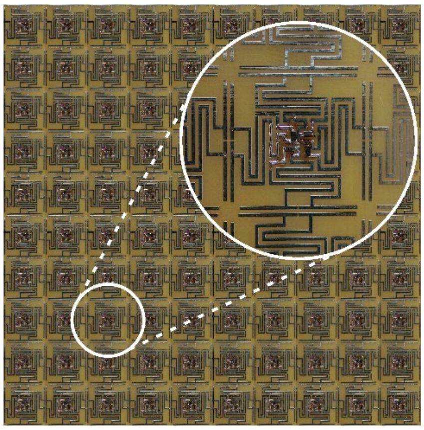
The used AFSS measurement setup consisted of two A.H. Systems Inc.-SAS-571 horn antennas (a transmitting and a receiving), cables, and a vector network analyzer (LiteVNA, Frequency range 50kHz – 6.5GHz; System dynamic range >90dB), the setup is shown in Fig. 5 (b).



(a)



(b)



(c)

Fig. 5. (a) Diode dc bias diagram. (b) Photograph of the measurement setup. (c) Photograph the fabricated prototype.

The comparisons of the measured and simulated results can be seen in Fig. 6 (a), Fig. 6 (b) and Fig. 6 (c). The measurement was performed within the UHF band. The resonant frequency of the measured result for case 1 is at 1.52 GHz, has 0.58 GHz bandwidth and -28.5 dB transmission coefficient. For case 2, the response is dual-band the first band has the resonance frequency equal to 0.94 GHz with

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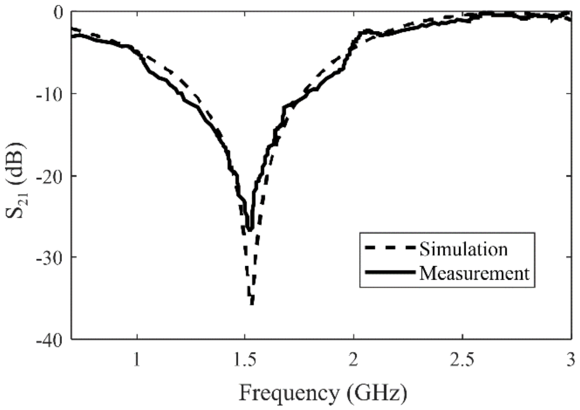
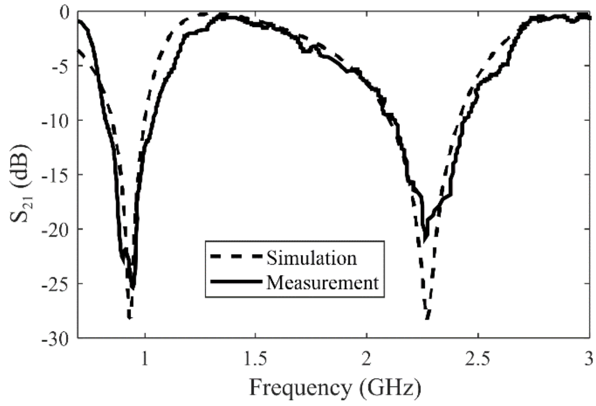
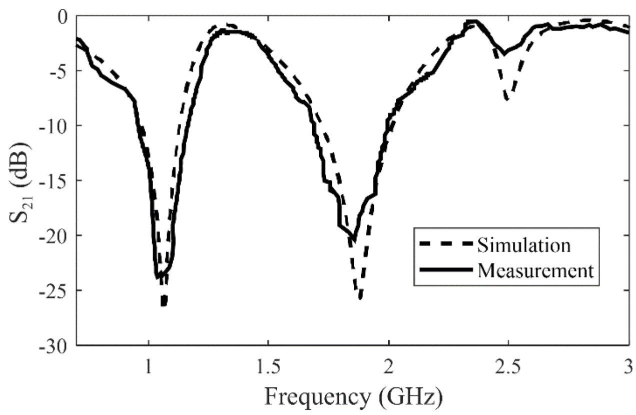
0.17 GHz bandwidth and the second has resonance frequency at 2.26 GHz and 0.33 GHz bandwidth. For case 3, the response is also dual-band with resonance frequencies at 1.03 GHz and 1.85 GHz the bandwidths are equal to 0.18 and 0.3 respectively.



(a)



(b)



(c)

Fig. 6. Measured and simulated transmission coefficients for the three AFSS operating modes: (a) Case 1; (b) Case 2; and (c) Case 3.

Fig. 7 (a) and Fig. 7 (b) presents the measurement for different angles θ of incidence of the electromagnetic wave. As in the simulation the measured results show that the structure has optimal angular stability and for angles up to 60° the rejection bands of the structure are maintained.

