A Complementary Frequency Selective Surface with Tri-Band Frequency Response for Applications in Wi-Fi and 5G

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***Abstract*—In this paper we proposed a novel tri-band complementary frequency selective surface (CFSS) with a traditional geometry composed of double concentric rings. The choice of this geometry is because of its very good angular stability. The proposed resonant frequencies were 2.5 GHz, 3.5 GHz, and 4.5 GHz. The CFSS is low profile and presents angular stability and polarization independence. Simulations were performed using HFSS software and they are compared with the experimental results for validation purposes. A very good agreement is observed between them.**

***Index Terms*—Tri-band, WLAN, 5G, CFSS.**

I. Introduction

FREQUENCY selective surface (FSS) is a two-dimensional periodic array, which is constructed by metal patches or aperture elements, which can reflect or transmit all the incident electromagnetic waves, in certain frequency bands, showing extremely high-frequency selective characteristics [1].

Therefore, FSS presents the function of electromagnetic wave filter [2]–[4], to reduce the radar cross-section (RCS) of the target [5], [6]. Also, FSS based absorbing materials have been widely used in hybrid radomes [7], [8]. FSS has been used as polarization converters to achieve high gain in antennas [9], [10].

Lockyer introduced the concept of complementary frequency selective surface in 2001 [11]. It had the advantage that complementary frequency selective surfaces create frequency responses highly stable for normal and oblique incidences and with polarization independence [12].

Complementary Frequency Selective Surfaces (CFSS) are formed by two FSS closed coupled with identical geometric elements, one formed by patch-type elements and the other by slot/aperture-type elements, thus one is complementary to the other [13].

To solve the problem of single frequency band response, several FSS have been intensively investigated in the last years [14]–[20]. These studies presented FSS with a tri-band response, but most of them do not present angular stability and polarization independence, or the geometries were too complex. In the study proposed in [14], polarization independence and angular stability up to 45 degrees are obtained for a single layer structure. However, the proposed unit cell is very complex. The structures proposed in the studies of [15] and [19] also have only one dielectric layer but suffer from the same problem of complex geometry unit cells. Furthermore, in both studies the structures are sensitive to the incident wave polarization. Single layer tri-band frequency selective surfaces are proposed in [16] and [18]. Although the structures are polarization insensitive, the unit cells are still complex, being composed of three different resonators. In the studies proposed by [17] and [20] the unit cells are composed of simple geometries. However, the angular stability is limited to 30 degrees.

Thus, this paper proposed a tri-band CFSS for

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application in Wi-Fi and 5G technologies, with angular stability, polarization independence, and a low profile. The proposed CFSS element geometry is composed of double concentric rings. The FSS with patch-type elements will present a dual-band response, while the aperture-type element will present a single-band response. The combination of the two types will give us a tri-band desired response. This work is an extension of a summary paper [21] including state of the art, parametric analysis, and measurements.

The paper is organized as follows. Section II presents the design of the proposed structure, describing the obtaining of its physical dimensions and the influence of each parameter on the frequency response. Section III provides the results obtained through numerical simulations. In Section 3, the measurements of the fabricated prototype and the comparison with the numerical results are shown. The work conclusions are presented in section V.

II. Parametric analysis of the proposed CFSS

Our CFSS is composed of double concentric rings. The choice of this geometry is because of its very good angular stability and polarization independence. The desired resonant frequencies are 2.5 GHz, 3.5 GHz, and 4.5 GHz. Fig. 1(a) illustrates the unit cell of the double circular ring apertures and their physical dimensions, and Fig. 1(b) illustrates the unit cell of the double circular ring patches, with its physical dimensions indicated. Beside this, two rings will give us the desired tri-band response. All the simulations performed in parametric analysis were obtained for normal incidence and for vertical polarization.

