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3D Printed Fingernail Antennas for 5G Applications

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ABSTRACT 3D printing of antennas on removable fingernail for on-body communications at microwave and millimetre waves is proposed. Aerosol Jet technology, a fine-feature material deposition solution, has been used to directly print microstrip patch antennas on an acrylonitrile butadiene styrene (ABS) removable finger nail substrate. Two antennas have been printed and assessed, one operating at 15 GHz and the other at 28 GHz. Nanoparticle conductive silver ink has been employed to create the microstrip patch antennas and corresponding transmission line using an Optomec machine. The inks are then cured using a PulseForge machine. A further copper layer is added to the millimeter wave antenna via an electroplating process. The antennas have been simulated and measured off-the-finger and on-the-finger. Simulated and measured reflection coefficients (S_{11}) and radiation patterns are found to be in good agreement. The proposed on-body antennas can find application in the Internet of Things (IoT) where large amount of sensing data can be shared at the microwave and millimetre wave spectrum of future 5G communications. The removable finger nails could include other electronic devices such as on-body sensors, computational, storage and communication systems.

INDEX TERMS 3D printing, wearable antenna, removable finger nail, millimeter wave, 5G communications.

I. INTRODUCTION

There has been an increasing need for large storage, exchange and exploitation of information for control/sensing. This calls for support of ubiquitous connectivity of large data volume by the next generation of wireless communication to cater for the progressively increasing demand for high data rates and mobility [1]. Demand also exist for higher capacity, increased connectivity and reliability, higher versatility as well as application specific topologies. 5G technology aims to provide reliable and robust global connectivity for communication between entities that can communicate creating massive Internet of Things (IoT) [2]. Its frequency spectrum

will span the microwave and millimeter wave frequencies [3]. Massive IoT will enable smart devices to independently mutually interact and share data [4]. Part of this network ecosystem will be Body Area Network (BAN). Advances in microelectronics miniaturization coupled with new communication technologies has facilitated wireless BANs. Wireless BANs have ignited interest in human body mountable antenna for wearable applications such as in sports, military, health etc., [5], [6].

On-body antennas can be mounted on or integrated on wearables for communication of uninterrupted monitored parameters e.g. body temperature, heartbeat etc or the wearer's location to other devices. They are generally light, flexible with small surface coverage to ensure an unobstrusive integration with body environment [7]. Various on-body

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antennas suitable for 5G technologies have been developed. Textile have been used as a substrate [8], [9] in some of these developments. In [10], button antenna is proposed at millimeter wave inspired by an earlier work at microwaves in [11]. Smart watches [12], armbands [13] and glasses [14], [15] are other type of wearables antennas developed. Antennas have also been attached directly to the skin [16] and on bandage [17].

Additive manufacturing (AM) or 3D Printing is a cluster of emerging technologies that enables creation of objects bottom-up through layer by layer addition of materials. AM use computer-aided design (CAD) virtual 3D models that are then translated into physical objects. 3D printing fabrication processes reduces waste; tooling and material costs; leads to fast production and enables realization of complex designs unfeasible with conventional fabrication processes [18], [19]. AM have been employed for development of antennas for various applications including antennas for 5G systems. AM can be used to print metallic structures [20], dielectric layers [21] or both layers [22] of an antenna. Dielectric lenses [23] and dielectric resonator antennas [24] are example of dielectric only printed antennas. Full 3D printing with metals has been realized using techniques such as Selective laser melting (SLM) [25] and metal binder jetting [26]. It has also been used for the development of complex microwave antennas [27] and millimeter wave and Terahertz (THz) antennas [28], [29]. However, these techniques do not offer the design flexibility that other direct write systems such as inkjet and aerosol systems can provide. Inkjet printing technique precisely deposits digitally controlled ink drops onto substrate surface as in [30]. Aerosol jetting involves aerodynamically focusing atomized nanoparticle inks droplets as collimated beam to print lines of magnitude of 10 microns as in [31].

AM has been used to develop wearable antennas that operate mainly at the UHF and microwave band [32], [33]. Examples include dipole antennas on 3D printed wrist bands using a variety of techniques for depositing the metallic layers [34], a wearable RFID applications manufactured using 3D direct-write dispensing on a fabric [35] and antennas printed on textiles [36]. More recently, a 5G millimeter wave antenna has been embedded into a medallion using a 3D printing technique which combines fused deposition modelling (FDM) for the substrate and syringe dispensing for the metallic layers [37].

