Flexible polymer/fabric fractal monopole antenna for wideband applications

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Abstract
A novel flexible polymer/fabric fractal monopole antenna with a wideband performance is presented. A thin sheet of highly conductive fabric and a natural rubber-based composite have been used for conductive and non-conductive parts of the antenna, which allow keeping the antenna as flexible and thin as possible. The proposed antenna has been simulated, prototyped and tested. Results show that the antenna has a simulated impedance bandwidth of 3.8 GHz (2.2–6.0 GHz) and a measured impedance bandwidth of 3.7 GHz (2.3–6.0 GHz) to cover the most commonly used standards in wireless communication systems. The radiation efficiency of the antenna reaches over 93% throughout the operating frequency band with satisfactory radiation patterns and gain.

1 | INTRODUCTION

Flexible antennas have recently attracted significant attention from both academia and industry due to their applications in personal communications, healthcare monitoring, sports, entertainment, rescue and public safety [1–3]. The shift from rigid to flexible and bendable antennas imposes the employment and investigation of different alternative conductive and substrate materials [4, 5]. Bendable materials such as conductive fabrics [6–8], liquid metal alloys [9], conductive fibres on textiles [10], polymer composites [1, 4, 6, 8, 11–17] and paper [18] have been widely used in current designs of flexible antennas. Various types of flexible antennas have been reported in the literature during the last years including monopoles [4, 6, 14, 19–21], dipoles [20], slot antennas [22], electromagnetic band gap backed monopole [23] and yagi-uda antennas [24], dipoles with a rectangular reflector [11, 13], artificial magnetic conductor surface backed Yagi antennas [25] and patch antennas [8, 15]. The majority of these antenna designs have a narrow bandwidth to cover only ISM 2.45 GHz [8, 11–13, 15, 20, 21, 23–25] and or WLAN 5.15–5.725/ISM 5.75–5.82 GHz [13, 21]. However, with the fast development of wireless communication systems, because of the requirement of higher data transfer rates, there is an increasing demand for wideband, low-profile and low-cost antennas [26, 27]. These antennas enable the same antenna to be used for multiple systems, which reduces the overall system size/weight. In References [1, 4, 6, 19], the authors present flexible broadband and ultra-wideband antennas. However, the bandwidth of most of these designs [1, 6, 19] does not cover some bands such as ISM 2.45 GHz, LTE2600 (Band 7) and WiMAX2500.

To address the problems above, in this work, a novel compact, flexible fractal monopole antenna is proposed, designed and measured. The proposed fractal antenna has...
several advantages compared to similar fractal monopole antennas presented in the literature. The most important is that it exhibits a wide bandwidth with a relatively small size to provide suitable coverage over several communication standards. A notable feature of the proposed antenna is its high efficiency (95%), which is very close to the maximum possible. The novelty in our design also lays in the fact that a rubber-based composite is used as substrate and a thin sheet of highly conductive fabric is used for conductive parts of the antenna, which allows keeping the antenna as flexible and low-profile as possible. The controllable electromagnetic properties and excellent mechanical flexibility of the synthesized natural rubber composite filled by SiO₂ together with high DC conductivity (2.5 × 10⁵ S/m) of the conductive woven fabric allow designing prototypes with improved performance and novel techniques, in comparison with conventional antennas. The rubber composite can stretch up to 750% before reaching its ultimate elongation, which causes it to break. Moreover, the elongation at break of the proposed composite filled by SiO₂ exceeds significantly the elongation of the materials used as flexible substrates in wideband antennas presented in the literature. Also, the radiation efficiency of the proposed antenna structure is non-sensitive to the conductivity of the fabric from which are fabricated antenna's radiating elements. Furthermore, the proposed antenna has a simple configuration, low cost and simple fabrication process. These features make the proposed antenna attractive for application in the next-generation flexible multifunctional devices in the future wireless networks. Also here, we report a technique for fabrication of flexible antenna structures, which provides a simple and low-cost approach to realize antenna's prototypes with a controlled shape.

