**Njogu, Peter, Sanz-Izquierdo, Benito, Elibiary, Ahmed, Jun, Sung Yun, Chen, Zhijiao and Bird, David (2020)** ***3D Printed Fingernail Antennas for 5G Applications.*** **IEEE Access, 8 . pp. 228711-228719. ISSN 2169-3536.**

Received October 30, 2020, accepted November 2, 2020, date of publication December 7, 2020,
date of current version December 31, 2020.

*Digital Object Identifier 10.1109/ACCESS.2020.3043045*

# 3D Printed Fingernail Antennas for 5G Applications

**PETER NJOGU[1], BENITO SANZ-IZQUIERDO[1], (Member, IEEE), AHMED ELIBIARY[2], SUNG YUN JUN[3], (Member, IEEE), ZHIJIAO CHEN[4], (Member, IEEE), AND DAVID BIRD[5]**

[1]School of Engineering and Digital Arts, University of Kent, Canterbury CT2 7NZ, U.K.
[2]Metal Jet 3D Printing, HP, 08174 Barcelona, Spain
[3]RF Technology Divisions, National Institute of Standards and Technology, Boulder, CO 80305, USA
[4]School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
[5]Centre for Process Innovation, Sedgefield TS21 3FG, U.K.

Corresponding author: Benito Sanz-Izquierdo (bsanz@kent.ac.uk)

This work was supported in part by the UK EPSRC HVMC Fellowship under Grant REF: EP/L017121/1, in part by the WISDOM project within the CHIST ERA under EPSRC Grant EP/P015840/1, in part by the project ''Low-Profile Ultra-Wideband Wide-Scanning Multi-Function Beam-Steerable Array Antennas'' under Grant EP/S005625/1, and in part by the Royal Society through International Exchanges 2019 Cost Share (NSFC) under Grant Ref: IEC\NSFC\191780.

**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 communciation 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 uniterruptedly 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

The associate editor coordinating the review of this manuscript and approving it for publication was Shah Nawaz Burokur.

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 manfucturing (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 respectivtly. 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 Studio$^{TM}$ 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 ($\varepsilon_r$) 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 $\varepsilon_r$ 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

