The bending effects on the performance of a flexible circular microstrip antenna on rubber-carbon substrates at 2.45 GHz

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ABSTRACT

In this paper, we studied the effects of bending on the performance of a flexible circular microstrip antenna on rubber-carbon substrates at the 2.45 GHz industrial, scientific, and medical (ISM) band. Several rubber compositions are analyzed which include natural rubber (no carbon filler), rubber with 20% carbon filler, rubber with 25% carbon filler, and rubber with 50% carbon filler. Four types of bending directions are applied in this work i.e., side-inward, side-outward, top-inward, and top-outward with bending radius ranging from 100-500 mm. It is observed that even though the resonant frequency of the antenna shifted a bit when bending is applied, the S_{11} at the intended frequency remains below -10 dB. The bandwidth and gain also maintain an acceptable performance despite all the directions and radius of the bending, due to the wide bandwidth characteristics of the antenna. With these results, the proposed antenna is shown to be usable for wearable applications at 2.45 GHz, in both flat and bent conditions. We also show that it is essential to design a flexible antenna with a wide bandwidth to guarantee that the antenna maintains optimal performance even under curved conditions.

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1. INTRODUCTION

Antennas play a crucial role in communication systems by enabling wireless information transmission and reception between two locations. The antenna for a particular application should be carefully chosen and constructed to maintain data accuracy and integrity. Some applications require high gain to support their operation, for transferring long-range information such as in satellite communication [1], [2]. Medical applications on the other hand, need the antenna to exhibit a wide bandwidth [3]-[5], have a compact structure, and most importantly be adaptable to the human body [6], [7]. Considering the application that involved the integration of the body with uneven surfaces, the designed application must have the physical ability to be bendable, stretchable, and conform to the human physique. The ability to be stretchable is critical in designing this application to adapt to the constraints caused by body gestures and movements. Conventional antennas are not suitable to be used in wearable applications that involve these uneven surfaces as they are not flexible, have brittle frameworks, and are not elastic [8].

A microstrip patch antenna is preferable to be used for many types of applications due to its compact size, low cost, and high efficiency [9]. A lot of research have been and are currently conducted to realize a more flexible and robust structure for wearable microstrip antennas. Instead of using conventional materials such as FR4 and RT-Duroid, flexible substrates like polydimethylsiloxane (PDMS) [10], RO3003 [11], [12], kapton polyimide [13]-[15], silicone [16], [17], and rubber [18]-[24] can be used for this purpose. Rubber is claimed to be fitting to be used as an antenna substrate due to its ease of manufacturing, low production cost, stable electrical properties, and high elasticity [18]. By compositing rubber with carbon filler, the dielectric constant and loss tangent of this composite can be varied, providing flexibility in designing the antenna [19]. On top of that, rubber can be accessed easily in Malaysia as it is one of the main export industries of the country [20]. In related works, the antenna proposed by [21] shows that the rubber can be used in antenna design to operate within the industrial, scientific and medical (ISM) band with an excellent return loss value of -31.03 dB with 4.06 dBi gain at 2.45 GHz. Another work by [22] also featured a rubber-based ISM antenna which exhibits a good return loss of -18.0 dB with 3.94 dBi gain at 2.45 GHz. These resources show that antennas on a rubber substrate are workable to be applied within the ISM band.

There are a lot of other research involved in flexible antennas to date [25]-[28], but not much are paying attention to the effects of antenna bending, which could possibly affect the whole performance of the antenna. Most of the investigations claimed that the antenna was flexible without proving and executing the antenna bending. This is important to show and prove that the antenna can at least radiate with the same performance as in flat conditions. As reported by [10], [14], [15], [21], [29], frequency shifting mostly occurs when the antenna is curved, which can impact the whole performance at the intended frequency. Variations to the bending directions and angles are also important to prove the antenna's ability to perform well in different bending conditions.

In this work, we conducted a thorough study on the effects of bending on a flexible circular microstrip antenna which is proposed to be used at 2.45 GHz for many wearable applications in ISM band such as medical, Wi-Fi, or WLAN. The antenna has been varied using different rubber-carbon compositions which are natural rubber (no carbon filler), rubber with 20% carbon filler, rubber with 25% carbon filler, and rubber with 50% carbon filler. Two other commonly used flexible antennas; PDMS and RO3003 are also included in the result section for comparison purposes. The performance is measured in terms of S_{11}, bandwidth and gain, where various bending conditions are applied. This project will execute different bending angles and directions to get a more comprehensive observation and result of the bending effects on the performance of the antenna. The bending angles are varied in the range of 100-500 mm cylindrical radius, with four bending directions: i) side-inward, ii) side-outward, iii) top-inward, and iv) top-outward. With this effort, hopefully, a more comprehensive flexible antenna design for wearable implementations can be realized in the future.