In this paper, 3D printed antennas on a removable fingernail for on-body microwave and millimeter wave communications are proposed. A patch antenna design is used to demonstrate this concept. Nanoparticle Silver inks are dispensed using Aerosol Jet Technology to produce the small features of the antennas. Two antennas have been fabricated to operate at 15 GHz and 28 GHz respectively. The 15 GHz band antenna has been tested directly after the printing and curing while an additional copper plating process is employed for the 28 GHz band antenna. To the best of authors' knowledge, it is the first time that antennas has been printed on a fingernail for 5G mid and high frequency bands [38]



FIGURE 1. Illustrative on-fingernail antenna communication environment.

TABLE 1. Dimensions of the patch of the 15 GHz antenna (mm).

Wg	Lg	Wp	Lp	Lm	x	y	z
15	19	7.8	6.5	13	1.5	1.75	1.0

applications. The antennas' removability can allow portability of the electronic equipment it is attached to from one individual to another or the antenna from one device to another. This facilitates reusability of the device. These can find applications in future on-body sensing and communications though manicure electronics as envisioned and illustrated in Fig 1. The rest of this paper is organized as follows. Section II describes the design and fabrication of the microwave removable nail antenna. Section III describes the millimeter wave antenna and Section IV is the discussion and conclusion.

II. 3D PRINTED MICROWAVE NAIL ANTENNA

A. ANTENNA DESIGN

The 15 GHz antenna was designed, simulated and tested using CST Microwave StudioTM for the antenna off- and on-finger. The fake finger nail substrate is made of an Acrylonitrile butadiene styrene (ABS) of 0.5 mm thickness with a relative permittivity (ϵ_r) of about 2.7 and loss tangent of 0.0051 [39]. The designed patch antenna comprises of a rectangular radiating patch with a microstrip transmission line and a rectangular ground on the back plane. The designed antenna is illustrated in Fig. 2 (a) and Table 1 represents its dimensions. Fig. 2 (b) shows the antenna curved to the shape of a nail while Fig. 2 (c) depicts the angle, 55.38° , of the curvature. On-finger simulation was conducted to determine the effect of human tissue on the antenna's performance as shown in Fig 3. Bone, fat, skin and nail tissues all of which have different ϵ_r were considered. Their estimated dimensions are skin (1 mm), fat (2.0mm), nail (0.5 mm), and bone (2 mm). Their electrical characteristics at 15 GHz are given in Table 2 [40]. Fig. 3(a) depicts the cross and Fig. 3(b) the longitudinal sections of the patch antenna on a non-homogenous human tissues layer.

The simulation reflection coefficient, S_{11} , results of the flat, curved antenna and the curved antenna on the finger are

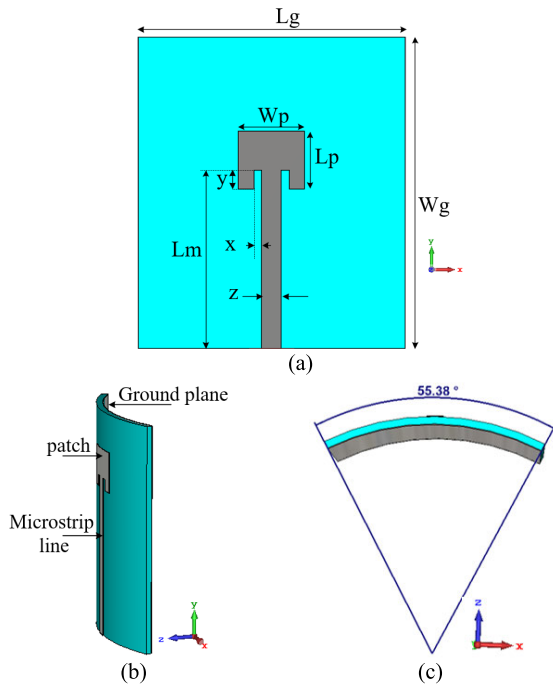


FIGURE 2. The designed (a) patch antenna design (b) after curving into an arc and (c) degree of curvature.

