

A Wide and Tri-band Flexible Antennas with Independently Controllable Notch Bands for Sub-6-GHz Communication System

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Abstract. *A wide-band and tri-band flexible antenna for fifth-generation (5G) sub-6-GHz communication systems is investigated in this paper. The proposed wideband antenna covers the 5G new radio (NR) mid-band, ranging from 2.8 to 5.35 GHz, while the tri-band antenna is resonating at three different allocated frequency bands (2.45 GHz, 3.5 GHz, and 4.7 GHz) for 5G sub-6-GHz communications. This functionality is achieved by introducing hexagonal split-ring resonators in the radiating element, which can be controlled independently without affecting antenna performance to avoid problems of interference in this frequency spectrum. In addition, the antenna also presents a good conformability characteristic, and the simulated results are confirmed with the measurements of the fabricated prototype.*

Keywords

Flexible antenna, sub-6-GHz, tri-bands, 5G mid-band, conformal structure

1. Introduction

Recently, the advancement of the emerging technologies in wireless communication has caused a superfluous of devices connecting to the internet which cannot be managed by the fourth generation of mobile connectivity [1]. Especially with the elaboration of the concept of internet of things (IoT), that predicts the production of more than 20 billion connected devices to the web in the horizon of 2020, all of which will claim a connectivity with a ubiquitous coverage and a huge capacity [2]. This is where the fifth generation of communication (5G) came, for its ability to solve previous mobile generation's issues in term of bandwidth, latency rate, and higher data rate transmission [3]. The 5G technology uses a different frequency spectrum. The first segment is called the low-band spectrum, currently used for previous mobile networks, which in-

cludes the frequencies 600, 800, and 900 MHz [4]. This portion is ideal for wide-area, outside-in, and indoor coverage. While the second segment is referred to as the mid-band or the "sub-6-GHz" portion, characterized by a long wavelength which provides the privilege of traveling long distances along with a great immunity against distortion and the ability to penetrate through buildings [5]. However, it has the disadvantage of having a lower bandwidth and data rate issues.

The last segment is called the millimeter-wave (mm-wave) band which will be used in 5G technology for its promising feature of transmitting a huge amount of data due to its short wavelength [5]. Moreover, mm-wave frequencies are highly distorted from atmospheric conditions and get affected by obstacles [6]. Therefore, using one portion of spectrum over other affects both the speed and the distance of coverage, which incites the 5G providers to envisage lower-band, mid-band and mm-waves together, to maximize the distance, reduce transmission difficulties and reach the maximal throughput possible. Among the ultimate suitable candidate to ensure the ever-increasing end-user performance requirements, microstrip antennas are widely used due to their low-cost, light-weight, low-profile, and ease of fabrication [7], [8]. Moreover, they are used to produce flexible antennas to be integrated with non-ideal conditions such as bent and twisted surfaces while still maintaining good radiation characteristics [9], [10]. This capability will allow the use of this antenna for future 5G communications especially in healthcare and medical monitoring by transmitting higher data rates using less expensive stitched or sewed antennas on wearable devices. It will also allow its use for personal communications, such as GSM, WiFi, Bluetooth, etc. [11].

5G antennas have drawn significant attention in the past decade, especially 5G mid-band antennas, due to limitations of the mm-waves. Since mm-wave devices are expensive to implement and they cover only very short ranges, as well due to the fact that densely populated areas require higher capacities [6]. Therefore, researchers have

proposed several kinds of antennas for the sub-6-GHz portion of the spectrum, operating at the proposed 5G frequencies [12–17]. Either these antennas suffer from larger dimension, higher volume, complex structure and rigid substrate which limit their applications for compact and flexible devices. On the hand, a flexible antenna for 5G communication is reported in [17], however, it still faces the disadvantage of bigger dimension along with no solution is proposed to mitigate the un-wanted sub-bands from the operating region. Moreover, the antennas presented in [12–17] did not cover the entire sub-6-GHz portion, ranging from 2.8–5.2 GHz, which has incited researchers to focus on the coverage of the entire 5G mid-band in order to satisfy end-user requirements.