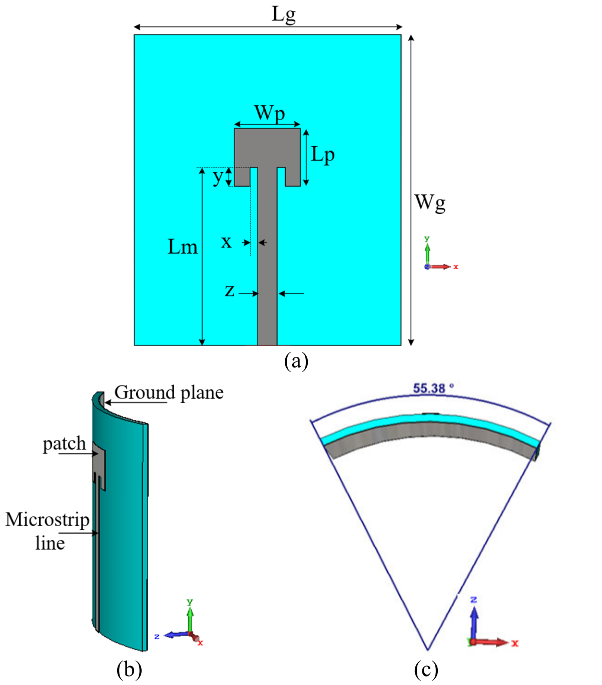



**FIGURE 2.** The designed (a) patch antenna design (b) after curving into an arc and (c) degree of curvature.

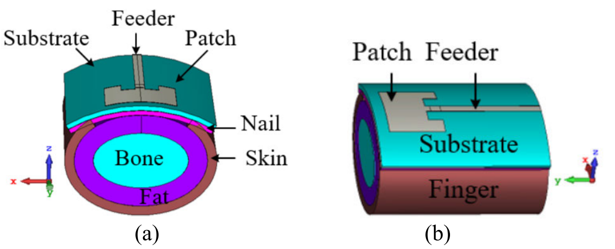



**FIGURE 3.** (a) cross, and (b) longitudinal section of the human finger model of the removable patch antenna.

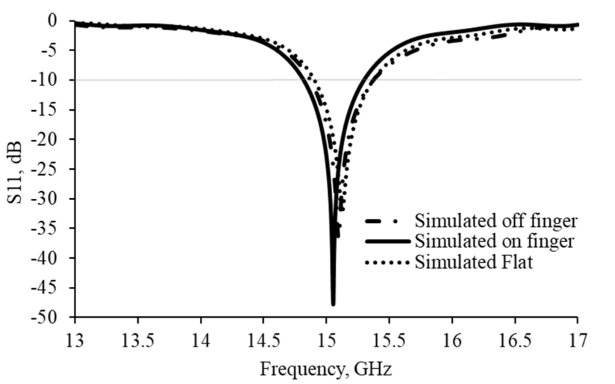



**FIGURE 4.** Simulated $S_{11}$ results of flat, curved off and on-finger simulated antenna at 15 GHz.

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, $\varepsilon_r$ | Conductivity, σ, (S/m) | Loss tangent, tan(δ) |
|---|---|---|---|
| **Fat** | 4.2647 | 0.93625 | 0.26309 |
| **Skin** | 26.401 | 13.847 | 0.62855 |
| **Nail/Bone** | 6.8698 | 3.1355 | 0.54695 |

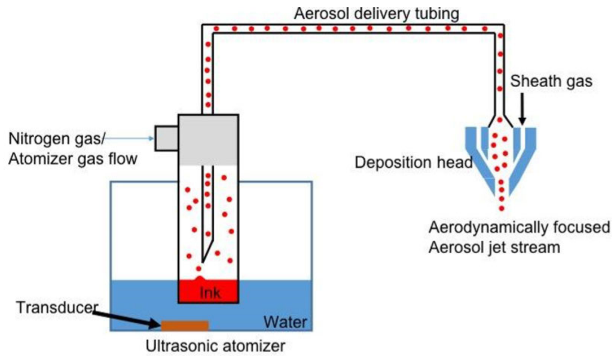



**FIGURE 5.** Schematic of Aerosol jet printing process [46].

(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. OPTOMEC'S 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

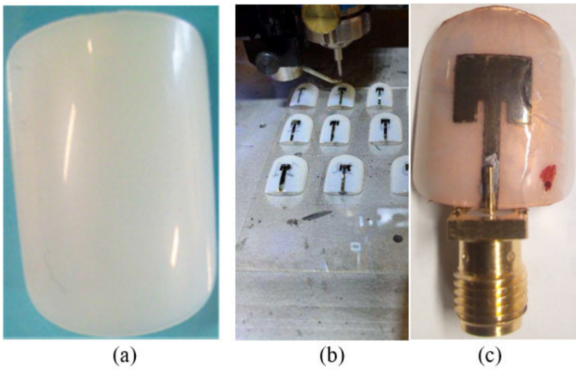



**FIGURE 6.** (a) The fake removable nail (b) printing of the antennas using the Optomec machine (c) the fabricated antenna.