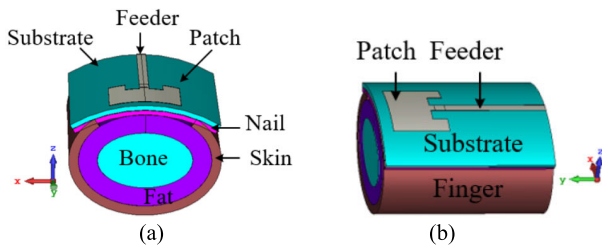


FIGURE 3. (a) cross, and (b) longitudinal section of the human finger model of the removable patch antenna.

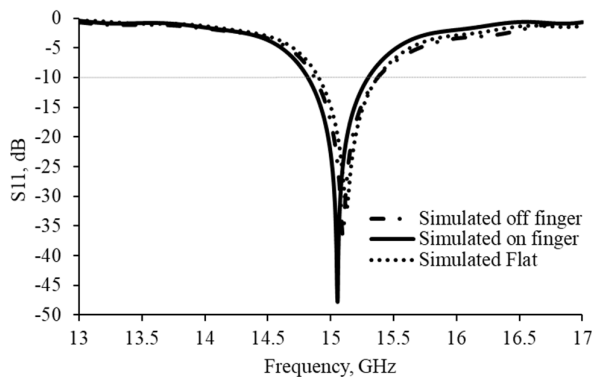


FIGURE 4. Simulated S_{11} results of flat, curved off and on-finger simulated antenna at 15 GHz.

shown in Fig. 4. Flat and curved antenna S_{11} off finger results are almost identical implying that bending had minimal effect on the S_{11} . However, with the antenna worn on finger, the resonant point slightly shifts to the left. The results indicates a –10 dB impedance bandwidth from 14.8 GHz to 15.3 GHz

TABLE 2. Electrical characteristics of human tissues at 15 GHz.

Tissue	Relative permittivity, ϵ_r	Conductivity, σ (S/m)	Loss tangent, $\tan(\delta)$
Fat	4.2647	0.93625	0.26309
Skin	26.401	13.847	0.62855
Nail/Bone	6.8698	3.1355	0.54695

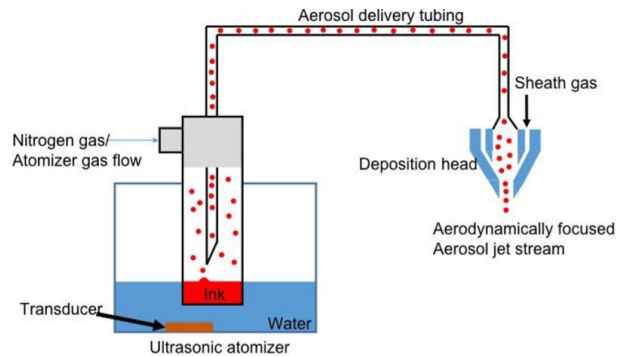


FIGURE 5. Schematic of Aerosol jet printing process [46].

(2.9%), 14.88 GHz to 15.37 GHz (3.2%) and 14.82 GHz to 15.30 GHz (3.2%) for the flat, curved off-finger and curved on-finger microstrip patch antennas respectively. The results indicate bandwidth consistency for the three cases.

B. OPTOMECS AEROSOL JET FABRICATION

The microstrip patch nail antennas were fabricated by depositing the conductive ink using Optomec’s aerosol jet technology. Aerosol Jet Printing manufacturing technology is emerging as a substitute for the traditional thick-film processes such as screen-print, photolithography and micro-dispensing and has been described as superior to inkjet printing [41]. Fig. 5 depicts working principle of the Aerosol Jet Technology. The Aerosol Jet process uses aerodynamics to deposit functional material aerosolized droplets onto a substrate. The functional liquid is aerosolized into globules and then focused as collimated beams of diameter of around 10 microns after it has been passed through a deposition head. The deposition head sends out the aerosol beam which impinges the droplet on the substrate [42]. To print the features, the deposition head is translated in the XYZ and Theta directions with respect to the substrate. The CAD design file generated tool path guides the deposition head translation. This allows the deposition head to print in any orientation. Thus, it can print on 3D surfaces and not just on smooth and flat surface.