In addition, multiband 5G antennas are widely investigated recently by antenna engineers, for their ability to replace multiple antennas by only one multi-band antenna, therefore, enabling multifunctional operations. Many 5G multi-band antennas have been reported in the literature. In [18], an efficient 5G antenna covering the frequency ranges from 3.45–3.8 GHz and 5–5.45 GHz is presented, while the provided response from [19] covers the LTE bands 42/43 and 46 ranging respectively from 3.4–3.8 GHz and 5.1–5.9 GHz. Similar work is presented in [20], which proposes a multiband printed planar Inverted-F antenna for 5G mobile handset. The covered bands by this antenna are ranging from 1.8–2 GHz and 2.3–2.8 GHz. From the literature review, it can be deduced that the reported multi-band 5G antennas do not cover all the proposed 5G mid-band frequencies by the Federal Communication Commission (FCC), which are 2.5 GHz, 3.5 GHz, and 3.7–4.2 GHz. Therefore, designing an antenna whose frequency can be set accordingly to the end-user indigence is highly required.

Taking into consideration the end-user performance requirements for future 5G devices, and current deficiencies in state-of-the-art antennas, it may be concluded that designing of a compact size flexible antenna, resonating at all the designated frequency bands for the 5G new radio (NR) is need of the time to realize the global 5G communication. Moreover, features like flexibility, independently controllable notch, the capability to suppress unwanted sub-bands, with good responses in term of return loss, bandwidth and radiation characteristics are still challenging for the researchers.

This paper presents a prototype of on-demand wide-band to triband frequency switchable flexible antenna for 5G sub-6-GHz-band communication systems. The presented antenna is capable to exhibit wide-band and tri-band characteristics according to end-user requirements, by controlling independently notch-bands introduced by etching slots in its radiating element. The presented antenna in this manuscript is characterized by a compact size, good return loss, and an acceptable omnidirectional gain, making it a suitable candidate for sub-6-GHz antenna for the future 5G communications. The rest of the paper is organized in the following sections; Section 2 discusses the

antenna topology and design, while Section 3 presents a comparison between simulated and measured results of the proposed antenna, then our work is concluded at the end.

The main contribution of this paper may be summarized as follow:

- To the best of authors’ knowledge, it is very first antenna targeting specifically 5G mid-band applications with on-demand switching ability for wide-band to tri-band characteristics.
- The presented antenna consists of simple geometry which minimizes the fabrication errors with mass-production suitability, while, flexibility analysis proves its stability to be used in flexible devices.
- Moreover, stable radiation pattern, moderate gain and compact size make the presented work a potential candidate for 5G mid-band applications.

2. Antenna Topology and Design

The schematics of the proposed antenna is shown in Fig. 1. The antenna geometry consists of an octagonal patch fed by a Co-Planar Waveguide (CPW), where a stub is introduced along the feedline which significantly enhances the bandwidth of the antenna. Finally, two hexagonal slots were utilized to introduce two notch bands, which can be easily controlled by changing the length of the slots. The conducting part of the antenna is made up of copper having a standard thickness of 0.035 mm, is printed on ultra-thin ROGERS RO4835T ($\tan\delta = 0.003$ and $\epsilon_r = 3.52$) having a thickness of 0.064 mm [21]. The simulations are carried out in High Frequency Structural Simulator (HFSS) while Microwave CST is used to analyze conformability analysis of the proposed antenna. Optimized