2. METHODOLOGY

This project is divided into several stages. First, the best composition of rubber and carbon were studied corresponding to the intended frequency of 2.45 GHz for ISM band applications. Second, the properties of the material (i.e., percentage ratio of carbon to rubber) were computed, and the antenna geometry was designed and simulated using computer simulation technology Microwave Studio software (CST MWS). Next, continuous optimization of the antenna parameters was conducted to achieve the best performance in terms of S_{11}, bandwidth and gain. Following this, analysis with different combinations of bending directions and angles (cylindrical radius) was conducted to investigate the bending effects on the antenna performance. Finally, comparison study of the proposed antenna with other flexible ISM antenna available in the literatures were presented to highlight the importance and novelty in this work.

The CST MWS was used to design and simulate the circular microstrip antenna. As the percentage of the carbon used in forming the rubber-carbon composite varied, the dielectric constant and the loss tangent of the substrate are expected to vary as well. Based on the conducted studies, four different compositions of rubber-carbon composite were used in this work which include natural rubber, rubber with 20% carbon filler, rubber with 25% carbon filler, and rubber with 50% carbon filler. The properties of the dielectric constant of rubber-carbon composites are tabulated in Table 1 [18]. Based on these data, natural rubber has a dielectric constant of 3.0 with 0 loss tangent, while rubber with 20% carbon filler has a dielectric constant of 4.6 with 0.0251 loss tangent. The dielectric constant and loss tangent value change as the carbon contents increase. The rubber with 25% carbon filler has a dielectric constant of 4.2 with 0.0311 loss tangent, and the highest dielectric constant and loss tangent value is observed on rubber with 50% carbon filler which has a dielectric constant of 8.8 with 0.0558 loss tangent.

The dielectric constant and loss tangent of the materials are set accordingly in CST MWS. By using the parameters of the rubber-carbon substrate from the conducted study, the properties of the materials can be set as desired using the built-in feature in CST MWS. Table 1 also displays the optimal antenna's parameters, where R_p stands for the patch's radius, W_f for the feeding line's width, D_h for the dielectric height, D_l for the dielectric length, D_w for the dielectric width, G_l for the ground length, G_w for the ground width, tan δ for the loss tangent, and $\mathcal{E}$ for the dielectric constant. Copper serves as the patch and ground plane, where a variety of rubber substrate compositions, including natural rubber, rubber with 20%, 25% and 50% carbon filler [30].

Table 1. The parameters and dimensions of the flexible circular microstrip antenna on various rubber-carbon compositions [30]

Parameters	R_p (mm)	W_f (mm)	D_h (mm)	D_l (mm)	D_w (mm)	G_l (mm)	G_w (mm)	tan δ	$\mathcal{E}$
Natural rubber	23.15	15.68	42.29	84.94	139.19	84.94	139.19	0	3.0
Rubber and 20% carbon filler	18.15	11.03	36.19	75.24	111.19	75.24	111.19	0.0251	4.6
Rubber and 25% carbon filler	19.69	12.45	39.59	64.04	112.54	64.06	112.54	0.0311	4.2
Rubber and 50% carbon filler	15.28	5.34	26.09	71.48	90.06	71.48	90.06	0.0558	8.8

The proposed antenna is then bent to observe the impact of bending on the performance of the antenna. This action can be executed by using the built-in function in CST MWS. The local WCS axis is manipulated to have four different types of bending directions which include side-inward, side-outward, top-inward, and top-outward. After defining the WCS axis, the antenna can be curved using the 'Cylindrical Bend' feature. The bending radius can be set by properly inserting the radius of the cylinder as shown in Figure 1. The cylindrical radius is also varied to obtain a more comprehensive result [29], which varies from 500 mm (minimum bending) to 100 mm (maximum bending) for every composition.