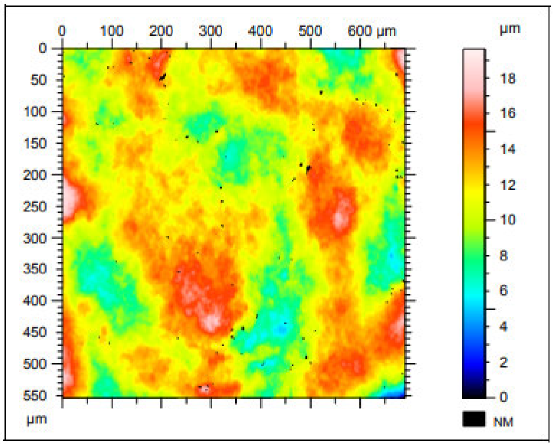



**FIGURE 7.** Surface profile of the antenna patch.

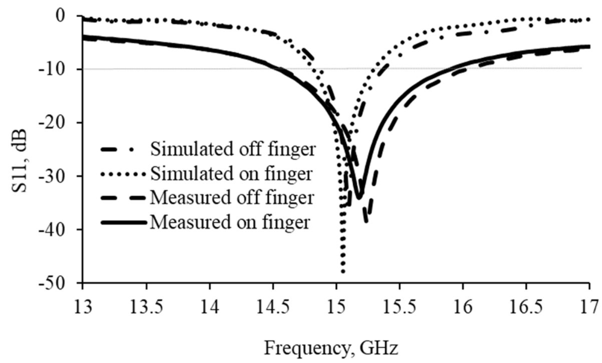



**FIGURE 8.** Reflection coefficient ($S_{11}$) of the optimized 15 GHz antenna.

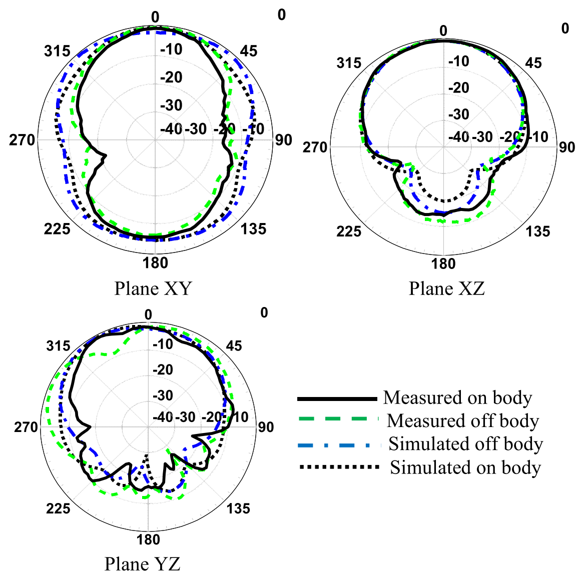



**FIGURE 9.** Radiation pattern for the XY, XZ and YZ planes at 15 GHz.

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, $\rho$:

$$\rho = R\frac{A}{l} \tag{1}$$

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 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, $\varepsilon_r$ | Conductivity, σ (S/m) | Loss tangent, tan(δ) |
|---|---|---|---|
| **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 it 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)

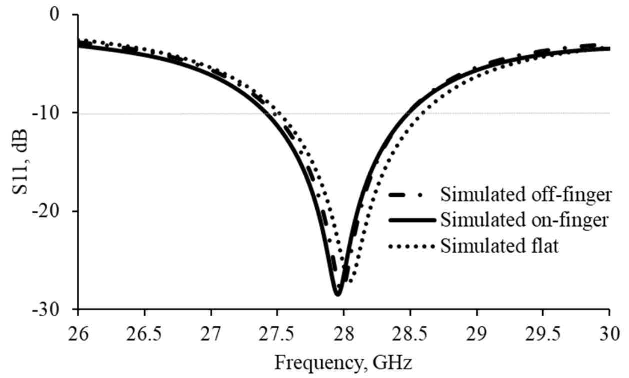



**FIGURE 10.** Simulated $S_{11}$ of the flat, curved off and on-finger antennas at 28 GHz.

**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 $\mu$m and 10.9 $\mu$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 $\mu$m. This implies that though a viable antenna was produced, the fabrication process produced uneven surface. The center line average surface roughness (Ra) was measured on the feedline section of the antenna, Fig. 13(a) and found to be 0.8 $\mu$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