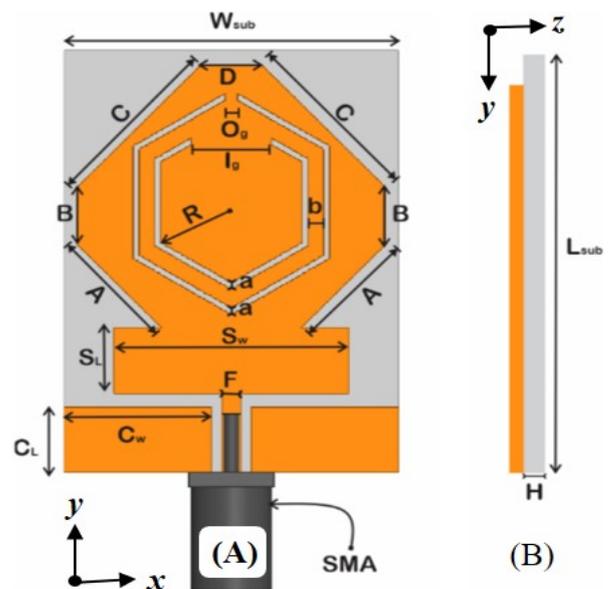


Fig. 1. Geometry of the proposed printed monopole antenna: (A) Front view and (B) side view.

parameters of the proposed antenna are as follow: $W_{\text{sub}} = 25$ mm, $L_{\text{sub}} = 32$ mm, $H = 0.064$ mm, $C_1 = 5$ mm, $C_w = 11$ mm, $S_L = 5$ mm, $S_w = 17.5$ mm, $F = 1.6$ mm, $A = 6.3$ mm, $B = 4.4$ mm, $C = 9.1$ mm, $D = 4.8$ mm, $O_g = 1$ mm, $I_g = 6$ mm, $a = 0.5$ mm, $b = 1.2$ mm, and $R = 6.1$ mm.

2.1 Design of the Wide-band Antenna

Initially, a CPW fed octagonal shaped antenna was designed to resonate at 3 GHz. The octagonal monopole antenna was extracted from the conventional rectangular monopole antenna whose length (L_t) can be approximated by using the equation

$$L_t = \frac{c}{2f_n \sqrt{1 + \frac{\epsilon_r}{2}}} \quad (1)$$

Here c is speed of light, f_n is fundamental resonating frequency, while ϵ_r is relative permittivity of the substrate.

Later, the lower and upper edges of rectangular radiator were truncated to further enhance the bandwidth of the antenna. A detailed discussion on effects of truncating ends of patch antenna on bandwidth has been explained briefly in [8]. The resultant antenna shows an impedance bandwidth of 480 MHz (2.7–3.18 GHz). Although the antenna has a compact size of 27 mm × 32 mm with good performance, still it lags in covering complete 5G sub-6-GHz-band allocated globally. In literature researchers adopted different techniques including fractal geometries [23], insertion of stubs [24], [25], and so on to achieve wide-band. Therefore, to further enhance the bandwidth of the antenna a rectangular stub was introduced at the bottom of patch. Thus by tuning the length and width of the stub impedance bandwidth increases more than 100% as compared to its parent antenna design. In fact, due to insertion of stub the surface charge distribution of radiator gets disturbed and starts supporting multiple resonances unlike the single resonance possessed by octagonal antenna. Thus, required wide bandwidth was achieved by simply insertion of a rectangular stub and can be control by detuning of length and width of the stub. The simulated return loss of the conventional patch antenna and wide-band stub loaded antenna are presented in Fig. 2. It can be seen clearly that octagonal patch has the narrow band as compared to the stub loaded antenna which covers the impedance bandwidth of 2.5 GHz (2.85–5.35 GHz) for $|S_{11}| < -10$ dB.

2.2 Design of Tri-band Antenna

Although a compact size wide-band antenna is designed in the previous section, however, different countries have allocated different band spectrums for 5G which lies inside this wide-band spectrum. While some other well-known commercial bands like WiMAX, 4 GHz C-band and others also exist in sub-6-GHz-band. Therefore, to avoid unwanted interference of 5G communication with other sub-bands, we introduce notch band in the antenna. Slots

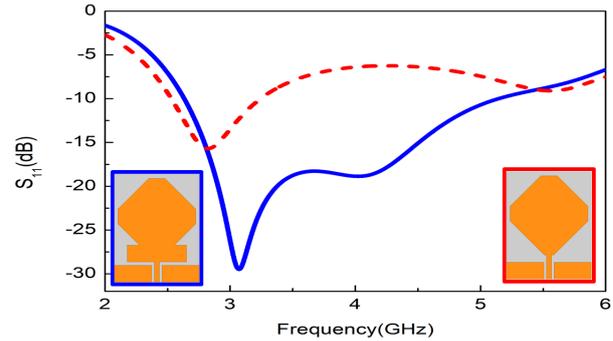


Fig. 2. $|S_{11}|$ of the conventional antenna and proposed wide-band antenna.

