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Materials for printed antennas for 5G network

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ABSTRACT

5G networks are expected to deliver data at up to 100 times the current rate. This will require advanced connectivity technologies to enable higher bandwidth and high-definition communications. When developing 5G communication, it is very important to design a suitable antenna for 5G technology. Various parameters of the antenna have to be considered to check if it is suitable for 5G technology. This thesis reviewes and discusses the different material properties and technology used in printed antennas. The thesis will focus on inherent challenges and future prospects of printed antennas. Finally, an insight into the application of flexible antenna on future wireless solutions is discussed.

Key word: 5G, printed antennas, materials, print technology

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1. Introduction

5G communication technology promises significant advancements, therefor, users can get a better experience. 5G brings to us mainly 8 key features, such as higher speed, lowered latency, increased connection density, and broader coverage with respect to other already used solutions, as illustrated in Figure 1. Thus, more reliable connections and faster speeds can be provided to users [1].

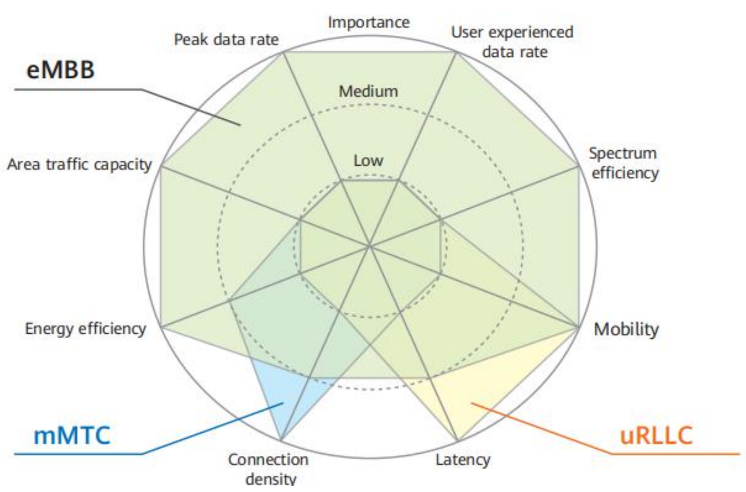


Figure 1. Importance of key features in diverse application scenarios [1].

This technology is supposed to utilize millimeter wave frequencies in many aspects of our daily lives and enables massive connectivity between people, between machines, and between people and machines. In the 5G era, instant, uninterrupted communication between large and small electronic devices will become ubiquitous, which is bound to trigger a wide range of new applications and innovations for future work and life. The implementation of Internet of Things (IoT), augmented reality (AR) or virtual reality (VR) applications, factory automation, vehicular communications and other applications where security, reliability, quality of service and efficiency are critical. Antennas are playing an increasingly important role in human social life. The performance of the antenna will directly affect the quality of 5G communication system [2].

5G technology antennas require greater capacity, wider wireless spectrum utilization, high gain, and steerability. Since traditional small-size antennas cannot meet high-frequency requirements during the manufacturing and installation process, under the premise of affordable costs, new antenna technologies pose challenges in terms of dynamic structure, adaptive array configuration and expansion performance, and energy-friendly operation. In any wireless application, the choice and design of the antenna vary depending on the environment, transmission strength, and frequency range: it means, different applications require different antennas, different applications require specific materials [3]. The performance of the antenna depends on the material used, the type of fabrication technique employed, and the substrate properties. Therefore, the selection of the used materials is of high importance, as illustrated in Figure 2.

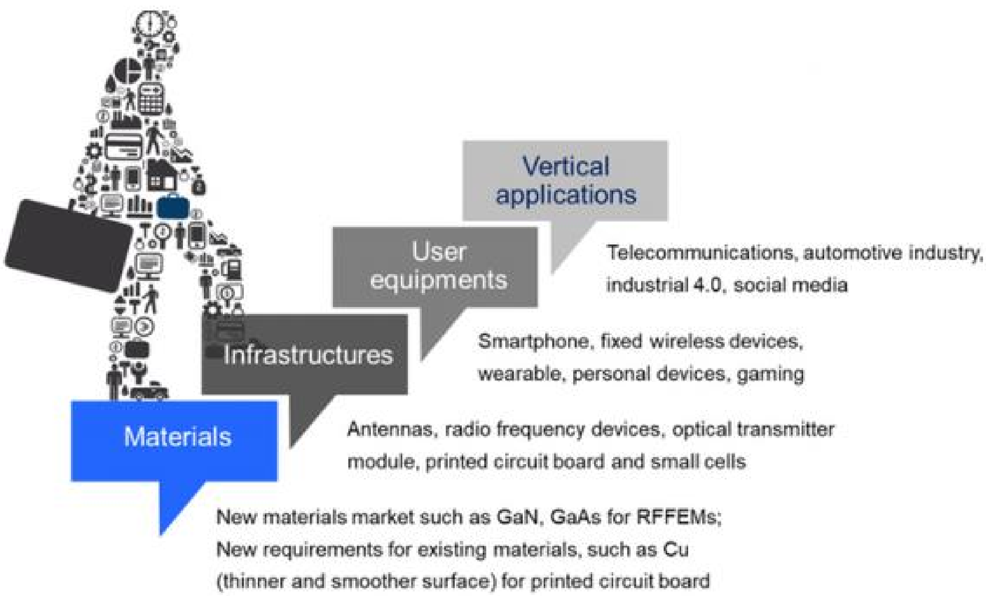


Figure 2. High performance materials can solve the problems of antennas [3].

