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Review

A Review of Printable Antenna Design and Fabrication for Future Wireless Applications

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Abstract: Extensive research has been conducted on printable antenna technologies, believed to be fast-growing due to their significant impact on wireless devices. It is necessary to study the progress of printable antenna technology as they are core devices for wireless technology today. This review work offers a comprehensive account of the previous and recent research achievements based on the principle of printable antenna, and parametric studies of several key design parameters, for future wireless network applications. The systems considered for evaluation include broadband techniques, large Bandwidth, high gain, dual/multi-band, or reconfigurable structure, low-profile, size-reduction, compact, linear, or circular polarization applications. It also highlights the fabrication procedures, and the numerous material characteristics affecting the antenna performance for various wireless applications with design considerations. Fully printed antennas on different substrates and conductive ink were investigated, including polyethylene terephthalate (PET), synthetic paper (Teslin), resin-coated photo paper, and Kapton polyimide substrates, among many others. The findings show that the fully inkjet-printed antenna made fabrication easy, improving the accuracy and conductivity of the printed patterns by concentrating on the inherently difficult problems and opportunities. Inkjet-printed antennas are believed to be the futuristic demand for sustainability and wireless solution in several ways.

Keywords: printable antenna; inkjet-printed; gain; Bandwidth; and broadband

1. Introduction

The printable antenna technology in wireless transmission rapidly attracts growing interest in mobile communication technology. It has broad growth prospects, a rich spectrum of resources, promising potential, and many different applications that can extend well to the high-frequency band. Thus, for practical applications, size reduction and bandwidth widening have emerged as key design challenges of printable antennas. A simple design of a copper Microstrip antenna achieved a stable in-band omnidirectional radiation pattern in the form of a wheel-shaped in the operation of the 24GHz frequency band [1,2]. The impacts of conductor thickness on a mathematical model on the centre frequency for the low profile, more economical antenna for 5G application was achieved [3]. An air-substrate antenna was designed and fabricated to reduce the fabrication cost and operate at the 28GHz frequency band [4,5]. Improved Bandwidth and gain were achieved on a microstrip patch and meander line antenna [6]. A boundary condition for substrate thickness and conductive material for a low-profile, cost-effective centre frequency, Bandwidth, gain, and efficiency of antenna operation was achieved [7]. Good radiation efficiency, wide Bandwidth, gain, and reduced mutual coupling between radiators were achieved by an air substrate [8]. In [9], a significant increase in Bandwidth was successfully achieved using a perforated stacked cylindrical dielectric resonator. The limitations of the printable antenna's large size and poor radiation efficiency were improved using a quasi-lumped element resonator antenna technology [10]. A high gain, cost-effective, low profile, and economical antenna operation were achieved using an effective thickness of conductive material and an air-substrate-based antenna [11].

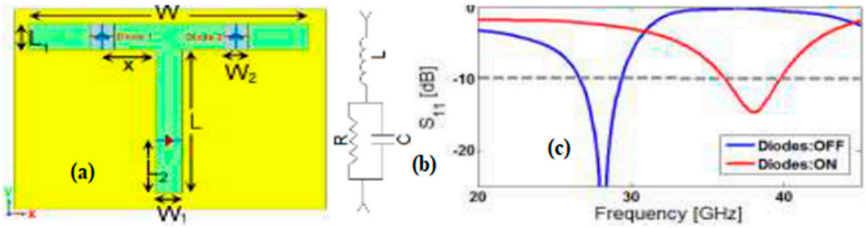


Figure 1. (a) schematic for a single-element antenna, (b) a model diode, and (c) results of S11 [12].

The antenna operating in mm-wave transmission demands high gain and wider Bandwidth because of faster transmission and the Bandwidth spectrum, which are the most critical wireless communication issues [13]. Antenna design in mm-wave wireless technology for mobile phones has been a challenging research topic for higher frequency band applications [14,15]. Microstrip and hollow waveguides have been used to build mm-Wave multi-beam antennas as traditional transmission lines technology in [14] and, antenna in packages operating in high frequencies reduces the high-demand interconnect loss with 5G deployment [16]. To handle significant loss in free space, high traffic rate, Bandwidth scarcity, gain, and quality of millimeter wave frequency and directive antenna system for future high-frequency band wireless applications. The future technology would employ wide signal bandwidth and high-frequency bands to boost transmission bit rates and improve coverage, which is the future's main objective of wireless networks with millimeter waves [17]. A microstrip antenna has the beam steering capability needed to facilitate wireless communication between mobile terminals due to its light, compactness, and integration into the module circuit. Supporting the mobile terminal of wireless communication networks is necessary. Recent development led to the design of an antenna that will transmit and receive high gain that can be operated in a high-frequency range, to achieve a higher data rate and improved antenna reliability by inkjet-printed technology [17].

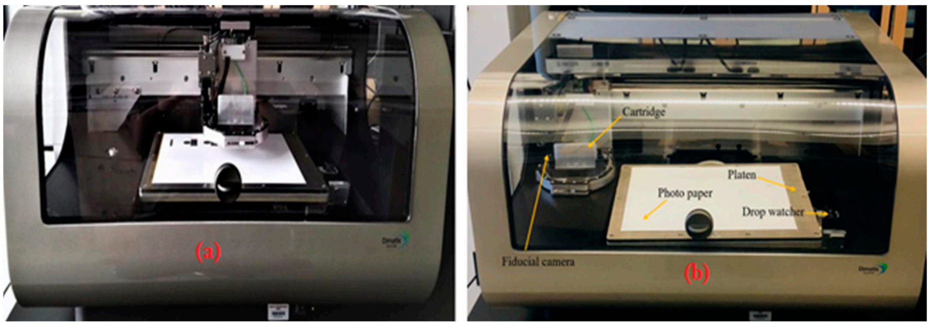


Figure 2. Antenna printed with an inkjet using silver nanoparticles and paper substrate. (a) When using the Fujifilm's Dimatix 2831 inkjet printer (b) Description of the Fujifilm's Dimatix Inkjet Printer, DMP 2831 [18].