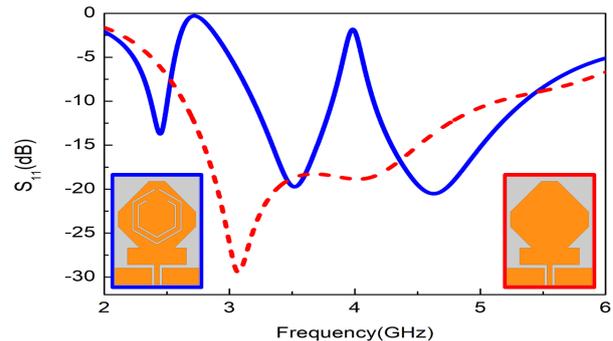


Fig. 3. $|S_{11}|$ of the proposed wide-band antenna with the proposed tri-band antenna.

are widely used to achieve notch bands in wide-band antennas, although the placement of the slots at the right position is the biggest challenge for the researchers [24]. Thus, a judicious analysis was carried out in order to identify the correct position of the slot. The length of these slots can be find using the following formula (2):

$$f_{\text{notch}} = \frac{c_0}{2L_{\text{slot}} \sqrt{\epsilon_e}} \quad (2)$$

where f_{notch} is the central frequency of the slot, L_{slot} is the total length of the slot, c_0 is the speed of light in free space and ϵ_e is effective dielectric constant and can be calculated by $(\epsilon_r + 1)/2$.

The first slot was introduced to mitigate the 4 GHz C-band while the second slot is utilized to stop the interference of Wi-Max band. Depending upon user requirements these notch bands can easily be controlled by changing the dimensions of slots. The simulated $|S_{11}|$ for wide-band and the tri-band antenna is depicted in Fig. 3. It can be seen that return loss shows high value in the band-stop region while a low value of > -20 dB is observed in band-pass resonance.

2.3 Independently Controllable Notch Bands

Since the past decade, on-demand frequency switchable antennas with independently controllable notch bands gain considerable attention due to ease of controlling notch bands according to user requirements [24]. The flexible antennas having the functionality of independently con-

trollable notch bands are suitable for modern flexible devices. Thus, the wide-band antenna presented in Sec. 2.1 is converted into a tri-band antenna in Sec. 2.2 in such a way that the individual notch bands can be controlled easily without effecting the other bands. Figure 4 presents the parametric analysis of the slots. It can be seen from Fig. 4(A) that changing the value l_g only affects the resonance of the second notch band, while the first notch band remains unchanged. A similar phenomenon is observed in Fig. 4(B) when we change the value of O_g . The effect of these slots can better be analyzed by using surface current (J_{surf}) distribution at the notch bands, as shown in Fig. 5. It can be seen that the maximum current density at 2.6 GHz is concentrated across the outer slot (Fig. 5(A)), which is responsible to mitigate the lower band. Similarly, as shown in Fig. 5(B), the maximum current density at 4 GHz is across the inner slot in case of lower notch band, which is responsible for the notching behavior in the upper band. In both cases, the current density is concentrated around one