In this review thesis, the different material properties and technology used in printed antennas are examinationed and discussed. In addition, the inherent challenges and future prospects of printed antennas are discussed, and in-depth view on the applications of printed antennas in future wireless solutions are presented.

2. Features of printed antennas

The MPA was first proposed in 1950s and it developed practically in 1970s [4]. Basic configuration of printed antennas consists of the radiating patch, a dielectric substrate, and a ground plane, see Figure 3 [5] [6]. Figure 4 shows the radiating patch be of different shapes like the rectangular, square, circular, annular ring, triangular, pentagonal, and square or circular ring [7], and printed on the dielectric substrate forces the EM waves to radiate at particular frequency. From this basic configuration, a variety of layouts emerged in the design of printed antennas.

The dimensions of the substrate and patch are selected based on the operating frequency and the properties of the dielectric substrate material used. The physical parameters of the antenna, such as the length and width of the patch, the length and width of the substrate, the feed position, the feed length and others can be calculated using various mathematical equations. The properties, dielectric constants, and conduction properties of dielectric material affect the fringing waves in the patch antenna [8]. The dielectric materials are chosen based on antenna application and cost. Different feeding techniques have been used to feed signals, such as microstrip line, proximity coupling, embedded feeding, aperture coupling, and coaxial probe feeding, These feeding techniques need to be transmitted using electromagnetic waves to feed the signal to the antenna, Figure 5 shows the different feeding technologies [9][10][11].

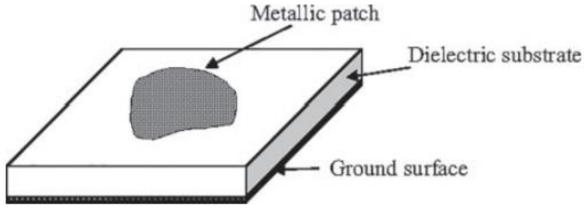


Figure 3. Basic configuration of printed antennas [6].

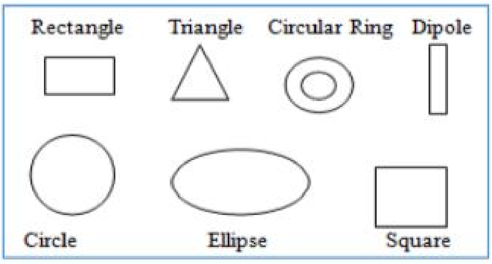


Figure 4. Shapes of microstrip-patch antenna [7].

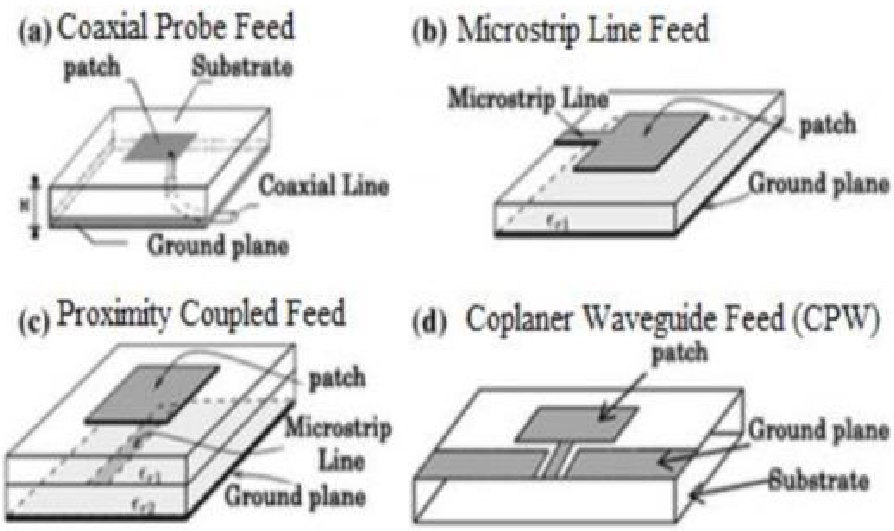


Figure 5. Feeding technologies: (a) Coaxial probe feed (b) Microstrip line feed (c) Proximity coupled feed (d) Coplanar waveguide feed [12].

Printed antennas have many advantages, such as small size, low profile, light weight, and conformability to curved surfaces, easy integration and good directionality. Printed antennas have been further developed both in theory and in the breadth and depth of applications and have shown their great potential in practical applications. Various new forms of printed antennas with new performance continue to appear, and are widely used in military fields such as satellite communications, navigation telemetry and remote control, weapon fuzes, and modern mobile communications, personal communications, biomedical, environmental protection, and other civilian fields.

