Printed Non-Metallic Textile-Based Carbon Antenna for Low-Cost Green Wearable Applications

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***Abstract*—Anticipated by 2035, a trillion wirelessly connected Internet of Everything (IoE) devices will be deployed in various pervasive applications. Therefore, sustainable and low-cost antennas are crucial for enabling an environmentally-friendly IoE. Furthermore, advances in carbon-based energy storage and harvesting devices motivates research in carbon-based antennas for wireless power transmission (WPT) applications. In this paper, we present the first non-metallic carbon-based microstrip patch antenna implemented on textiles for wearable applications. The antenna is fabricated on a standard felt/woven-polyester fabric substrate using stencil casting and demonstrated for S-band applications. The antenna maintains a wide 10% fractional bandwidth from 3.16 to 3.49 GHz, in agreement with the simulated bandwidth. The achieves at least 30% radiation efficiency, 10.4 dBi measured directivity, and 6.1 dBi measured gain. Based on the measured radiation properties of the patch, it is concluded that non-metallic carbon-based antennas are suitable for future wearable IoE applications.**

***Index Terms*—Antennas, body area networks, Goubau lines, human body communications, on-body communications, propagation, single-wire transmission line, wearable antennas.**

I. Introduction

By 2035, it is expected that the Internet of Everything (IoE) will grow to over a trillion connected devices [1]. As a result, ultra low-cost and environmentally-friendly antennas are required for future IoE applications. With Body Area Network (BAN) antennas attracting significant research interest for communication [2], and energy harvesting applications [3], [4], realizing sustainable, low-cost, and environmentally-friendly antennas on textiles using simple fabrication processes is of paramount importance for future BANs.

Carbon-based electronics are attracting increasing attention, with emerging applications in "green" energy storage and harvesting. Recently, a flexible e-textile rectenna filament was integrated with a carbon-based supercapacitor [5], for wearable RF energy harvesting. Carbon nanotubes (CNTs) and conductive polymers have been widely used to realize antennas on flexible films such as Kapton and PET. In [6], a broadband monopole was demonstrated based on PEDOT:PSS conductive polymer with over 85% radiation efficiency. However, CNTs are significantly more expensive compared to carbon black/graphite [7]. Wearable antennas on the other hand are typically realized using conductive fabrics [3], [4], flexible circuit filaments [5], and printed silver inks [8]. In [9], silver and gold-loaded CNT fibres were utilized in an e-textile patch antenna, both of which are more fragile than carbon black and are of higher cost. To-date, no e-textile antenna has been demonstrated based on all-carbon materials, and no antenna has been demonstrated based on printable carbon black ink.

An additional motivation behind high-efficiency and ultra low-cost textile-based antennas is enabling wireless power transmission (WPT) and RF energy harvesting, both widely seen as enablers of a "green" and low environmental footprint IoE. Using low-cost non-metallic antennas, [10], for connecting and power wearables eliminates the need for batteries, maintenance and reducing electrical and electronic waste (WEEE) [11]. Wearable e-textile WPT and RFEH antennas and rectennas have been mostly developed based on electroplated conductive fabrics [3], [4], flexible copper-coated polymers [12], and printed silver inks [13]. While these materials offer the flexibility required for wearable operation, their cost may be prohibitive in certain applications, and they pose additional WEEE implications upon disposal of the e-textile garment.

In this paper, a printable carbon black microstrip patch antenna is presented on textiles for S-band (3-3.5 GHz) applications; and the first carbon-based non-metallic antenna realized on a textile substrate for wearable applications. Despite its low bulk conductivity, the carbon patch maintains a 10.4 and 6.1 dBi measured directivity and gain, indicating a total efficiency over 37%, and 330 MHz bandwidth, demonstrating that non-metallic carbon-based microstrip antennas are suitable candidate for future IoE applications, and a promising device for integration with carbon-based supercapacitors for RF-powered e-textiles. In Section II, the carbon ink preparation and antenna fabrication method are introduced, with the antenna's measured characteristics presented in Section III, and compared to state-of-the-art non-metallic e-textile antennas.

II. Carbon Antenna Fabrication & Design

To demonstrate the feasibility of an all-carbon antenna for wearable applications, a simple square microstrip patch is designed with the dimensions shown in Fig. 1(a). Microstrip patch antennas are widely preferred for wearable applications, for both RF energy harvesting and communications, due to their off-body radiation patterns and high isolation.