The chosen dielectric was the FR-4 with a thickness of 0.8 mm, ε_r = 4.4, and loss tangent 0.02. The proposed structure is composed of two closed coupled FSS, due to the thin substrate used to separate them. This proximity between the FSSs causes a strong electromagnetic coupling, giving the final CFSS tri-band response, with three resonant frequencies of 2.55 GHz, 3.55 GHz, and 4.50 GHz.

To obtain the physical dimensions, which allow the desired frequency response, a parametric analysis was performed for the dimensions of the unit cell elements, d_1 (=$2r_1$), d_2 (=$2r_2$), w_1, w_2, and for the dielectric thickness, h. The periodicity is chosen as p = 24 mm because this value allows for the non-appearance of grating lobes.

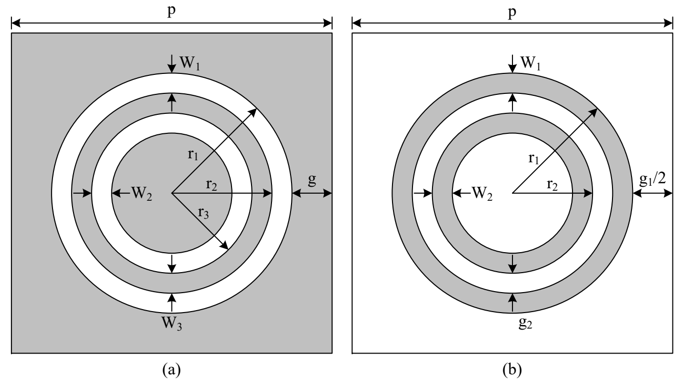

Fig. 1: Unit cell of the double circular ring: (a) bottom view and (b) top view.

An important parameter in the design of this type of CFSS is the diameter of the external ring. This dimension controls the first resonance. For loop arrays, the resonance occurs as a function of frequency where the loop circumference becomes equal to the wavelength. Therefore, the length of the circumference must be near a wavelength at this frequency. For 2.5 GHz, the wavelength is 120 mm. So, d_1 must be near 19.2 mm. We started with 20 mm. For all parametric analyses, the periodicity was p = 24 mm. The other dimensions were w_1 = 1 mm, d_2 = 16 mm, w_2 = 1.8 mm. An FR-4 superstrate with 0.8 mm of thickness and ε_r = 4.4 was used. We changed d_1 from 20 mm to 23 mm, with a step of 1 mm. When we increase d_1, the outer rings stay closer, and the capacitance between the outer rings of two adjacent unit cells increases. So, the resonant frequency of the first band decreases. Some effect is observed in second and third resonances but it is not as significant as for the first resonance. For d_1 = 23 mm we can obtain the desired first resonance, 2.5 GHz. We also improve the insertion losses of the transmission bands. The transmission coefficient response is illustrated in Fig. 2.

Another investigation is on the effect of the diameter of the internal ring. This dimension controls the second and the third resonance, but the effect is bigger at the third resonance. The length of the circumference ($2\pi d_2$) must be near to a wavelength at a geometric mean of these frequencies. For 4 GHz, the wavelength is 75 mm. So, d_2 must be near 12 mm. We started with 16 mm. For all parametric

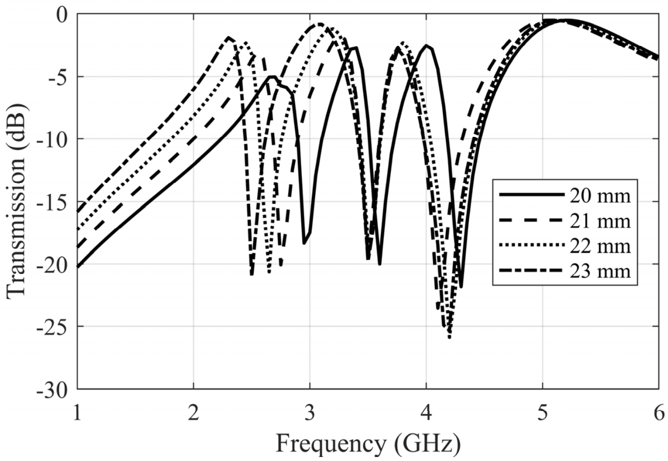

Fig. 2: Simulated transmission for different values of d_1.