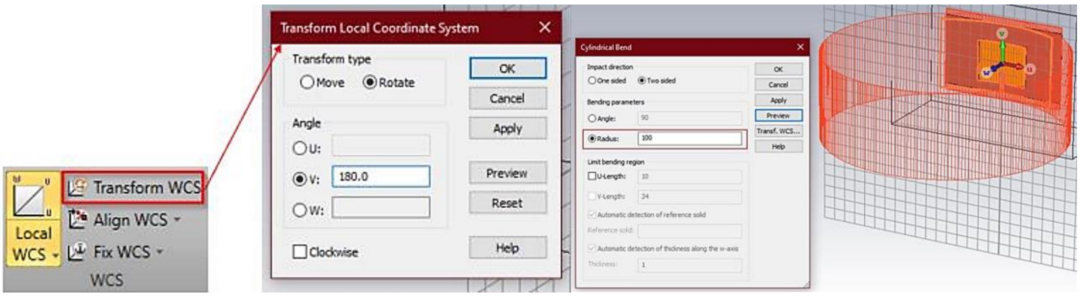

Figure 1. The process of defining the bending radius in CST MWS

3. RESULTS AND DISCUSSIONS

Figure 2(a) shows the S_{11} of the antenna on natural rubber and rubber with varying carbon filler content (20%, 25%, and 50%) at 2.45 GHz in a flat condition. All antennas resonate at 2.45 GHz, with S_{11} values ranging from -17.36 dB to -26.46 dB as carbon content increases. The bandwidth also increases with carbon filler, from 1147.1 MHz for natural rubber to 2314.9 MHz for rubber with 50% carbon filler, consistent with the rise in loss tangent. This supports the claim made by Razali *et al.* [19] that a rise in antenna loss tangent causes a bandwidth increase. According to these findings, the antenna with 50% carbon infill is recorded to have the broadest bandwidth. This outcome was anticipated given that the loss tangent value for rubber with 50% carbon filler was the highest among all four; tan δ=0.0558, which can be seen in Table 1. Following this, the same antenna design is further investigated by bending the structure which is critical to validate the flexibility of the wearable antenna. Four types of bending directions are applied in this work, which include side-inward (Figure 2(b)), side-outward (Figure 2(c)), top-inward (Figure 2(d)), and top-outward bending (Figure 2(e)).

3.1. Side-inward bending

Figures 3(a)-(d) compares the S_{11} parameter for natural rubber and rubber with varying carbon filler content (20%, 25%, and 50%) during side-inward bending. It also presents the antenna's bandwidth (Figure 3(e)) and gain (Figure 3(f)), with a bending radius ranging from 500 mm (minimum) to 100 mm (maximum). For side-inward bending, the antenna's performance at 2.45 GHz remains stable with S_{11} values below -10 dB, even with varying bending radii. There is a shift in operating frequency, but the wide bandwidth ensures 2.45 GHz remains within range. The antenna's gain stays relatively high (6-9 dB) with minimal variation, except for the rubber with 50% carbon filler, which shows lower gain (~3.8 dB). Rubber with 50% carbon filler exhibits the widest bandwidth (>2,000 MHz), with the highest gain observed in the natural rubber substrate (9.24 dB).

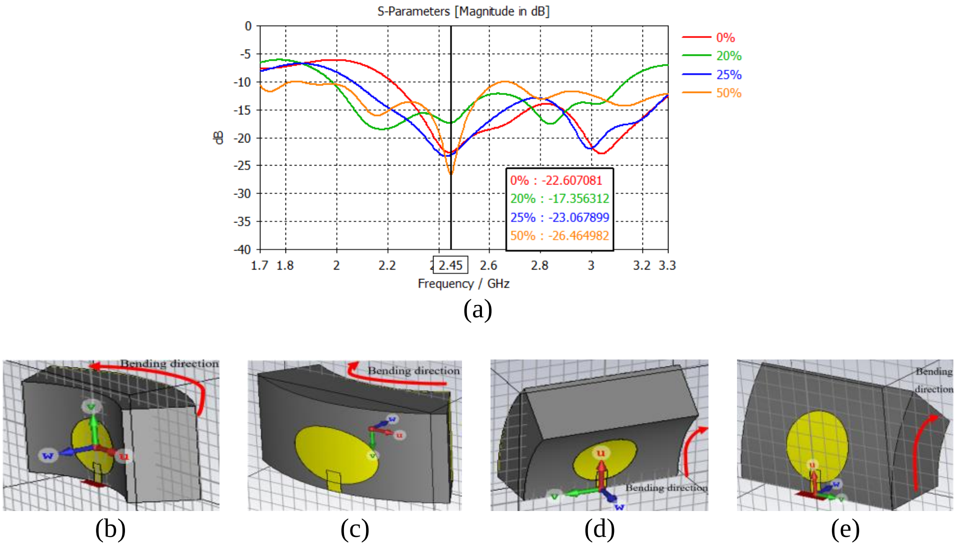

Figure 2. Simulation performance of: (a) S_{11} in flat condition, and applying, (b) side-inward bending, (c) side-outward bending, (d) top-inward bending, and (e) top-outward bending

