Inkjet-Printed Antennas for 28 GHz 5G Applications

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Inkjet-Printed Antennas for 28 GHz 5G Applications

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***Abstract*- This paper presents the layout and results of an inkjet-printed antenna for 5G applications operating at 28 GHz. The inkjet-printing based antenna was modelled using silver nanoparticle ink on flexible Kapton substrate, with copper for the ground plane. Simulation results of the antenna have been presented. The antenna shows a resonant frequency at 27.75 GHz at a return loss of more than 16 dB. The distribution of surface currents of the antenna at the resonant frequency is provided and shows majority of the current concentrated along the edges and in the middle of the antenna. Obtained radiation patterns show bidirectional patterns in the E-plane and omnidirectional patterns in the H-plane. Additionally, the gain and the efficiency of the antenna have also been presented; with the values at the resonant frequency being 0.43 dBi and more than 18 % respectively. Furthermore, the effects of varying the conductivity and the thickness of the silver nanoparticle ink have also been investigated and the results presented.**

I. INTRODUCTION

Inkjet printing is fast becoming an emerging technology to produce printed electronics owing to its direct-write procedure. The global printed electronics market is expected to reach $24.25 billion by 2018. As compared to conventional etching methods, it is able to reduce the waste materials generated and the material usage. Inkjet printing is simpler, generally faster and is low cost than other additive manufacturing techniques.

In recent years, inkjet printing technology has been implemented in a wide range of applications: from displays and lighting to radio frequency (RF) and microwave applications, including inkjet-printed antennas being reported in published work [1]–[3]. Some have been intended for integration within sensor systems [1], broadband applications [2], while others have been proposed for RFID systems [3].

Since 4G has almost achieved maturity, researchers and industries are focusing on the development of 5G communications. 5G will is projected to have higher data rates, faster latency rates, lesser in costs and usage of energy and more supported devices [4].

The evolving 5G mobile networks will be required to support capacities of as much as 100× of today's capacity by 2020 and as much as 1000× by 2030 [5]–[6]. In order to meet these demands, the use of mm-wave bands seems the best option owing to the large amount of available spectrum which could be used for that purpose [6].

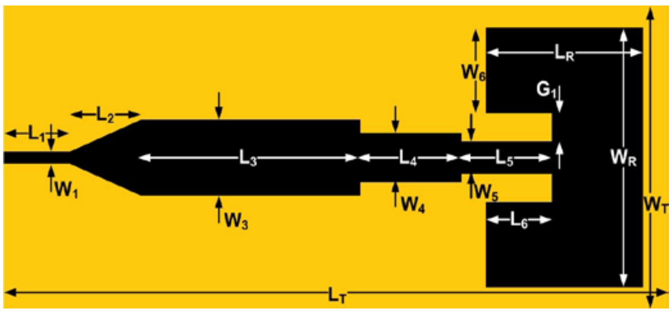
Despite the wide implementation of inkjet printing, there has been no reported work on employing inkjet printing technology for mm-wave 5G antenna applications. Hence, this paper proposes an inkjet-printed mm-wave antenna operating at 28 GHz for 5G applications.

II. DESIGN AND PRINTING OF PROPOSED ANTENNA

A. *Structure Layout*

The antenna is based on microstrip technology. Inkjet-printed antennas inside wireless 5G systems should be conformal and robust. Hence, the chosen substrate is 50 µm thick, flexible Kapton polyimide film of a dielectric permittivity of $\varepsilon_r = 3.4$ and a dielectric loss factor of $\tan\delta = 0.0021$. Although there are various substrates available for inkjet printing, Kapton has been chosen because of a good balance between its physical and electrical properties and advantages over other substrates, such as being very robust with a tensile strength of 231 MPa even at its low thickness, having a temperature rating of -269°C–400°C and a dielectric strength of 240 V/m [7].