Broadband antennas are necessary because several wireless applications, both established and new, operate across a wide range of frequency bands. Many design issues must be resolved for reasonable tradeoff inconsistencies in technology design, low-profile, or low-cost manufacturing techniques. This work aims to review the optimization of printable antenna design and fabrication. And it examines the latest developments in the different methods to give readers an idea of its possible advantages over conventional low-gain antennas. The information provided in this review is assumed to be used as a reference, especially for new researchers taking up a career in printable antenna technology, presenting an easy-to-read summary of recent accomplishments and comparison points for new antenna technology. The spectrum of printable antenna prototypes, low-profile, compact designs, broadband with increased gain, reconfigurable designs, a survey of linear and planar arrays, and integrated systems are all covered in this article on printable antenna technologies. Printable antennas on polymer-based materials represent one of the solutions for the low degree of freedom [19]. Short-range communications and wireless coverage of complex network environments were improved [17]. To achieve data rates of up to 10 Gbps and latency of below 1 ms using a printable antenna operating in a millimeter-wave frequency band is necessary [20].

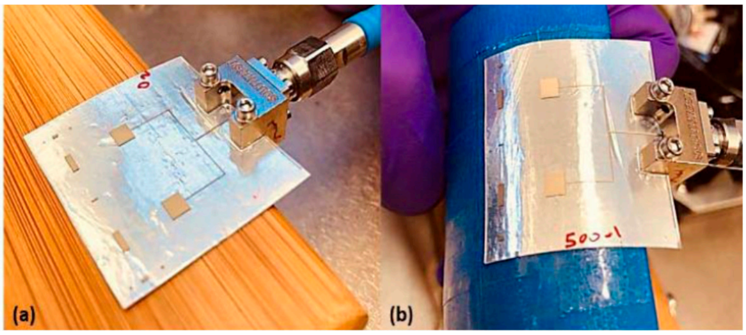
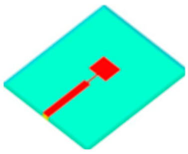
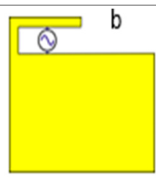
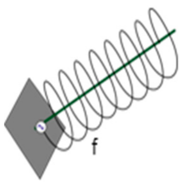
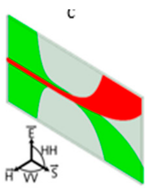
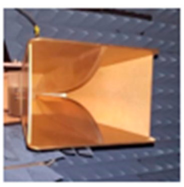
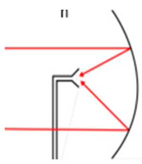


Figure 3. (a) Printed antenna placed in a flat position on a wood surface (b) Tensile bending over a mandrel with a 1-inch radius [21].

Table 1. Various types of antennas with their functions [22].

Types	Name and Functions	Types	Name and Functions
	Narrow Band		
	Microstrip Patch=> A resonant patch to a 50-ohm transmission line		Inverted F Antenna=> Phones use single-sided resonant structures as their GPS antenna
	Yagi-Uda=> Narrowband directional antenna, used for point-to-point communications		Helical Antenna=> Narrowband directional or omnidirectional antenna based on dimensions of helix
	Wide Band		
	Planar Bow Tie=> Wideband planar antenna, here seen as a single-sided configuration		Antipodal Vivaldi=> Wideband planar antenna, the same geometry used in this thesis
	Horn Antenna=> Wideband antenna, 1 GHz to 18 GHz calibration		Parabolic Reflectors=> are used as "Satellite Dishes" with horn antenna for satellite TV.

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2. Antenna Design and Fabrication

Most of the 3D Printing approaches fall into two primary categories polymer/dielectric or all-metal, the preferred 3D printers produce objects with high spatial resolution, thin build layers, and smooth surfaces, with the printed pieces' quality significantly affecting the antenna's performance [23]. A dual-band stacked microstrip patch array antenna and a 3D electromagnetic-based have been designed and fabricated for wide bandwidth efficiency and low-cost implementation [24]. A relatively straightforward U-slot microstrip patch antenna was designed and fabricated with wide Bandwidth and a very good beam width [25]. A high-order mode cavity-backed cross-dipole antenna and High-efficiency layer-driven air-filled waveguide feeder and a unique hybrid coupler were designed. and cheap fabrication cost to increase the gain by lowering the feed loss [26]. Due to the high-speed signal transmission, the antenna needs to have changed from single-band to dual-band, from SISO to MIMO implementations for antenna diversity, and now from single-band to multi-band [27]. Due to its small size and economical form, a Wide tuning band frequency configurable antenna could be easily integrated with modern communication equipment like smartphones, laptops, and other portable electronic devices [28].

