Inkjet-Printed Millimetre-Wave PET-Based Flexible Antenna for 5G Wireless Applications

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***Abstract*—This paper presents a millimetre-wave (mm-wave) flexible antenna designed on Polyethylene Terephthalate (PET) substrate for the 5th generation (5G) wireless applications. The antenna geometry comprises of a T-shaped patch integrated with symmetrically designed slot arrangements. The defected ground structure (DGS) concept is utilised for bandwidth enhancement and a coplanar waveguide (CPW)-fed slotted monopole antenna is embedded within an aperture cut inside the ground plane. The measurements of the inkjet-printed antenna prototype depict an impedance bandwidth of 26-40 GHz, consistent omnidirectional radiation pattern and a peak gain of 7.44 dBi at 39 GHz. The conformity and flexibility suggest potential applications of the proposed antenna in future 5G applications especially in wearables such as uniform or casual clothing.**

***Index Terms*—5G; antenna; flexible; PET; wireless.**

I. Introduction

Millimetre-wave (mm-wave) communication networks are anticipated to bring an influential advancement towards resolving the issues related to congestion, limited bandwidth and restricted channel capacity of current wireless systems [1, 2]. Future 5G architecture is expected as highly-dense, diversified, versatile as well as a unified technology with an extra-ordinary bandwidth availability for almost unlimited upgradation [3]. Antenna design is one of the major considerations to realise mm-wave based 5G front-ends. Patch antennas have made a massive contribution in wireless cellular networks and regarded as the most optimal choice in mobile phones and smart devices because of the planar structures. Recently, the drastic recognition of wearable wireless devices in the market has influenced the research trends towards the implementation of flexible antennas and conformal circuitries [4]. Significant efforts have been made in developing efficient and cost-effective ways of robust fabrication in this regard. Inkjet printing by using metallic inks is a fast and precise fabrication technique for low-cost mass production [5]. A large variety of commercial flexible substrates such as textiles, polyesters, polymers and polyamides are available varying in film thickness, surface coating, texture, and electrical properties. Polyethylene terephthalate (PET) is a flexible thermoplastic polymer usually employed as a substrate in the antenna designs [6, 7].

Defected ground structures (DGS) are among the commonly-used techniques to excite additional resonances within the antenna structure. DGS are usually slots cut inside the ground plane or sometimes in antenna patch to change the surface current distribution by creating resonant gaps [8, 9]. In this paper, the antenna geometry is developed based on DGS by introducing slots in the patch and an aperture is also placed in the ground plane. The appropriate placement of these DGS geometries resulted in multiple resonances which are then combined into a continuous bandwidth of the K_a-band. In addition to the previous work reported in [10], this paper contributes the experimental validation of the proposed results of a PET-based flexible antenna designed to offer high bandwidth of complete K_a-band (26.5-40 GHz). Furthermore, the inkjet printing process by using silver nanoparticle ink for the antenna prototyping is explicitly demonstrated. The conductivity of the inkjet-printed antenna is one of the critical aspects which controls the magnitude of the return loss as well as the radiation efficiency of the antenna. The presented research work also highlights the effect of improved sintering on the antenna return loss and shows stable performance when mounted on a conformal surface.

II. Antenna Design and Fabrication

The single-sided printed antenna demonstrated in this section consists of a CPW-fed T-shaped patch geometry. The ground plane is extended on the substrate surface along the dimensions and an aperture is cut inside it for the positioning of the patch. A slot assembly is designed and introduced as DGS geometry in the patch unlike the most of conventional DGS placements on ground planes. The DGS slots in patch also serve the same purpose of generating multiple resonating bands in the frequency range of 20-40 GHz. PET film (NB-WF-3GF100 from Mitsubishi Paper Mills Ltd.) of thickness 135 ± 12 µm, dielectric constant (ε_r) of 3.2 and a loss tangent (tan δ) of 0.022 at 10 GHz is selected for antenna design. The proposed mm-wave antenna is designed to fit within the dimensions of 16×16 mm^2. The ground aperture also acts as a DGS slot to add perturbations in current density at the edges of the patch. Right-angled-shaped slots each of 2 mm width and placed 5 mm apart are loaded in the T-shaped patch at optimised positions, as shown in Fig. 1 (a).

Dimatix inkjet Printer (DMP-2831) with silver nanoparticle conducting ink has been used for antenna fabrication. Inkjet printing is an anisotropic deposition process that performs patterned writing without any need of a mask. It is a low-cost process as compared to industrial manufacturing based on lithography, with much fewer complications and high material-conservation due to controlled consumption of ink. However, several issues need to be handled to achieve precise and reliable fabrication. The two determining factor of print quality are resolution, measured in dots per inch (dpi), and the minimum feature size that can be fabricated accurately, which is measured in micro-metres. The ink properties also impact the printing quality in particular wettability of dilute solutions are of essential importance while carrying out inkjet printing. The contact angle of nozzles which controls falling drops of ink is associated with the computational fluid dynamics to examine fluid viscosity and surface tension of the ink.