Due to its unique advantages, microstrip antennas are particularly suitable for use as conformal antennas. Conformal microstrip antennas have always been a hot research topic. Not only the traditional aerospace industry has a strong demand for high performance conformal microstrip antennas, but also with the rapid development of mobile communications, conformal microstrip antennas have good application prospects as base station antennas and portable antennas. Conformal microstrip antennas are low-weight, easy to fabricate and can be integrated with microwave and millimetre-wave circuits. In recent years, with the development of materials, wearable conformal microstrip antenna is presented, it use special methods or special materials to integrate the antenna on the carriers that the human body often wears, such as clothes, hats, and backpacks. The integrated antenna should maintain a good conformal shape with the human body, and try not to affect the normal use of the carrier and the comfort of the human body. In military, some man-portable combat backpack radar and man-portable communication systems have adopted wearable conformal microstrip antenna technology; in medicine, research and use wearable conformal microstrip antennas for breast cancer detection and the development of other real-time medical diagnostic systems. The substrate of conformal microstrip antenna should be highly deformable and mechanically robust and must exhibit high tolerance levels of bending repeatability [13].

For a printed antenna, its performance depends on the material used, the type of manufacturing technology used, and the characteristics of the substrate.

3. Materials for printed antennas

Antennas are made using a variety of conductive materials and substrates. Substrates are selected based on their dielectric properties, tolerance to mechanical deformation (bending, twisting, and wrapping), sensitivity to miniaturization, and durability in the external environment. Conversely, the conductive material selected based on electrical conductivity determines the antenna performance, such as radiation efficiency.

3.1 Conductive Materials

In wireless applications, the realization of conductive patterns with superior electrical conductivity. Conductivity is essential for ensuring high gain, efficiency, and bandwidth. Additionally, resistance is essential for ensuring high gain, efficiency, and bandwidth.

3.1.1 Metal based materials used as conductive part in antennas

Liquid metal can be injected into microfluidic channels to create highly flexible and mechanically stable antennas. Compared with conventional semi-rigid copper foil, the liquid metal material does not suffer irreversible deformation after bending, and the antenna material has good electrical properties. The use of conducting liquids as radiating elements allows the design of more flexible and highly re-configurable antennas compared to solid conductors [14][15]. Antennas containing LM are usually highly flexible and deformable while maintaining high conductivity.

The common components of liquid metals used as conductive materials for antennas and their properties are shown in the Table 1. Most of these materials are based on liquid metals and consist of suspended particles of conductive nanostructures with a typical conductivity that in the range of 10^6 S/m [16].

Conventional LMs include mercury and gallium-based alloys such as Galinstan and eutectic gallium-indium. Mercury is typical material that available as a liquid at room temperature with a melting point of -39 ◦C and a conductivity of 1×10^6 S/m, and also with good antistatic properties and low oxidation rate low [17]. However, mercury has great toxicity leading to its limited use in antenna design. LMs based on Ga alloys form a thin oxide skin when exposed to air, and can behave an elastic property. The oxide layer provides mechanical stability to this elastic antenna when it is 3D printed [18][19]. EGaIn, a liquid metal alloy composed of 75% gallium and 25% indium (8), is characterized by an electrical conductivity of 3.4×10^6 S/m and a melting point of 16 ◦C. Its non-toxic nature makes it a popular choice for antenna materials. Galinstan, another non-toxic liquid metal alloy widely used as an antenna radiating element [20], has a much lower melting point than room temperature (-19 ◦C) and it consists of 68.5% gallium, 21.5% indium and 10% tin. The addition of 0.30% oxygen to Galinstan by stirring gives it sufficiently strong surface tension and adhesion properties so that it can be used as LM ink. The LM ink based on GaIn10 consists of 90% gallium, 10% indium and about 0.026% oxygen, and has a conductivity of 2.9×10^6 S/m. In addition, composites made of nanoparticles of metals can be applied to conductive materials for the antennas [21]. For example, the addition of walled carbon nanotubes (SWNT) can make the conductivity of the base fluid greatly enhanced. Silver nanoinks are one of the composite fluid materials that have excellent conductivity of 20×10^6 S/m, however, the price of this composite material is relatively high [22]. Silver nanowires were embedded into PDMS can achieve conductivity of 0.813×10^6 S/m. In addition, it was found by researchers that suspended EGaIn nanodroplets were formed in ethanol by ultrasonic method and then deposited into nanoparticles, and then the nanoparticles could be made to form interconnected electrical pathways by the applied pressure [23]. The conductive ink which consists of silver nanoparticles are frequently used in inkjet print machine. The conductivity of the conductive ink varies from 0.4 to 2.5×10^7S/m, depending on the temperature and duration of the curing [24] invested the difference between heating temperatures of 100° C and 150° C after 15 minutes of curing. At the lower temperature, larger gaps exist between the particles, resulting in a poor connection. When the temperature is increased, the particles begin to expand, and gaps start to diminish. That guarantees a virtually continuous metal conductor, providing a good percolation channel in which the conduction electrons can flow, See from Figure 6. Therefore, after printing conductive elements with metallic nanoparticle inks, there must be an additional sintering step, which is usually achieved by heating to a certain temperature.To ensure the conductivity performance, the dipoles were inkjet-printed using two layers of SNP ink and sintered at 150 °C for 15 min to increase conductivity [25].