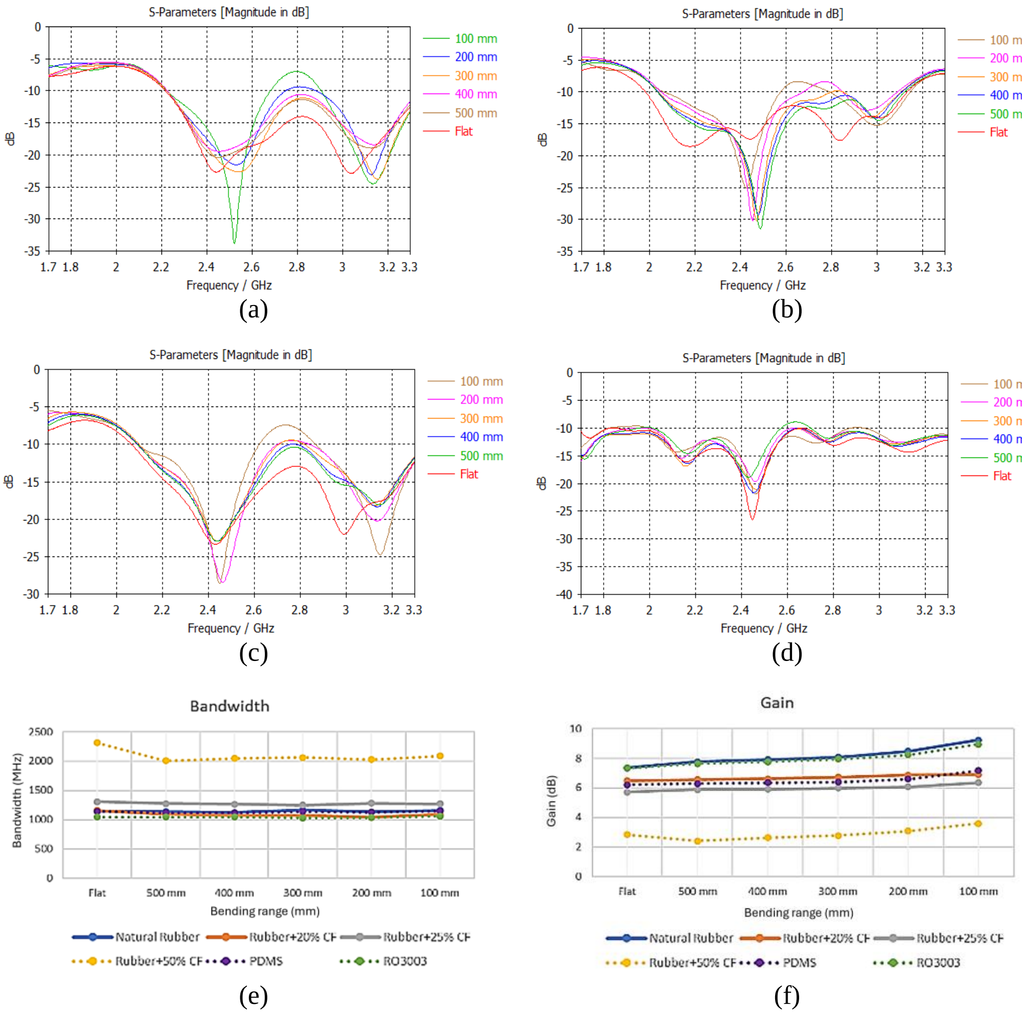

Figure 3. Simulated performance of the antenna applying side-inward bending comprising of: (a) S_{11} on natural rubber, (b) S_{11} on rubber with 20% carbon, (c) S_{11} on rubber with 25% carbon, (d) S_{11} on rubber with 50% carbon, (e) bandwidth, and (f) gain

3.2. Side-outward bending

The S_{11} parameter for natural rubber and rubber with varying carbon filler percentages (20%, 25%, and 50%) during side-outward bending are displayed in Figures 4(a)-(d). Additionally, with a bending radius ranging from 500 mm to 100 mm, it displays the antenna's bandwidth (Figure 4(e)) and gain (Figure 4(f)). For side-outward bending, the S_{11} at 2.45 GHz remains below -10 dB for antennas on various substrates, though performance degrades compared to flat conditions. Despite degradation, the antennas continue to function effectively, with the rubber-carbon composites maintaining S_{11} below -10 dB. Rubber with 50% carbon filler shows the highest bandwidth (2429.8 MHz), while natural rubber provides the highest gain (7.36 dB). However, the gain decreases as the bending angle increases, particularly for rubber with 50% carbon filler.