The printer is provided with a piezo-electric transducer which permits control over the shape and size of the ink droplet. The cartridge used in DMP comprises of sixteen nozzles and ejection of silver ink is controlled by adjusting the voltage to 15 V, jetting frequency to 4 KHz and several other parameters. The operation of DMP could be visualized as a spray of liquid ink onto substrate which creates a pattern. PET substrate is placed on the platen and printhead scans and ejects ink drops in horizontal strips. The temperature of the platen is adjusted to 28˚C to enhance the ink deposition and drying on the substrate. Moreover, the temperature of the printhead is also adjusted according to the wettability of ink. The PET sheet is equipped with self-sintering characteristics due to a thin chemical layer on the surface which enhances adhesion, allows rapid drying of ink and sinters the patterns to improve conductivity. However, the conductivity is further enhanced with additional heat treatment by baking the antenna in an oven at 150 ˚C for 30 min. This process has significantly improved the return loss of the antenna. The inkjet-printed antenna is shown in Fig. 1 (c) and optimised dimensions are provided in Table I.

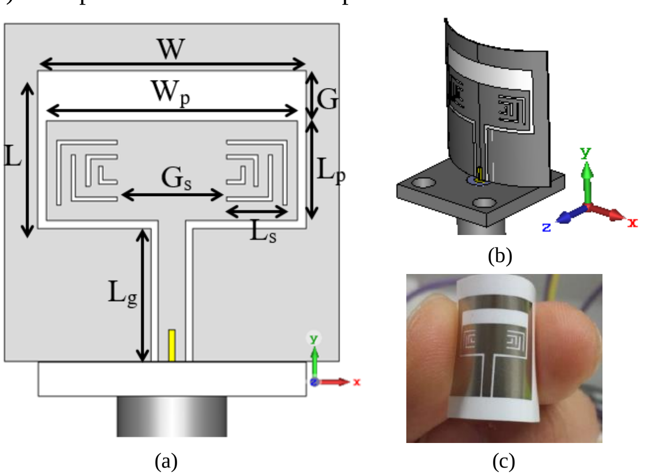

Fig. 1. Flexible inkjet-printed antenna on PET film: (a) simulated model; (b) simulated conformal antenna; (c) conformal fabricated antenna prototype.

TABLE I. DIMENSIONS OF FLEXIBLE INKJET PRINTED ANTENNA

Optimised Dimensions of the Flexible Inkjet-Printed Antenna			
Parameters	***mm***	***Parameters***	***mm***
Aperture Width, W	12.8	Gap of patch from the ground, G	2.4
Aperture Length, L	7.5	CPW Ground Length, L_g	6.3
Patch Width, W_p	12	Length of the slot assemblies, L_s	2.9
Patch Length, L_p	4.7	Gap between slot assemblies, G_s	5.2

III. RESULTS AND DISCUSSIONS

The proposed mm-wave flexible antenna is modelled and parametrically optimised by the CST software, and the fabrication is carried out by inkjet printing. The validation of simulated results is performed by testing and measurements. Near-field scanning is used for the evaluation of radiation characteristics of the antenna and the results are used for the calculation of antenna gain. This section presents the simulated and measured results of bandwidth, E and H plane radiation plots, and a peak gain of the antenna with respect to the frequency of operation.

A. Impedance Bandwidth:

Fig. 2 shows a bandwidth of 26-40 GHz in the simulated and measured S_{11} plots of mm-wave inkjet-printed antenna also taking into account the conformity effect in the simulations. The antenna shows steady performance in bending posture. S_{11} is significantly improved by heat sintering in addition to self-sintered chemical layer due to better conductivity. However, some mismatches and slight shifts are due to imperfect calibrations or cable losses.

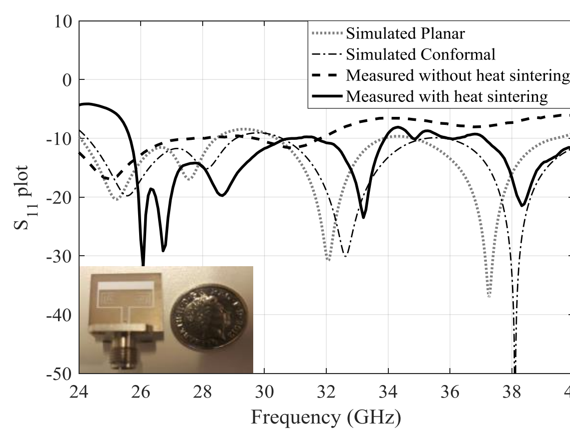

Fig. 2. The S_{11} plot of the flexible inkjet-printed antenna on PET film.