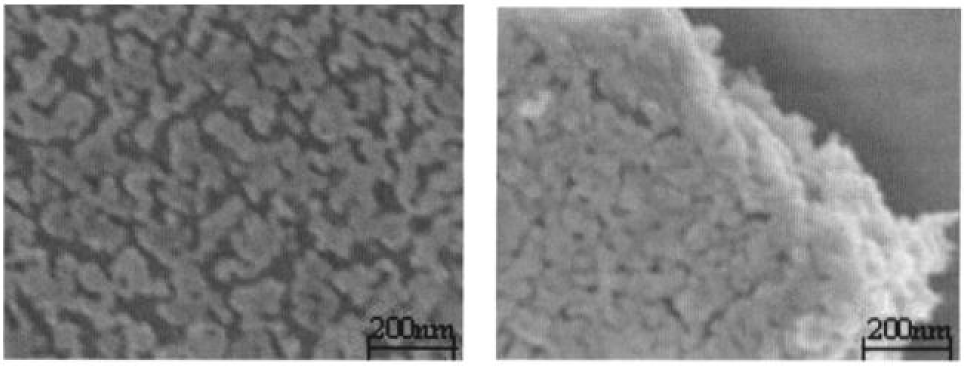


Figure 6. Scanning electron microscope images of a layer of printed silver nanoparticle ink, after curing for 15 minutes at 1000 C (top) and 1500 C (bottom) [24].

Table 1. The common components of metals used as conductive materials for antennas and their properties [26].

Liquid Metal Material	Composition	Electrical Conductivity (unit:10^6 S/m)	Melting Temperature	Density @25 ∘C (g/cm3)
Mercury	High purity Hg	1	-38.87	13.55
EGaIn	75% Ga, 25% In	3.4	16	6.25
Galinstan	68.5% Ga, 21.5% In, 10% Sn	3.4	-19	6.44
GaIn10 LM ink	~90% Ga, ~10% In, 0.026 wt% O	2.9	16	~6.05
EGaIn + 0.5% SWNT	~74.6% Ga, 24.9% In, 0.5 wt% SWNT	~6.8	-	-
EGaIn nanoparticles	EGaIn nanoparticles in PDMS substrate	0.0925(max)	-	-
EGaIn nanoparticles	72 wt% Ag in organic solvent	~20	-	-
Silver nanoink	AgNW in PDMS substrate	0.813	-	-

3.1.2 Carbon based materials for the conductive part of printed antennas

Because the available bandwidth is inversely proportional to the antenna size, the carbon-related nanomaterials antennas have smaller size and thinner dimensions, capable of emitting high frequencies.

As we all know, Graphene is the thinnest two-dimensional material in the world, with a thickness of only 0.35 nm. Its special structure contains rich and novel physical phenomena, which make graphene with excellent flexibility and exceptional electrical and thermal conductivity. In addition, as a carbon material, graphene has better chemical stability and adaptability to complex environments than metals [27][28]. Graphene has mobility of charge carrier of 2,00,000 cm2 V−1 s−1 at room temperature, Young’s modulus of 1.5 TPa, the fracture strength of 125 GPa, and thermal conductivity of 5,000 W m−1 K−1, and also has a high conductivity of up to 4.9 × 108 S/m and sheet resistance of less than 30 Ω/m with 90% optical transparency. Due to its excellent switching characteristics and tunable properties, graphene has become an attractive material.

The conductivity of graphene monolayer can be computed using the formula as:

$$\delta_s = \frac{2e^2 k_B T}{\pi \hbar^2} \, ln\,(\,2cosh\frac{\mu_c}{2k_B T})\,\frac{i}{\omega\,+\,i\tau^{-1}}$$

$$+\frac{e^2}{4\hbar}[\frac{1}{2}+\frac{1}{\pi}arctan\frac{\hbar\omega-2\mu_c}{2k_B T}-\frac{i}{2\pi}ln\frac{(\hbar\omega+2\mu_c)^2}{(\hbar\omega-2\mu_c)^2+4(k_B T)^2}]$$

where i is the imaginary unit, e is the charge number of an electron, ω is the angular frequency, $\hbar$ is the reduced Planck constant, k_B is the Boltzmann's constant and τ is the relaxation time. In this work, τ is set as 1 ps. From this formula, we can see the frequency from 20~40 GHz or temperature from 250~350K have a negligible effect on conductivity. So, graphene materials antenna can not affected by environment because of the stable. As shown in Figure 7.

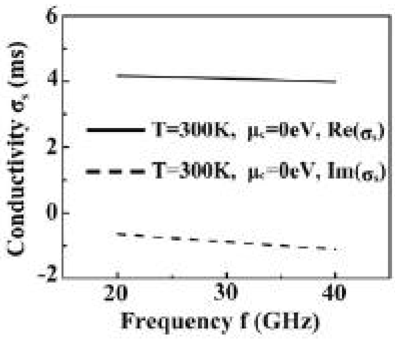


Figure 7. The relationship between conductivity and frequency [29].