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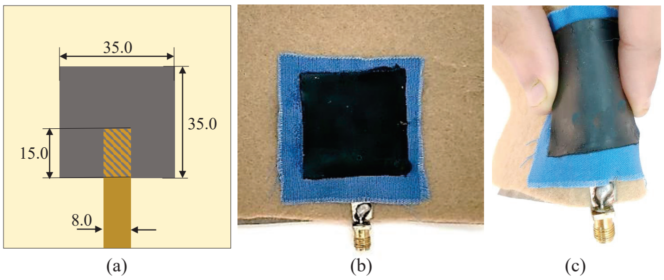

Fig. 1. The proposed non-metal textile-based proximity-fed patch: (a) dimensions in mm; (b) photograph of the antenna; (c) antenna bending.

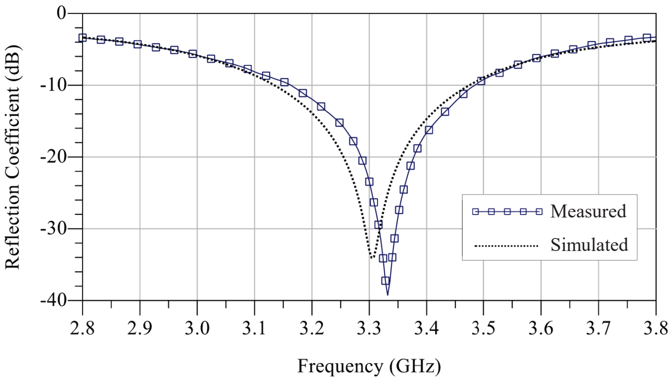

Fig. 2. Simulated and measured reflection coefficient of the carbon patch.

The antenna is designed to achieve a 50 Ω characteristic impedance with a buried line microstrip feed. By utilizing a proximity-coupled microstrip feed, the recyclable or detachable driving electronic circuity can be "connected" seamlessly to the patch's radiating aperture without the need for physical interconnects such as solder or through-textile vias.

The carbon paste was prepared by mixing 1 g of carbon black powders with 0.6 g of Ethylene vinyl acetate (EVA) polymer binder and 3.5 ml of solvent 1,2,4-trichlorobenzene. The conductive carbon black powder with a medium particle diameter of 35 nm was supplied by Smart Fabric Inks Ltd., UK. Carbon black amounts to 62.5% of the mixture by mass. The carbon paste is deposited onto a thin woven 65/35 polyester-cotton textile substrate (Klopman, Italy) using stencil casting with a Teflon mask thickness of 5 mm, the required thickness to reach a conductivity suitable for microwave antenna applications. The printed carbon patch is cured for 8 hours at room temperature (about 23°C) with the mask, followed by 50°C curing without air ventilation for 2 hours. The curing process is repeated for 6 times until all solvent evaporated. At a thickness of 3 mm above the fabric, the cured carbon sheet exhibits a sheet resistance of 3 Ω/square, comparable to that of inkjet printed silver ink on textiles [2]. Fig. 1(b) and (c) show photographs of the fabricated prototype.

To simplify the attachment of the connector, an adhesive-backed copper film is used for the microstrip line feeding the antenna. Nevertheless, it was confirmed in simulation that the feed results in under -15 dBi radiation, implying that any measured radiation is predominantly from the carbon antenna.

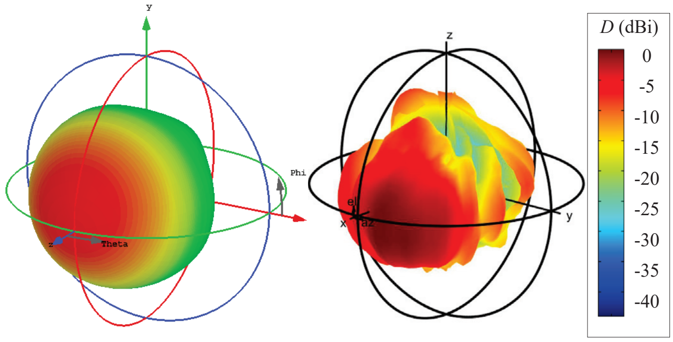

Fig. 3. Simulated (left) and measured (right) 3D co-polarized normalized directivity of the proposed antenna.

III. Simulated and Measured Results

The antenna was simulated in CST Microwave Studio based on the measured conductivity of σ=800 S/m, a 1 μm surface roughness, and the dielectric properties (ϵ_r=1.2, tanδ=0.02) of the felt substrate. The fabricated antenna was characterized using a Rohde & Schwarz ZVB4 VNA to measure its impedance response, both in free space and on-body. Fig. 2 shows the simulated and measured S_{11} of the antenna.

The antenna's radiation patterns were simulated in CST and measured experimentally. The measurements were performed in a an echoic indoor environment using the low-cost setup detailed in [14]. Fig. 3 shows the simulated and measured 3D co-polarized patterns at 3.3 GHz, normalized to the peak measured directivity of 10.4 dBi. Both the simulated and measured 3D patterns demonstrate that the antenna maintains broadside radiation, and is well-suited for off-body wearable communications and wireless power harvesting [4].