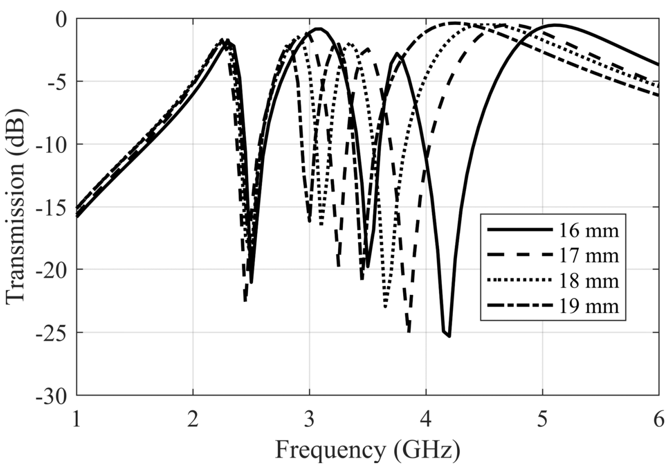

Fig. 3: Simulated transmission for different values of d_2.

analyses, the periodicity was p = 24 mm. The other dimensions were w_1 = 1 mm, d_1 = 23 mm, w_2 = 1.8 mm. We changed d_2 from 16 mm to 19 mm, with a step of 1 mm. When we increase d_2, the inner rings stay closer to the external rings, and the capacitance increases. So, the resonance frequency of the second and the third band decrease. For d_2 = 16 mm we can obtain the desired second and third resonances, 3.5 GHz and 4.5 GHz. The transmission coefficient response is illustrated in Fig. 3.

The third effect parameter analyzed was the width of the external ring's strip, w_1. This dimension controls the first resonance changing the inductance of the external ring. We started with 0.5 mm. For all parametric analyses, the periodicity was p = 24 mm.

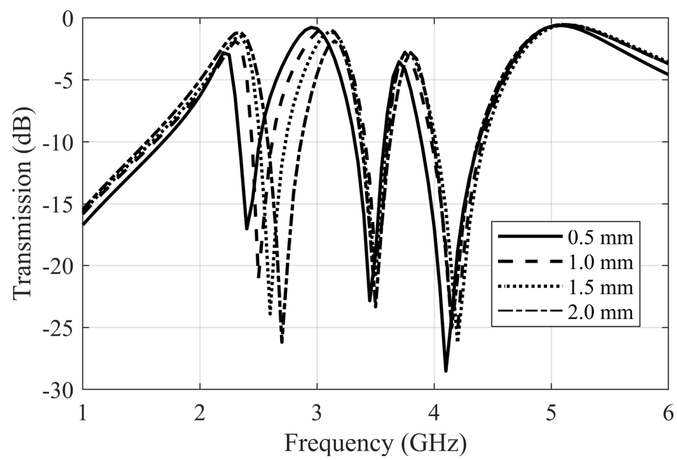

Fig. 4: Simulated transmission for different values of w_1.

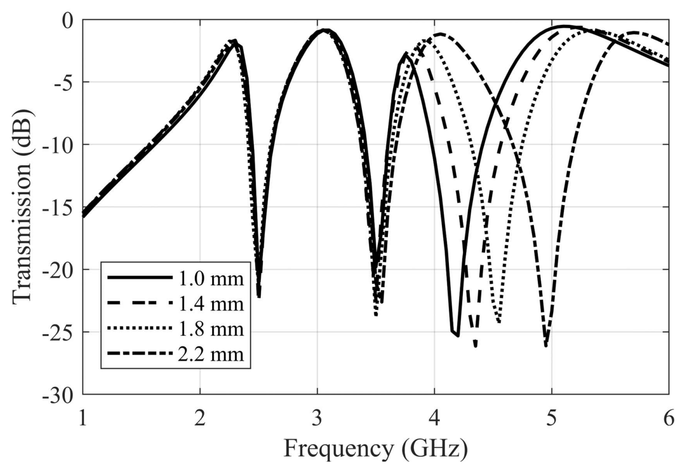

Fig. 5: Simulated transmission for different values of w_2.

