Conformal Antenna with Reconfigurability of Monopole-like and Broadside Patterns Realized with Polymer-Conductive Textile Composite

Roy B. V. B. Simorangkir[#1], Bahare Mohamadzade[*], Ali Lalbakhsh[*],
Sanjeev Kumar[#], John L. Buckley[#], Toni Björninen[+], Brendan O'Flynn[#]
[#]Tyndall National Institute, University College Cork, Dyke Parade, T12R5CP Cork, Ireland
[*]School of Engineering, Macquarie University, Sydney, NSW 2109, Australia
[+] Faculty of Medicine and Health Technology, Tampere University, 33720 Tampere, Finland
[1]roy.simorangkir@ieee.org

Abstract — **A conformal antenna with a capability of electronically switching between monopole-like and broadside radiation modes is presented. The design is based on a proximity-fed circular patch, loaded with a ring patch and four rectangular slots. The reconfigurability is achieved through activation and deactivation of the slots using PIN diodes, to switch between TM_{02} (monopole-like) mode and perturbed TM_{02} (broadside) mode. Polymer-conductive textile composite material is used to implement the antenna, with all antenna elements including DC biasing circuit and associated electronic components fully integrated inside the polymer. This configuration makes the antenna robust against deformation and harsh environment. Experimental investigations on the antenna RF performance including bending tests are presented. The measurements demonstrated that under bending, the antenna retained its reconfigurability with stable impedance and radiation performance relative to those of the flat case, i.e., 17.9% overlapping bandwidth of the two radiation modes and peak realized gains of 1.75 and 2.9 dBi at 5.2 GHz in monopole-like and broaside modes, respectively.**

Keywords — **Broadside pattern, conductive textile, conformal, flexible antenna, microstrip antenna, monopole-like pattern, pattern reconfigurable, polymer.**

I. Introduction

Antenna with monopole-like and broadside patterns reconfigurability has gained a growing research interest for their capability to enable multifunctional wireless communication with enhanced quality of service [1]. Driven by the rapid development of modern wireless communications, current research efforts also include the development of such a reconfigurable antenna that is physically conformal. The revolutionized concept of 5G and emerging Internet of Things (IoT), for instance, have invoked the need for highly integrated networks which impose challenges in infrastructure, particularly in urban area, and also the users' compliance. In this sense, a conformal pattern reconfigurable antenna, as opposed to its rigid counterpart, would benefit from its flexible deployment on the system platform regardless the surface contour, allowing for an optimum use of limited space of existing infrastructure and possibly making the antenna unobtrusive. When a reconfigurable antenna becomes concurrently conformal, its applications can also be extended into wider spectrum including the emerging body-worn applications where users' comfort is of paramount importance [2], [3].

In the last decade, there have been significant advancements demonstrated in antennas with electronically-tunable monopole-like and broadside radiation modes made of rigid conventional materials [1], [4]–[10]. The progress, however, has been relatively slow when it comes to the realization of antennas with such capability using flexible materials [3]. There was an interesting work in [11] which shows a potential to have an antenna with pattern tuning between monopole-like and broadside patterns on textile materials. However, the electronic tuning of the antenna with actual switches have not been demonstrated yet.

One problem causing the aforementioned phenomenon is the complexity of the antenna design which challenges its implementation on flexible materials. For instance, to enable monopole-like and broadside patterns reconfiguration often requires a complex feeding network, shorting posts, and several RF switches along with other associated electronic lumped components. Not to mention, often the designs are not completely planar. Another challenge involved is to achieve a robust integration of those rigid lumped components on the surface of flexible materials. Being exposed on such a dynamic environment, the components are at risk of being detached, thus compromising the performance of the antenna.