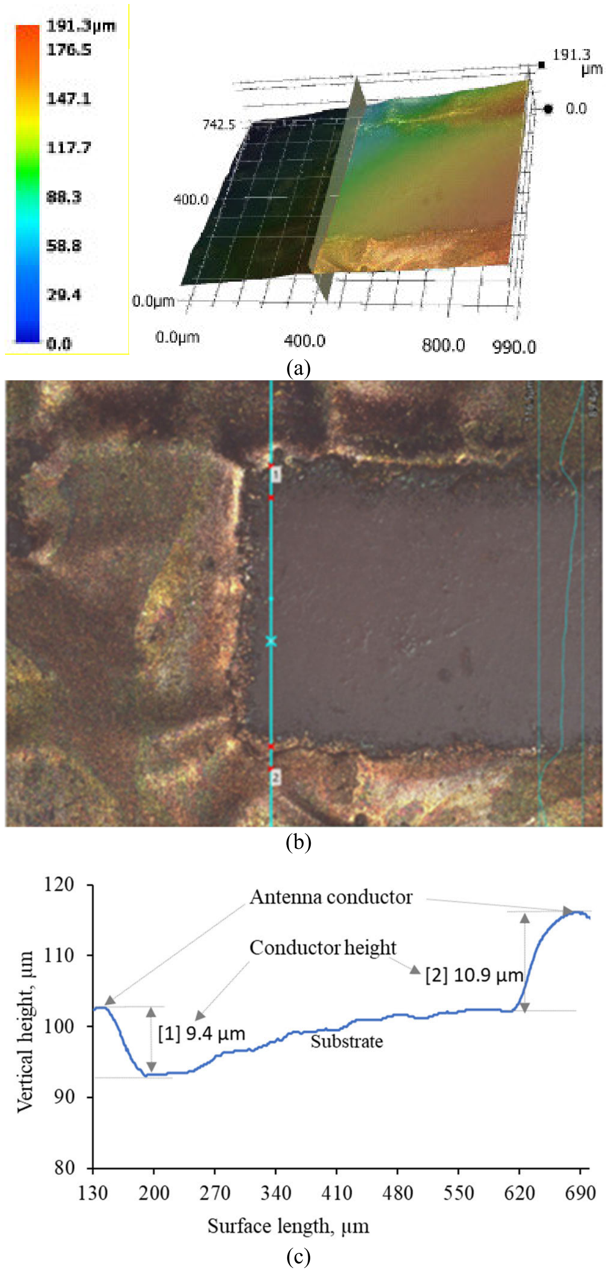



FIGURE 12. Evaluation of the conductor height, (a) conductor height profile (b) measurement point (c) the height at the two inset points.

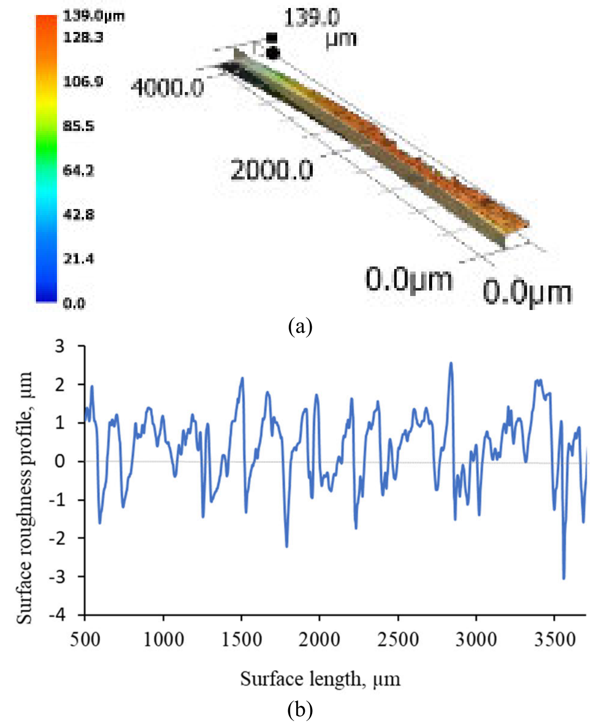



FIGURE 13. Evaluation of microstrip feed line surface profile. (a) The feedline (b) its roughness profile.

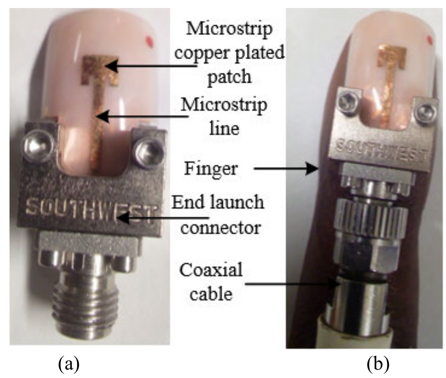



FIGURE 14. The (a) fabricated antenna (b) antenna worn on a finger.

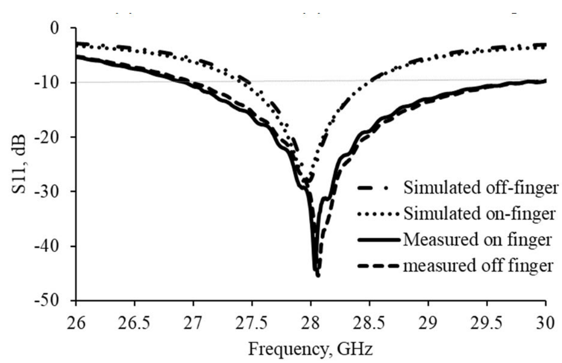



FIGURE 15. Reflection coefficient ($S_{11}$) of the optimized antenna.

copper tape with and 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.

