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PDMS-Based Angle-Stable and Flexible Reconfigurable Frequency Selective Surface for Shielding in GSM, 5G Sub-6 GHz, and 5 GHz Bands

Wahaj Abbas Awan* (1), Musa Hussain(2), Dongkyu Sim(1), and Nam Kim(1)
(1) Department of Information and Communication Engineering, Chungbuk National University, Cheongju, South Korea
(2) School of Engineering and Built Environment, Gold Coast Campus, Griffith University, Gold Coast, QLD 4222, Australia
*wahajabbasawan@chungbuk.ac.kr

Abstract

This paper proposes a highly compact reconfigurable Frequency Selective Surface (RFSS) having frequency and mode agility. The conventional square-loop FSS is designed for 5G sub-6 GHz shielding applications. Subsequently, three capacitors, along with an RF-PIN diode, are incorporated to achieve on-demand reconfigurability, switching from a single band at 3.5 GHz to a dual-band response at 1.8 GHz and 4.9 GHz. The unit cell is fabricated using a highly flexible silicone-based substrate, polydimethylsiloxane (PDMS), with a thickness of 1 mm and a dielectric constant of 2.7, while the FSS structure is realized using nickel–copper-coated ripstop conductive fabric. The proposed FSS features a highly compact size of 0.12 $\lambda s \times$ 0.12 λs, where λs corresponds to the free-space wavelength at the lower resonance of 1.8 GHz. Moreover, analysis shows that in the diode-On state, the FSS provides broadband shielding, covering 2.78–4.2 GHz. In contrast, in the diode-Off state, the FSS exhibits a dual-band response with bandwidths of 1.69–1.99 GHz and 4.52–5.34 GHz. Furthermore, a comparative analysis with state-of-the-art reconfigurable FSS designs is presented, highlighting the unique contributions of the proposed work for shielding applications.

1. Introduction

Electromagnetic (EM) shielding is typically defined as the reduction of EM waves by reflecting them away from the device or diverting them in specific directions to achieve specific advantages. EM shielding has become critically important in today's life due to the presence of multiple devices per user [1-2]. Moreover, EM shielding is widely used to block external radiation and prevent the leakage of internal signals, which consequently results in signal integrity, a significant reduction of noise in electronic devices, and ensures safety in healthcare and military applications [3-4].

Additionally, due to the increased applications and the use of multiband or different frequency bands by a variety of devices, the need for reconfigurable frequency selective surfaces (FSS) has drastically increased [5]. As a result, a number of works have emerged to meet this growing demand [6-10]. A four-square looped shape connected structure is loaded with 16 diodes to control each unit cell. Although, dual band to single band switching is achieved, yet, the 16 diode per unit cell requires high power and complex biasing circuits to operate effectively. In [7] another four-square looped shaped FSS is designed, which is then loaded with four pin diodes to achieve reconfigurability between dual band mode (2.45 GHz and 6.25 GHz) and single band mode with operating frequency of 3.9 GHz. Contrary to the above works, an interesting approach is adopted in [8], where four diodes per unit cell are placed in such a way that two pairs are formed. At a time one pair is switched on while the other will be in switch off state, which results in either wideband mode or triband mode.

A simple yet effective technique is utilized in [9] where each unit cell is controlled by one diode, moreover, the unit cells are connected with each other, which results in simple biasing circuit. However, the RFSS only works for single band in both state along with setback of narrow band. Finally, in [10] an optically controlled RFSS is designed in such a way that four optical switches are placed in each unit cell, which switched on when placed near to the light source and vice versa. Although this technique is effective and doesn't require any biasing circuits, it is not effective for outdoor applications. Moreover, none of the reported work has the potential to work along with conformal services due to the rigid structure.