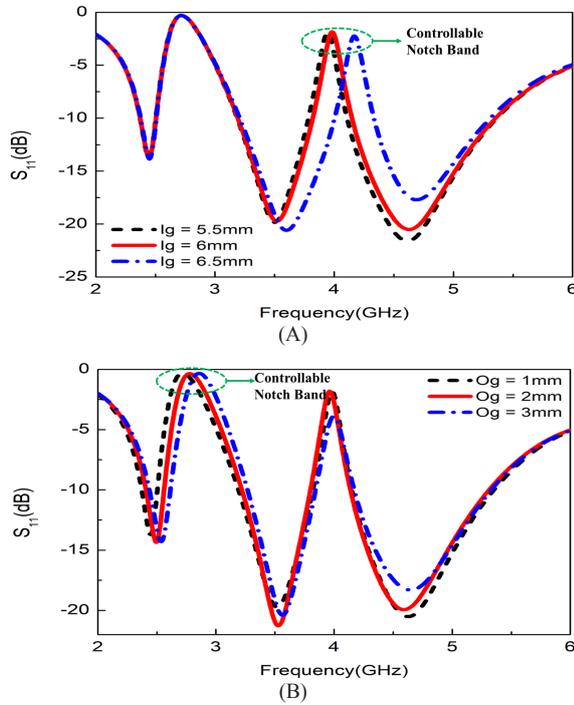


Fig. 4. Parametric analysis of the length of the slot to independently control (A) upper notch band and (B) lower notch band.

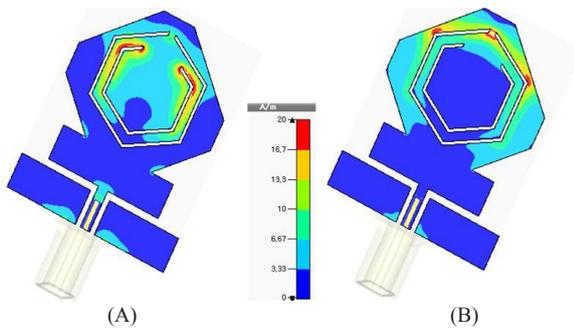


Fig. 5. Surface current (J_{surf}) of the proposed tri-band antenna at (A) 2.6 GHz and (B) 4 GHz.

slot while the other slot has a negligible current, which enables the easy and independently controlling of the pass-band and the rejection band.

3. Result and Discussion

In order to demonstrate the validity of the proposed antenna for 5G mid-band applications, a prototype of the proposed antenna is fabricated and measured.

3.1 Return Loss

Figure 6(A) presents simulated and measured return loss results of the wide-band antenna without notching characteristics. It is clearly shown from the plot that simulated and measured results are in good agreement. Both simulated and measured antennas are covering the same bandwidth, ranging from 2.85 to 5.35 GHz, i.e. 50% of FBW, with a minimum reflection coefficient equal to -28.58 dB. On the other hand, Figure 6(B) shows both simulated and measured return loss response of the proposed antenna with notching characteristics. The simulated results agree well with the measured results. The antenna rejects two on-demand frequency bands, that is from 2.5–3 GHz and 3.9–4.1 GHz. Therefore, the proposed antenna is resonating at three different operating frequencies, which are 2.45, 3.5, and 4.7 GHz, with return loss coefficients equal to -15 dB, -19 dB, and -22 dB, respectively. It is worth noting that these pass-bands cover the frequency bands allocated for 5G NR at sub-6-GHz.