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.**

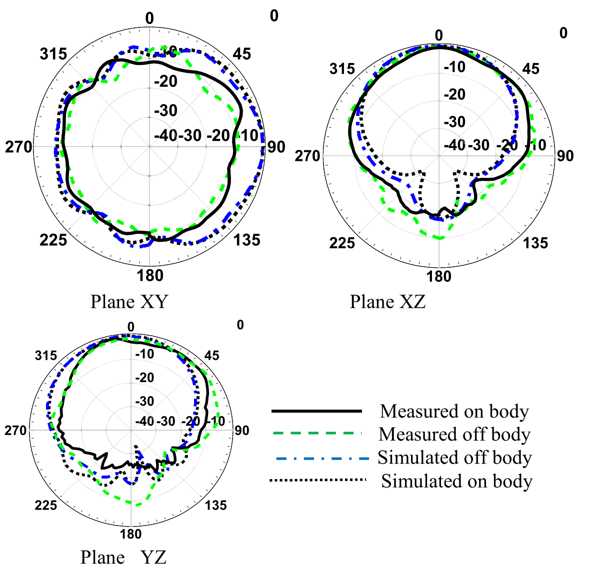



**FIGURE 17.** **Radiation patterns at XY, XZ and YZ planes at 28 GHz.**

**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 manly 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.

## ACKNOWLEDGMENT

The authors would like to thank S. Jakes for help with fabrication and A. Mendoza for help with the radiation pattern and gain measurements. Mathew Armes from Keyence helped with surface profile measurements while Dr. Mike Green and Ayman helped in tiding up the profile pictures.

## REFERENCES

[1] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

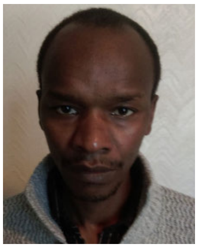
[2] H. Rahimi, A. Zibaeenejad, and A. A. Safavi, "A novel IoT architecture based on 5G-IoT and next generation technologies," in *Proc. IEEE 9th Annu. Inf. Technol., Electron. Mobile Commun. Conf. (IEMCON)*, Vancouver, BC, Canada, Nov. 2018, pp. 81–88.

[3] M. Shafi, J. Zhang, H. Tataria, A. F. Molisch, S. Sun, T. S. Rappaport, F. Tufvesson, S. Wu, and K. Kitao, "Microwave vs. millimeter-wave propagation channels: Key differences and impact on 5G cellular systems," *IEEE Commun. Mag.*, vol. 56, no. 12, pp. 14–20, Dec. 2018.

[4] S. Li, L. D. Xu, and S. Zhaof, "5G Internet of Things: A survey," *J. Ind. Inf. Integr.*, vol. 10, pp. 1–9, Jun. 2018.