The need for flexible EM shielding with minimal weight is critically important for applications such as wearable electronics, flexible displays, and antennas. These surfaces can selectively block or transmit certain frequencies, enabling precise control over EM waves [11]. Their flexibility allows integration into various curved or mobile devices, enhancing performance without compromising on space or comfort [12]. However, designing flexible and transparent FSS presents challenges, such as ensuring high transparency without sacrificing performance [13]. Thus, maintaining a balance between flexibility, durability, and efficiency is complex but critically important. Therefore, by addressing the aforementioned challenges, a compact frequency- and mode-reconfigurable FSS is designed. The FSS is constructed using highly flexible and transparent materials that offer high durability and stable performance when placed close to or on conformal surfaces. Furthermore, the FSS is designed to possess features of angular stability as well.

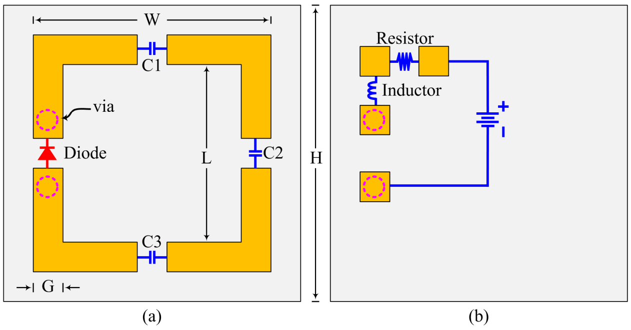

Figure 1. Geometerical configuration of proposed reconfigurable metasurface (a) top-view (b) back-view contining the baising circuit.

2. Design and Analysis

Figure 1 illustrates the geometrical configuration of the unit cell of proposed RFSS. The proposed FSS is designed using the highly flexible silicone-based polydimethylsiloxane (PDMS) material having the dielectric constant of 2.76 while the tangent loss varies from 0.03 to 0.06 with an increase in frequency from 3 GHz to 7 GHz. Detailed discussion on the manufacturing process along with the measured results of the PDMS material is present in [14]. The topside of the RFSS is made using nickel–copper-coated ripstop conductive fabric having conductivity of 5.4×10^4 S/m, where the structure consists of a square loop loaded with three capacitors and along with a very low capacitance RF-PIN diode having model number SMP1345-SC79 by Skyworks [15]. The optimized parameters of the proposed RFSS are as follow W = 18.2, L = 16.2, H = 20, G = 1, C1 = C2 = C3 = 9 nF, Resistor = 1 kΩ, Inductor = 27nH.

Impedance matching is a critically important parameter in designing the FSS. Ideally the reflection coefficient ($\Gamma = S_{11}$) must be equal to 0 which refers to perfect reflection, however, considering the losses possess by the material the impedance can be calculated as:

$$Z = \frac{Z_0}{1 - {S_{11}}^2} \tag{1}$$

Here the Z_0 is the characteristic impedance of the medium. Equation (1) suggests if S_{11} is zero or close to zero, then $Z \approx Z_0$. Moreover, the transmission coefficient (S_{21}) must have a very low value, resulting in no effective transmission through the FSS. The transmission coefficient can be expressed in terms of impedance using the following equation:

$$Z_0 = \frac{2\,Z_0}{Z_0 + Z_{FSS}} \tag{2}$$

Z_{FSS} is the impedance of FSS, which should be matched with Z_0 for effective radiation pattern. Thus, FSS must possess a low reflection, $S_{11} \approx 0$, and high transmission S_{21} to work effectively as a reflector for EM-waves or in other words behave as a shielding of EM-waves.

Figure 2 depicts the S-parameter performance of the RFSS for both the switched-on and switched-off states. In the switched-on state, the $S_{12} < -10$ dB bandwidth ranges from 2.78 GHz to 4.2 GHz, with a minimum value of -37.8 dB at 3.5 GHz. In contrast, S_{11} remains close to 0 dB throughout the targeted band, with cutoff values around -0.5 dB, as shown in Figure 2. On the other hand, when the diode is switched off, the FSS operates in dual-band mode, with resonances around 1.85 GHz and 4.9 GHz, exhibiting respective S_{12} values of -28.3 dB and -28.6 dB. The FSS shows strong performance in the ranges of 1.69–1.99 GHz for the lower band (1.85 GHz) and 4.52–5.34 GHz for the upper band (4.9 GHz), respectively.