Motivated by the above, in this paper we present an antenna designed at 5.2 GHz WLAN frequency, that is physically conformal and has a dynamic electronically pattern-tuning capability between monopole-like and broadside modes. As opposed to most of previously reported works, the antenna is planar in structure and free of rigid shorting posts and complex feeding network, and hence facilitates very well its realization on flexible materials. To fabricate the antenna, we employ our previously reported approach based on polymer-conductive textile composite, which has been tested effective for realization of robust flexible antenna incorporating electronic lumped elements [12]–[14] . It should be noted that through this approach, all antenna parts including RF switches as well as associated simple DC biasing circuit, wires, and other lumped components are encapsulated inside the polymer, maintaining a robust integration to the flexible textile. Experimental investigations on the antenna performance in flat condition and under deformation are then presented to demonstrate the robustness of the proposed antenna.

II. Antenna Design

The proposed antenna design is based on a proximity-fed circular patch, loaded with a ring patch (see Fig. 1). The circular patch is designed to operate in its TM_{02} mode for its monopole-like radiation mode [15] with desirable quality of gain and azimuthal omnidirectional pattern [16]. The ring is added to shift down the operating mode to the target frequency 5.2 GHz. These radiator patches are placed on a polydimethylsiloxane (PDMS) polymer substrate with a rectangular-shaped ground plane underneath. Four slots, each bridged to a rectangular pad by a PIN diode (SMP1345-079LF from Skyworks), are added to the radiator patches to enable the pattern reconfigurability. The quantity of slots was chosen considering a trade-off between design simplicity and effectiveness in achieving the reconfigurability. The ring is connected to the circular patch by 1 mm wide strip to provide a same DC plane. Underneath the ground plane, separated by a 0.3 mm thick PDMS layer, the DC biasing circuit of the antenna is integrated. This eliminates the need for external cables usually associated with the bias network, which can affect the antenna performance. As can be seen in Figs. 1(a) and (c), the circuit is connected to the ring and the four rectangular pads at points A (positive polarity) and B (negative polarity), respectively, by using thin wires (approx. diameter of 0.5 mm) piercing through the PDMS. The wire insulation isolates the pads and the rings from the RF ground. A 3 V coin cell battery is used as the DC voltage supply, which is connected to a MCDHN-02F-V dip switch from Multicomp Pro for switching the state of the diodes. An 82 Ω surface mount resistor (MC 0805) from Multicomp Pro is added to limit the current passing through each diode and a 100 nH chip inductor (0805CS-060XJLB) from Coilcraft is used as an RF choke. Extra PDMS layers are added at the bottom and the top of the antenna as encapsulation.

The conductive parts of the antenna are realized with nickel-copper coated ripstop from Less EMF Inc., which was modeled in simulation as a slab with 0.08 mm thickness and an approximate conductivity of 5.4×10^4 S/m [13]. The PDMS layers, on the other hand, were modeled with a permittivity of 2.76 and frequency dependent loss tangent from 0.03 to 0.06 based on the measurements conducted with Agilent 85070E Dielectric Probe Kit from 3 to 7 GHz.

III. Mechanism of Pattern Reconfiguration

The strategy to achieve the pattern reconfigurability feature is explained as follows. Firstly, the balance of the radial current distribution of the TM_{02} mode of the patch is disturbed through the inclusion of the four slots. It was found that by properly tuning the dimensions (e.g., l_i and l_o) and positions of the slots (e.g., α_i, α_o, r_i, and r_o,), the current can be diverted so that the null of the E-field shifts away from its original broadside position (see Fig. 2), leading to a transformation from monopole-like to broadside mode. Secondly, PIN diodes are used to deactivate (diodes ON) and to activate (diodes OFF) the slots, to allow for a dynamic switching between TM_{02} (monopole-like) mode and perturbed TM_{02} (broadside) mode.