Silver nanoparticle ink has been used as the top metallisation. The antenna is designed with a centre frequency of 28 GHz. The antenna has an inset-fed transmission line. The feedline starts as a 50 Ω port, where the antenna is fed from. The length of the port is 3 mm (L_1) in order to provide an adequate connection for an SMA connector. The port then transitions to a transmission line of an impedance of 11 Ω. This is then connected to a quarter-wavelength transformer. The quarter-wavelength transformer feeds directly in to the radiating element. The main parameter determining the resonant frequency of the inkjet-printed antenna is the length of the radiating element, i.e. L_R. The bottom metallisation, i.e. the ground plane, is a sheet of copper of a thickness of 17.5 µm. The copper sheet is fixed to the Kapton with silver epoxy adhesive on the edges. The total effective area occupied by the antenna is extremely small at 2.62 mm × 11.545 mm.



(a)

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(b)

Figure 1. (a) Top view and (b) cross-sectional view of the geometry of the inkjet-printed antenna.

TABLE I
VALUES OF ANTENNA'S DIMENSION PARAMETERS

Parameter	Value (mm)		Parameter	Value (mm)
W_T	3.5		L_4	1.34
L_T	15.5		W_5	0.5
W_1	0.1		L_5	0.85
L_1	3		W_6	0.785
L_2	0.41		L_6	0.65
W_3	0.79		G_1	0.275
L_3	6.55		W_R	2.62
W_4	0.51		L_R	3.045

B. *Inkjet Printing Process*

Inkjet printing, one of the latest techniques for the fabrication of radio frequency components, will be used to print the antenna. Various metallic nanoparticle inks are commercially available; such as copper, silver, gold, zinc oxide, tungsten oxide and nickel nanoparticle inks. For the proposed antenna, as stated earlier, silver nanoparticle ink — Novacentrix JS-B80HV — is chosen and used for the top metallisation, i.e. the radiating element, because of the balance between costs and electrical properties. For printing the top metallisation using this ink, the inkjet printer Dimatix Materials Printer DMP-3000 is used. Since inkjet printing is an additive process where the printer jets the ink on a substrate, the output of the ink needs to be controlled. The inkjet printer has a number of settings which have to be set accordingly; such as the speed of ink delivery, direction of ink delivery and volume of the deposited ink. Drop spacing determines the distance covered by the jetting nozzle between each successive drop of ink. Hence, the drop spacing also decides the thickness of the printed ink layer. For the proposed antenna, where the wanted thickness of the ink layer is 1 µm, the printer is set to a drop spacing of 25 µm. This also allows the droplets of the ink to adequately overlap each other. The amplitude of the driving waveform is 25 V and the printing frequency is set to 2 kHz. The cartridges containing the silver nanoparticle ink are arranged in a horizontal formation and have a nozzle volume of 10 pL. Horizontal formation results in the printing of the antenna in its longitudinal direction. Once printing is completed, the antenna is sintered and cured in a sintering furnace at a curing temperature of 200°C for 45 minutes. This ensures the coarse printed lines of the silver nanoparticle ink to form continuous electrically conductive transmission lines, providing a good channel for the flow of current. Since inkjet printing technology involves ink droplets being deposited on a substrate, the process and the settings are important and can significantly affect the performance of the antenna.

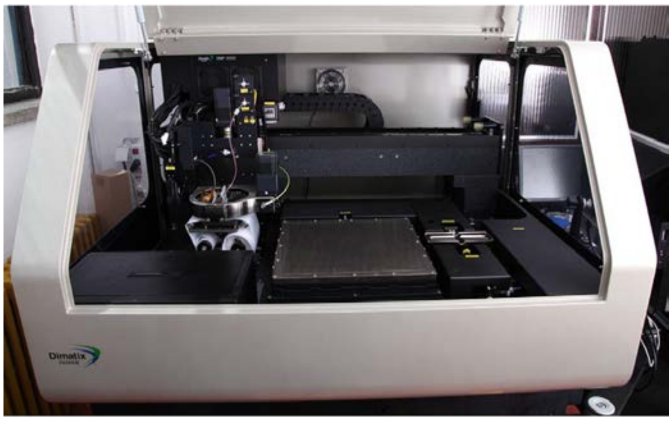

Figure 2. Photograph of the Inkjet Dimatix Materials Printer DMP-3000.

III. RESULTS

The antenna was modelled and simulated using the commercial software CST Microwave Studio. Each layer of the antenna was modelled with its respective physical and electrical properties. The return loss, surface current distribution, radiation patterns, gain, and efficiency of the antenna were obtained.