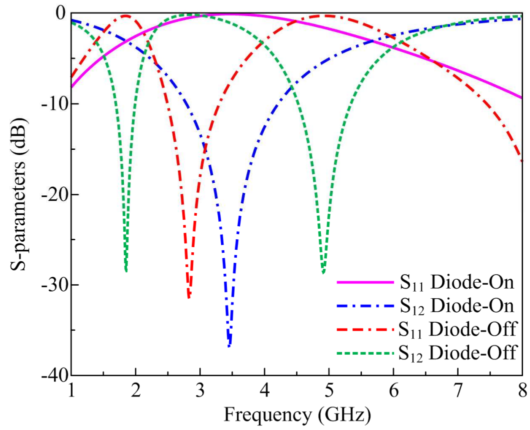

Figure 2. S-parameters of the reconfigurable FSS for switch on and switch off case.

The current surface of the proposed RFSS is presented in Figure 3, which better illustrates the operation of the RFSS. In the switched-on state, when the FSS is functional at 3.5 GHz, the current is distributed along the top and bottom sides of the square loop, as shown in Figure 3(a). However, when the diode is in the on state, the surface current shows its maximum value across the diode at 1.85 GHz, while the other side exhibits a lower value, as depicted in Figure 3(b). Similarly, Figure 3(c) shows that the current is distributed across the entire structure at 4.9 GHz. Thus, the redistribution of current in the diode-on state results in frequency reconfigurability, while the high induced current due to the presence of the capacitor results in higher frequencies, whereas the lower frequency is mainly due to the diode being in the on state.

To verify the angular stability of the proposed RFSS, the analysis is carried out for both the elevation plane (varying θ) and the azimuthal plane (varying ϕ), as depicted in Figure 4. For the elevation plane, as the angle increases from 0^0 to 75^0, the bandwidth begins to increase, while the targeted band remains constant for all values, as shown in Figure 4 (a). On the other hand, when the angle varies in azimuthal plane, there is almost no difference in s-parameter performance, as shown in Figure 4 (b). Thus, it is evident from Figure 4 that the proposed RFSS offers high angular stability up to 75^0 in both elevation and azimuthal planes.

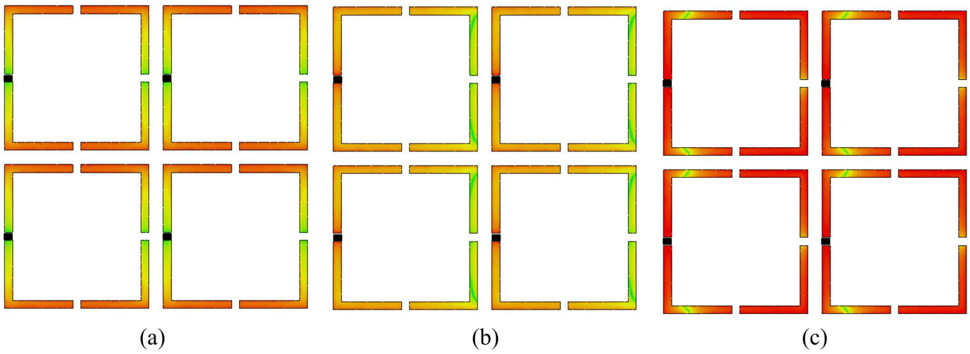

Figure 3. Surface current distribution of RFSS for switch On-state at (a) 3.5 GHz, and for switch off-state at (b) 1.85 GHz (c) 4.9 GHz. The black box in the RFSS represent the location of the diode in each unit cell.