The simulated and measured co- and cross-polarized patterns, at 3.3 GHz, over the principal E-plane are compared in Fig. 4. The simulated and measured radiation patterns closely agree in the antenna's main lobe, validating the simulation model and showing that the full carbon construction of the patch does not affect its surface current distribution and subsequently the radiation patterns. The high measured cross-polarization level is attributed to the measurements taking place in an echoic environment.

Based on the CST simulation far-field monitors, the antenna achieves at least 30% total efficiency over its S_{11} bandwidth. Recently-reported microstrip antennas implemented on the same substrate have efficiencies ranging from 30–70%, using printed silver or e-textile metallized patches [2], [4]. As a result, the proposed antenna demonstrates that non-metallic patch antennas are suitable for future wearable applications, where its radiation efficiency is less than 10% lower than its silver (single-layer) counterpart achieving 37% efficiency, [2]. Experimentally, the gain was measured using two identical antennas at a fixed distance, with VNA time-domain gating to

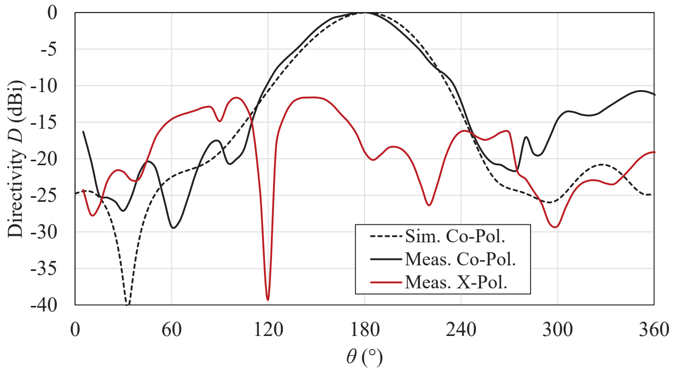

Fig. 4. Simulated and measured normalized directivity of the carbon antenna over the E-plane.

TABLE I
COMPARISON WITH RECENT FLEXIBLE CARBON/POLYMER-BASED ANTENNAS

	This work	2010 [9]	2018 [15]	2018 [16]
Freq (GHz)	3.3	2.45	0.868/0.915	2.4
Antenna	Patch	Patch	Dipole	Patch
Rad Eff.	39%	-2 dBC†	-0.5 dBD*	28%
Gain	6.1 dBi	6 dBi	1.45 dBi	NR
Conductor	Carbon-black ink	Ag/CNT	Graphite films	PEDOT: PSS
Substrate	Textile	Polymer	PET	Textile

*relative to a copper dipole on the same substrate; †relative to a copper patch on the same substrate

minimize additional reflections, with the path loss calculated using the free-space equation. The realized gain of the antenna was measured to be 6.1 dBi. Comparing the measured gain to the 10.4 dBi measured directivity, the antenna achieves a ∼39% measured total efficiency, showing comparable performance to its silver-based inkjet printed counterpart with approximately 50% radiation efficiency.

The proposed carbon-based e-textile antenna is compared in Table I to recently reported composite and polymer antennas implemented on textiles. Compared to [9] and [10], the proposed antenna is based on an all-carbon ink, making it more suited to low-cost and environmentally-friendly wearable applications, compared to CNTs which are more difficult to fabricate and are significantly higher in cost. While the graphite dipole in [7] achieves a higher radiation efficiency than the proposed patch, this is attributed to the lower losses in a free-standing wire-type dipole relative to a patch antenna, where a copper microstrip antenna on the same substrate will still exhibit a lower efficiency. Furthermore, the proposed antenna maintains a higher measured efficiency all-polymer PEDOT:PSS was demonstrated on textiles in [16], demonstrating the carbon-based conductive inks can be a favorable alternative to conductive polymers for RF applications.

IV. CONCLUSION

In this paper, a non-metallic printed microstrip patch antenna was presented for the first time on textiles for wearable applications. The realized antenna exhibits similar gain to its counterparts fabricated using metal-loaded CNTs and fabrics, despite using lower-cost carbon-black ink compatible with direct printing on textile substrates. The antenna achieves a measured S_{11} bandwidth of 330 MHz from 3.16 to 3.49 GHz, a measured directivity of 10.4 dBi, and at least 30% radiation efficiency. Based on the measured performance of the proposed antenna, future "green" BAN antennas can be realized using printed non-metal conductors. Furthermore, the promising RF performance of carbon-based antennas promises improved integration with carbon-based components such as textile-based supercapacitors and batteries for RF-powered e-textile wearables.

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