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REGULAR ARTICLE

Design and Analysis of Poly-Cotton Substrate-based Textile Antenna for mm-Wave 5G, and WBAN Applications

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This paper presents the design, fabrication, and comprehensive experimental evaluation of a compact textile antenna intended for mm-Wave 5G and wireless body area network (WBAN) applications. The antenna is realized on a flexible poly-cotton textile substrate with compact dimensions of $20 \times 25 \times 0.7$ mm^3, making it highly suitable for integration into wearable electronic platforms. The proposed antenna demonstrates stable impedance matching over the frequency range of 23.6-29.8 GHz, effectively covering key mm-Wave 5G bands. Radiation characteristics reveal a peak realized gain of 5.59 dBi with an overall radiation efficiency of approximately 82 %, indicating efficient power utilization despite the use of a lossy textile material. To assess mechanical robustness under practical wearable conditions, bending analysis was performed along both the X-axis and the Y-axis directions. The results confirm minimal performance degradation under mechanical deformation, validating the antenna's flexibility and structural reliability. Specific absorption rate (SAR) tests on anthropomorphic hand and leg phantoms showed the highest values of 0.182 W/Kg and 0.246 W/Kg, respectively, which are well within current international safety limits. All these findings together support the safety, effectiveness, and adaptability of the antenna in the next-generation wireless communication systems of wearable gadgets.

Keywords: Antenna, Poly-Cotton, mm-Wave, 5G, WBAN, SAR.

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1. INTRODUCTION

The swift implementation of fifth-generation (5G) wireless communication networks has catalyzed a heightened interest in millimetre-wave (mm-Wave) frequency bands, as these bands provide a substantial contiguous spectrum that facilitates multi-gigabit per second data transmission rates, minimal latency, and compact, high-gain antenna designs that are particularly advantageous for densely populated urban environments and short-range communication links. Recent analyses underscore the pivotal role of mm-Wave antenna technologies in actualizing the anticipated capacity and latency enhancements associated with 5G, while also asserting that innovative antenna configurations and integration methodologies are essential to satisfy the overarching system-level constraints [1]. Simultaneously, wearable and textile-integrated wireless platforms have emerged as pivotal facilitators of personal communication, health surveillance, and on-body sensing applications. Textile antennas, constructed from conductive threads, fabrics, and adaptable substrates, offer numerous advantages, including mechanical flexibility, lightweight design, minimal profile, and seamless integration with garments and soft systems, making them exceptionally appealing for wearable 5G front-end applications. Recent comprehensive reviews have encapsulated the swift advancement in the research of wearable textile antennas and underscored the practical implementations of electronic textiles in the domains of communication and sensing [2].

The rapid advancement of fifth-generation (5G) wireless communication systems has created a need for a new generation of antenna technology that can be effectively utilized at the mm-Wave frequency, spanning 24 to 100 GHz [3]. In this respect, textile antennas have become an especially productive candidate for wearable computing and Internet-of-Things (IoT) platforms, due to their inherent flexibility, low weight, and the ability to be easily incorporated into clothes and smart fabrics substrates [4]. The requirement to support high-speed and low-latency communication in 5G networks has triggered more recent studies into textile-based antennas to operate well in the millimetre-wave spectrum and still support structural integrity under flexural and tensile forces [5]. The importance of textile antennas to millimetre-wave 5G uses is that it is possible to provide the creation of advanced wearable communication systems, which can be used in intelligent health care, augmented reality and military applications [6]. In comparison with traditional,

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rigid antennas, textile-based designs are more comfortable, have a longer lifespan, and are more versatile, thus making them particularly suitable to be used in body-worn devices [7].

A triple-band mm-Wave flexible antenna was designed on a liquid crystal polymer (LCP) substrate. The antenna has a good working range at frequencies of 25 GHz, 39 GHz, and 60 GHz. Throughout the manufacturing process, we have performed stringent bending tests on the antenna and measured its specific absorption rate (SAR) when attached to a phantom with the shape of a helmet. The outcomes of the electrical characterization and mechanical robustness tests provide useful references in future studies of textile-based mm-Wave antennas [8]. A wideband textile antenna was designed, which was targeted at on-body radio-frequency energy harvesting. The antenna was built on a 310 μm long woven polyester substrate, and an etched polyimide copper laminate was used. Its peak gain is 7 dBi, and the efficiency of the entire structure is between 40-60 % in the band of operation. These striking values are, as far as we know, the first known example of a textile-based rectenna front-end that can be useful in mm-Wave energy harvesting [9-10].