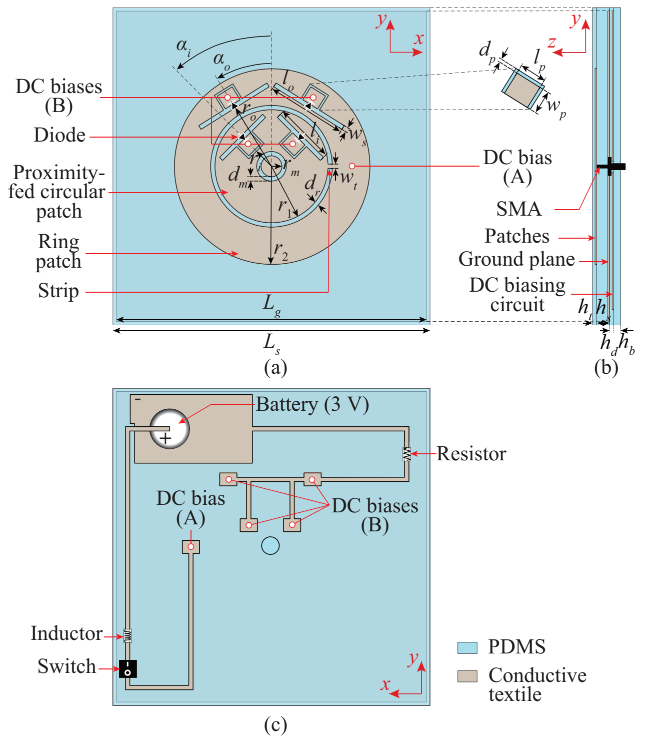


Fig. 1. Proposed antenna design: (a) top view, (b) side view, and (c) rear view. Final dimensions (in millimeters): r_m = 2.4, d_m = 1, r_1 = 13, r_2 = 22.5, d_r = 1, l_i = 14, l_o = 18.5, w_s = 1, r_i = 4.9, r_o = 15.8, α_i = 45°, α_o = 32°, l_p = 4, w_p = 3.5, d_p = 0.5, w_t = 1, L_s = 70, L_g = 68, h_t = 0.3, h_s = 5.5, h_d = 0.3, and h_b = 0.5

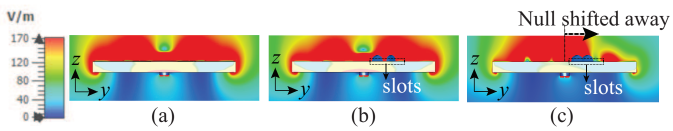


Fig. 2. Simulated average E-field distribution of the antenna at 5.2 GHz: (a) without slots, (b) with slots and diodes ON, (c) with slots and diodes OFF. When the diodes are ON, E-field distribution of the antenna is similar to the case before the slots inclusion. When the diodes are OFF, the current diversion around the slots leads to a shift of the E-field null towards the location of the slots.

To clearly illustrate the role of the slots in reconfiguring the pattern, we show in Fig. 3 the current distribution and 3D total radiation pattern of the antenna with varying slot parameters (i.e., set 1 to 3 (Final design)), while maintaining the other design parameters and all diodes OFF. The slot dimensions of sets 1 and 2 are not detailed here for brevity. These slots parameters have been selected to show that, by optimizing the slots configuration, the monopole-like pattern of the antenna can be tilted towards the location of the slots (i.e., positive theta direction). Once the null of the monopole-like pattern

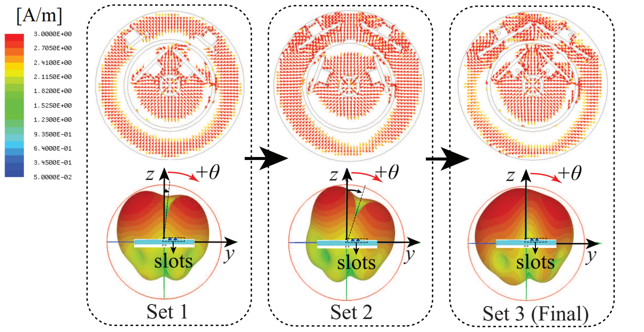


Fig. 3. Simulated current distribution and corresponding antenna pattern at 5.2 GHz for different slots parameters. When varying slot parameters from set 1 to 3, diodes are OFF and all other antenna parameters are fixed.