In wireless communication, a microstrip patch antenna is commonly used to emit electromagnetic waves into space, made up of four basic parts: ground, substrate, patch, and feed, and has a ground plane on one side and a dielectric constant on the other and can be square, elliptical, circular, rectangular, or even a ring in shape. It is used in many industries, such as automotive, logistics, GPS, and microwave communication [29]. To realize multiband operation and better impedance matching, a modern dual annular ring microstrip antenna with gaps generates optimal high gain and impedance performance Bandwidth [30]. A microstrip slot antenna is chosen because it is low profile and easy to design and fabricate, giving researchers a greater understanding of how antennas function and their features [31].

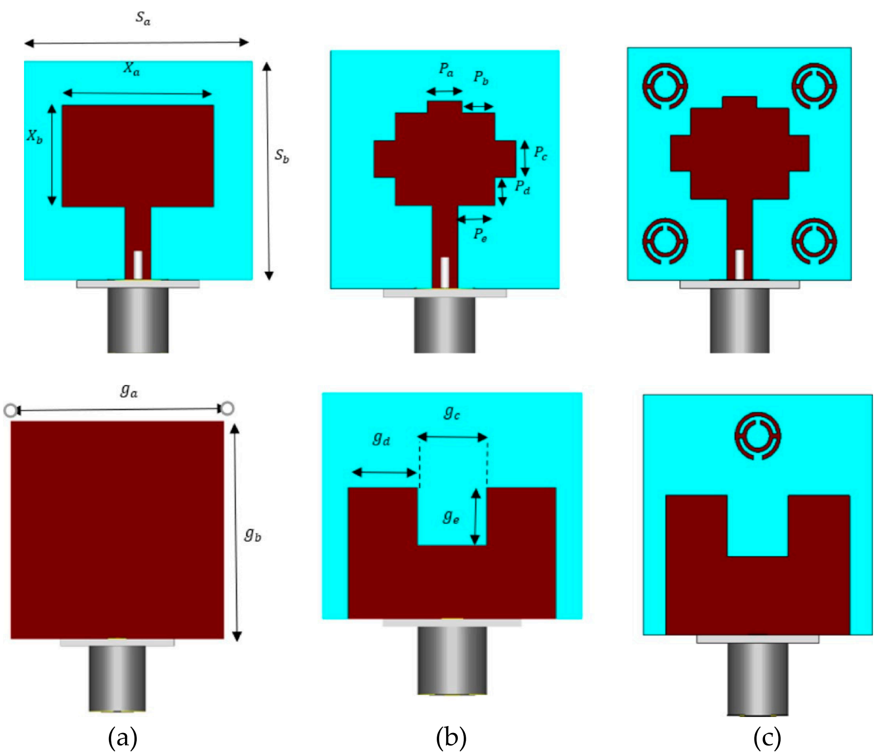

Figure 4. The proposed dual-band staircase patch antenna filled with CSRR unit cells in the design stages (a) an antenna with a rectangular patch and a complete ground plane (b) A staircase patch antenna with a defective ground plane that has been optimized (c) CSRR unit cells are fitted into the final planned optimized Staircase antenna [32].

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Microstrip Patch Antenna could be determined as the length and width (in millimetres) of a rectangular patch antenna using equations 1 to 9, as well as the radius of the patch antenna can be determined by equations as shown below. The following equations can calculate the design parameters, and a crucial design parameter, the resonance frequency is determined by the patch length.

The antenna's patch length L is specified as:

$$Length = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)}\right) \quad (1)$$

$$L = \frac{c_o}{2f_r\sqrt{\varepsilon reff}} \quad (2)$$

The patch's length is greater electrically than its physical, the length L is provided as follows when considering the normalized extension of the length:

$$L = \frac{c_o}{2f_r\sqrt{\varepsilon reff}} - 2\Delta l \quad (3)$$

The effective dielectric constant, which is less than the actual dielectric constant, gives rise to ΔL it uses this effective dielectric constant to explain the fringing phenomenon.

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{reff}+0.258)(\frac{W}{h}+0.8)} \quad (4)$$

The width calculation equation is presented as:

$$width = \frac{c}{2f_o\sqrt{\frac{\varepsilon_R+1}{2}}} \quad (5)$$

$$W = \frac{c_o}{2f_o}\sqrt{\frac{2}{(1+\varepsilon_r)}} \quad (6)$$

The effective dielectric constant's value is given as shown below:

$$\varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12(\frac{h}{W})}}\right] \quad (7)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}[1+12\frac{h}{W}]^{-1/2} \quad (8)$$

The substrate's acceptability determines the dimensions. The electrical resistance the patch's characteristics are also dependent on the antenna's size and permittivity. The ground plane's length (Lg) and width (Wg) are calculated using equations 3 & 7.

A resonant cavity antenna concept is used in the design and fabrication of an innovative all-metal antenna; the figures below show the various antenna configuration comprising a 140 GHz simulated antenna radiation pattern [33].