2 | ANTENNA DESIGN AND FABRICATION

2.1 | Antenna structure and design

The design goals of this work are to develop an antenna with high efficiency and mechanical flexibility for application in the next-generation flexible multifunctional devices (such as flexible smartphones and other flexible intelligent devices) in the future wireless networks. This antenna is required to have a wide bandwidth to cover the different frequency bands, which are essential for future wireless networks as 2.3–2.4 GHz (MBAN), 2.4–2.48 GHz (2.45 ISM), 2.585–2.69 GHz (LTE Band 7, 15, 16 and WiMAX), 3.4–3.6 (WiMAX), 5.15–5.725 GHz (WLAN) and 5.75–5.82 GHz (ISM) with a minimum gain of +1 dBi.

Figure 1 shows the geometry of the proposed flexible fractal monopole antenna. The antenna radiator is fed by a 50-Ω coplanar waveguide (CPW) transmission line. The CPW is preferred over other feeding techniques since no via holes or shorting pins [3] and allows to keep the antenna as flexible and thin as possible. The antenna design and optimization are performed by using xFDTD (xFDTD, Remcom Inc., State College, PA, USA), a finite-difference time-domain method (FDTD)-based simulation software.

The design process steps are presented in Figure 2, and the simulated reflection coefficient curves are plotted in Figure 3. A conventional equilateral triangular monopole is designed (Antenna 1 in Figure 2a) to obtain a resonance at 2 GHz. It is found that the bandwidth of the Antenna 1 is from 1.81 to 2.22 GHz with |S₁₁| < −10 dB, that is, the fractional bandwidth is about
20%. In the second step, to broaden the bandwidth of Antenna 1, two techniques are implemented: (a) a direct modification to the antenna element to manipulate the input impedance of the antenna to increase the bandwidth and (b) insert multiple-band resonators, such as the fractals into the antenna structure. First, the triangular-shaped monopole is rotated, as shown in Figure 2b (Antenna 2), which shifts the resonance from 1.97 to 2.5 GHz. As a result, a wide bandwidth is generated 2.25–5.45 GHz as can be seen from Figure 3.

Compared to Antenna 1, the fractional bandwidth of Antenna 2 increases from 20% to 83%, respectively. Second, a Sierpinski gasket monopole antenna (Antenna 3 in Figure 2c) is obtained by applying a geometric transformation on the triangular monopole Antenna 2. The results in Figure 3b demonstrate that with applying of the Sierpinski fractal, the inductive reactance of the antenna decrease, while the antenna resistance increase in the frequency range of 5.5 to 6 GHz. Consequently, this modification results in an improvement of

**Figure 3** Simulated. (a) $|S_{11}|$ curves and (b) input impedance curves versus frequency of the Antenna 1, Antenna 2 and Antenna 3.
the impedance matching from 5.5 to 6 GHz (as shown in Figure 3b) in order to cover 5.725–5.875 ISM band. Overall, the impedance bandwidth of the Antenna 3 is improved from 2.22 to 6.00 GHz, that is, the fractional bandwidth increases from 83% for Antenna 2 to 92% for Antenna 3. Furthermore, to create a simple structure, only one iteration is used.

To achieve flexibility, the antenna is designed on a natural rubber-based substrate (NRS). Among available materials, the natural rubber-based composite is chosen as a substrate since it is hydrophobic. Also, it exhibits a good balance of mechanical (flexibility and thermal stability) and electromagnetic (low permittivity and low loss tangent) properties over a wide frequency range [13]. The low production cost is also an added advantage for the rubber composite [12].

2.2 | Parametric study

In order to optimize the antenna design, the proposed flexible antenna has been investigated for variation of design parameters. The parametric study of antenna has been carried out by changing only one dimension at a time. The radiation efficiency, bandwidth and input impedance stability have been employed as criteria for optimization.

We observed that the gap between the central conducting strip and two ground conducting strips of the CPW (denoted by G1 in Figure 1) has a significant impact on both the resonant frequency and impedance bandwidth as shown in Figure 4.