To fabricate the antennas, the digital model was exported from CST Microwave Studio™ to an STL file. The metallic layers that constitutes the radiator and the microstrip transmission line were uniformly deposited onto the fake nail using the Optomec’s aerosol jetting process that sprays Cabot CS-32 silver conductive ink. The antennas were left to dry for about 24 hours before being transferred to a NovaCentrix PulseForge [43] machine to cure. The fabrication was done at the Centre for Process Innovation (CPI) [44]. Fig. 6(a) shows

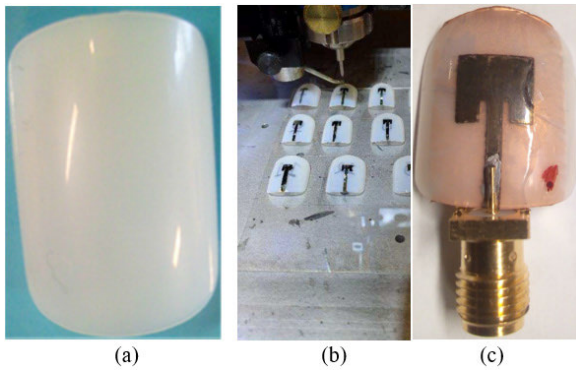


FIGURE 6. (a) The fake removable nail (b) printing of the antennas using the Optomec machine (c) the fabricated antenna.

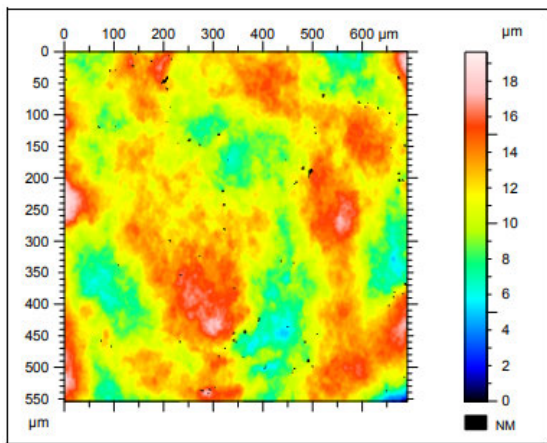


FIGURE 7. Surface profile of the antenna patch.

the fake nail on which the antennas was printed, Fig. 6(b), the fabrication process and Fig. 6(c), the fabricated antenna. An SMA Connector was attached to the feedline of the antenna (Fig. 6 (c)). Analytical tests on printed tracks on the nail were carried out using the equation for the resistivity, ρ :

$$\rho = R \frac{A}{l} \quad (1)$$

where R is the measured resistance, A is the cross-sectional area and l is the length of the track. The resistance was measured with a multi-meter. Resistivity was then calculated from (1) and found to be consistent with the expected value of $2 \times 10^{-7} \Omega m$ for silver ink [45]. Fig. 7 shows the surface profile of the silver ink layer of the patch element of antenna. This was analysed using Talysurf CCI and showed a roughness of about $1 \mu m$. The ground plane of the antenna was created using adhesive copper tape which was attached to the back of the ABS nail.

C. RF MEASUREMENTS

The S_{11} and radiation pattern of the fabricated antenna were measured to determine its performance. The S_{11} measurements were obtained using an Anritsu 37397C vector network analyzer for the nail antenna off- and on-finger. A graph of the measured and simulated S_{11} results is shown

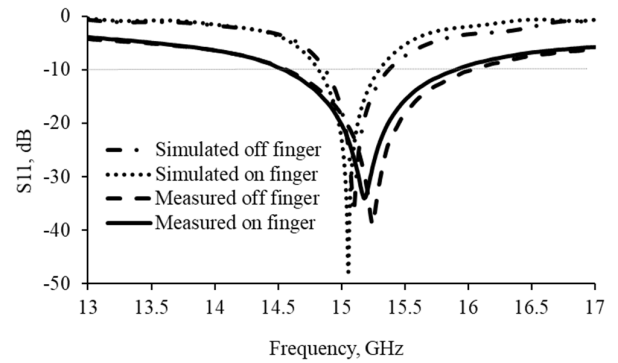


FIGURE 8. Reflection coefficient (S_{11}) of the optimized 15 GHz antenna.