The other dimensions were d_1 = 23 mm, d_2 = 16 mm, w_2 = 1.8 mm. We changed w_1 from 0.5 mm to 2.0 mm, with a step of 0.5 mm. When we increase w_1, the outer ring's inductance decreases. So, the resonance frequency of the first band increases. Occurs some effect in second and third resonances but it is almost insignificant. For w_1 = 1 mm we can obtain the desired first resonance, 2.5 GHz. The transmission coefficient response is illustrated in Fig. 4.

The fourth effect parameter analyzed was the width of the internal ring's strip, w_2. This dimension controls the third resonance changing the inductance of the internal ring. We started with 1 mm. For all parametric analyses, the periodicity was p = 24 mm.

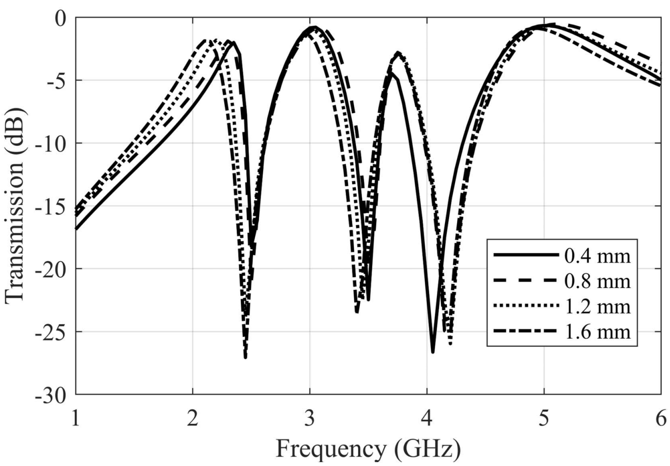

Fig. 6: Simulated transmission for different values of h.

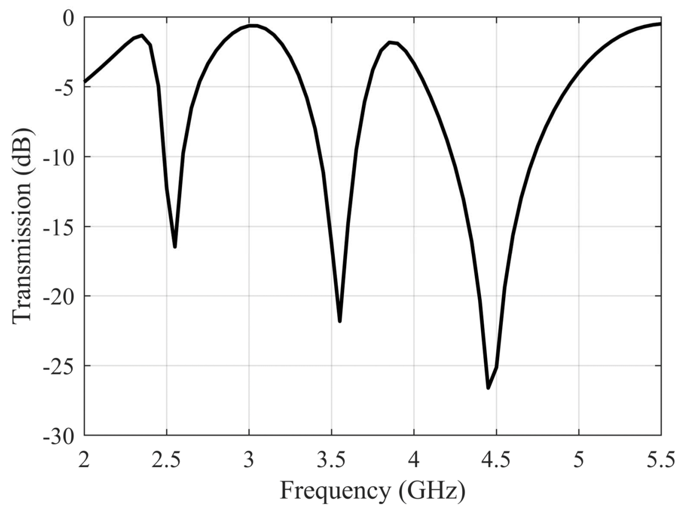

Fig. 7: Simulated transmittance of the proposed CFSS for normal incidence.

The other dimensions were d_1 = 23 mm, d_2 = 16 mm, w_1 = 1 mm. We changed w_2 from 1.0 mm to 2.2 mm, with a step of 0.4 mm. When we increase w_2, the inner ring's inductance decreases. So, the resonance frequency of the third band increases. No effects are observed in first and second resonances. For w_2 = 1.8 mm we can obtain the desired third resonance, 4.5 GHz. The transmission coefficient response is illustrated in Fig. 5.