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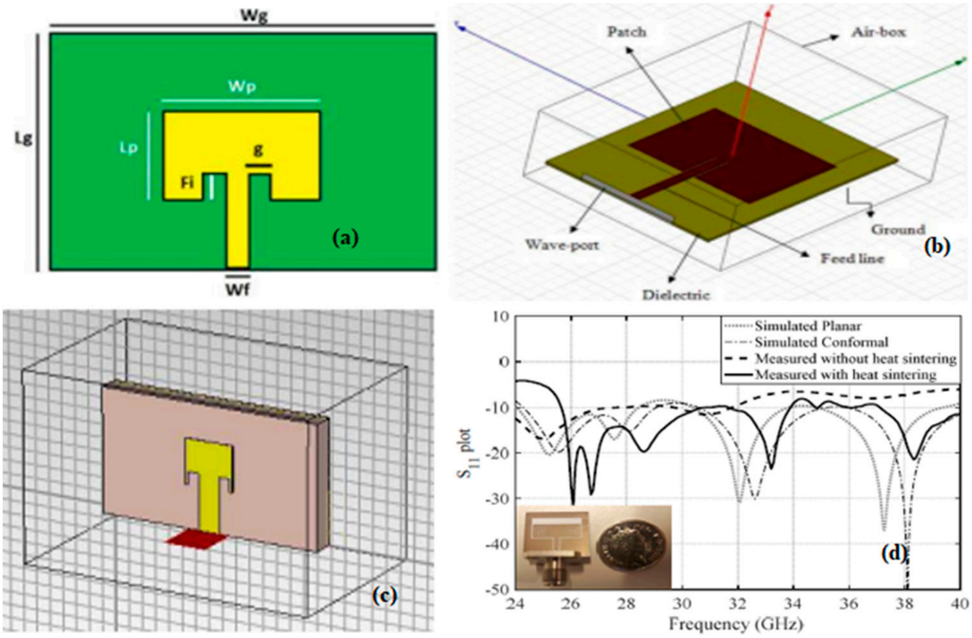

Figure 5. (a) Microstrip patch antenna, (b) radial system for IEEE 33 buses (c) Microstrip patch antenna simulation in CST (d) The flexible inkjet-printed antenna's S11 plot on PET film [29,34].

A horizontal array of polarized antennas: According to antenna array principles, element-to-element spacing close to is desired to radiate in the broadside direction, and all the array's elements are created to be excited in phase at the center frequency of the operating band (28 GHz) [35], The horizontally polarized antenna array's design principles are also applied to the vertically polarized array [36]. An antenna array often referred to as a phased array, is a set of 2 or more antennas. A small 28-GHz phased array antenna focuses on the observed radiation patterns, which, even without calibration, exhibit good features (Beam steering range, beamwidth, side lobe level, cross-polar discrimination, etc) [37]. A small, phased array antenna with a low profile obtains hemispherical coverage in one direction only in the boresight direction [38].

A dual-polarized patch operating at 28 GHz, the antenna array built using a printable antenna method supports both horizontal and vertical polarizations and is appropriate for integrating phased array modules [39]. The feeds for leaky-wave antennas are designed in printable form, and the lenses are manufactured of plastic to produce a low-profile and inexpensive solution. To increase the array element aperture efficiency, the feeds' near-field region features lenses that are optimized for it [40]. New antenna design and integration techniques enable a low-cost, scalable antenna in-package phased-array system for wideband wireless communication [41]. To maximize array performance, an air-filled substrate-integrated waveguide cavity-backed patch antenna array with eight dual-polarized elements transmits high-speed data reliably between access points and end-user terminals [42]. A 2x64 dual-beam array with low cost is fabricated using flip-chip technology, and a dual-polarized 5G transmitter phased antenna array achieves at 50 and 25 GHz and has an EIRP of 52 dBm at Psat, respectively [43].

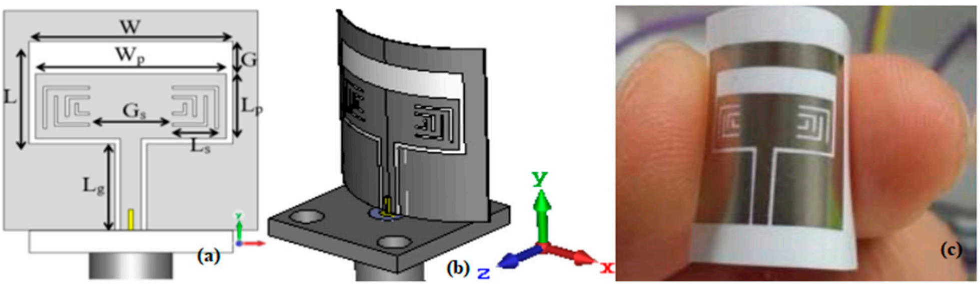

Figure 6. Antenna on PET film with inkjet printing: (a) model simulation; (b) conformal antenna simulation; (c) antenna prototype that was conformally fabricated [34].

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Table 2. Various types of antennas with their functions [22].