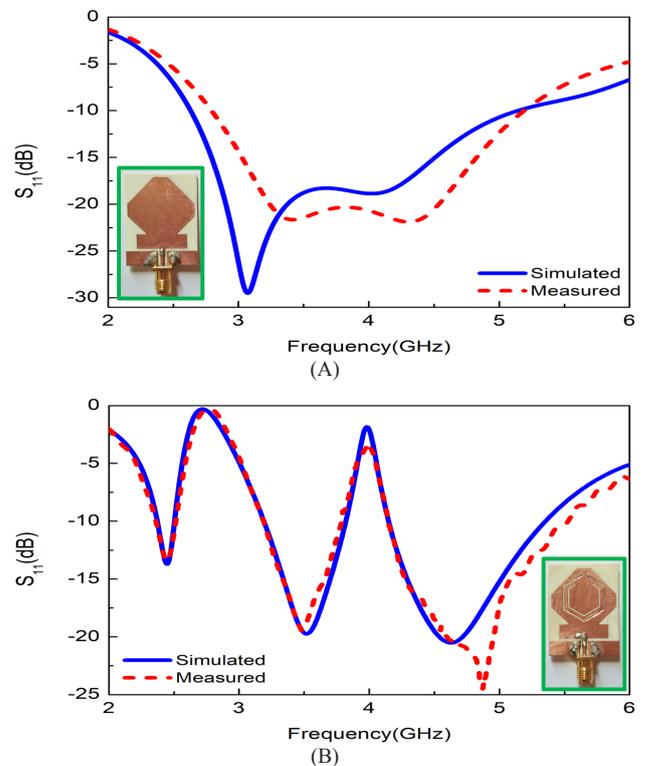


Fig. 6. Return loss comparison: (A) wide-band antenna and (B) tri-band antenna.

3.2 Peak Gain

The realized peak gain of the proposed antenna, which describes the input power concentration in the main beam direction is investigated in Fig. 7. The simulated and measured peak gain results of the proposed antenna without notching characteristics are plotted in Fig. 7(A). The gain increases from 2.5 dBi to 3.75 dBi all along the covered spectrum demonstrating a good agreement between the simulated and its counterpart. However, the gain of the tri-band antenna (Fig. 7(B)) reduces to negative values exactly at the cut-off frequencies that we are aiming to reject, while shows the stable and moderate gain levels at the pass-bands.

3.3 Radiation Pattern

Figure 8(A–F) presents simulated and measured radiation pattern plots of both wide-band and tri-band antenna, in *E*-plane ($\phi = 0^\circ$) and *H*-plane ($\phi = 90^\circ$). The wide-band antenna exhibits an omnidirectional radiation pattern in *E*-plane along with a bidirectional radiation pattern in the *H*-plane at all the investigated frequencies (3.5, 4.2, and 4.6 GHz) as shown in Fig. 8(A–C), which proves the stability of the proposed antenna over the entire band. Moreover, a good agreement between simulated and measured results is noticed. The same observations are noticed for the tri-band antenna as depicted in Fig. 8(D–F), demonstrating the identical radiation patterns at the desired frequency bands.

3.4 Conformability Analysis

In this section, we carried out conformability tests on the proposed wide-band and tri-band antenna to validate

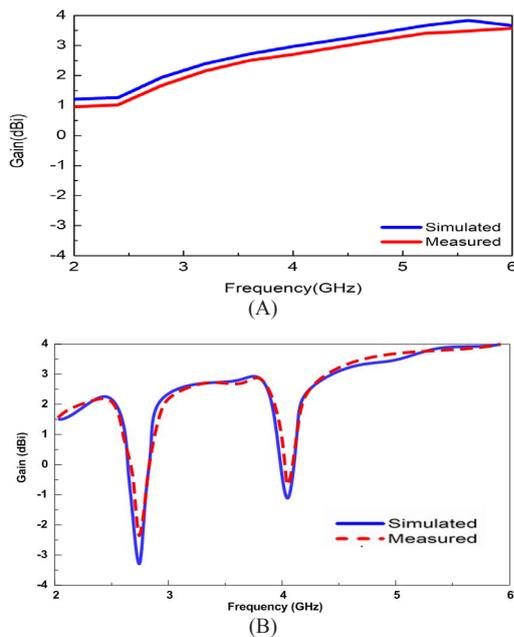


Fig. 7. Realized peak gain vs. frequency plot comparisons of (A) wide-band antenna and (B) tri-band antenna.