The basic configuration of graphene-based nanoantenna is shown in Figure 8 (a). The nanoantenna is composed of a graphene layer (the active element), along with a metallic flat surface (the ground layer), and a dielectric material layer in between the former two layers [30]. The use of graphene material makes antenna size can hundreds of times smaller than conventional microstrip antennas. And they can provide inter-core communications in the terahertz band.

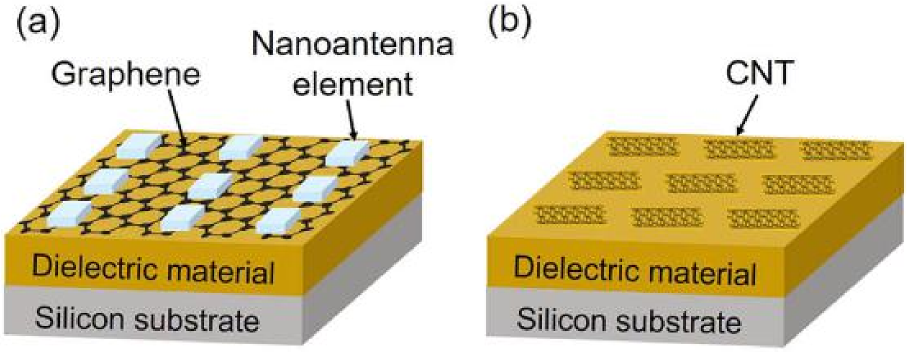


Figure 8. graphene-based nanoantennas(a); CNT-based nanoantennas(b) [30].

CNTs also use for nanoantenna materials. They are one-dimensional material with electronic and electromagnetic properties including aligned axial transition dipoles, large absorption cross-sections, and high quantum efficiencies. CNTs minimizing resistive losses and extremely high conductivity in the antenna. CNT-based nanoantennas suffer much less from power loss due to surface and edge roughness. The configuration of CNT-based nanoantennas is shown in Figure 8(b). With respect to a metal wire of the same size CNT-based nanoantennas have a low power dissipation, leading to high antenna efficiency.

CNTs and graphene have the high thermal conductivity (CNTs more than 2,000 W/(m K) and grathene about 5,000 W/(m K)) and the lager area, so they can withstand the high temperature. But, about 700k, CNTs can be oxidized at the temperature that significantly affecting the electromagnetic properties. One way to prevent CNTs-based nanoantennas from the damage of high temperature is CNTs incorporate with ceramics. The conductivity and the imaginary parts of permittivity value for SiO2 matrix reinforced by 10 vol% CNT are almost stable from 400 to 800 K.

Table 2. Comparison of the properties of graphene, CNTs, and copper [30].

	Electrical conductivity (S/m)	Electron mobility (cm2 V-1 s-1)	at room temperature Current density (A cm-1)	Thermal conductivity (W m-1 K-1)	tensile strength
Graphene	108	2*105	109	5000	1.5TPa
CNT	106-107	8*104	109	3000	50-500GPa
Copper	5.96*107	32	106	400	587MPa

3.2 Substrate used in printed antennas

The substrate material used in printed antenna needs to possess minimal dielectric loss, low relative permittivity, low coefficient of thermal expansion, and high thermal conductivity [31]. Such a constraint is driven by the need for increased efficiency (in different environments) at the cost of larger antenna size. An exception to the above-mentioned fact is the need for large dielectric constant for miniaturized antennas. Five types of substrates have often used in the fabrication of printed antennas, there are RF substrates, Polydimethylsiloxane (PDMS) substrates, textile substrates, paper substrates and plastic substrates.

3.2.1. Traditional RF substrates

The thin substrates among the traditional substrates such as FR4, Teflon, Taconic or Rogers, some are available for printed antennas. In the printed antenna design, Rogers materials have superior physical and electrical properties to ensure the antennas with stable characteristics (see Table 3). In addition, flexibility of Rogers materials provides the tendency to deform without breaking, cracking, loosening the copper, ensuring reliable, long-life performance of the antenna.

See Figure 9 , Sallam et al [32] used a 0.2-mm-thick flexible Rogers RO4003C to design an antenna with 60 mm × 80 mm size for WLAN or WiMAX systems. Tang et al [32] used the 0.127-mm thick Rogers RT5880 to design a CPW-fed antenna which reached the gain of 5.76 dBi at the resonant frequency of 1.55 GHz.

(a) (b)

Figure 9. CPW-fed bow-tie slot antenna (a) Sallam et al., 2017 [31], (b) Tang et al., 2015 [33].

Table 3. The electromagnetic, recycling ability and flexibility properties of some typical substrate materials.