2. ANTENNA DESIGN

The fabric antenna that is being considered has been carefully designed on Poly-Cotton with a relative permittivity of 1.69 and a dissipation factor that is equal to 0.045. The substrate alone is 0.7 mm thick and is 20 mm by 25 mm. The mathematical formulations pertinent to the design of an annular ring patch are delineated in equations (1) to (4).

$$A = \frac{\lambda}{2\pi\sqrt{\varepsilon_r}} \tag{1}$$

Where A symbolizes the radial measurement of the innermost edge of the annular structure, λ denotes a specific wavelength, and ε_r indicates the substrate's dielectric parameter.

$$B = A + W \tag{2}$$

Where B signifies the external radius of the annular configuration and W denotes the width of the annular ring.

$$W = \frac{\lambda}{4\sqrt{\varepsilon_r}} \tag{3}$$

Equation (7) is employed to determine the antenna's resonant frequency (f_r).

$$f_r = \frac{c}{\pi(A+B)\sqrt{\varepsilon_r}} \tag{4}$$

The systematic development of the antenna design is outlined in Fig. 1, which contains four subsequent prototypes named ANT I to ANT IV. The preferred configuration (Prototype ANT IV) is the subject of the current study. In the first design step, ANT I would be modelled by a simple radiating patch in the form of a circle with a full ground plane in the background, Fig. 1. This setup reveals the resonances across 23.5-25 GHz and 30-31 GHz, which are supported by the data in Fig. 2. In the next phase, ANT II is modified into a circular annular ring with a defective ground structure (DGS), as shown in Fig. 1.

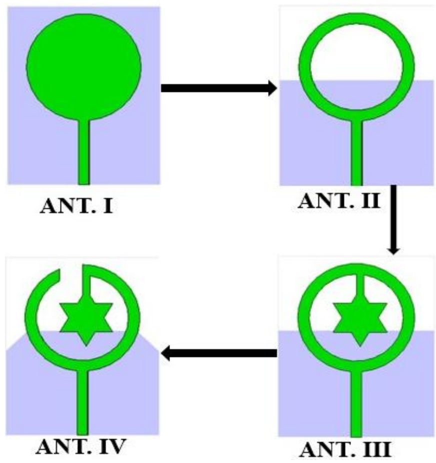


Fig. 1 – Evolution process of the proposed antenna

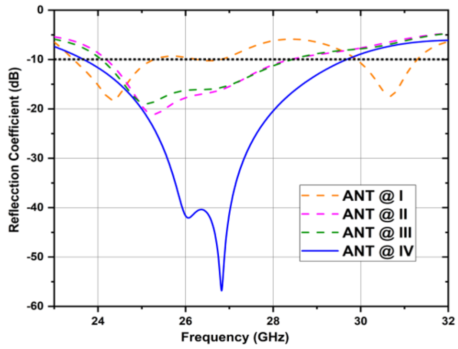


Fig. 2- S_{11} for various iterations of antenna

The updated design has resonances throughout the frequency range of 24.2-28.3 GHz, as shown in Fig. 2. Fig. 1 represents ANT III, which incorporates a star-shaped geometry. The last design, which is ANT IV and depicted in Fig. 1, has truncated corner edges on the ground plane and an annular ring trace being etched in a rectangular layout, which is effective in the frequency range of 23-29.5 GHz.

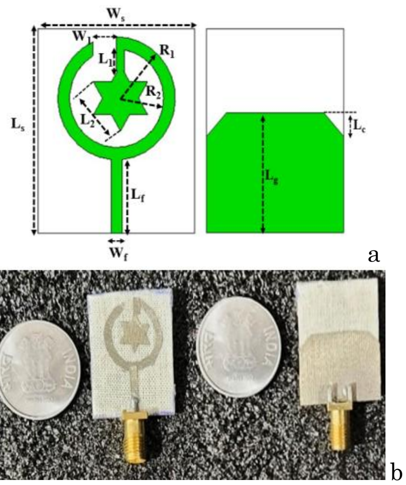


Fig. 3- Structure of the antenna (a) Dimensional image (b) Fabricated prototype

In Fig. 3(a), the dimensional layout of the antenna is represented with special focus on key design parameters, which include the radiating element, the size of the feedline, and the layout of the ground plane. Fig. 3(b) is the prototype of the antenna that was fabricated.

Table 1 – Optimized dimensional parameters of the antenna

Parameter	Value (mm)	Parameter	Value (mm)
L_s	25	L_f	10
W_s	20	W_f	1.4
R_1	7.5	L_g	15
R_2	6	L_c	3
L_1	3.7	W_1	3
L_2	7		

Table 1 summarizes the preferred, optimized dimensions that were finally used in the final antenna design.

3. RESULTS AND DISCUSSIONS

In the current research, the antenna itself was carefully designed and thoroughly tested by CST Microwave Studio to put under scrutiny the range of performance properties. The design undertaking shows resonance at the frequency range of 23.6-29.8 GHz.