Fc (GHz)	Materials (Substrates)	*Technology*	ε_r	Eff. %	Size (mm³)	BW (GHz)	Gain (dBi)	RL (dB)	Ref.
125/280	glass & Kapton	inkjet print.	NA	NA	63.5×63.5×0.05	35/70	24/145	10	[44]
94	LCP	inkjet print.	2.6	NA	210×297×0.15	8.1	7.65	10	[45]
28	Ultra-thin glass	inkjet print.	5.4	80	7.13×5.4×0.147	5.4	6.96	10	[46]
26.5/37	PET	inkjet print.	3.2	95	16×19×0. 135	1.2/3	7.2/9.7	10	[47]
60	PET	inkjet print.	NA	NA	50×60×0.11	2.7	24.4	10	[48]
28	ABS Fingernail	inkjet print.	2.7	70	14.96×117.45×0.5	2.87	7.5	10	[49]
28	FLGR02	inkjet print.	3	NA	5×9×1.7	8	5	10	[50]
34	PET	inkjet print.	3.2	NA	11×25.4×0.147	12.7	6.2	10	[51]
26.26	PET	inkjet print.	3.2	NA	3.1×3.4×0.15	NA	NA	10	[21]
39	PET	inkjet print.	3.2	NA	12×4.7×0.123	26–40	7.44	NA	[34]
28	PET	Spray coating	3.38	70	7.11×3.556×0.508	2.5	8.8	10	[52]
35	LCP	inkjet print.	2.9	NA	11×12×0.1	14	9	NA	[53]
28	Polyester fabric	Screen print.	2.2	NA	25x12.7x 0.35	7.8	4.2	18	[54]
28	RO4350	PCB	2.2	45.6	3.53×3.53×0.16	6.72	19.2	10	[55]
28	Roger RO3003	PCB	3	-	130×70×0.762	24	8	10	[13]
28	FR-4	PCB	2.2	N/A	2.50×3.20×0.1	1	11.23	10	[56]
28	TLY-5A	PCB	2.17	N/A	3.3×3.3×0.254	0.9	10	13.8	[57]
28 &38	RT 5880	PCB	2.2	N/A	NA	2 & 4	10	13	[12]
28	FR4	PCB	4.4	85	NA	7.2	10.8	10	[58]
28 & 38	RT/D6002	PCB	2.2	63/81	30 × 30× 1.52	4.3/5.3	8.7/8.2	10	[32]
28	RO4003C	PCB	2.2	N/A	2×2.2×0.25	4	5.5	12	[16]
50	FR 04	PCB	4.4	N/A	40×34×4.8	20	7.5	10	[59]
60	N/A	PCB	-	85	15× 15×3	3.6	18.5	10	[60]
60	Isola tachyon	BGA	3.02	90	9.6×2.8×0.568	3.6	10.51	<10	[61]
60	RT 5880	PCB	2.2	NA	NA	4	17.1	40	[62]
60	PTFE	PCB	2.2	57.2	44.5×20.0×2.16	5.6	15.6	2.1	[63]
140	RGD837	LTCC	NA	77.5	7×7 ×2.5	19.17	15.5	13	[33]

* BW = Bandwidth; N/A = Not Available, Fc = Centre Frequency, εr = Dielectric Constant, LTCC = Low-temperature co-fired ceramic, PET = Polyethylene Terephthalate, LCP = Liquid Crystal Polymer, PTFE =poly tetra fluoro ethylene, BGA = Ball Grid Array, TLY-5A = Butler matrix, Duroid = D

3.1. Fabrication Methods for Printable Antennas

Different types of various parameters determine the performance of the antenna, such as the conductivity of the radiation element, different design considerations, dielectric substrates, Bandwidth, efficiency, and gain. Selecting a suitable dielectric material to enhance the critical performance of the antenna and gain and efficiency are believed to be decreased for a greater value of dielectric substrate loss [123]. Different substrates determine the performance of a printable antenna using the fabrication process. The common fabrication methods include screen printing and inkjet printing, wet-etching, and other special techniques for fabricating flexible and wearable antennas [13,64]. A branch line coupler with pliers-shaped ends and its transition layer was used to fabricate a low profile and compact novel 2x2 slot array antenna, making the feeding network layers suitable for future wireless applications [65]. Graphene ink was created by the radiating element and the active channel of field effect transistors are inkjet printed using graphene flakes. The printable substrate used to print circuitry for antenna and electronics on a flexible surface and the radiation-emitting materials' flexibility and rate of oxidation obtained [66].

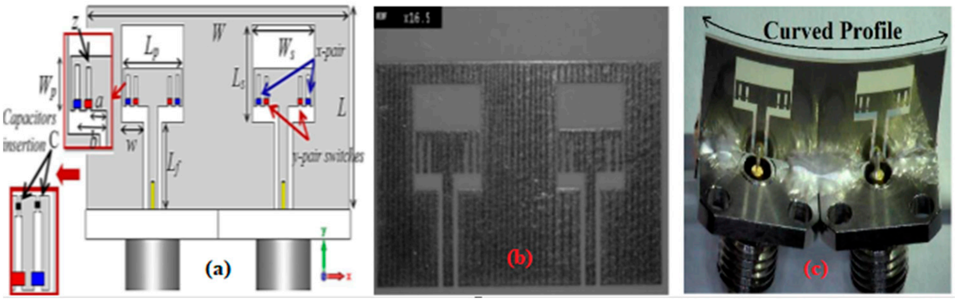

Figure 7. Proposed printable MIMO antenna with two elements: (a) model of a simulated antenna; (b) fabricated antenna prototype that was inkjet printed; (c) actualized conformal 2-element MIMO antenna [51].

3.2. Conductive materials

Achieving conductive patterns in wireless applications with superior electrical conductivity is necessary to guarantee a wide bandwidth and higher gain. Moreover, resistance deterioration brought on by mechanical deformation is the desired feature of the conductive material. Fabrics must be tightly knitted and made of adequately conductive material, and deviations from the main current flow in the opposite direction must be avoided [67]. Copper/silver are frequently chosen for the fabrication of printable antennas because they possess a high electrical conductivity due to the low rate of oxide formation copper nanoparticles are edged by silver nanoparticle ink [23,68].

Table 3. Radiation characteristics measured using various conductive layer materials [67].