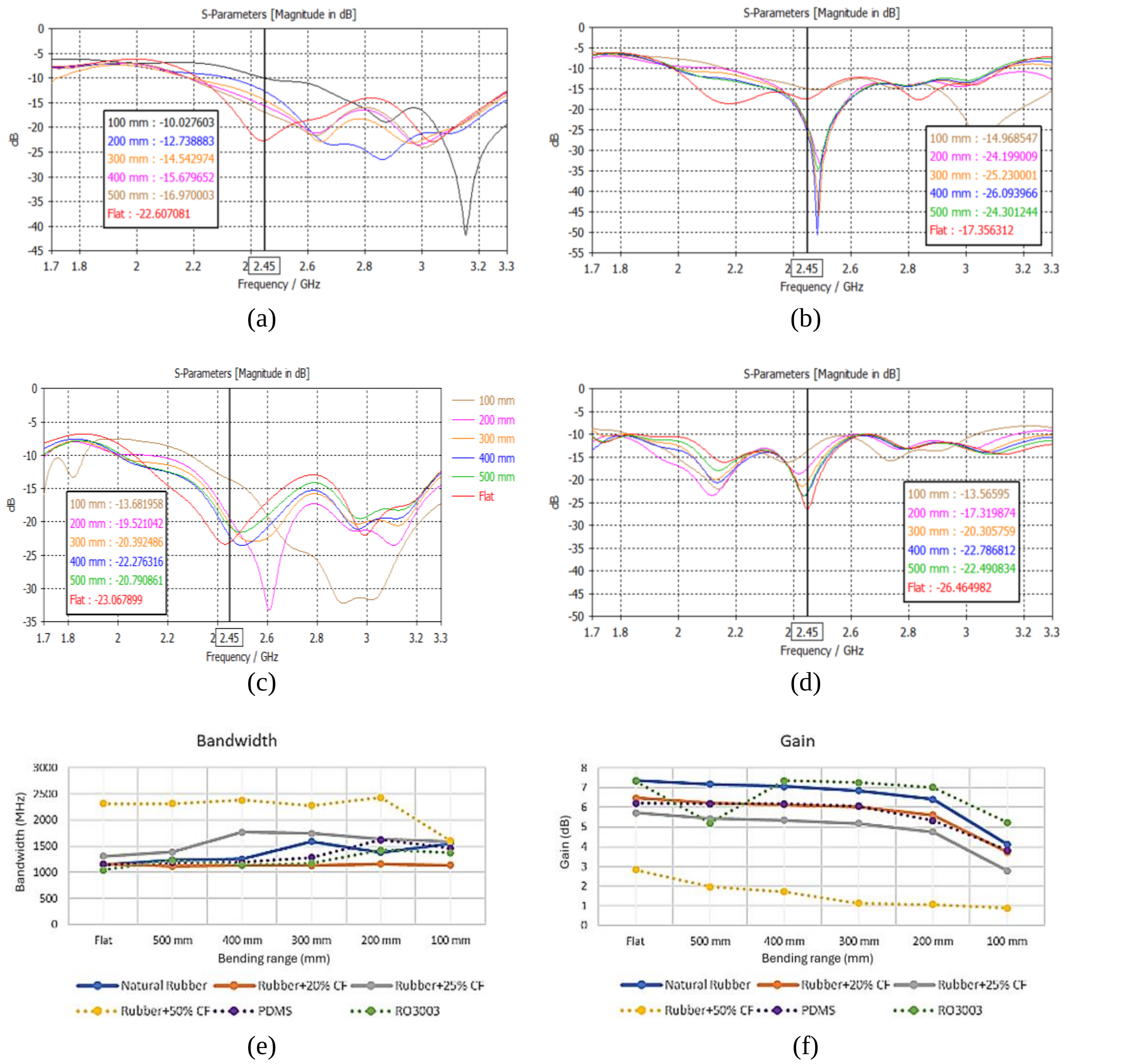

Figure 4. Simulated performance of the antenna applying side-outward bending comprising of: (a) S_{11} on natural rubber, (b) S_{11} on rubber with 20% carbon, (c) S_{11} on rubber with 25% carbon, (d) S_{11} on rubber with 50% carbon, (e) bandwidth, and (f) gain

3.3. Top-inward bending

Figures 5(a)-(d) compares the S_{11} parameter for natural rubber and rubber with varying carbon filler content (20%, 25%, and 50%) during top-inward bending. It also presents the antenna's bandwidth (Figure 5(e)) and gain (Figure 5(f)), with a bending radius ranging from 500 mm (minimum) to 100 mm (maximum). For top-inward bending, the antenna's S_{11} at 2.45 GHz remains below -10 dB across all bending radii, though performance is slightly worse than in flat conditions. Rubber with 50% carbon filler has the widest bandwidth (2318.9 MHz), with consistent performance in both flat and bent conditions. Natural rubber substrate shows the highest gain (8.43 dB) at maximum bending but gain generally increases with bending angle for all substrates. Rubber with 50% carbon filler shows low gain (~1 dB) under severe bending conditions.