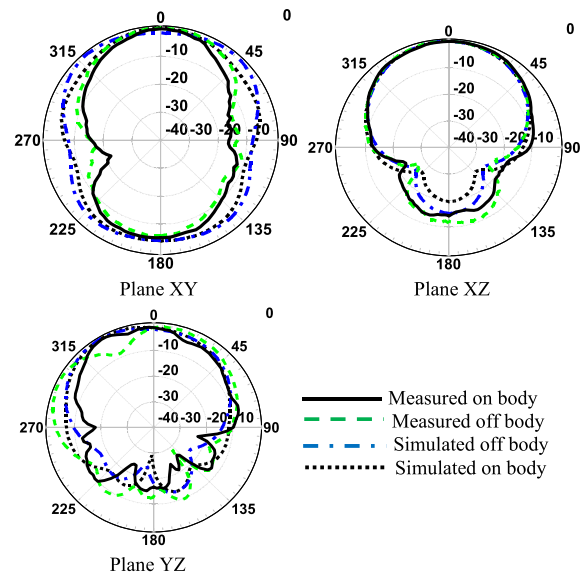


FIGURE 9. Radiation pattern for the XY, XZ and YZ planes at 15 GHz.

in Fig. 8. The measured S_{11} results shows a better matching and wider -10 dB impedance bandwidth relative to the simulated results. This could be due to further resistive losses in the materials not accounted for, connectors and errors in the fabrication. The resonant points also shifted slightly to the right. -10 dB impedance bandwidths from 14.6 to 16.0 GHz (9.8%) and 14.5 to 15.9 GHz (9.1%) for the antenna off- and on-finger respectively are realized. A slight shift of the resonance point to the left is observed for the on-finger antenna.

Far field radiation pattern was performed in an anechoic chamber. Fig. 9 shows the radiation patterns for both off- and on-finger for the simulated and fabricated antennas. Patterns are as expected for a patch antenna on a small curved ground plane with a main lobe out of the fingernail and lower radiation towards the finger and body. Radiation pattern for both simulated and fabricated antennas shows consistency in XY, XZ and YZ planes for both off- and on-finger situation. The slight variations are attributable to fabrication and measurements errors as well as the antenna connector. The simulated gain and efficiency on body were about 6.9 dBi and 80% respectively at 15 GHz while off-body was about 0.3 dB

TABLE 3. Dimensions of the 28 GHz patch antenna (mm).

Wg	Lg	Wp	Lp	Lm	x	y	z
14.96	17.45	3.72	3.25	10.0	0.44	1.06	1.10

TABLE 4. Electrical characteristics of human tissues at 28 GHz.

Tissue	Relative permittivity, ϵ_r	Conductivity, σ (S/m)	Loss tangent, $\tan(\delta)$
Fat	3.6985	1.6979	0.29471
Skin	16.552	25.824	1.0016
Nail/Bone	5.1671	4.9427	0.6141

higher. The measured gain was almost the same for on and off-body. It was about 6.4 dBi, and the antenna efficiency was 70%. The measured gains and corresponding efficiency includes any potential impedance mismatch.

III. MILLIMETER WAVE NAIL ANTENNA

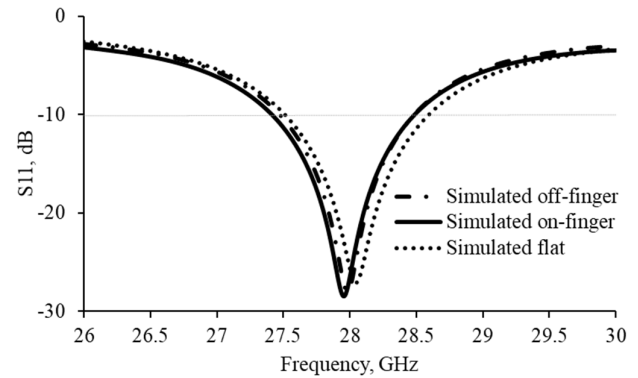
A. ANTENNA DESIGN

Higher frequencies can typically increase the communication bandwidth and thus the amount of data that can be transferred. For the higher frequency, a higher conductivity antenna surface material is preferable. To improve conductivity, a layer of copper can be added to the metallic tracks using an electroplating process. A millimeter wave frequency antenna with dimensions shown in Table 3 was designed, simulated and tested for both off- and on-finger. On-finger worn antenna was simulated to determine the effect of human tissues on the antenna performance at the millimeter wave. Table 4 [40] shows the electrical characteristics of the same human body tissues considered for the microwave antenna for on-body antenna simulation at 28 GHz. Reflection coefficient and radiation pattern performance parameters were used to gauge the performance of the antennas. Fig. 10 shows the simulated S_{11} of the flat, bent off-finger and on-finger antennas. The antenna resonance at 28 GHz have only a minor frequency shifts for the three cases. The results indicate a -10 dB impedance bandwidth of 27.5 GHz to 28.6 GHz (3.9%), 27.5 GHz to 28.5 GHz (3.6%) and 27.5 GHz to 28.5 GHz (3.6%) of the flat, curved off-finger and on-the-finger microstrip patch antenna respectively.