	Gain (dBi)	X -polarization ratio (dB)		Beam width (deg)	
Solid copper tape	7.35	-20.42 (E)	-18.55 (H)	73 (E)	60 (H)
Knitted copper fabric	6.77	-16.03	-17.74	75	54
Vertically cut copper tape	6.82	-17.73	-18.52	74	61
Horizontally cut copper tape	5.01	-20.83	-17.99	74	62
Horiz. cut and soldered copper tape	7.26	-24.72	-18.90	73	62
Aracon fabric	0.57	-12.09	-15.73	75	60

3.3. Substrates

The material used as the substrate in printable antennas needs low relative permittivity, low thermal expansion coefficient, good thermal conductivity, and minimal dielectric loss conductivity in different environments, such is motivated by the requirement for greater efficiency at the expense of higher antenna size. It is mentioned earlier, an exception to this fact is the need for a miniaturized antenna for a huge dielectric constant. Three different categories of substrates have regularly surfaced in the fabrication of printable antennas, thin glass, plastics or polymer, and metal foil substrates [69]. a high-density inductively linked plasma at low temperature (90–170 °C) vapor deposition method is required, allowing any substrate to be used for a printable antenna; it has the desired electrical characteristics for antenna applications [70].

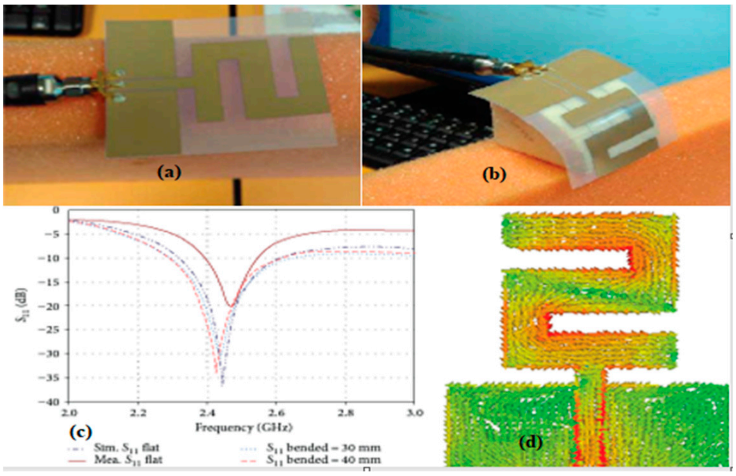

Figure 8. Z-shape antenna fabricated using the inkjet printing method on PET substrate (a) flat condition (b) state of bending (radius: 20mm) (c) reflecting factor S11 in decibels (d) The antenna's simulated current distribution at 2.45GHz [71].

3.4. Chemical Etching

Chemical etching was part of the printable antenna industry in the process of fabricating metallic patterns using etchants and photoresists corrosively mill out a chosen area [72]. It is the ideal option over other fabrication techniques for accurately fabricating complicated designs with high resolution [73].

Figure 9. Fabrication Prototype (a) printed design (b) polyimide Kapton film with copper tape (c) chemical substances (d) designed transferred (e) complete prototype.

4.1. 3D-Printed Antenna

Creating completed parts that might be utilized for final user applications without any process is a desirable aspect of metal three-dimensional (3D) printing for time and cost. Stainless steel 316L and aluminium AlSi10Mg are common choices for materials [74]. Two planar transitions from the rod antenna microstrip to excite the orthogonal modes are proposed, along with a dielectric rod antenna with dual polarization for polarization diversity applications at a 35 GHz frequency band. The antenna is printable using a commercial 3D printer, which results in a very low fabrication cost [75]. The developed filtering antenna has very small profiles and demonstrates great selectivity, gain, and efficiency. It blends a selective filter and Yagi-Uda-like antenna within a 3D printable metal construction [76]. A monopole microstrip antenna design was fabricated using a 3D-printed curved substrate fed with a microstrip line and a partially formed ground plane [77].

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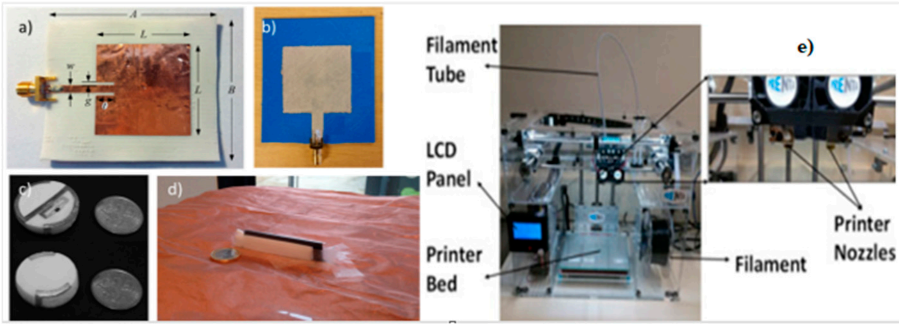

Figure 10. Examples of Antennas made via 3-D printing: (a) Ninja Flex substrate with a square patch antenna, (b) a 3-D printed substrate with a brush-painted wearable antenna, (c) 3-D radio-frequency identification (RFID) tag antenna in the form of a button, (d) Inverted antenna made via 3D printing [23] and, (e) a 3-D printer [78].

4.2. Screen Printing

Screen printing is an easy, inexpensive, fast, and effective method for fabricating an antenna by printing using conductive inks or pastes onto low-cost substrates such as PET, textiles, and paper [79]. Planar dielectric antennas are introduced using thick film screen-printing technology to serve as a magnetic wall boundary, and a micron-sized thick film formed of a low-loss substrate is printed using high-permittivity dielectric paste., low-permittivity microwave substrate [80]. Transparent silver nanowire is used in screens printed on a flexible PET substrate, for innovative applications demanding transparent and flexible antennas [81].