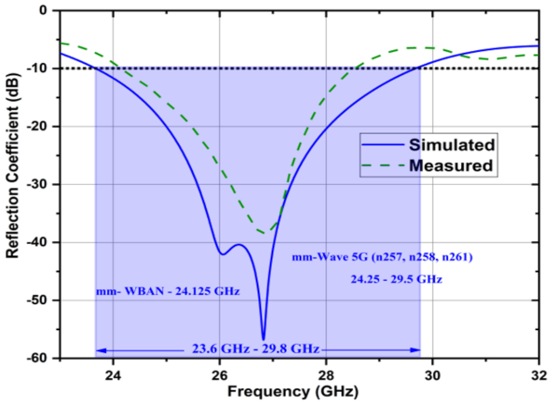
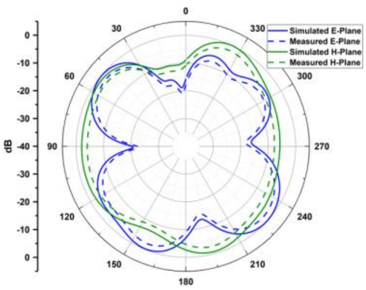
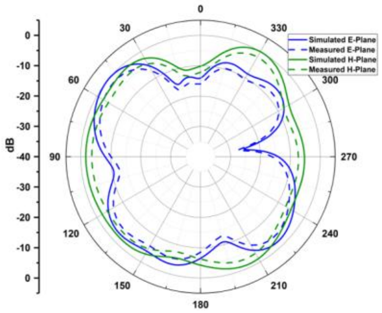


Fig. 4 – S_{11} versus the frequency of the antenna

The S_{11} parameter, or as it is commonly referred to, the return loss, is the parameter used to gauge the effectiveness of energy transfer by measuring the percentage of signal reflected by impedance mismatch. Fig. 4 shows the simulated and measured S_{11} responses, indicating a high correlation, which validates the operational bandwidth of the antenna.



a



b

Fig. 5 – 2D Radiation patterns of an antenna at (a) 24.125 GHz (b) 27 GHz

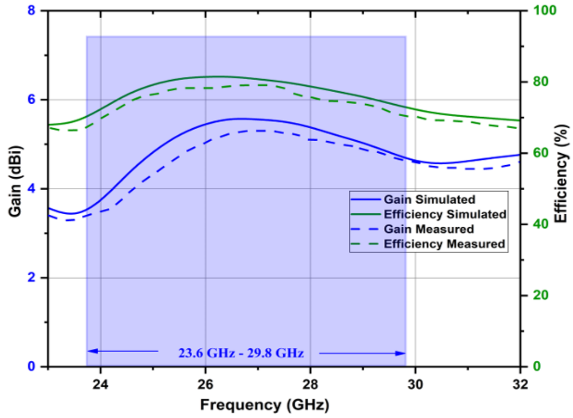
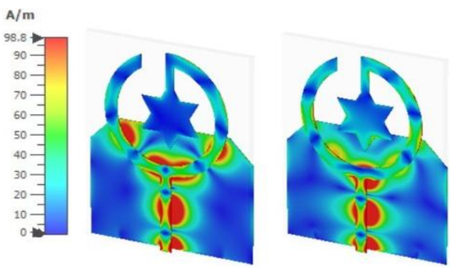


Fig. 6- Gain and efficiency of the antenna

Fig. 5 shows the two-dimensional radiation patterns of the proposed antenna at the frequencies of 24.125 GHz and 27 GHz. The antenna attains a peak gain of 5.59 dBi, and the efficiency is approximately 82 % within the working band, hence justifying its efficient radiation behaviour as shown in Fig. 6.

Fig. 7 traces out the field of currents of the surface, radiating patch and ground plane at two different working frequencies. Fig. 7(a) demonstrates that the strongest concentration of current is concentrated along the microstrip feed line at 24.125 GHz, which is important since it plays a critical role in stimulating the resonant mode. On the other hand, at 27 GHz, Fig. 7(b) indicates that the ground plane, feed line and radiating patch work together to support the resonance as seen by the enhanced current distribution in the entire regions.

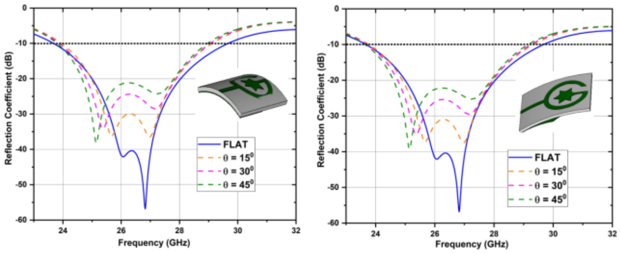


a b

Fig. 7 – Surface current distributions of the antenna at (a) 24.125 GHz, (b) 27 GHz