B. Radiation performance

Simulated and measured radiation patterns of the proposed mm-wave flexible antenna are presented in Fig. 3 in dotted and bold-line plots respectively. A fairly-consistent omnidirectional radiation pattern is observed from E and H plane cuts at distinct frequencies of impedance bandwidth. Measured results also show radiation profile similar to the simulations.

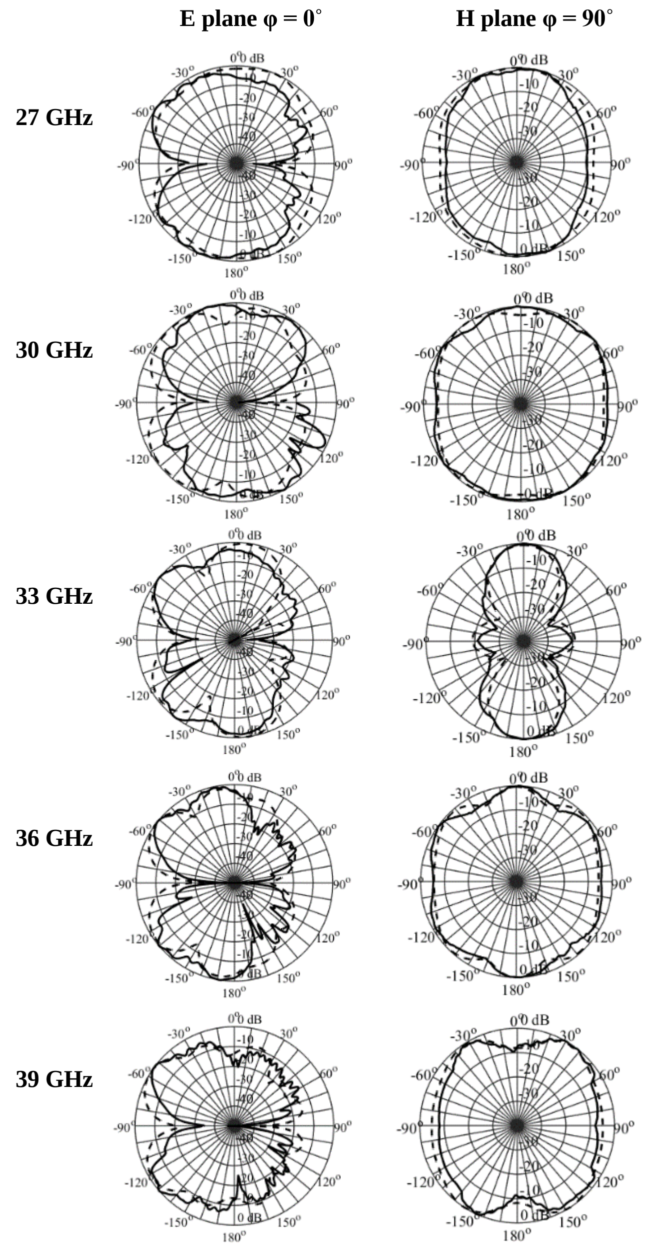

Fig. 3. Simulated and measured normalised radiation patterns of the flexible inkjet printed antenna at distinct frequencies of the operating range.

C. Peak gain

Table II presents the realised gain of the proposed mm-wave flexible antenna at distinct frequencies. The initial estimations of peak gain of the antenna in simulations are validated by testing of the antenna prototype and then two antenna gain method is used for gain calculations. The results shows close agreement in both simulations and measurements with the peak measured gain of 7.44 dBi at 39 GHz.

TABLE II. PEAK REALISED GAIN OF THE INKJET-PRINTED ANTENNA

Frequency (GHz)	***f* = 27**	***f* = 30**	***f* = 33**	***f* = 36**	***f* = 39**
CST Gain (dBi)	5.49	5.23	5.83	6.12	7.93
Measured Gain (dBi)	4.35	4.12	4.84	6.14	7.44

IV. CONCLUSION

The paper presents an inkjet-printed flexible antenna on a low-cost PET substrate with a bandwidth that covers K_a-band. The design geometry is simple and utilised a T-shaped patch antenna and right-angled-shaped slots' assemblies to generate multiple resonances based on the DGS concept. The impedance bandwidth of the proposed antenna is 26-40 GHz. Measurements validate the claim of the omnidirectional and fairly consistent radiation pattern in the operating bandwidth. The measured results also depict that the gain of the antenna is above 4 dBi in the complete range of operation, where the peak gain of 7.44 dBi is observed at 39 GHz. The features of high bandwidth that covers intended 5G bands, omnidirectional radiation and reasonable gain performance make this antenna capable of fulfilling the demands of advanced 5G networks with suitable integration in wearable applications.

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