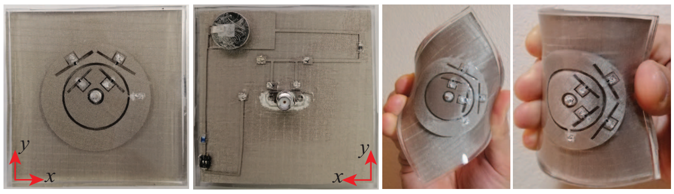
is slanted further from the broadside direction, a broadside pattern is produced. We noted that for a good transformation to happen, the slots optimization should aim for concentrating the current disturbance only at one side of the poles of the antenna and maximizing the current diversion around the slots.

IV. Antenna Prototype and Measurements

An antenna prototype was fabricated through a layer-by-layer approach detailed in [12], [13]. Once all layers from the bottom encapsulation layer to the radiator patches were completed, the PIN diodes were attached before continuing to the top encapsulation layer. The wires and remaining components (i.e., the inductor, resistor, dip switch, battery, and SMA connector) were connected once the antenna was cured and peeled off from the mold, by removing some parts of the PDMS encapsulation layers with razor blade. Upon the attachments, uncured PDMS was poured again to those peeled locations to fully cover these components, except for the battery, the SMA port, and the slide of the switch, for measurements practicality. The conductive textile attachment to the cured PDMS layer was done by using uncured PDMS, while the attachment of the electronic components and wires to the conductive textile was done by means of silver epoxy. On the other hand, adhesive tape was applied to maintain the battery connection with the conductive textile used as the positive and negative battery terminals. Fig. 4 show photographs of the fabricated prototype including that of under 30 mm radius of bending which demonstrates conformability of the proposed reconfigurable antenna.

The antenna performance was evaluated in flat and under deformation scenarios. For the measurements of the latter scenario, a hollow plastic tube with an outer radius of 40 mm and wall thickness of approx. 1 mm was used. The antenna was conformed over the tube by the help of adhesive tape and the investigations were conducted in two bending configurations, i.e., along $x-$ and y-axis directions (see Fig. 5(a)). A foam spacer was added between the antenna and the tube to create a gap for the battery. A hole was made on the tube to facilitate the attachment of a coaxial cable for RF measurements.

Figs. 5(b) and (c) show the input reflection coefficient $|S_{11}|$ results of the antenna in flat and deformed conditions for both radiation modes. For the flat case, the measured results



(a) (b) (c)

Fig. 4. Fabricated reconfigurable antenna prototype: (a) top view, (b) rear view, and (c) view when physically deformed.

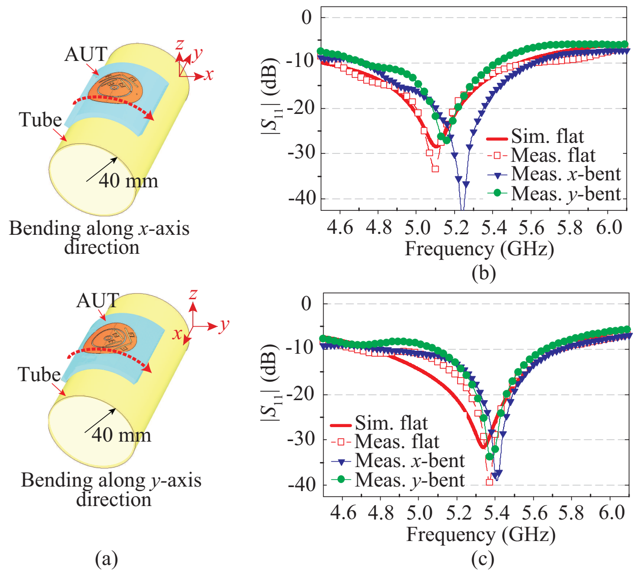


Fig. 5. (a) Illustration of the deformation scenario used in antenna performance evaluation. $|S_{11}|$ performance of the antenna in both flat and deformed scenarios: (b) when all diodes ON (monopole-like mode) and (c) when all diodes OFF (broadside mode).

are compared to the simulated results, which shows a good agreement. Slight discrepancies between them are most likely attributed to the fabrication tolerances. It is shown in the results that upon the change of the diodes state, the antenna resonance frequency slightly shifts. However, the targeted frequency of 5.2 GHz is still covered within the 10-dB return loss bandwidth of both states. The measured overlapping bandwidth of the two radiation modes is from 4.67 to 5.59 GHz (17.9%). One of the highlights is shown by the results under bending, i.e., the antenna remains operational even under deformation. The shifts in resonance after bendings are expected as the results of the changes in the current paths upon the physical deformation of the body of the antenna.