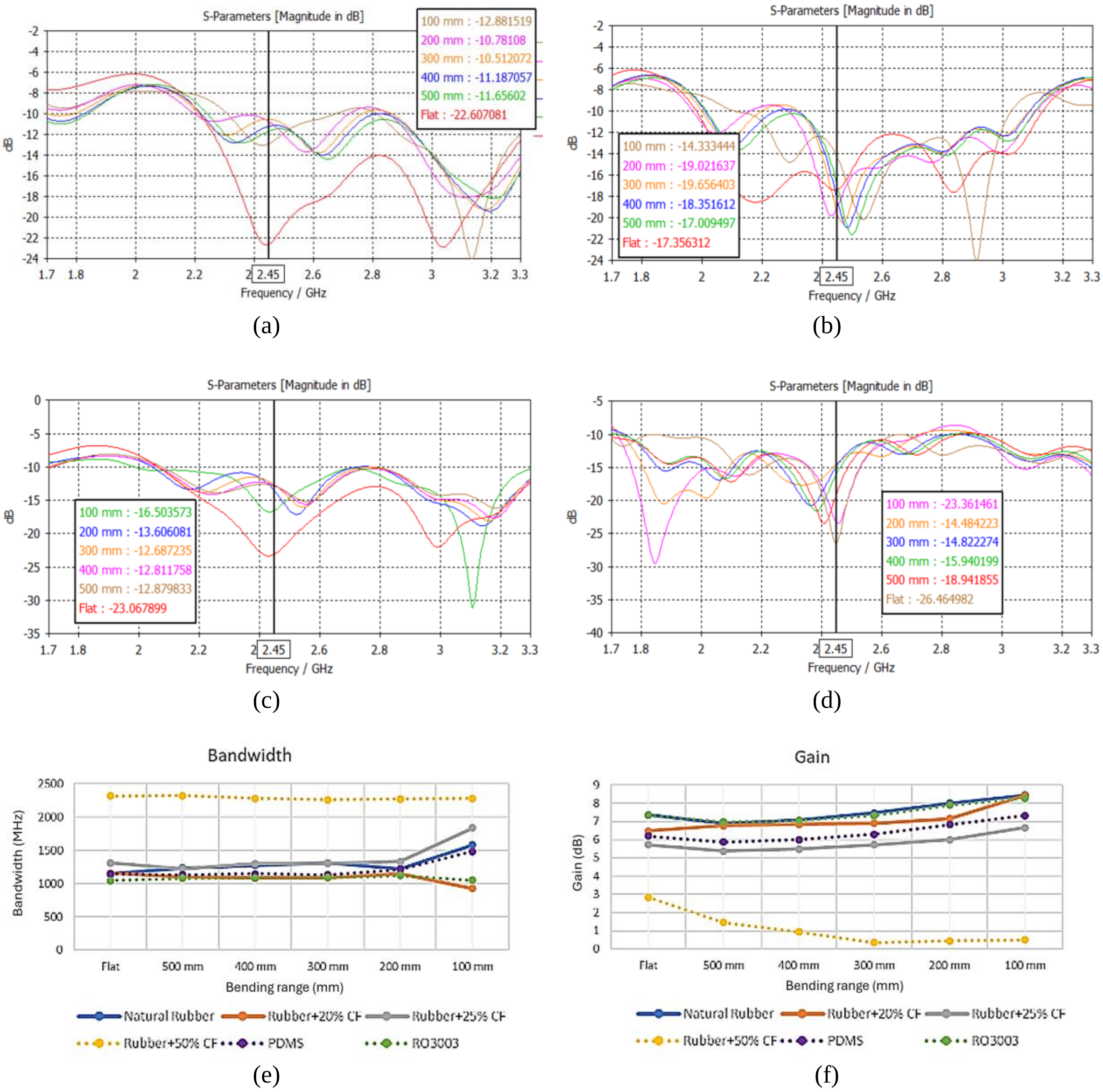

Figure 5. Simulated performance of the antenna applying top-inward bending comprising of: (a) S_{11} on natural rubber, (b) S_{11} on rubber with 20% carbon, (c) S_{11} on rubber with 25% carbon, (d) S_{11} on rubber with 50% carbon, (e) bandwidth, and (f) gain