B. MILLIMETER WAVE ANTENNA FABRICATION, SURFACE ANALYSIS AND MEASUREMENTS

The 28 GHz antenna was fabricated using the same fabrication process of the 15 GHz antenna. After the radiator and microstrip transmission line were printed and cured, a copper layer was added through an electroplating process.

A digital microscope from Keyence (UK) Limited was used to observe the antenna surface, measure its roughness and photograph the surface. Fig. 11 shows the surface of the copper plated radiator and its feedline at x50 magnification. Surface roughness measurements of the radiator and feedline are shown in Fig 12 and Fig 13. Fig. 12 (a) shows the conductor height profile at the patch inset edge of Fig 12(b)

**FIGURE 10.** Simulated S_{11} of the flat, curved off and on-finger antennas at 28 GHz.**FIGURE 11.** Blown out photo of the patch antenna and feedline.

which shows the two points at which the measurements were taken at either side of the feedline inset. Fig 12 (c) depicts the actual measurements readings of $9.4 \mu\text{m}$ and $10.9 \mu\text{m}$ at the conductor edge on both sides of the inset shown in Fig. 12 (b). The conductor height measured at the inset/patch point longitudinal to the feedline was also measured and found to be about $13.5 \mu\text{m}$. This implies that though a viable antenna was produced, the fabrication process produced uneven surface. The center line average surface roughness (R_a) was measured on the feedline section of the antenna, Fig. 13(a) and found to be $0.8 \mu\text{m}$ in the profile depiction shown in Fig. 13(b).

The patch antenna microstrip feedline matches the 50Ω impedance of a low profile 2.92 mm SMA Jack (female) end launch connector from Southwest Microwave, Inc. as shown in Fig. 14. Fig. 14(a) shows the fabricated antennas after the electroplating process while Fig. 14(b) depicts the antenna worn on a finger. Fig. 15 shows that the measured S_{11} of the fabricated antenna and its comparison with simulations for both the unworn and worn antennas. The measured antenna operates at 28 GHz with a minor difference off and on the body. The measured bandwidth was 27.0 GHz to 29.8 GHz (10%) and 26.9 GHz to 29.8 GHz (10.25%) for off- and on-finger antennas respectively. Measurements compare well with simulations in terms of resonant frequency. The fabricated antenna has better matching and wider -10dB impedance bandwidth compared to the simulated one for both the off- and on-finger states. This could be due to electrical losses not accounted for in simulations, connectors and errors in the fabrication. The metal ground plane was made using

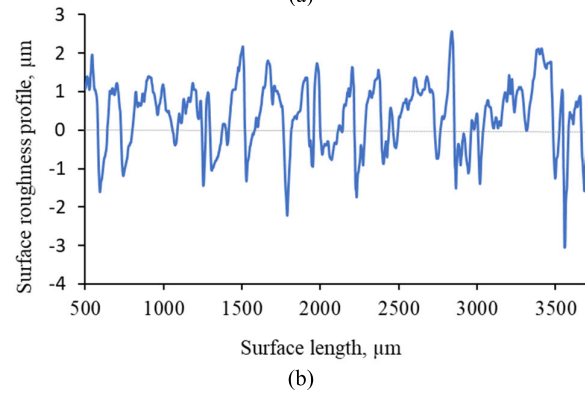
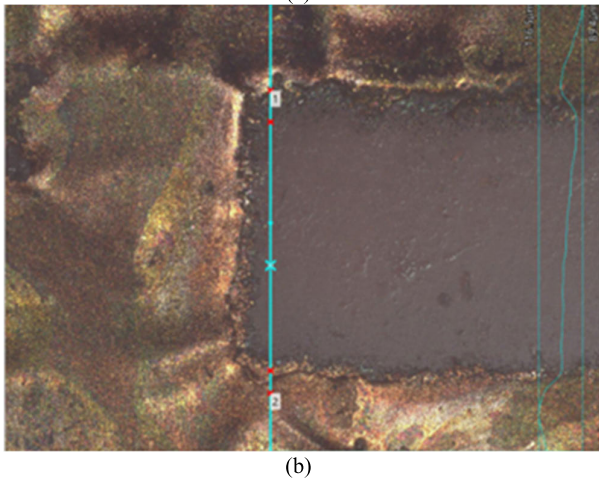
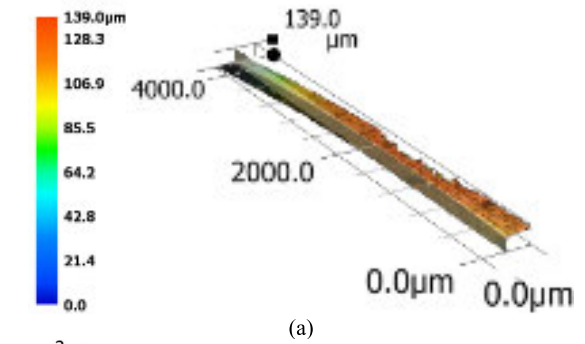
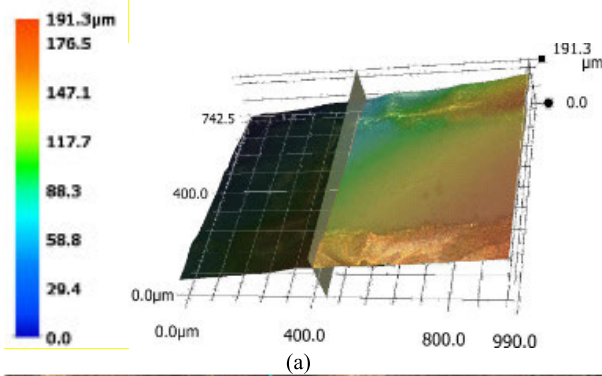