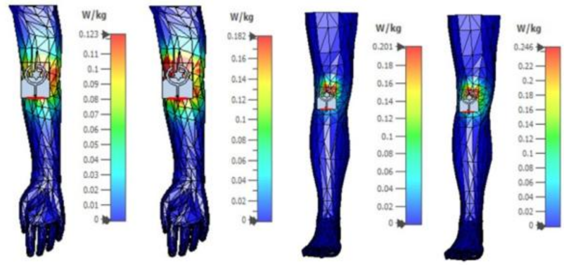
4. STRUCTURAL DEFORMATION

In WBAN applications, the wearable antennas are bound to be bent in the normal use environment. Such mechanical deformation must not affect signal integrity or shift resonant frequencies. A structural deformation analysis involves the bending of the antenna through a range of bending arrangements to determine how stable the antenna behaves in operation. The performance of the device was measured in *X*-axis bending, which is a scenario of on-body kinematics. Fig. 8(a) shows that the S_{11} shows a small reducing pattern with the bend, but the operational bandwidth is not different among all the angles investigated. Fig. 8(b) describes the response of S_{11} when the antenna is bent along the *Y*-axis.



a b

Fig. 8 – S_{11} characteristics when the antenna is bent along (a) *X*-axis (b) *Y*-axis



a b

Fig. 9 – SAR analysis of antenna at 24.125 and 27 GHz (a) On hand (b) On leg

5. SPECIFIC ABSORPTION RATE

The SAR quantifies the electromagnetic radiation absorbed by human tissue. SAR assessments were conducted at 24.125 GHz and 27 GHz for an antenna designed for placement on a human hand. At a power input of 0.5 W, SAR values measured were 0.123 W/kg and 0.182 W/kg.

Similar evaluations on antenna placement on the leg yielded SAR values of 0.201 W/kg and 0.246 W/kg at the respective frequencies, which are presented in Fig. 9. Table 2 illustrates the comparative analysis of the proposed antenna with previous works.

CONCLUSION

In this study, a compact textile antenna was effectively developed on a poly-cotton substrate for use in mm-Wave 5G and WBAN applications. The device has a frequency range of 23.6-29.8 GHz, its peak gain is 5.59 dBi, and the efficiency is 82 %. Notably, the antenna has strong performance even when bending both along the *X*-axis and *Y*-axis, which is why the antenna is appropriate in wearable technologies. Moreover, the specific absorption rate(SAR) measurements were conducted on adult human hand and leg phantoms, and the values were significantly lower than the international safety limits, with the highest SAR measured at 0.182 and 0.246 W/kg, respectively.

Table 2 – Comparative analysis with the previous works

Ref. No	Size (mm³)	Operating Frequency (GHz)	Gain (dBi)	SAR (W/Kg)
[11]	23 × 18 × 0.35	25.5-26.5	6.13	0.32
[12]	30 × 30 × 0.508	23-28	3.55	–
[13]	45 × 40 × 0.508	2.4, 5.5, 28	3.76	–
[14]	55 × 110 × 0.508	28, 38	7.18	–
This Work	20 × 25 × 0.7	23.6-29.8	5.59	0.246

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Проєктування та аналіз антени на основі полібавовняної підкладки для міліметрових хвиль 5G та застосувань WBAN

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У статті представлено проєктування, виготовлення та комплексну експериментальну оцінку компактної текстильної антени, призначеної для застосування в міліметровому діапазоні 5G та бездротових мережах на тілі (WBAN). Антена реалізована на гнучкій полібавовняній текстильній підкладці з компактними розмірами 20 × 25 × 0,7 мм^3, що робить її дуже придатною для інтеграції в носимі електронні платформи. Запропонована антена демонструє стабільне узгодження імпедансу в діапазоні частот 23,6-29,8 ГГц, ефективно охоплюючи ключові діапазони міліметрового діапазону 5G. Характеристики випромінювання показують піковий реалізований коефіцієнт посилення 5,59 дБі із загальною ефективністю випромінювання приблизно 82 %, що свідчить про ефективне використання потужності, незважаючи на використання текстильного матеріалу з втратами. Для оцінки механічної міцності в практичних умовах носіння було проведено аналіз вигину вздовж осі *X* та осі *Y*. Результати підтверджують мінімальне погіршення продуктивності при механічній деформації, що підтверджує гнучкість та структурну надійність антени. Випробування питомого коефіцієнта поглинання (SAR) на антропоморфних фантомах рук та ніг показали найвищі значення 0,182 Вт/кг та 0,246 Вт/кг відповідно, що повністю відповідає чинним міжнародним нормам безпеки. Усі ці результати разом підтверджують безпеку, ефективність та адаптивність антени в системах бездротового зв'язку наступного покоління для носимих гаджетів.

Ключові слова: Антена, Полібавовна, Міліметрові хвилі, 5G, WBAN, SAR.