Finally, the last parameter analyzed was the thickness of the dielectric layer, h. We chose four values for h, 0.4 mm, 0.8 mm, 1.2 mm, and 1.6 mm. For this parametric analysis, the dimensions were p = 24 mm, d_1 = 23 mm, w_1 = 1 mm, d_2 = 16 mm, and w_2 = 1.8 mm. The effect of the thickness is to increase the bandwidths and maintain the resonance frequencies almost the same. The transmission coefficient response is illustrated in Fig. 6. The values of some parameters in the two layers are slightly different as they allow better tuning of the desired frequencies.

III. Simulation of the Designed CFSS

The frequency response of the transmission coefficient of the proposed structure is shown in Fig. 7, for normal incidence. Analyzing the results, we can see that the frequency response can reject the three desired frequency bands, with nulls at 2.55 GHz, 3.55 GHz, and 4.45 GHz, with bandwidths of 120 MHz, 222 MHz, and 468 MHz, respectively. The bandwidth is obtained for - 10 dB Transmission level. As can be seen, the resonant frequencies cover Wi-Fi and 5G bands.

In Fig. 8 we illustrated the transmission for oblique incidence with vertical polarization. The simulated results can prove the angular stability of the proposed CFSS. As we can see, the frequency response of the proposed CFSS unchanged for oblique incidence up to 45°. In addition, to measure angular stability, we used the methodology presented in [20], and we analyzed the ratio between the resonance frequency and the ratio between the bandwidth (BW) for normal and 45° oblique incidence. For the resonant frequency, the simulated results show that the 45° ratio of the proposed FSS is 1.00 for the first, second, and third frequencies. For the 45° BW, the ratios were 0.93, 0.90, and 0.87 for the first, second, and third bands, respectively.

The simulated results obtained by the HFSS, for horizontal polarization, are illustrated in Fig. 9. The frequency response remains the same for oblique incidence of up to 45°. For the resonant frequencies, the simulated results show that the 45° ratio of the proposed FSS is 1.00 for the first, second, and third resonance frequencies. For the 45° BW of the proposed FSS, the ratios were 1.20 for the first band, 1.18 for the second band, and 1.22 for the third band. The simulated results show that the proposed CFSS has great angular stability and polarization independence.

To explain the angular stability we need to understand the electromagnetic effect in terms of the

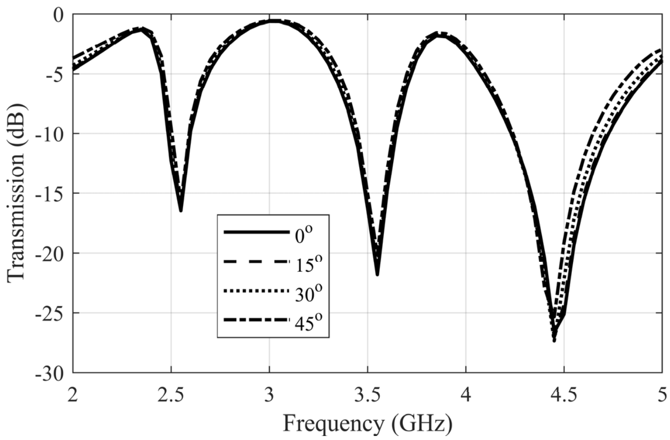

Fig. 8: Transmission for oblique incidence with vertical polarization.

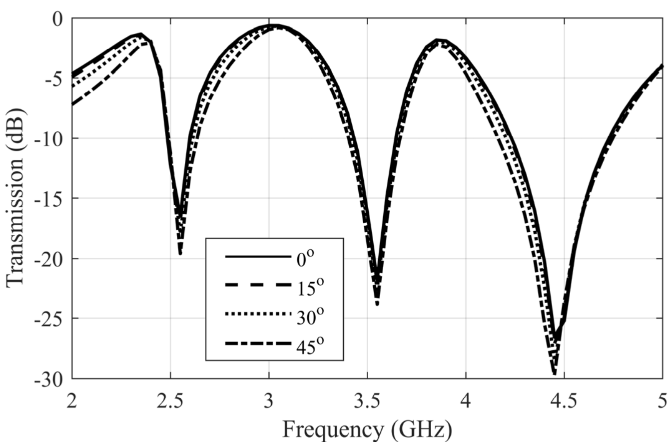

Fig. 9: Transmission for oblique incidence with horizontal polarization.