A. *Return Loss*

The return loss of the antenna is shown in Fig. 3. The simulated result shows the resonant frequency at 27.75 GHz. The return loss of the inkjet-printed antenna at this point is 16.3 dB. The bandwidth of the antenna is > 230 MHz. The minor -0.3 GHz shift between the obtained frequency and the desired frequency indicates that the length of the antenna needs to be slightly optimised. Although this slight difference may be ignored now, it can be fixed during the next modelling and the fabrication. In the stopband region, i.e. when the return loss < 10 dB, the antenna has a good stopband selectivity since no frequency fluctuations can be seen.

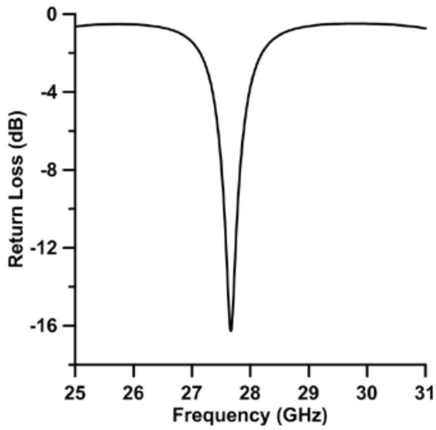

Figure 3. Return loss of the inkjet-printed antenna.

B. Distribution of Surface Currents

The distribution of the surface currents at the resonant frequency of 28 GHz was simulated and is given in Fig. 4. As seen, the scattering of the surface current is evenly spread over the radiating element. A larger quantity of current is seen flowing along the edges and in the middle of the patch.

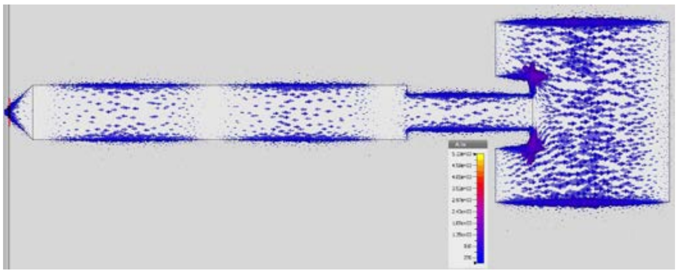

Figure 4. Distribution of surface currents of the inkjet-printed antenna.

C. Radiation Patterns

The simulated radiation patterns in the E-plane and the H-plane were obtained at the resonant frequency of 28 GHz and are shown in Fig. 5. At this frequency, maximum radiation is emitted at the top of the antenna as seen by the main radiation lobe in the E-plane. The antenna loses energy as signified by the minor and side lobes as shown in the bottom half of the E-plane. Stable omnidirectional patterns are present in the H-plane; implying the antenna radiates in all directions.

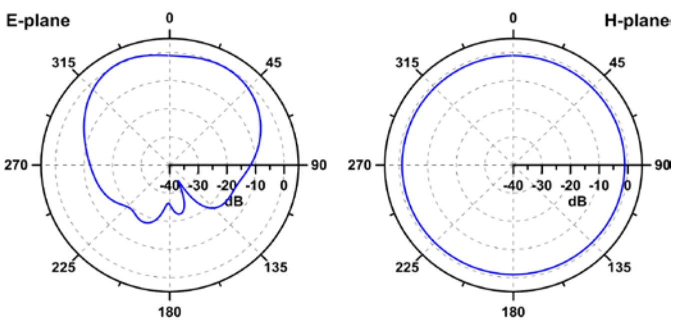

Figure 5. Radiation patterns of the inkjet-printed antenna.

D. Gain and Efficiency

The simulated gain and efficiency of the antenna are shown in Fig. 6. Between 25–31 GHz, the gain varies from -5.49–0.43 dBi; with the peak value, i.e. 0.43 dBi, being at the resonant 27.75 GHz 5G frequency. The efficiency plot echoes the gain plot. The efficiency result shows a peak corresponding to the 5G frequency of 27.75 GHz. The peak is present at an efficiency of about 18.6 %. Within the stopband region, the efficiency falls significantly and is less than 2 %.