3.4. Top-outward bending

The S_{11} parameter for natural rubber and rubber with varying carbon filler percentages (20%, 25%, and 50%) during top-outward bending are displayed in Figures 6(a)-(d). Additionally, with a bending radius ranging from 500 mm to 100 mm, it displays the antenna's bandwidth (Figure 6(e)) and gain (Figure 6(f)). For top-outward bending, the S_{11} remains below -10 dB at 2.45 GHz, but performance is inferior compared to flat conditions. Rubber with 50% carbon filler provides the widest bandwidth (2314.9 MHz), while other substrates have moderate bandwidths (1000-1500 MHz). The highest gain (7.36 dB) is observed with the natural rubber substrate in flat conditions, while rubber with 50% carbon filler consistently shows the lowest gain (~3 dB), which further decreases under bending.

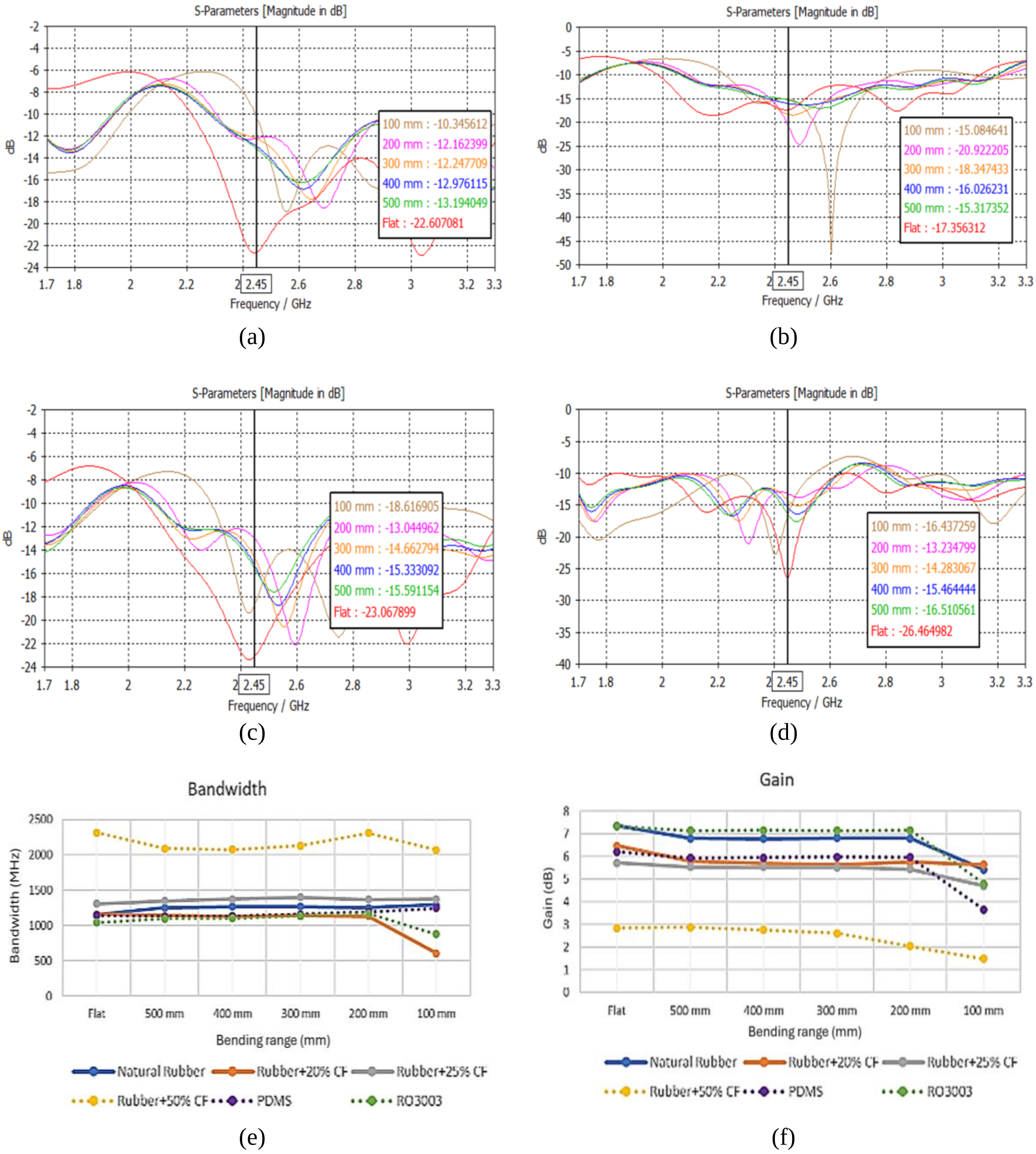

Figure 6. Simulated performance of the antenna applying top-outward bending comprising of: (a) S_{11} on natural rubber, (b) S_{11} on rubber with 20% carbon, (c) S_{11} on rubber with 25% carbon, (d) S_{11} on rubber with 50% carbon, (e) bandwidth, and (f) gain