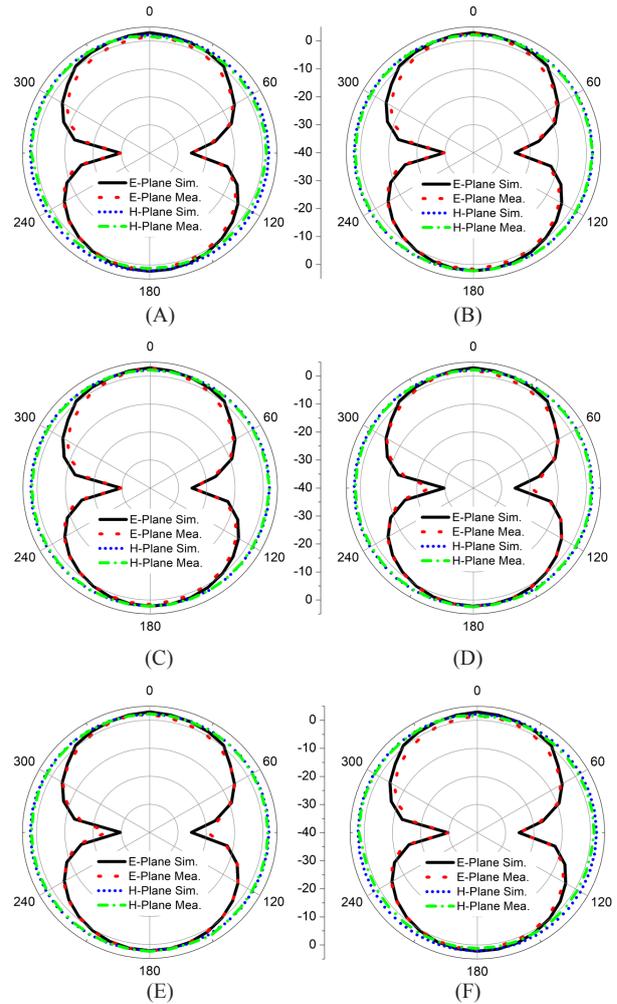


Fig. 8. Comparison of simulated and measured radiation patterns of wide-band antenna [(A) 3.3 GHz, (B) 3.5 GHz, (C) 3.7 GHz] and tri-band antenna [(D) 2.5 GHz, (E) 3.5 GHz, (F) 4.6 GHz].

their flexibility. To do so, the ultra-thin antenna is bent for the various radii (S) of the cylinder. For measurement purposes, styrofoam of various radius is used, while the antenna is wrapped around it. The measured results and their comparison with simulated ones are presented. Figure 9 shows the conformability analysis comparison between simulated and measured results of the antennas. A good agreement between simulated and measured results is observed for the wide-band antenna as well as the tri-band antenna. It can be seen that the antennas have a negligible effect on the return loss for various bending radius. A similar phenomenon is also observed in the reported antennas [25]. Thus, it can be concluded that the proposed antenna can be used in flexible devices without deteriorating its performance.

3.5 Comparison with State-of-the-Art Works

Table 1 presents a comparison of the proposed antenna with similar state-of-the-art works [12, 13, 17–19, 26, 27]. It can be seen that this design has a miniaturized size compared to the designs presented at [12, 13, 17, 18, 26, 27],