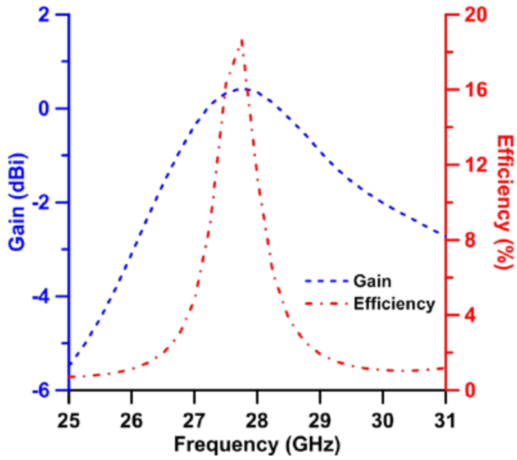

Figure 6. Gain and efficiency of the inkjet-printed antenna.

E. Effects of Varying the Conductivity of Ink

So as to observe the effects of the conductivity of the silver nanoparticle ink on the return loss, gain, and efficiency of the antenna, a parametric investigation was carried out by varying the conductivity of the ink while keeping the thickness of the ink fixed to the initial value of 1 µm.

The return loss results, shown in Fig. 7, indicate the considerably low conductivity of the silver nanoparticle ink as one of the main sources of the antenna losses. As seen from the results, doubling the electrical conductivity from the initial value of 2.0×10^7 S/m to 4.0×10^7 S/m increases the return loss by a margin of 4.76 dB, resulting in 21 dB. When the conductivity is again doubled from 4.0×10^7 S/m to 8.0×10^7 S/m, the results show a further rise in the return loss by a factor of 7.5 dB, resulting in 28.54 dB. Practically, the conductivity of the silver nanoparticle ink may be increased by increasing the percentage of silver content in the ink solution and/or by adjusting the curing temperature and the time.

The resultant gain and the efficiency of the antenna by varying the conductivity of the ink are given in Fig. 8. At the resonant frequency of 27.75 GHz, the original antenna has a peak gain and efficiency of 0.43 dBi and 18.6 % respectively. When the conductivity is doubled to 4.0×10^7 S/m, the gain and the efficiency increase as well. The values become 1.07 dBi and 22.8 % respectively. Another twofold increase of the conductivity to 8.0×10^7 S/m results in the gain and the efficiency going up to 1.58 dBi and 25.7 % respectively.

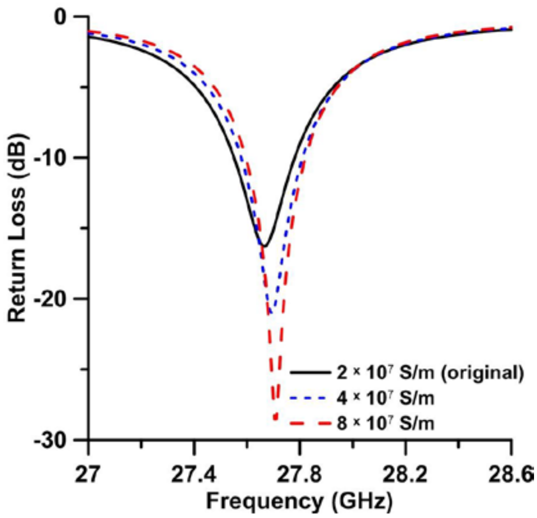

Figure 7. Return loss with varying conductivity of ink.

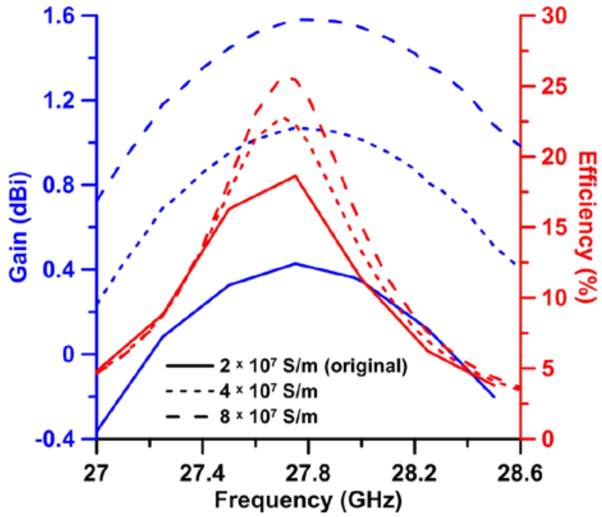

Figure 8. Gain and efficiency with varying conductivity of ink.