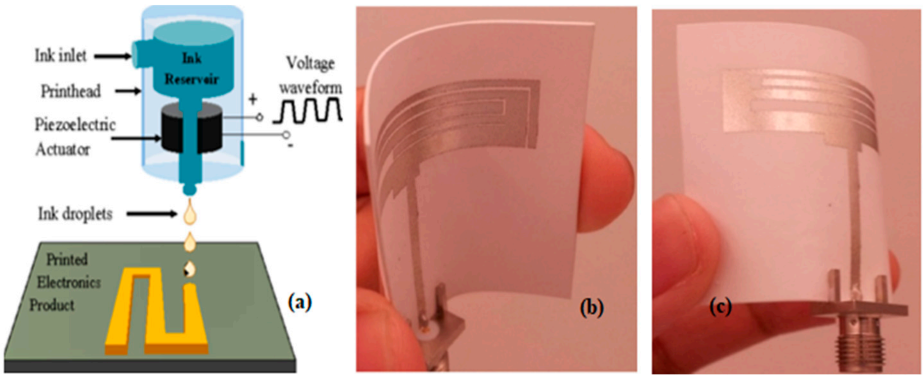

Figure 11. (a) Typical piezoelectric inkjet printing mechanism [87], Prototype of the proposed flexible antenna on Synthetic Paper substrate (b) forward bending (R = 20mm) (c) backward bending (R = -20mm) [82].

4.3. PCB Printing

Different conductive materials and substrates are used to fabricate PCB antennas and the substrate should be selected based on its dielectric properties and electrical conductivity. These must be tolerance to persistence in the external environment and mechanical deformations; the radiation efficiency determines the antenna performance based on the selection of conductive material. The small antenna structure was developed using HFSS software to show the 3D view to achieve a wideband resonating response, the PCB structure the copper patch's top geometry is etched, and FR-4 substrate coaxial feed is applied in depicts the structure’s dimensions [83,84]. A full-wave analysis of a resonant cavity antenna served as the basis for the design of an all-dielectric phase-correcting structure that is 3D printable [85]. The phase correction was accomplished by simultaneously varying the permittivity and height of the dielectrics [86].

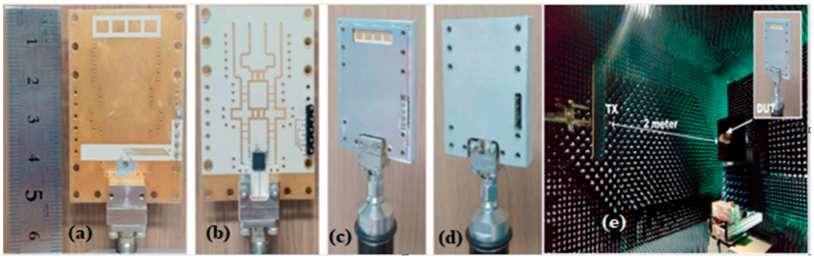

Figure 12. The fabricated antennas in pictures (a) Antenna side (b) Butler matrix side (c) A metal enclosure's antenna side, (d) a metal enclosure's reverse side, (e) Test configuration for the radiation pattern in the anechoic chamber [87].

4.4. Inkjet Printing

Technology for inkjet printing has developed alternatively to traditional fabrication methods such as milling and etching. The method is additive; thus, the design is directly applied to substrate 3 without masks and guarantees minimal wasting of materials [88]. A circularly polarized antenna construction is proposed to be formed on adhesive copper for a practical prototype. The dielectric support will be 3D-printed in Poly Lactic Acid, wisely chosen for its intriguing low losses qualities [89]. The inkjet printing technology's promise of reactive inkjet printing for commercializing wearable electronics based on graphene has guaranteed the antenna's mechanical flexibility and extremely low production costs [90]. The production of patch antennas, circuit boards, biological sensors, frequency selection surfaces, and various electronic gadgets has extensively used inkjet printing [91]. substrate-integrated waveguides and antenna-in-package are printed entirely with inkjet technology to improve the performance of three parts: via holes, wire bonding, and flexible antenna arrays [92]. Fabrication of planar antennas for inkjet printing technical issues concerns the dimensions of the manufactured structures, as well as the efficient nanoparticle ink is applied to a PET substrate using a piezoelectric printhead [93].

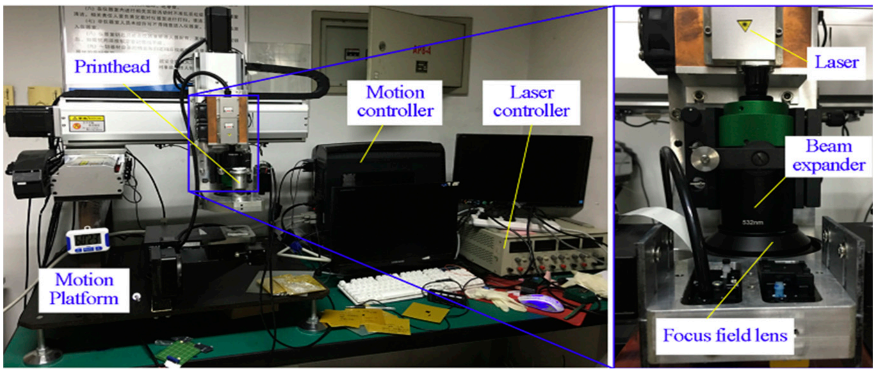

Figure 13. Experimental platform for laser sintering [91], An inkjet-printed Antenna using silver nanoparticles on a paper substrate.

Table 4. Comparatives Analysis of Different Inkjet-Printed Antenna Designs for Operating at Different Frequencies.