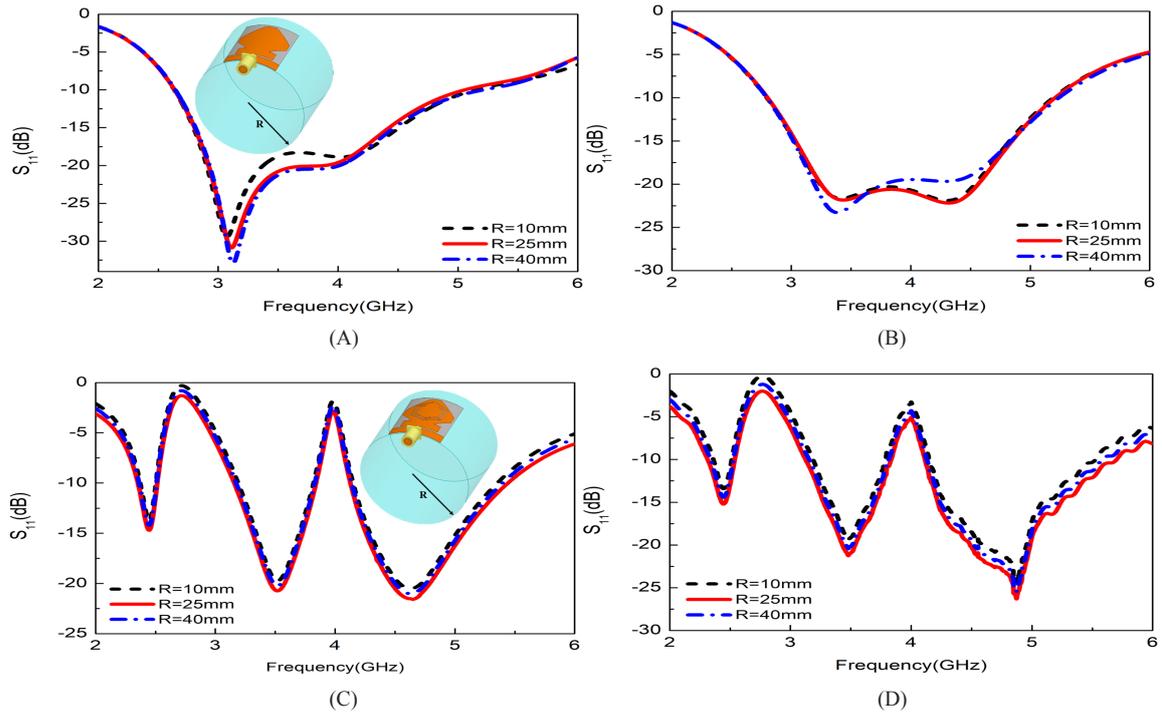


Fig. 9. Performance analysis of the conformal wide-band antenna [(A) simulated, (B) measured] and tri-band antenna[(C) simulated, (D) measured].

Sr. No.	Dimension (mm ²)	Operation Mode	Bandwidth (GHz)	Peak Gain (dBi)	Flexibility
[12]	70 × 70	single-band	3.14–3.83	8.6	No
[13]	200 × 200	single-band	1.71–2.83	>8	No
[17]	60 × 75	single-band	7–13	5	Yes
[18]	35 × 53	single-band dual-band	3.4–4.2 2.3–2.5/5.2–5.5	2.5 1.7/3.4	No
[19]	23 × 31	single-band dual-band	2.8–4.5 2.7–4.2/6–7.2	4.01 4.60/4.6	No
[26]	30 × 60	dual-band	2.52–2.62/3.31–3.64	2.39/1.75	Yes
[27]	31 × 59	single-band dual-band	2.34–2.5 2.27–2.45/3.5–3.77	1 0.7/0.79	Yes
This Work	25 × 32	single-band tri-band	2.85–5.35 2.35–2.5/3.18–3.82/4.15–5.42	3.75 2.1/2.8/3.5	Yes

Tab. 1. Performance comparison of the proposed antenna with other state-of-the-art works in literature.

having the additional functionalities of structural conformability and frequency switching capability. Although the antenna reported in [19] offers the advantages of compact size, it has a setback of a rigid body which limits its usage in modern flexible devices. Moreover, no solution is proposed to mitigate the specific band from 5G mid-band spectrum. In conclusion, the proposed antenna, characterized by a stable gain, frequency switching, structural flexibility, and independently controllable notch band can be considered as a potential candidate for both rigid and flexible devices operating in 5G sub-6-GHz band spectrum.

4. Conclusion

A flexible wide-band to tri-band frequency switchable antennas with independently controllable notch bands for 5G sub-6-GHz communication systems is presented. A wide impedance bandwidth is achieved using a stub,

while slots were utilized to achieve two independently controllable notch bands. Moreover, a good agreement between the simulated and measured results validates our findings. The properties like compact size, conformability, stable gain, omnidirectional radiation pattern, and independently controllable notch bands make it a potential candidate for the 5G mid-band applications.

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