Fig. 6 depicts the simulated and measured radiation patterns of the antenna at 5.2 GHz for flat and deformed cases. The measured and simulated results of the flat case, which agree each other well, displays the targeted pattern transformation upon changing the state of the diodes. When all the diodes are ON (slots deactivated), the antenna produces a monopole-like pattern, but when the diodes are OFF (slots activated), the antenna produces a broadside pattern. At 5.2 GHz, peak realized gains of 1.75 and 2.9 dBi with 52 and 64% radiation efficiencies are obtained from the measurement

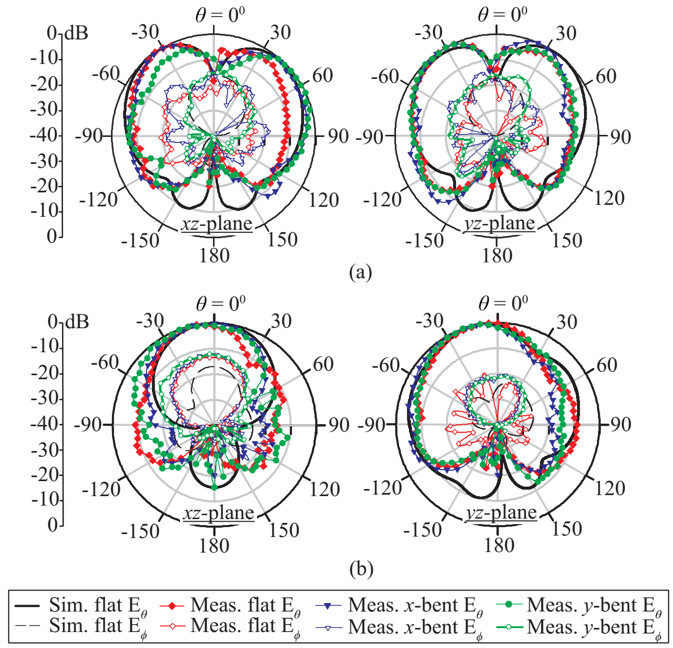


Fig. 6. Normalized simulated and measured radiation patterns of the antenna in flat and deformed scenarios: (a) when all diodes ON (monopole-like mode) and (b) when all diodes OFF (broadside mode).

of monopole-like and broaside modes, respectively. Under bending, the measured antenna gain performance in both radiation modes was found to be relatively stable, i.e., peak realized gains of 1.6 and 2.6 dBi when bent in x-axis direction and peak gains of 1.85 and 2.8 dBi when bent in y-axis direction. The most important highlight is that, despite slight deviations in the patterns due to the shape deformation, the antenna has very well retained its pattern reconfigurability even under bending. This particularly confirms that the integration of the rigid components associated for electronic tuning on the flexible body of the antenna, are indeed maintained even under bending, demonstrating a resilience against deformation.

V. Conclusion

A conformal antenna with electronically-tunable monopole-like and broadside patterns has been successfully demonstrated. Unlike most of previously reported works, the proposed antenna is completely planar in structure, without any use of rigid shorting posts and complex feeding network, which facilitates very well its realization on flexible materials. The implementation of PDMS-conductive textile composite to fabricate the antenna, in which all antenna elements are integrated inside the PDMS, provides a physical robustness to the antenna. This has been validated experimentally through bending tests where the antenna demonstrated a well-retained reconfigurability with relatively stable RF performance, confirming it suitability for conformal modern wireless applications.

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References

[1] P. Qin, Y. J. Guo, A. R. Weily, and C. Liang, "A pattern reconfigurable U-slot antenna and its applications in MIMO systems," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 516–528, 2012.