In light of these findings, we strongly advise developing a wearable flexible antenna with a broad bandwidth to guarantee that the antenna maintains optimal performance even in bent conditions. To summarize, our proposed antenna offers a more comprehensive analysis of bending effects compared to other flexible ISM antennas in the literature, as shown in Table 2. It examines four bending directions (i.e., side-inward, side-outward, top-inward, and top-outward) and five bending angles (cylindrical radius ranging from 100-500 mm), maintaining an S_{11} of less than -10 dB across all conditions. However, bending leads to frequency shifts, resulting in decreased gain and bandwidth, a trend also observed in other studies by [10], [14], [15], [21]. Despite this, the proposed antenna still provides the necessary bandwidth for the ISM band at 2.45 GHz. This study highlights the importance of assessing bending effects in flexible antenna designs to ensure reliable performance in both flat and various bent conditions for wearable applications.

Table 2. Comparison of the proposed antenna in this work with other flexible ISM antenna available in literature in terms of S_{11}, bandwidth, gain, and bending study

Antenna	Flexible substrate	Freq (GHz)	S_{11} (dB)		Bandwidth (MHz)		Gain (dB)		Bending study
			Flat	Bent	Flat	Bent	Flat	Bent	
This work	Natural rubber	2.45	-22.61	<-10.0	1147.1	>1148.3	7.36	>4.23	4 bending directions and 5 bending angles
	Rubber and 20% CF		-17.36	<-14.0	1158.3	>586.5	6.56	>1.54	
	Rubber and 25% CF		-23.07	<-13.0	1308.3	>1284.8	5.83	>2.85	
	Rubber and 50% CF		-26.46	<-13.0	2314.9	>1564.4	2.92	>0.57	
[10]	PDMS	2.45	-18.0	<-14.0	100	>250	2.25	NR	1 bending direction and 3 bending angles
[14]	Kapton Polyimide	2.45	-32.0	<-1.5	NR	NR	3.27	NR	1 bending direction and 3 bending angles
[15]	Kapton Polyimide	2.45	-36.0	<-11.0	1707	>750	3.0	>0	1 bending direction and 2 bending angles
[21]	Natural rubber	2.45	-31.0	<-14.0	541.5	>105	4.06	>3.33	2 bending directions and 1 bending angle
[22]	Natural rubber	2.45	-18.0	-	<200	-	3.94	-	No bending study
[23]	Natural rubber	2.4	-49.7	-	NR	-	8.16	-	No bending study
[25]	Textile (jeans)	2.45	-35.0	-	<50	-	3.00	-	No bending study
[26]	Dupont	2.4	< -10.0	-	80.0	-	1.44	-	No bending study
[27]	Glossy paper PET	2.4	< -20.0	-	<1000	-	-2.31	-	No bending study
[28]	PDMS and glass	2.46	-11.3	-	NR	-	NR	-	No bending study

Bent refer to maximum bending applied in the work (worst scenario). CF=carbon filler and NR=not reported.

4. CONCLUSION

The performance of a flexible circular microstrip antenna on a rubber-carbon substrate is presented. Based on the simulation results of the proposed antenna, it can be concluded that the antenna design on natural rubber, rubber with 20%, 25% and 50% carbon filler, exhibits an acceptable S_{11}, bandwidth and gain at 2.45 GHz in flat conditions. To validate its flexibility for wearable applications, the effects of bending were investigated across four bending directions (side-inward, side-outward, top-inward, and top-outward bending) and five radii. Despite frequency shifts due to bending, the antenna's S_{11} stays below -10 dB, with bandwidth remaining suitable for the ISM band and gain within acceptable limits. Based on these results, we highly recommend designing a wearable flexible antenna with a wide bandwidth to ensure functionality under various bending conditions. Future work will explore different carbon filler percentages and include experimental validation of the simulated results.

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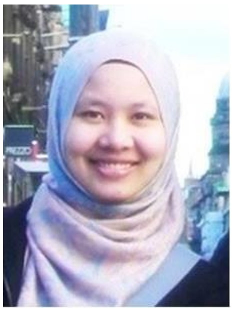

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