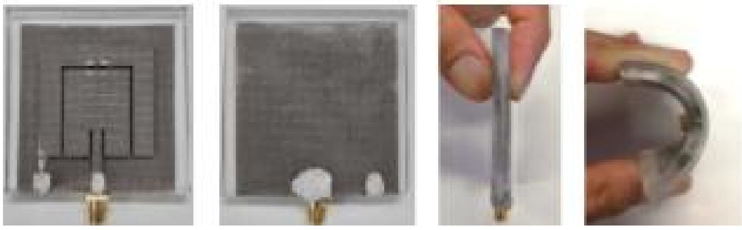
Substrate	ε_r (at up to 20 GHz)	tan δ(at up to 20 GHz)	Recycling ability	Flexibility	Cost
Rogers RT5880(thin)	2.2 ± 0.02	0.0009	No	Yes	High
PDMS	2.68–3	0.02–0.04	No	Yes	Medium
Textile	1.22–2.12	0.0004–0.0098	Yes	Yes	Low
PET, PEN	3.2–3.5	0.015–0.02	Yes	Yes	Low
Paper	2–5	0.04–0.1	Yes	Yes	Very low

3.2.2. PDMS substrates

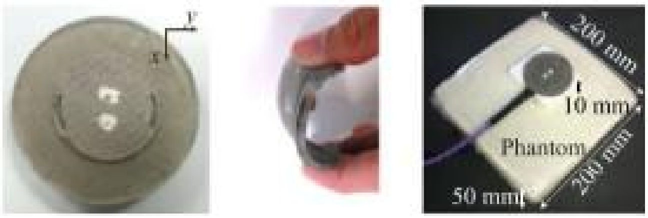
PDMS substrates, commonly known as silicone and in some studies mentioned, are flexible, stainable, optically transparent and biocompatible for medical applications.

See from Table 3, PDMS substrates have a dielectric constant (ε_r) between 2.68-3 and a loss tangent (tan δ) between 0.02-0.04. The properties of PDMS are suitable for printed antenna. In combination, PDMS substrates are flexible, optically transparent, and biocompatible with many applications. However, PDMS substrates do not permit metal deposition using the direct-write method, which causes some challenges for cost-effective large-scale production.

See Figure 10, Simorangkir et al [34] introduced antenna structures on PDMS used for body-centric communications such as a simple dual-band microstrip antenna structure operating at 2.4 GHz and 5.8 GHz using NCS95R-CR conductive fabric from Marktek Inc or a frequency-reconfigurable antenna with two varactors with the same NCS95R-CR conductive fabric. Jiang et al [35] proposed a PDMS-based circularly polarized antenna with AgNWs ink for Wireless Body-Area Networks applications.



(a)



(b)

Figure 10. photographs of fabricated reconfigurable antenna: (a) Simorangkir et al. [34], (b) Simorangkir et al. [35].

3.2.3. Textile substrates

Designed antennas on textile substrates can be incorporated into clothing for both wearable and biomedical applications. Table 4 shows dielectric properties of some normal textile fabrics [36]. There is a very narrow range of their permittivity, from 1.22 to 2.12, and their loss tangent (tan δ) is rather low (0.01 – 0.05).

Table 4. Dielectric properties of normal fabrics [36].

Non-conductive Fabric	ε_{r1}	tan δ
Felt	1.22	0.016
Cordura®	1.90	0.0098
Cotton	1.60	0.0400
100% Polyester	1.90	0.0045
Quartzel®Fabric	1.95	0.0004
Cordura/Lycra®	1.50	0.0093
Silk	1.75	0.012
Tween	1.69	0.0084
Panama	2.12	0.05
Jeans	1.7	0.025
Moleskin	1.45	0.05

M.Virili et al (2012,2014) designed a patch antenna with transformer based on textile materials and operating in the frequency band 2.4–2.4835 GHz [37][38]. Ahmed et al (2017) compared three Bluetooth microstrip-fed rectangular patch antennas designed on various textile materials, Goch, jean and leather for wearable applications and found, that in term of fabrication and performance, the leather textile material is the best choice [39]. Textile substrates are very user-friendly for wearable and biomedical applications. However, their porous and compressible nature makes it challenging to control their thickness at low pressures. Moreover, since most antennas designed on these substrates will be integrated on clothing, they can become wet due to human sweat, which can change the dielectric properties of the tissue and affect the radiation characteristics of the antenna.

3.2.4. Plastic substrates

Flexible plastic materials such as polyethylene terephthalate (PET), polyethylenenaphthalate (PEN), Plastic films for insulation are the potential candidates for a broad range of applications. In particularly, PET is highly preferred in applications which require a high degree of flexibility and transparency. Table 3 shows the dielectric properties of plastic substrates PET and PEN. In addition, flexible plastic substrates have low cost, lower loss tangent (tan δ=0.005) than some other flexible materials. However, a heat treatment process under high temperature is needed after printing. This needs to be strictly controlled as the polyester may start to contract strongly.

See Figure 11, Castro and Sharma (2017) proposed a wideband (7.7 GHz – 8.3 GHz) circularly polarized microstrip patch array antenna 4 × 4 designed and fabricated on PET [40]. It can reach over 15 dBi gain and over 75% radiation efficiency over all designed band. Paracha et al (2018) proposed a 2.45-GHz ISM band CPW-fed Z-shape antenna on PET realized by an office printer [41]. The antenna was found to have good performance, matched well at the resonant frequency, omni-directional with the maximum gain of 1.44 dBi and more than 60% radiation efficiency.