[5] B. Sanz-Izquierdo, E. A. Parker, J. C. Batchelor, and J. Miller, "Body armour with integral high impedance surface," in *Proc. 5th Eur. Conf. Antennas Propag. (EUCAP)*, Rome, Italy, Apr. 2011, pp. 1061–1064.
[6] A. Sabban, *Novel Wearable Antennas for Communication and Medical Systems*. New York, NY, USA: CRC Press, 2019.
[7] M. L. Scarpello, I. Kazani, C. Hertleer, H. Rogier, and D. V. Ginste, "Stability and efficiency of screen-printed wearable and washable antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 838–841, 2012.
[8] N. Chahat, M. Zhadobov, L. Le Coq, and R. Sauleau, "Wearable endfire textile antenna for on-body communications at 60 GHz," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 799–802, 2012.
[9] M. Joler and M. Boljkovac, "A sleeve-badge circularly polarized textile antenna," *IEEE Trans. Antennas Propag.*, vol. 66, no. 3, pp. 1576–1579, Mar. 2018.
[10] G. S. Karthikeya, K. K. Devaiah, R. S. G. Sharma, M. H. B. Patel, N. R. Mandi, and T. Thyagaraj, "Wearable button antenna array for V band application," in *Proc. IEEE 5th Asia–Pacific Conf. Antennas Propag. (APCAP)*, Kaohsiung, Taiwan, Jul. 2016, pp. 283–284.
[11] B. Sanz-Izquierdo, J. A. Miller, J. C. Batchelor, and M. I. Sobhy, "Dual-band wearable metallic button antennas and transmission in body area networks," *IET Microw., Antennas Propag.*, vol. 4, no. 2, pp. 182–190, Feb. 2010.
[12] A. Shafqat, F. A. Tahir, and H. M. Cheema, "A compact uniplanar tri-band antenna for wearable smart watches," in *Proc. 18th Int. Symp. Antenna Technol. Appl. Electromagn. (ANTEM)*, Waterloo, ON, Canada, Aug. 2018, pp. 1–3.
[13] S. M. Abbas, K. P. Esselle, and Y. Ranga, "An armband-wearable printed antenna with a full ground plane for body area networks," in *Proc. IEEE Antennas Propag. Soc. Int. Symp. (APSURSI)*, Memphis, TN, USA, Jul. 2014, pp. 318–319.
[14] S. Hong, S. H. Kang, Y. Kim, and C. W. Jung, "Transparent and flexible antenna for wearable glasses applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2797–2804, Jul. 2016.
[15] Y.-Y. Wang, Y.-L. Ban, Z. Nie, and C.-Y.-D. Sim, "Dual-loop antenna for 4G LTE MIMO smart glasses applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 9, pp. 1818–1822, Sep. 2019.
[16] I. Gani and H. Yoo, "Miniaturized scalp-implantable antenna for wireless biotelemetry," in *Proc. Int. Workshop Antenna Technol. (iWAT)*, Seoul, South Korea, Mar. 2015, pp. 348–349.
[17] A. Shamim, "3D inkjet printed flexible and wearable antenna systems," in *Proc. Int. Symp. Antennas Propag. (ISAP)*, Oct. 2017, pp. 1–2.
[18] H. Xin and M. Liang, "3-D-Printed microwave and THz devices using polymer jetting techniques," *Proc. IEEE*, vol. 105, no. 4, pp. 737–755, Apr. 2017.
[19] B. Sanz-Izquierdo and E. A. Parker, "3-D printing of elements in frequency selective arrays," *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 6060–6066, Dec. 2014.
[20] C. R. Garcia, H. H. Tsang, J. H. Barton, and R. C. Rumpf, "Effects of extreme surface roughness on 3D printed horn antenna," *Electron. Lett.*, vol. 49, no. 12, pp. 734–736, Jun. 2013.
[21] J. Ren and J. Y. Yin, "3D-printed low-cost dielectric-resonator-based ultra-broadband microwave absorber using carbon-loaded acrylonitrile butadiene styrene polymer," *Materials*, vol. 11, no. 7, p. 1249, 2018.
[22] G. McKerricher, D. Titterington, and A. Shamim, "A fully inkjet-printed 3-D honeycomb-inspired patch antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 544–547, 2016.
[23] H. Yi, S.-W. Qu, K.-B. Ng, C. H. Chan, and X. Bai, "3-D printed millimeter-wave and terahertz lenses with fixed and frequency scanned beam," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 442–449, Feb. 2016.
[24] Z.-X. Xia, K. W. Leung, and K. Lu, "3-D-Printed wideband multi-ring dielectric resonator antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 10, pp. 2110–2114, Oct. 2019.
[25] B. Zhang, Z. Zhan, Y. Cao, H. Gulan, P. Linner, J. Sun, T. Zwick, and H. Zirath, "Metallic 3-D printed antennas for millimeter-and submillimeter wave applications," *IEEE Trans. THz Sci. Technol.*, vol. 6, no. 4, pp. 592–600, Jul. 2016.
[26] R. Xu, S. Gao, B. S. Izquierdo, C. Gu, P. Reynaert, A. Standaert, G. J. Gibbons, I. Dmitry, W. Bosch, and M. E. Gadringer, "140 GHz additive manufacturing low-cost and high-gain Fabry–Perot resonator antenna," in *Proc. Int. Workshop Antenna Technol. (iWAT)*, Bucharest, Romania, Feb. 2020, pp. 1–4.