current distribution at the three resonant frequencies, for normal and oblique incidence at 45°. Fig. 10(a) corresponds to current distribution at 2.55 GHz, with normal incidence, while Fig. 10(b) shows the current distribution for oblique incidence of 45°. Fig. 10(c) corresponds to the current distribution at 3.55 GHz, with normal incidence, while Fig. 10(d) shows the current distribution for oblique incidence at 45°. Fig. 10(e) corresponds to the current distribution at 4.45 GHz, with normal incidence, while Fig. 10(f) shows the current distribution for oblique incidence at 45°, at 4.45 GHz. We can see in these figures that the current distribution is symmetric, which guarantees angular stability [9].

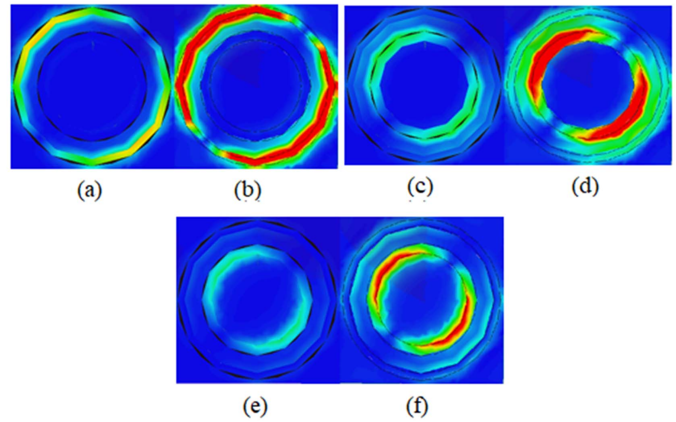

Fig. 10: Surface current distribution: (a) 2.55 GHz and normal incidence, (b) 2.55 GHz and oblique Incidence at 45°, (c) 3.55 GHz and normal incidence, (d) 3.55 GHz and oblique Incidence at 45°, (e) 4.45 GHz and normal incidence, (f) 4.45 GHz and oblique Incidence at 45°.

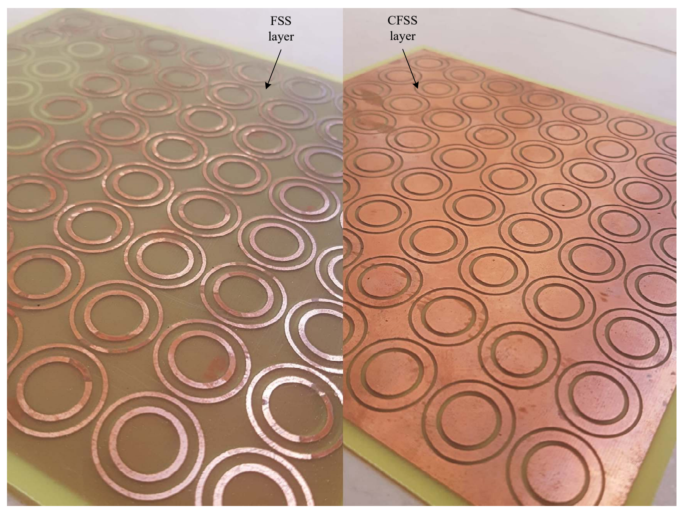

Fig. 11: Photography of the top and bottom view of the built prototype.