FIGURE 13. Evaluation of microstrip feed line surface profile. (a) The feedline (b) its roughness profile.

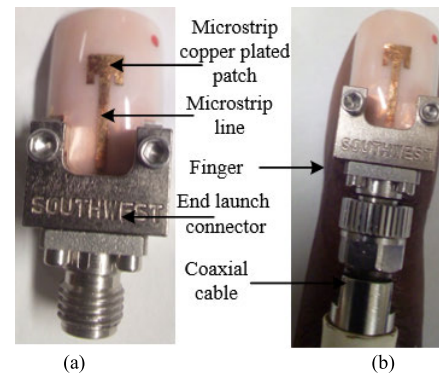
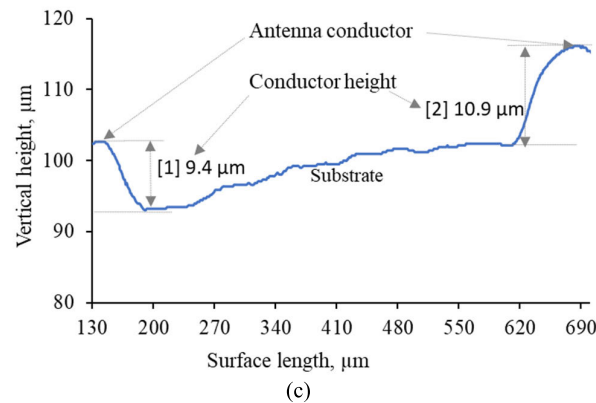


FIGURE 14. The (a) fabricated antenna (b) antenna worn on a finger.

FIGURE 12. Evaluation of the conductor height, (a) conductor height profile (b) measurement point (c) the height at the two inset points.

copper tape with an adhesive layer and was attached by hand. This may add air gaps which could potentially increase matching and bandwidth.

Fig. 16 shows the antenna on-body radiation pattern measurement process. After health and safety assessment, a platform was built and fixed at the base of chamber pole. The antenna wearer stood on the platform during the measurement process. The white plastic pole observed in the figure was fixed to the platform. The cable connecting the antenna was attached to the pole using the plastic straps. The antenna was fixed at all times. The wearer used this stable set up to keep the finger touching the antenna during the on-body measurement.

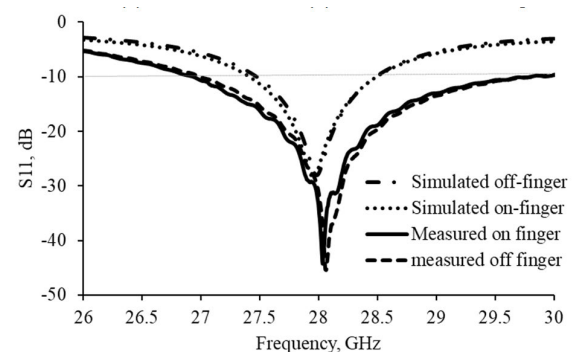


FIGURE 15. Reflection coefficient (S_{11}) of the optimized antenna.