The adjustment of the gap from 1.5 to 0.5 mm improves the impedance bandwidth and shifts the resonance from 3.3 to 2.5 GHz. On one hand, the value of G1 specifies the CPW characteristic impedance (Ze) and thus, the antenna matching [6]. To illustrate this, the variation of the characteristic impedance, |S11| and |S21| versus frequency of the CPW transmission line are included in Figure 5. The characteristic impedance of the CPW is close to 50 Ω in the whole frequency range when the G1 is 0.5 mm. The impedance increases as the width of the gap G1 is increased, and the maximum characteristic impedance occurs when the G1 is 1.5 mm. Consequently, the gap between the central and ground lines is a crucial parameter to change the CPW characteristic impedance and have to be carefully set in addition to the other antenna parameters [6].

Another important factor regarding the impedance matching and bandwidth is the width of the central conducting strip of the CPW (denoted by Lc in Figure 1).

Variation of |S11| versus frequency for different widths of the central conducting strip Lc is shown in Figure 6. It can be seen that for Lc = 1 mm, the matching is poor, and the impedance bandwidth of the proposed antenna is significantly narrowed. Also as the Lc increases, the matching corresponding to the first resonance (at 2.45 GHz) also increases. In addition, as the width of the central conducting strip is 3 mm, the −10 dB simulated impedance bandwidth of the antenna becomes broader.

The effect of the ground conducting strip size (denoted by L1 and L2 in Figure 1) on the antenna performance also has been investigated. The results are shown in Figure 7. By changing the size L1 from 30 to 40 mm and L2 from 32 to 36 mm an insignificant effect on both resonant frequency and impedance bandwidth was observed since the current is distributed primarily along the edges of the strips and the inner edges of all the ground lines (Figure 8).

In Figure 8 can be found the current density distribution in the proposed antenna at 2.44, 2.535, 3.45, 5.5 and 6 GHz. It can be seen that the surface current mainly concentrates on three areas: the central conducting strip of the CPW, along the gasket edge and at the narrow metallic strips of the Sierpinski gasket, and also along the edges of the ground conducting strips of the CPW. However, as the frequency increases above 5 GHz, the amplitude of the current around the edges of the ground of CPW becomes lower.

2.3 | Prototype fabrication

The prototype is fabricated on a NRS with a thickness of 2 mm. The composition of the NRS composite in phr (parts per 100 parts of rubber) is as follows: natural rubber STR 10—100.0, zinc oxide—3.0, stearic acid—2.0, isopropyl-phenyl-p-phenylenediamine—1.0, N-tert-butyl-benzothiazole-sulfenamide—1.5, sulphur—2.0 and SiO2—30.0 as a filler.

The block diagram of the fabrication process of the proposed antenna is shown in Figure 9. As first step, the natural rubber, vulcanization accelerators, compatibilizers, and filler were mixed in an open laboratory two rolls mill with rolls dimensions L/D 320 × 160 mm and 1.27 friction. The speed of the slow roll was 25 min⁻¹. Next, the test sample was vulcanized to a plate with dimensions 150 × 150 × 2 mm in vulcanization optimum, determined according to its vulcanization isotherm.
ISO 3417:2010 at 160°C in an electrically heated vulcanization hydraulic press at 10 MPa using a steel press form.

In the second step, the resonant perturbation method was used for characterisation of the electromagnetic properties (complex permittivity, effective conductivity and tangent of the dielectric loss angle) of the natural rubber-based composite and double-sided tape. This method is a well-known method for extracting electromagnetic properties of dielectrics, semiconductors, magnetic materials and composite materials [28]. The cavity used for the measurement of the complex permittivity in the frequency range between 2 and 6 GHz was a rectangular brass waveguide with inner dimensions 610 (length), 61.2 (width) and 10 mm (height). The TE_{101}, TE_{103}, TE_{105} and TE_{107} modes were used for the complex permittivity measurement in the frequency range between 2 and 3 GHz. Moreover, additional three different cavities, designed to resonate at approximately 3.128 GHz (TE_{103}), 4.061 GHz (TE_{105}) and 6.148 GHz (TE_{105}) were used to determine the electrical parameters of the composite and double-sided tape in the frequency range between 3 and 6 GHz. The cavities were
connected to a network analyser. The tested sample was introduced into the cavity, placed at the position of maximum intensity of the electric field. The electromagnetic parameters of the sample were deduced from the change in the resonant frequency and quality factor. The formulas for the real ($\epsilon_r^\prime$) and imaginary ($\epsilon_r^\ast$) parts of the relative permittivity are as following:

$$\epsilon_r^\prime = \left(\frac{f_c - f_s}{2f_s}\right) \left(\frac{V_c}{V_s}\right) + 1$$

$$\epsilon_r^\ast = \left(\frac{V_c}{4V_s}\right) \left(\frac{1}{Q_c} + \frac{1}{Q_s}\right)$$

where $f_c$ and $Q_c$ are resonant frequency and Q-factor of the cavity without an inserted sample, $f_s$ and $Q_s$ are with an inserted sample, respectively; $V_c$ is the volume of the cavity; $V_s$ is the volume of the sample.

The obtained values for $\epsilon_r^\prime$ and $\epsilon_r^\ast$ of the composite and double-sided tape in the frequency range between 2.2 and 6.2 GHz are depicted in Figure 10. The measurements reveal a slight decrease of the real and imaginary part of relative permittivity in the 2.2–6.2 GHz range.

The obtained values of electromagnetic parameters of the composite at 2.565 GHz ($\epsilon_r^\prime = 2.503, \epsilon_r^\ast = 0.039, \sigma = 0.006$ S/m and $\tan\delta = 0.015$) were used in the numerical model of the antenna (for the substrate) during the steps of the design process described in Section 2.1.

As the third step, the antenna was designed and optimized by an FDTD-based simulation software as described in the Section 2.1. After completing the antenna design and optimization, the computer-aided-design (CAD) drawings of the antenna elements were developed. Next, the created CAD pattern file was imported into a cutting machine (Cricut Explore Air2). The antenna radiating elements were directly shaped on a highly conductive woven fabric (PI168 supplied by Adafruit, Italy) with a cutting machine, Figure 9 (Step 4). The selected fabric is consisting of woven mesh polyester fibres coated with copper and nickel, which has a DC conductivity of $2.5 \times 10^5$ S/m and a thickness of 0.08 mm. Each cut was completed by the machine that received instructions from the computer software. This process of cutting allows for greater accuracy (tolerance 0.01 mm). The soldering points of the woven fabric with the coaxial cable were tin-plated at 250°C.

Then, the antenna's elements were assembled by hand using a double-sided tape (manufactured by 3M). The double-sided tape has a very thin adhesive on both sides (0.09 mm), that allows two parts of the antenna (conductive elements and elastomer substrate) to be bonded together by the tape between them. Finally, a 1.13 mm mini-coaxial cable (200 mm length) with a U. FL connector was soldered to the CPW. Figure 9 (Step 6) shows photographs of the fabricated prototype.
3 | SIMULATION AND EXPERIMENTAL RESULTS

The antenna performance has been verified by simulation and measurement of the reflection coefficient magnitude, gain, radiation efficiency and radiation pattern.

3.1 | Reflection coefficient, gain and radiation efficiency

Figure 11 shows the simulated and measured $|S_{11}|$ curve versus frequency of the proposed antenna. From the results, it can be seen that the $-10$ dB simulated impedance bandwidth reach 3.8 GHz. Consequently, the bandwidth can cover all commonly used frequency bands in the wireless communication systems including BAN (2.36–2.4 GHz), ISM (2.4–2.48 GHz and 5.75–5.82 GHz), LTE2300 (2.35–2.36 GHz), LTE2600 (2.5–2.69 GHz), WiMAX2500 (2.5–2.69 GHz), WiMAX3600 (3.4–3.6 GHz), WLAN (5.15–5.725 GHz). The measured $|S_{11}|$ results indicate a very good agreement with the simulated one. The measured bandwidth is 3.7 GHz (2.3–6.0 GHz). However, a little bit shift of the resonant frequency is observed in the measurement. This difference is primarily attributed to fabrication and assembly inaccuracies and also due to the fact that the coaxial cable and U. FL connector were not integrated into the FDTD simulations.

The simulated maximum gain and radiation efficiency are plotted in Figure 12. The conductive elements of the antenna were modelled as perfect electrical conductors (PECs) and as an electrical conductor having a DC conductivity of $2.5 \times 10^5$ S/m, which corresponds to DC conductivity of the woven fabric to illustrate the influence of the non-perfect conductive material on the radiation efficiency of the antenna.