IV. Experimental Results

With validation purposes of the simulations obtained in this work, we built and measured an CFSS prototype with double concentric rings on an FR-4 substrate of 21 x 21 cm^2, with ε_r = 4.4, and 0.8 mm thickness. Fig. 11 illustrates the bottom and top views of the built prototype. The measurement setup was the same presented in [21]. A supporting structure with 80 x 60 cm^2 coated on one side with pyramidal RF absorbers and aluminum foil,

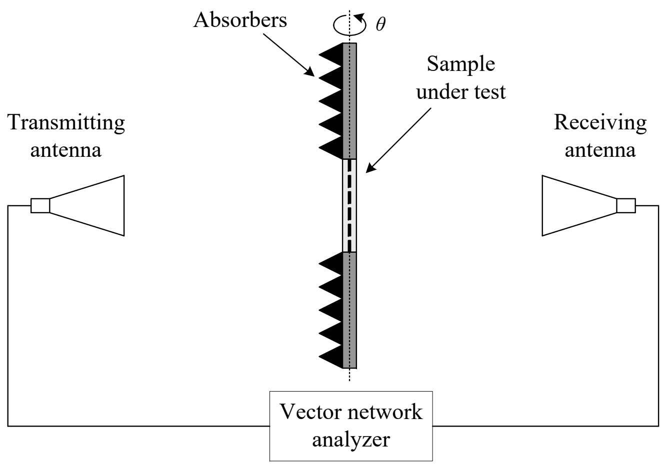

Fig. 12: Transmission coefficient measurement setup.

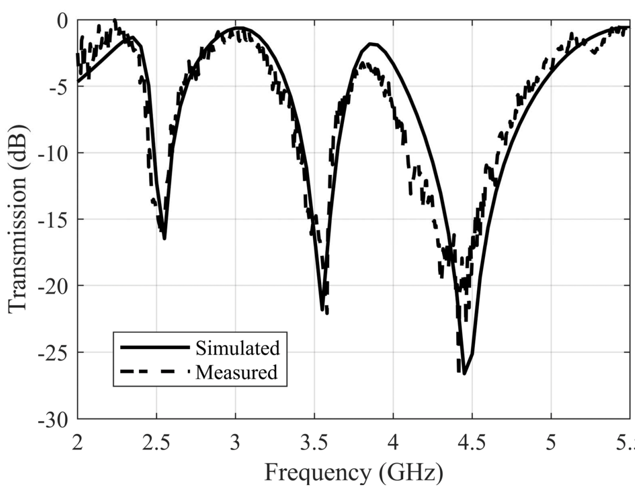

Fig. 13: Comparison between simulated and measured results.

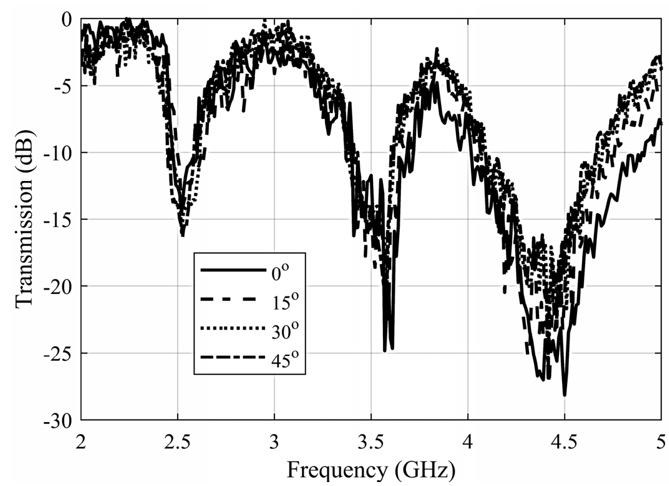

Fig. 14: Measured results for oblique incidence and vertical polarization.