[27] S. Y. Jun, B. Sanz-Izquierdo, E. A. Parker, D. Bird, and A. McClelland, "Manufacturing considerations in the 3-D printing of fractal antennas," *IEEE Trans. Compon., Package., Manuf. Technol.*, vol. 7, no. 11, pp. 1891–1898, Nov. 2017.
[28] C. Gu, S. Gao, V. Fusco, G. Gibbons, B. Sanz-Izquierdo, A. Standaert, P. Reynaert, W. Bösch, M. Gadringer, R. Xu, and X. Yang, "A D-band 3D-printed antenna," *IEEE Trans. THz Sci. Technol.*, vol. 10, no. 5, pp. 433–442, Sep. 2020.
[29] R. Xu, S. Gao, B. S. Izquierdo, C. Gu, P. Reynaert, A. Standaert, G. J. Gibbons, W. Bosch, M. E. Gadringer, and D. Li, "A review of broadband low-cost and high-gain low-terahertz antennas for wireless communications applications," *IEEE Access*, vol. 8, pp. 57615–57629, 2020.
[30] S. Y. Jun, A. Shastri, B. Sanz-Izquierdo, D. Bird, and A. McClelland, "Investigation of antennas integrated into disposable unmanned aerial vehicles," *IEEE Trans. Veh. Technol.*, vol. 68, no. 1, pp. 604–612, Jan. 2019.
[31] I. Piekarz, J. Sorocki, M. T. Craton, K. Wincza, S. Gruszczynski, and J. Papapolymerou, "Application of aerosol jet 3-D printing with conductive and nonconductive inks for manufacturing mm-Wave circuits," *IEEE Trans. Compon., Package., Manuf. Technol.*, vol. 9, no. 3, pp. 586–595, Mar. 2019.
[32] K. N. Paracha, S. K. Abdul Rahim, P. J. Soh, and M. Khalily, "Wearable antennas: A review of materials, structures, and innovative features for autonomous communication and sensing," *IEEE Access*, vol. 7, pp. 56694–56712, 2019.
[33] A. Kiourti, "RFID antennas for body-area applications: From wearables to implants," *IEEE Antennas Propag. Mag.*, vol. 60, no. 5, pp. 14–25, Oct. 2018.
[34] S. Y. Jun, A. Elibiary, B. Sanz-Izquierdo, L. Winchester, D. Bird, and A. McCleland, "3-D printing of conformal antennas for diversity wrist worn applications," *IEEE Trans. Compon., Package., Manuf. Technol.*, vol. 8, no. 12, pp. 2227–2235, Dec. 2018.
[35] M. Rizwan, M. W. A. Khan, H. He, J. Virkki, L. Sydänheimo, and L. Ukkonen, "Flexible and stretchable 3D printed passive UHF RFID tag," *Electron. Lett.*, vol. 53, no. 17, pp. 1054–1056, Jun. 2017.
[36] W. G. Whittow, "3D printing, inkjet printing and embroidery techniques for wearable antennas," in *Proc. 10th Eur. Conf. Antennas Propag. (EuCAP)*, Davos, Switzerland, Apr. 2016, pp. 1–4.
[37] M. Fawaz, S. Jun, W. B. Oakey, C. Mao, A. Elibiary, B. Sanz-Izquierdo, D. Bird, and A. McClelland, "3D printed patch antenna for millimeter wave 5G wearable applications," in *Proc. 12th Eur. Conf. Antennas Propag. (EuCAP )*, London, U.K., 2018, pp. 492–495.
[38] *5G Spectrum GSMA Public Policy Position*, GSMA, London, U.K., 2020.
[39] P. I. Deffenbaugh, R. C. Rumpf, and K. H. Church, "Broadband microwave frequency characterization of 3-D printed materials," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 3, no. 12, pp. 2147–2155, Dec. 2013.
[40] Italian National Research Council. *Calculation of the Dielectric Properties of Body Tissues in the Frequency Range 10 Hz–100 GHz*. Accessed: Nov. 19, 2019. [Online]. Available: https://niremf.ifac.cnr.it/tissprop/htmlclie/uniquery.php
[41] Optomec's Aerosol Jet. (2014). *Aerosol Jet Printed Electronics Overview*. Accessed: Dec. 18, 2020. [Online]. Available: https://optomec.com/wp-content/uploads/2014/04/AJ_Printed_Electronics_Overview_whitepaper.pdf
[42] J. A. Paulsen, M. Renn, K. Christenson, and R. Plourde, "Printing conformal electronics on 3D structures with Aerosol Jet technology," in *Proc. Future Instrum. Int. Workshop (FIIW)*, Gatlinburg, TN, USA, Oct. 2012, pp. 1–4.
[43] *NovaCentrix*. Accessed: Nov. 13, 2019. [Online]. Available: https://www.novacentrix.com/
[44] Centre for Process Innovation. (Nov. 13, 2019). *CPI, C. F. P. Innovation*. Accessed: Nov. 13, 2019. [Online]. Available: https://www.uk-cpi.com/
[45] P. S. Karthik and S. P. Singh, "Conductive silver inks and their applications in printed and flexible electronics," *RSC Adv.*, vol. 5, no. 95, pp. 77760–77790, 2015.
[46] S. Agarwala, G. L. Goh, and A. W. Y. Yeong, "Optimizing aerosol jet printing process of silver ink for printed electronics," in *Proc. IOP Conf., Mater. Sci. Eng.*, Bangkok, Thailand, 2017, Art. no. 012027.
[47] D. Sharma, S. K. Dubey, and V. N. Ojha, "Wearable antenna for millimeter wave 5G communications," in *Proc. IEEE Indian Conf. Antennas Propogation (InCAP)*, Hyderabad, India, Dec. 2018, pp. 1–4.
[48] X. Tong, C. Liu, Y. Chen, J. Zhu, X. Yang, H. Guo, and X. Liu, "A dual-mode multi-polarization millimeter wave wearable antenna for WBAN applications," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Nanjing, China, May 2019, pp. 1–3.