Far field pattern results are shown in Fig. 17 for both off- and on-finger antennas for planes XY, XZ and YZ. The



FIGURE 16. Measurement of the on-body radiation pattern in the anechoic chamber.

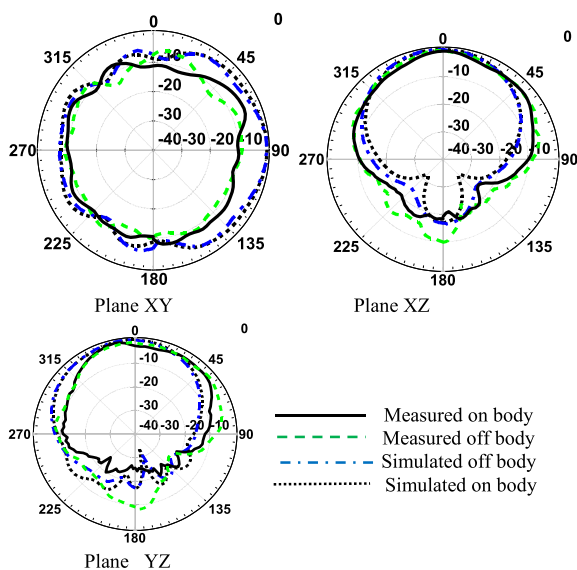


FIGURE 17. Radiation patterns at XY, XZ and YZ planes at 28 GHz.

TABLE 5. Comparison between proposed antenna and other wearable antennas at 28 GHz.

Reference	Frequency (GHz)	Bandwidth (GHz)	Gain (dB)	Substrate
[37]	28	1	7	PLA Medallion
[47]	28	15	3.5	Jeans
[48]	28	2.68	2.1	Rogers 5880
[49]	26/28	10	7	woven polyester
[50]	77	5	11.2	PremixGroup
[51]	60	9.8	9.6	flexible printed circuit board
This work	28	2.87	7.5	ABS fingernail

results show the expected patch antenna’s hemispherical radiation pattern with moderate directivity. The main lobe points out of the fingernail while low back radiation is realised. Back radiation is also lower than for the antenna at 15 GHz (Fig. 9) due to the smaller size of the patch at 28 GHz in relation to the metallic ground plane. The simulated and measured patterns were in reasonable agreement. The main differences between simulations and measurements, particularly in the YZ plane,

were due to the metallic parts of the end-launch connector (Fig. 14).

The simulated gain and efficiency were about 7.5 dBi and 81% respectively at 28 GHz for both on and off body. The measured gain and efficiency were about 7.4 dBi and 80% respectively.

Table 5 compares the proposed antenna with previous wearable antennas. The benefit of this patch antenna is that it offers a good gain and body movements will not affect it.

IV. DISCUSSION AND CONCLUSION

Microwave and millimeter wave antennas on removable fingernails have been demonstrated. On-body patch antennas on ABS nails that operate at 15 GHz and 28 GHz have been developed and tested. Aerosol Jet printing and flush curing were successfully employed to deposit layers of Silver ink on the curved nails. The technique produced the high resolution required for the printed antennas as well as smooth and thin metallic layers. An additional copper layer was added to the 28 GHz through a copper plating. The fabricated antennas provided good performance in terms of impedance match and bandwidth. Radiation patterns were as expected for patch antenna with a main lobe out of the fingernail and low radiation towards the finger and body. The 28 GHz antenna provides lower back radiation and higher gain than the 15 GHz mainly due to the smaller size of the patch in relation to the ground plane. The antenna designs presented in this work can potentially be deployed in IoT solutions for 5G technology. The proposed nail antenna design is light, cheap, easy to install, part of beauty accessory, which occupies a small surface area and is easy to wear. The requirement of different equipment at different stages presents a case for a production chain process. This could enable scaling up to a mass production industrial process. Further, multiple fingers on a human hand can make antenna arrays and diversity systems feasible for signal reception improvement.

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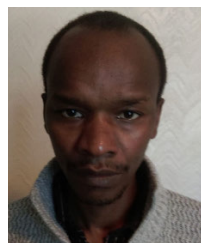
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