As can be seen, the gain of the antenna does not change when the conductivity is $2.5 \times 10^5$ S/m. The radiation efficiency drops only with about 0.5% when the conductivity of the radiating structure is changed from PEC to $2.5 \times 10^5$ S/m. Consequently, we can conclude that the proposed antenna structure is non-sensitive to the conductivity of the fabric from which are fabricated antenna's radiating elements.

From Figure 12 it can be observed that the simulated radiation efficiency is quite stable in the whole frequency range (between 93.5 and 95%), while the maximum gain varies from one to four dBi. The variation in the gain values is related to the directivity of the antenna. It is well known that the antenna gain is a product of radiation efficiency and directivity [29]. The directivity is solely determined by the radiation pattern of the antenna [30]. The 3D radiation patterns at 2.3, 2.8, 3.8, 5.3 and 6 GHz are shown in Figure 13.
As shown in Figure 13, the shape of the antenna pattern changes as the frequency is changed. As expected, the radiation pattern exhibits very low directivity and resembles isotropic at 2.3, 2.8 and 5.3 GHz where the gain is 2.09, 1.17 and 1.68 dBi, respectively. The directivity of the radiation pattern increases at 3.8 and 6 GHz, providing the antenna peak gain from 4.21 and 4.26 dBi, respectively. However, it should be noted that the radiation efficiency (power radiated into space divided by total power into the antenna) is less than 100% due to the power absorbed at the rubber composite substrate.

The measured maximum gain and radiation efficiency at 2.44, 2.535, 3.45 and 5.5 GHz, which are the central frequencies of ISM 2.45 GHz, LTE 2.6 GHz, WiMAX 3.6 GHz and WLAN 5.5 GHz, respectively are summarized in Table 1. The measurements of the gain have been performed using the gain transfer method in a semi-anechoic chamber.

### 3.2 Radiation pattern

The simulated and measured co- and cross-polarized components of the normalized 2D radiation pattern for the proposed antenna in xy- and yz-planes at 2.44, 2.535, 3.45 and 5.5 GHz are shown in Figure 14. It is seen that the normalized radiation patterns in the xy-plane are nearly omnidirectional. From the results, we also can see that in yz-plane the antenna has a low cross-polarization at 2.44, 2.535 and 3.45 GHz. The measurements have been performed in a semi-anechoic chamber. Moreover, the measured radiation patterns correspond well to simulation predictions with only slight discrepancies.

### 4 COMPARISON

Finally, a performance comparison between the proposed flexible wideband antenna and previously published in the
literature wideband antennas printed on flexible substrates concerning their radiation efficiency, gain, bandwidth, size and covered wireless technologies and standards is depicted in Table 2. We see that the proposed antenna has better radiation efficiency than [4, 6, 21] and broader bandwidth than [4, 32]. Also, the proposed antenna has better maximum gain compared to the antenna in References [19, 21, 31, 32] and small size than [4, 6, 16].

Moreover, to demonstrate excellent mechanical flexibility of the proposed substrate the elongation at break of the composite was characterized according to ISO 37:20020 and EN 12803 and compared (see Table 3) with this of materials used as substrates in References [4, 16, 19, 21, 32] and a natural rubber-based composite filled with carbon black at the same filler content (30 phr) [33]. The mechanical properties were determined using 78 mm double-sided test specimens having a working area of 20 mm in length and 4 mm in width. The specimens were cut from a rubber sheet of 150 × 150 × 2 mm. The elongation is defined as the percentage increase, or strain, in the original length of a material with the application of a tensile force, or stress.