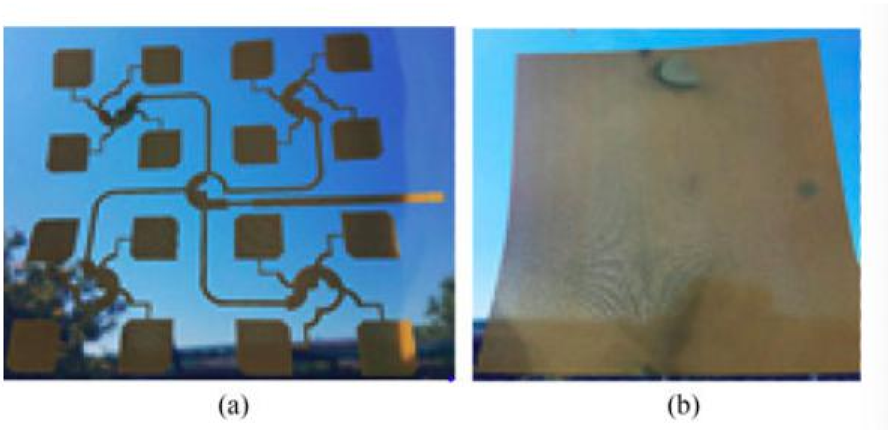


Figure 11. Photographs of the inkjet-printed antenna on a flexible PET substrate material: (a) microstrip patch array layer and (b) ground plane layer [40].

3.2.5. Paper substrates

The growing requirement for large-scale production has led to paper being the best choice for printing substrates. Paper substrates has been found with better quality than polyester when be written directly. It is also cost effective and can be manufactured on a large scale [42]. The properties of paper substrates can fluctuate based on their structure and composition. The paper substrate can realize a wide range of properties with the right ingredients and fabrications. See from Table 3. Paper substrates usually possess higher loss than many other flexible substrate materials. For paper, because of its small thickness and non-homogeneity, the process of RF characterization is difficult to be performed with high accuracy. The dielectric constant of dry paper substrates is typically in the range of 2-5 (up to 20 GHz), which is lower than that of dry cellulose (≈ 6-8). The loss tangent of paper is in the range of 0.04 – 0.1 (up to 20 GHz). So, the paper substrates have acceptable electrical performance up to 24 GHz [43].

Compared to plastics substrates, paper-based substrates are less expensive and eco-friendly. In addition, paper has higher dimensional stability at temperature than plastic. A sheet of paper can withstand temperatures of about 140°C for a few seconds. However, the cost of printing inks is still high due to their nanoparticle manufacturing technology. To take advantage of its flexibility, thin paper is often used, which leads to difficulties in designing CPW feedthroughs with very narrow slots. Interconnection remains a real problem due to the very fragile paper substrate.

See Figure 12, Abutarboush et al (2018) proposed an antenna printed on a low-cost commercial photo paper substrate using two PIN diodes [44]. The antenna can cover most of the mobile and wireless bands between 1.5 to 4 GH and has a gain and efficiency of 2 dBi and 50%, respectively. Wang et al (2019) demonstrates a particularly favorable, reliable, low-cost solution processing procedure for the fabrication of next-generation flexible electronic devices based on paper substrates [45]. A highly adhesive flexible metal antenna with low resistivity is synthesized on a paper substrate by inkjet printing combined with surface modification and electroless deposition (ELD) for radio frequency identification device (RFID) tags.

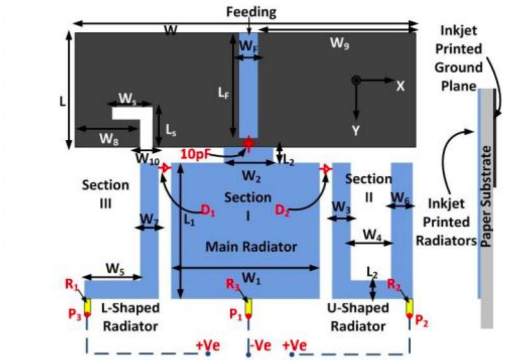


Figure 12. layout of antennas printed on a low-cost commercial photo paper substrate [44].

3.2.6. Other substrate materials

Apart from the above mentioned substrates, there are also other ones that can be used in printed antennas such as LCP (liquide crystaline polymer) , semiconductor, silicone elastomer, NinjaFlex 3-D printable material and natural rubber. In the section of perspectives of the materials for the printed antennas, other substrate materials will be introduced.

4. Material suitability for technology used in printed antennas

Figure 13 shows the classification of printing techniques. Non-contact printing techniques are becoming more popular due to their simplicity, economy, high speed, adaptability to the manufacturing process, high resolution and ease of control. In addition, other printing methods such as nanoimprinting, microcontact printing or dry transfer printing have recently become attractive, especially for inorganic single-crystal semiconductor flexible substrates. Summary of material suitability for technology used in printed antennas are show in Table 5.

Inkjet printing jets the single ink droplet from the nozzle to the desired position. This new technology of inkjet printing, utilizing conductive paste, can rapidly fabricate prototype circuits, without iterations in photolithographic Therefore, no waste is created, resulting in an economical fabrication solution. Inkjet printing provides an easily achievable multilayer structure by sequentially depositing different types of inks to form each layer [46]. This is due to its ability to directly deposit a variety of materials such as conductive, dielectric and semiconductor inks on a variety of substrates, including paper, glass, semiconductor wafers and polymers.