F. Effects of Varying the Thickness of Ink

In order to further understand the effects of the silver nanoparticle ink involved in the inkjet printing of the proposed antenna, the thickness of the ink layer was varied while the conductivity of the ink was kept fixed to the original value of $2.0{\times}10^7$ S/m.

As shown in Fig. 9, the thickness of the silver nanoparticle ink was revealed to be another contributor to the losses incurred by the inkjet-printed antenna, but not as significant as the conductivity. When the thickness was doubled from the initial value of 1 µm to 2 µm, the difference in the return loss was only 0.07 dB. By increasing the thickness two-fold further to 4 µm, the rise in the return loss of the antenna at the resonant frequency was about 0.58 dB. Against thicknesses of 8 µm and 16 µm, the increase in the return loss was 0.95 dB and 1.59 dB. Further increase of the thickness of the silver nanoparticle ink showed no significant increase in the results.

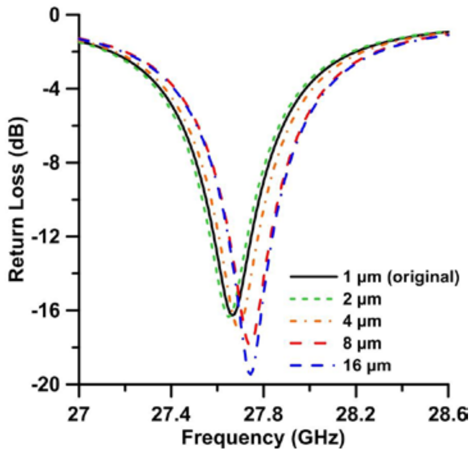

Figure 9. Return loss with varying thickness of ink.

IV. CONCLUSION

Fabrication of wireless systems, such as 5G communication systems, using inkjet printing is one of the main forthcoming technologies. The design of mm-wave antennas for 5G systems fabricated using inkjet printing technologies would bring new and significant challenges for radio frequency designers. Therefore, in this paper, an antenna for 5G wireless applications operating at 28 GHz, realised using inkjet printing of silver nanoparticle ink on flexible Kapton substrate, has been demonstrated. The design and the printing process of the antenna have been provided. Results of the antenna have been provided. Return loss results show the resonant frequency to have been reasonably achieved at the 5G applications' band. Other results, such as the distribution of the surface currents, the gain and efficiency, have also been presented and discussed. Furthermore, the effects of varying the conductivity and the thickness of the ink have been shown.

REFERENCES

[1] R. Vyas, V. Lakafosis, H. Lee, G. Shaker, L. Yang, G. Orecchini, A. Traille, M. M. Tentzeris, and L. Roselli, "Inkjet printed, self powered, wireless sensors for environmental, gas, and authentication-based sensing," *IEEE Sensors Journal*, vol. 11, no. 12, pp. 3139–3152, December 2011.

[2] B. S. Cook and A. Shamim, "Inkjet printing of novel wideband and high gain antennas on low-cost paper substrate," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 9, pp. 4148–4156, Sep. 2012.

[3] L. Yang, A. Rida, R. Vyas, and M. M. Tentzeris, "RFID tag and RF structures on a paper substrate using inkjet-printing technology," *IEEE Transactions on Microwave Theory and Techniques*, vol. 55, no. 12, pp. 2894–2901, December 2007.

[4] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5G be?," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, June 2014.

[5] W. Roh, J. Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, and K. Cheun, F. Aryanfar, "Millimeter-Wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results," *IEEE Communications Magazine*, February 2014.

[6] P. Pietraski, D. Britz, A. Roy, R. Pragada, and G. Charlton, "Millimeter wave and terahertz communications: feasibility and challenges," *ZTE Communications*, vol. 10, no.4, pp. 3–12, December 2012.

[7] DuPont™ Kapton® Datasheet [Online] Available: http://www.dupont.com