[49] M. Wagih, A. S. Weddell, and S. Beeby, "Millimeter-wave textile antenna for on-body RF energy harvesting in future 5G networks," in *Proc. IEEE Wireless Power Transf. Conf. (WPTC)*, London, U.K., 2020.
[50] A. Meredov, K. Klionovski, and A. Shamim, "Screen-printed, flexible, parasitic beam-switching millimeter-wave antenna array for wearable applications," *IEEE Open J. Antennas Propag.*, vol. 1, pp. 2–10, 2020.
[51] M. Ur-Rehman, T. Kalsoom, N. A. Malik, G. A. Safdar, H. T. Chatha, N. Ramzan, and Q. H. Abbasi, "A wearable antenna for mmWave IoT applications," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Boston, MA, USA, Jul. 2018, pp. 1211–1212.



**PETER NJOGU** is currently pursuing the Ph.D. degree in electronic engineering with the University of Kent, Canterbury, U.K. His research interests include wearable antennas, multiband antennas, millimeter wave antennas, and 3-D printed antennas.

**BENITO SANZ-IZQUIERDO** (Member, IEEE) received the B.Sc. degree from ULPGC, Spain, and the M.Sc. and Ph.D. degrees from the University of Kent, U.K.

He was Research Associate with the School of Engineering, University of Kent, in 2013, became a Lecturer in electronic systems, and a Senior Lecturer, in 2018. In 2012, he worked for Harada Industries Ltd., where he developed novel antennas for the automotive industry. His research has been funded through a variety of sources, such as the UK EPSRC, the Royal Academy of Engineering, and the Royal Society. His research interests include multiband antennas, wearable electronics, additive manufacturing (3D printing), substrate integrated waveguides components, metamaterials, electromagnetic band-gap structures, frequency selective surfaces, and reconfigurable devices. He has received awards and recognition for his work on wearable antennas (mention in the House of Lords and the IEEE IWAT Best Paper Award), frequency selective surfaces (best paper at an IET Workshop on Aerospace Applications Award), and reconfigurable antennas (2017 CST University Publication Award for an IEEE TRANSACTIONS Article) amongst others.

**AHMED ELIBIARY** received the B.Eng. and M.Sc. degrees from the University of Kent, U.K. His master's thesis was based on the use of 3D printing for plastics and metals for 3D antennas, with a focus on wearable devices.

After his studies, he worked with a growing 3D printing company, London, U.K., for 14 months, being exposed to a wide range of 3D Printing Technologies, such as FDM, SLA, SLS, and binder sintering, and then moved to work as a Writing Systems Engineer for Metal Jet 3D Printing with HP, Barcelona, Spain.

**SUNG YUN JUN** (Member, IEEE) received the M.S. degree in electrical engineering from Syracuse University, USA, in 2008, and the Ph.D. degree from the University of Kent, U.K., in 2018. Since December 2018, he has been a Postdoctoral Researcher with the National Institute of Standards and Technology, Boulder, CO, USA. His current research interests include antenna design, millimeter-wave channel measurements, and modeling of radio propagation.

**ZHIJIAO CHEN** (Member, IEEE) received the B.Sc. degree from the Beijing University of Posts and Telecommunications, in 2010, and the Ph.D. degree from the Queen Mary University of London, in 2014. In 2014, she joined the School of Electronic Engineering, Beijing University of Posts and Telecommunications, as a Lecturer. She was a Secondment with Ace-Axis Wireless Technology Laboratories Ltd., Essex, U.K., in 2012. In 2013, she joined Northeastern University, Boston, MA, USA, as a Visiting Student. Her research interests include dielectric resonator antennas, millimeter wave antennas, and 3D printed antennas. She was a recipient of the Best Paper Award from iWAT 2013, Karlsruhe, Germany, the third prize Student Paper Competition from APS/URSI 2013, Orlando, FL, the TICRA Travel Grant in EuCAP 2014, Hague, The Netherland, and the third place from QMUL Three-Minute Thesis (3MT) Competition Final 2014, London, U.K.

**DAVID BIRD** received the Engineering Doctorate degree, in 2008, sponsored by DuPont Teijin Films on nano-scale coatings on films for flexible electronics. He is currently a Technology and Innovation Officer with The Centre for Process Innovation (CPI)-Electronics, UK's National Printable Electronics Centre, has 17 years' experience working with materials science for large-area electronics and supporting companies innovating in this area. In 12 years with CPI, he has 25 IP submissions (for patent, publication, or internal Know-how). His work has focused on the patterning and deposition of semiconductors, vacuum-deposition of barrier materials, and large-area devices.