Antenna Type	Fc GHz	Tech.	substrate	Ink type	Sub ε_r	Sub. tan δ	Size (mm²)	SH mm²	BW (GHz)	Gain (dBi)	Ref.
Multi-Band	5	Inkjet Print.	Teslin	Nanoparticles	2.00	0.022	35×40	0.26	1	2	[82]
Monopole	12.4	Inkjet Print.	polyimide	silver nanoparticle	3.5	0.0027	13×13	0.125	5.4	4.4	[94]
NA	2.4	Inkjet Print.	PET	GO ink	3.2	0.022	75 *5		0.84	NA	[95]
Multiband	3.4	Inkjet Print.	Photo paper	silver nanoparticle	3.2	0.05	30 x 40	0.44	2.5	2	[96]
mimo monopole	3.4	Inkjet Print.	Kapton polyimide	silver nanoparticle	3:4	NA	22*31	0.125	3.43 to 10.1	2.31	[97]

 doi:10.20944/preprints202305.0335.v1

Patch Antenna	4.9	Inkjet Print.	Kapton polyimide	silver nanoparticle	3.4	NA	22 × 31	0.245	0.25	4.5	[98]
monopole	2.4 5.2	Inkjet Print.	photo paper	silver nanoparticle	3	NA	51 *34	0.18	0.45 1.60	1.4 2.78	[99]
Dual-Ban	2.45/5.8	Inkjet Print.	PET	silver nanoparticle	3.2	0.022	45×40	0.135	0.83/2.55	1.81/3.92	[100]
Dual-Band	2.4/ 5.2	Inkjet Print.	photo paper	nanoparticle silver	3	NA	210 × 282.5	0.177	0.5/2.9	3.74/4.96	[101]
graphene	5.65	Inkjet Print.	Polyamide	graphene	3.5	0.002	9 × 7	0.125	3	0.35	[102]
Patch antenna	2.45	Inkjet Print.	Ninja Flex	Silver paste	2.8	0.05	65×54	0.2	0.99	7.2	[78]
Dipole	2.45	Inkjet Print.	porous elastomer	Graphene	3.6	0.06	NA	NA	0.9	0.3	[103]
Patch	1.11	Inkjet Print.	PET	Silver ink	4	0.01	30 × 40	0.135	0.037	NA	[104]
Monopole	2.55	Inkjet Print.	Textile substrate	Silver ink	3.74	0.15	37.5 × 23	0.49	2.09	1.5	[105]
monopole	2.4/5.8	Inkjet Print.	photo paper	silver nanoparticle	3.2	0.05	86.25/22	0.22	0.71/1.96	2.24/4.42	[106]
Dipole	3.8	Inkjet print.	Wound dressing	Nano silver Ink	3.2	0.05	43.5×42.5	0.7	3.2–4.6	0.67	[107]
monopole	2.45	Inkjet print.	PET	Silver nanoparticle	2.7	0.135	30×40	0.125	NA	1.44	[71]

* tan δ = loss factor; SH = thickness of the substrate, ε_r = dielectric,

5. Future Prospects and Challenges of Inkjet-printed Antennas

The research on inkjet-printed antennas for use in wireless devices attracted considerable attention because of their ability to conform to the standards of wireless applications. An inkjet-printed antenna is one of the essential parts to replace conventional rigid substrates in the fabrication process for wireless systems [108]. Consequently, the first challenge of designing an inkjet-printed antenna is finding an appropriate substrate; compared to traditional substrates like Rogers or FR4, which need a dielectric constant of about 3 to 10 and a loss tangent of 0.001 to 0.02, typical inkjet-printed substrates have low dielectric constants [109]. Though, this dielectric constant value helps attain better radiation efficiency, and Bandwidth, when miniaturization is needed, it causes difficulty with antenna functionality. For inkjet-printed textile antennas, the uneven thickness is another problem. The electro-textile substrate is predisposed to crumble easily and be absorbent of liquid.

6. inkjet-printed Antenna for Future Wireless Solutions

As a result of the increased demand for wireless applications, inkjet-printed antennas are expected to be used in a wide range of frequencies for future wireless solutions. There are various antenna techniques, including reconfigurable, single-band, and multiband antennas. Frequently, multiband design is required; for instance, in 5G wireless technology, devices should operate in the mm-wave 28GHz and above range. Additionally, the design would assure that the characteristics of the antenna remain constant under design specification conditions. In a previous article, an inkjet-printed multiband antenna was designed and fabricated at a low-cost [110]. Based on a Kapton polyimide-based material, the innovative triangular iterative design features a coplanar waveguide feed inkjet-printed substrate was applied to achieve multiband operation with wider Bandwidth [111].

7. Conclusions

The findings from this study present the significance of printable antennas in various frequency bands, with challenges and restrictions along with various miniaturization strategies. The problems with the conducting ink and substrate were analyzed for wireless system solutions in the future, including with reference to contemporary literature. The selection of materials for printable antenna fabrication depends on application preferences such as the environment, smooth integration with rigid and non-rigid devices, cost, and components of the fabrication process.

The inkjet-printed antenna technology is ideal for current and future wireless communication devices due to their simplicity of fabrication, lightweight, small-form component, inexpensive production, and capacity to fit non-planar surfaces among many more. The conductive patterns in the inkjet-printed antennas have been more viable alternatives to the conventional ones, due to highly conductive materials including Ag nanoparticle paints, Cupper tape, or clad conductive polymers. And graphene-based materials such as printing ink. PET, PEN, PANI, liquid crystal polymer, electro-textile, paper, and Kapton polyimide substrates to ease the fabrication process. The major challenge of antenna design for inkjet printing is substrate material selection, which requires a low-loss material to improve antenna efficiency.

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