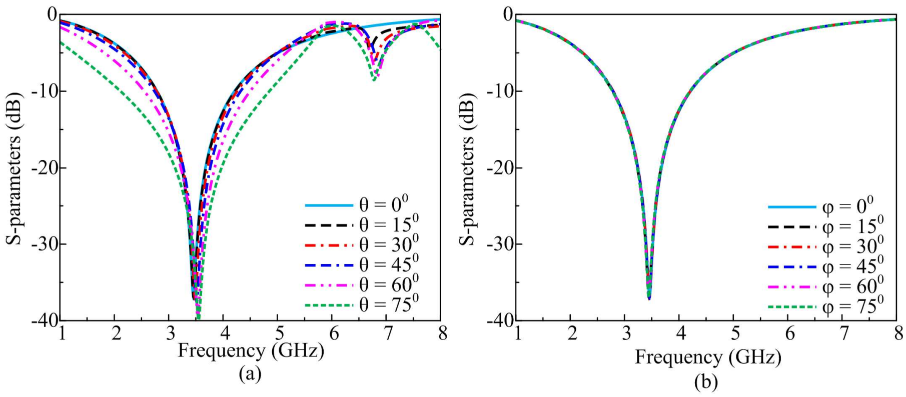

Figure 4. Angular stability analysis of proposed FSS along (a) elevation plane (b) azimuth plane.

Table 1. Comparison with realted work for similar applications.

Ref.	Size ($\lambda_s \times \lambda_s$)	Targeted bands (GHz)	Angular Stability Theta | Phi (Degree)	No. of diode per unit cell	Flexibility
[6]	0.49 × 0.49	10 | 17 | 20	N.S.	16	✗
[7]	0.13 × 0.13	2.5 | 4.8 | 6.5	75^0 | 30^0	4	✗
[8]	0.12 × 0.12	3.5 | 6.5 | 11.5	30^0 | 30^0	4	✗
[9]	0.32 × 0.32	4.3 | 6.7	N.S.	1	✗
[10]	0.27 × 0.27	2.5 | 4.9	20^0 | 10^0	4*	✗
Prop.	0.12 × 0.12	1.8 | 3.5 | 5	75^0 | 75^0	1	✓

*Light-dependent resistors, λ_s wavelength at the lower resonance, N.S. not studied.

3. Comparison with Literary Works

Table 1 presents a comparison between the proposed RFSS and related works reported in the literature. The proposed design offers a compact size compared to most literature, except for [3], where a similarly sized reconfigurable metasurface is designed. However, the work in [3] requires four diodes per unit cell, whereas our proposed design utilizes only one diode per unit cell. It is also observed that the proposed RFSS exhibits high angular stability along both the azimuthal and elevation planes. Moreover, the number of diodes per unit cell is lower than in other works, except for [4], where a dual-band, large-sized metasurface is designed. Lastly, the literature works have a high profile, making their structures rigid. In contrast, the proposed RFSS is designed using a thin substrate, making it flexible and suitable for applications on curved surfaces, such as the edges of vehicles.

4. Conclusion

A compact size frequency and mode reconfigurable frequency selective surface (RFSS) is presented in this manuscript. A square loop shaped frequency selective surface (FSS) is designed initially to operate on 3.5 GHz, globally allocated band for 5G sub-6-GHz application, with an impedance bandwidth of 40.6% ranging 2.78 – 4.2 GHz. Afterwards, three capacitors along with RF-PIN diode is inserted in loop to achieve a dual band response at 1.8 GHz and 4.9 GHz with respective bandwidths of 16.7% (1.69 – 1.99 GHz) and 16.7% (4.52 – 5.34 GHz). Moreover, the RMS offered stable angular performance for both principal elevation and azimuthal planes. Furthermore, the comparison with state-of-the-art literature shows that the proposed RFSS overperform the rest of the work. Along with that, the switching state of the pin diode triggers the on demand wideband mode or dualband mode covering the band spectrum allocated for numerous applications not limited to Global System for Mobile Communications (GSM), Personal Communications Service (PCS), LTE Band 3,9, 42, 43 and 48, Public safety communication, Wi-Fi, C-band satellite communication, military and defense radar, Dedicated Short-Range Communications(DSRC) for Vehicle-to-Everything (V2X) applications.

5. Acknowledgements

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