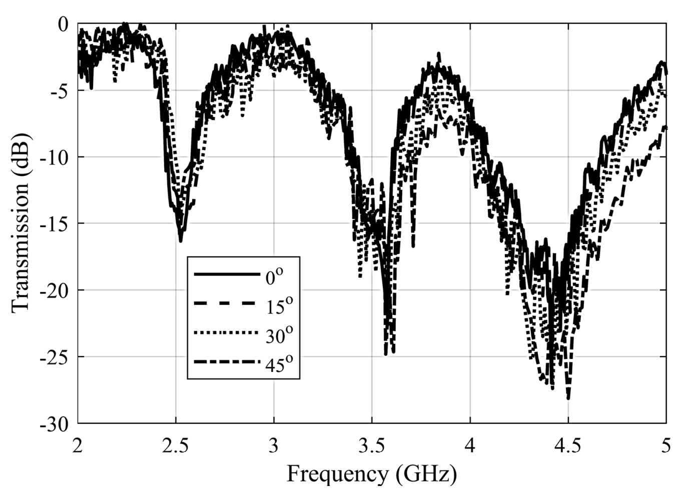

Fig. 15: Measured results for oblique incidence and horizontal polarization.

to avoid diffraction contamination of measurements, is used to fix the CFSS. For the normal incidence measurement, the transmitter and receiver sides were connected to two identical horn antennas. For oblique incidence measurements, the supporting structure with the CFSS can be rotated, as can be seen in Fig. 12. A VNA Agilent E5071 C is used for measurements.

A comparison between simulated and measured results, for normal incidence, is illustrated in Fig. 13. For simulated results the resonant frequencies were 2.55 GHz, 3.55 GHz, and 4.45 GHz. For measured results these resonance frequencies were 2.53 GHz, 3.58 GHz, and 4.42 GHz. The bandwidths of simulated results were 120 MHz, 222 MHz, and 468 MHz, for the first, second, and third resonances, respectively. For measured results, these bands were 138 MHz, 204 MHz, and 539 MHz. We can observe a very good agreement between simulated and measured results. These results are presented in Tab. I, for comparison purposes.

In Fig. 14 and 15 we can see measured results for vertical and horizontal polarization, with oblique incidence. The angles of incidence range from 0° to 45°. The measured results show that the bandwidth does not suffer significant degradation, for different incidence angles, confirming the angular stability.

Tab. II compares the proposed FSS with other work given in [14]–[20], considering the aspects

TABLE I: Comparison of simulated and measured results.

Parameter	Simulated (MHz)	Measured (MHz)
f_{R1}	2250	2530
f_{R2}	3550	3580
f_{R3}	4450	4420
BW_1	120	138
BW_2	222	204
BW_3	468	539

TABLE II: Comparison of most recent articles published with tri-band FSS and our work.

Ref.	Geometry complexity	Angular stability	Pol. Indep.	No. of layers	No. of Sub-resonators
Our work	Low	Up to 45°	Yes	2	2
[14]	Very high	Up to 45°	Yes	1	3
[15]	Very high	No	No	1	4
[16]	Medium	No	No	1	3
[17]	Low	Up to 30°	Yes	1	4
[18]	Medium	No	No	1	3
[19]	Very high	Up to 30°	No	2	2
[20]	Low	Up to 30°	-	1	2

of Geometry complexity, profile, angular stability, and polarization independence. As seen in Tab. II, the proposed CFSS has low complexity, low profile, angular stability up to 45°, and polarization independence. No proposed FSS in the other works assembly all of these characteristics, which proves the novelty of our CFSS.

V. Conclusion

In this paper, we present a tri-band CFSS with very closely spaced resonant frequencies. The resonant frequencies are 2.5 GHz, 3.5 GHz, and 4.45 GHz. The bandwidths of 120 MHz, 222 MHz, and 468 MHz, for the first, second, and third bands. These frequencies and bands show that the structure can be applied in Wi-Fi and 5G technology. The simulated results show that the chosen geometry has a good angular stability and polarization independence until 45°. This is possible because of the CFSS structure and geometry of the unit cell. The CFSS is low-cost and easy to fabricate. A very good agreement between simulated and measured results was observed.

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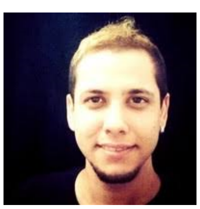

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