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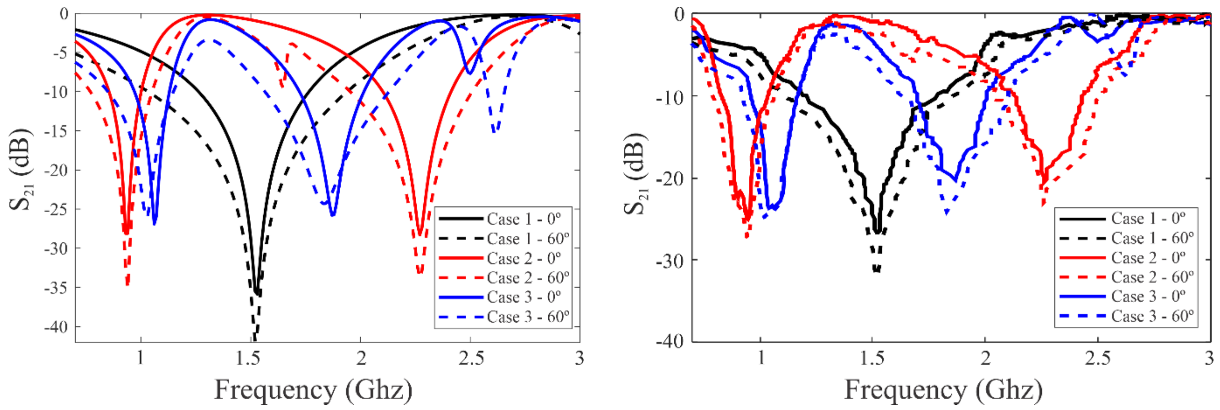

(a) (b)

Fig. 7. AFSS transmission coefficients for different angles of incidence and modes of operation: (a) Simulated; and (b) Measured.

Table I, II and III show a summary for better visualization of the measured and simulated AFSS results for the three cases.

TABLE I. COMPARISON OF MEASURED AND SIMULATED RESULTS AFSS CASE 1.

θ	First Resonant Band					
	Frequency (GHz)		S21 (dB)		BW (GHz)	
	Simulation	**Measurements**	**Simulation**	**Measurements**	**Simulation**	**Measurements**
0	1.53	1.52	-35.86	-28.50	0.52	0.58
60°	1.52	1.52	-41.93	32.62	0.79	0.72

TABLE II. COMPARISON OF MEASURED AND SIMULATED RESULTS AFSS CASE 2.

θ	**First Resonant Band**					
	Frequency (GHz)		S_{21} (dB)		BW (GHz)	
	Simulation	**Measurements**	**Simulation**	**Measurements**	**Simulation**	**Measurements**
0	0.93	0.94	-28.11	-25.61	0.15	0.17
60°	0.94	0.94	-35.15	-28.35	0.28	0.24
θ	**Second Resonant Band**					
	Simulation	**Measurements**	**Simulation**	**Measurements**	**Simulation**	**Measurements**
0	2.27	2.26	-28.30	-21.62	0.32	0.33
60°	2.27	2.25	-33.77	-24.37	0.54	0.51

TABLE III. COMPARISON OF MEASURED AND SIMULATED RESULTS AFSS CASE 3.

θ	**First Resonant Band**					
	Frequency (GHz)		S21 (dB)		BW (GHz)	
	Simulation	**Measurements**	**Simulation**	**Measurements**	**Simulation**	**Measurements**
0	1.06	1.03	-26.91	-24.10	0.17	0.18
60°	1.03	1.00	-25.98	-25.87	0.27	0.25
θ	**Second Resonant Band**					
	Simulation	**Measurements**	**Simulation**	**Measurements**	**Simulation**	**Measurements**
0	1.87	1.85	-25.79	-21.00	0.30	0.30
60°	1.83	1.83	-24.30	-24.88	0.56	0.57

Tables I, II and III show a very good agreement of the measured results with the simulated ones, with a maximum percentage deviation of 3 % for the resonance frequencies. The tables also show that the responses of the structure are stable for incidence angles up to 50°. The reconfigurable FSS presents the resonance frequency shifting capability for the different diode biasing cases, with all rejection bands close to and within the UHF range. The structure can be used for different applications in the 900 MHz and 2.4 GHz ISM bands and also in the L-band (950 MHz to 2150 MHz), for example.

IV. Conclusion

In this work, an electronically reconfigurable FSS with convoluted dipole-based elements is proposed. The scattering properties of the FSS have been investigated. The structure shows an optimal angular stability with the angle ranging from 0° to 60° for TE and TM polarizations. The reconfiguration was achieved by using Schottky diodes inserted in the central region of the patch. Therefore, the proposed AFSS presents five resonances divided into three cases of diode polarization. With the reconfiguration it is possible to obtain three distinct responses of the FSS within the UHF band, enabling the use of the FSS for different applications in the ISM bands of 900 MHz and 2.4 GHz, L-band (950 MHz to 2150 MHz) and also different GSM bands.

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