Table 3 shows that the proposed natural rubber composite filled by 30 phr SiO₂ can stretch up to 750% prior to reaching its ultimate elongation, which causes it to break. However, the elongation at break of the proposed natural rubber composite filled by SiO₂ is bigger than that of the natural rubber-based composite filled with carbon black at

| Frequency, GHz | Radiation efficiency (%) | Maximum gain, dBi |
|---------------|--------------------------|-------------------|
| 2.44          | 88                       | 1.83              |
| 2.535         | 85                       | 1.78              |
| 3.45          | 90                       | 2.85              |
| 5.5           | 86                       | 2.20              |

FIGURE 11 Simulated and measured |S₁₁| curve versus frequency of the proposed antenna

FIGURE 12 Simulated maximum gain and radiation efficiency curves versus frequency

FIGURE 13 Simulated 3D radiation patterns at 2.3, 2.8, 3.8, 5.3, 6 GHz and scale
the same filler content [33]. In addition, the elongation of the composites with SiO₂ exceeds significantly that of the materials used as flexible substrates in wideband antennas [4, 16, 19, 21, 32].

A comparison of the parameters and characteristics of the proposed antenna with other similar fractal monopole antennas recently reported in the literature is given in Table 4 to highlights the improvement and novelty of the antenna structure. It can be seen that the proposed fractal antenna has two main advantages compared to antennas in References [34–40]. The primary advantage of the proposed antenna structure is that it exhibits a wide bandwidth with a relatively small size.
A novel flexible polymer/fabric fractal monopole antenna has been proposed and investigated. The antenna covers 2.3–6.0 GHz frequency range with $|S_{11}| \leq 10$ dB. Moreover, exhibits relative omnidirectional radiation pattern with more than 93% radiation efficiency for the entire frequency range. The designed antenna has a simple configuration, low cost and covers the most commonly used frequency bands in the wireless communication systems including the BAN (2.36–2.4 GHz), ISM (2.4–2.48 GHz and 5.75–5.82 GHz), LTE2300 (2.35–2.36 GHz), LTE2600 (2.5–2.69 GHz), WiMAX2500 (2.5–2.69 GHz), WiMAX3600 (3.4–3.6 GHz), WLAN of 5.15–5.725 GHz (Unlicensed National Information Infrastructure [U-NII]: U-NII-1: 5.15–5.25 GHz; U-NII-2: 5.25–5.35 GHz and U-NII-2 Extended: 5.470–5.725 GHz). Hence, the proposed antenna can be applied in the future wireless communication networks.

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Table 4: Comparison between proposed flexible fractal monopole antenna and other fractal monopole antennas

| Reference | Proposed antenna | [34] | [34] | [35] | [36] | [37] | [38] | [39] | [40] |
|-----------|------------------|------|------|------|------|------|------|------|------|
| Antenna type | PFTMA | PTMA | LPTMA | PFTMA | PFTMA | LPMA | PFTMA | PFTMA | PFTMA |
| Centre freq., GHz | 4.1 | 0.965 | 1.03/1.88 | 2.4/5.5 | 2.5/6 | 1.5 | 0.8 | 0.97/5.1 | 1.05/2.4 |
| Fractional bandwidth, % | 92.68 | 19.68 | 14.6/8 | 26.6/17.2 | 4/14.8 | 184.7 | 50 | 18.9/35.4 | 28.6/8.3 |
| Maximum radiation efficiency, % | 95.1 | - | 82 | - | - | 78.85 | - | - | - |
| Maximum gain, dBi | 4.2 | - | 2.1 | - | 6.2 | 2.18 | - | 4.2 | 4.7 |
| Antenna size | 1.09λ | 3.10^{-2}λ | 0.29λ × 2.2λ | 0.37λ × 1.6λ | 0.55λ × 3.1λ | 0.22λ × 4.1λ | 0.24λ × 5.6λ | 0.23λ | 0.8λ |
| Substrate material | Natural rubber-based composite | Rogers RT6010 | Rogers RT 5880 | Rogers RT 6010 | Rogers RT 5880 | Rogers RT Duriod | FR4 | FR4 |

Note: λ is wavelength at the central frequency of the operating band.

Abbreviations: LPMA, loaded with SRR planar monopole antenna; LPTMA, loaded PTMA; PFTMA, planar fractal triangular monopole antenna; PTMA, planar triangular monopole antenna.

*Fractional bandwidth = (\(|f_2 - f_1|\)/\(f_2\)) × 100%, where \(f_1\) and \(f_2\) are the lowest and highest usable frequency of the antenna for \(|S_{11}| \leq -10\ dB\), respectively, and \(f_c\) is the center frequency of the operation band.

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