[2] B. Mohamadzade, R. M. Hashmi, R. B. V. B. Simorangkir, R. Gharaei, S. Ur Rehman, and Q. H. Abbasi, "Recent advances in fabrication methods for flexible antennas in wearable devices: state of the art," *Sensors*, vol. 19, no. 10, p. 2312, 2019.

[3] B. Mohamadzade, R. B. V. B. Simorangkir, S. Maric, A. Lalbakhsh, K. P. Esselle, and R. M. Hashmi, "Recent developments and state of the art in flexible and conformal reconfigurable antennas," *Electronics*, vol. 9, no. 9, 2020.

[4] W. Lin, H. Wong, and R. W. Ziolkowski, "Wideband pattern-reconfigurable antenna with switchable broadside and conical beams," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2638–2641, 2017.

[5] Y. Yang, R. B. V. B. Simorangkir, X. Zhu, K. Esselle, and Q. Xue, "A novel boresight and conical pattern reconfigurable antenna with the diversity of 360 ^{o} polarization scanning," *IEEE Trans. Antennas Propag.*, vol. 65, no. 11, pp. 5747–5756, 2017.

[6] X. Tong , Ch. Liu , X. Liu, H. Guo, and X. Yang, "Switchable on/off body antenna for 2.45 GHz WBAN applications," *IEEE Trans. Antennas Propag.*, vol. 66, no. 2, pp. 967–971, 2017.

[7] J.-S. Row and Y.-J. Huang, "Reconfigurable antenna with switchable broadside and conical beams and switchable linear polarized patterns," *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3752–3756, 2018.

[8] J. Zhang, S. Yan, and G. A. E. Vandenbosch, "Realization of dual-band pattern diversity with a CRLH-TL-inspired reconfigurable metamaterial," *IEEE Trans. Antennas Propag.*, vol. 66, no. 10, pp. 5130–5138, 2018.

[9] X. Yang, H. Lin, H. Gu, L. Ge, and X. Zeng, "Broadband pattern diversity patch antenna with switchable feeding network," *IEEE Access*, vol. 6, pp. 69 612–69 619, 2018.

[10] M. Tang, Y. Chen, X. Chen, D. Mu, and R. W. Ziolkowski, "Design and testing of a simple, compact antenna with reconfigurable broadside and monopole-like patterns," *IEEE Antennas Wireless Propag. Lett.*, vol. 19, no. 6, pp. 897–901, 2020.

[11] S. Yan and G. A. Vandenbosch, "Radiation pattern-reconfigurable wearable antenna based on metamaterial structure," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1715–1718, 2016.

[12] R. B. V. B. Simorangkir, Y. Yang, K. P. Esselle, and B. A. Zeb, "A method to realize robust flexible electronically tunable antennas using polymer-embedded conductive fabric," *IEEE Trans. Antennas Propag.*, vol. 66, no. 1, pp. 50–58, 2018.

[13] R. B. V. B. Simorangkir, Y. Yang, R. M. Hashmi, T. Björninen, K. P. Esselle, and L. Ukkonen, "Polydimethylsiloxane-embedded conductive fabric: Characterization and application for realization of robust passive and active flexible wearable antennas," *IEEE Access*, vol. 6, pp. 48 102–48 112, 2018.

[14] R. B. V. B. Simorangkir, D. Le, T. Björninen, A. S. M. Sayem, M. Zhadobov, and R. Sauleau, "Washing durability of PDMS-conductive fabric composite: realizing washable UHF RFID tags," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 12, pp. 2572–2576, 2019.

[15] R. Garg, R. Bhartia, I. Bahl, and A. Ittipiboon, "Circular disk and ring antennas," in *Microstrip Antenna Design Handbook*. Boston: Artech House, Inc., 2001, ch. 5, pp. 317–398.

[16] J. Tak and J. Choi, "Circular-ring patch antenna with higher order mode for on-body communications," *Micro and Opt. Tech. Letters*, vol. 56, no. 7, pp. 1543–1547, 2014.