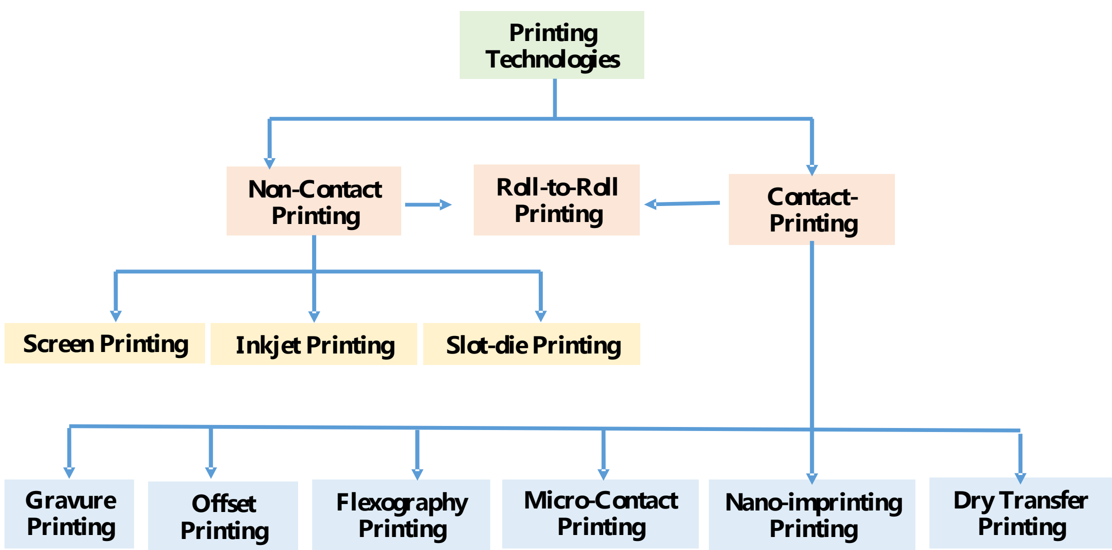


Figure 13. The classification of printing techniques [47].

A simple screen printer consists of screen, squeegee, press bed and substrate [47][48], where the ink is spread to the substrate through the screen by means of the squeegee. This printing technique gives good thickness of the metal (3 – 30 μm) with good conductivity of 1.7*106 S/m without repetitive printing multiple layers so is less time-consuming than inkjet printing. Screen printing has demonstrated its feasibility through a number of printed electronic components such as sensors, multi-layer active devices and circuits.

In a slot die printing process, the solution is poured from top through a via-opening and a substrate mounted on a rotating cylinder [47]. This type of printing is favorable for large areas, but patterning of high-resolution structures is difficult to obtain so that it is not suitable for antennas with small dimensions. Gravure printing is a contact printing technique that supplies inks through physical contact of the engraved structures with the substrate. Khan et al (2015) presented the scheme of a gravure printer in where ink is delivered from a nozzle dispenser, then transferred to a capillary to the substrate [49].

Flexographic printing is used for printing electronics at high speeds and is more attractive than gravure and offset for high resolution patterns [47]. A wide variety of inks (solvent-based, water-based, electron beam curing inks, UV curing inks, and two-part chemical curing inks, etc.) can be used for flexographic printing. The main weakness of flexographic printing is the high roughness of the printed layer surface, which leads to errors in the implementation of electronic circuits. Microcontact printing is a photolithography technique based on relief patterns on the PDMS master stamp that forms ink patterns on the surface of the substrate [47][48]. One of the challenges of this technique is that the deformation of the PDMS stamp due to its elasticity can lead to distortion of the printed pattern. Nanoimprint lithography creates patterns through mechanical deformation of the imprinted resist, a monomer or polymer formulation that is cured by heat or UV light during the imprinting process [47], and a subsequent process. In this process, the adhesion between the resist and the template is properly controlled. The use of this technique for flexible electronics is still challenging and is currently being investigated. Dry transfer uses dry transfer for decals that can be applied without water or solvents. This technique is typically used on semiconductor substrates.

Table 5 Summary of material suitability for technology used in printed antennas

Printing method	Substrate	Thickness of printed metallic layer, μm	Resolution, μm
Inkjet printing	All substrates	0.01 – 1	15 – 100
Screen printing	All substrates	3 – 30	50 – 100
Slot-die printing	All substrates	0.15 – 60	200
Gravure Printing	Printing and writing paper, Polymer film, not for fragile substrates	0.1-12	15-75
Offset Printing	Paper, Polymer film	0.5-2	20-50
Flexography Printing	Paper/cardboard, Polymer film, glass, metal, applicable for fragile substrates	0.5-8	40-80
Micro-Contact Printing	All substrates	0.18-0.7	1-20
Nano-imprinting Printing	All substrates	0.18-0.7	1-20
Dry Transfer Printing	Semiconductor substrates	0.23-2.5	4-50

5. Printed antenna for implantable application

Based on the concept of conformal microstrip antenna, with the close cooperation of telecommunications and medicine, the combination of implantable printed antennas and medicine has become very interesting and very beneficial to patients and the nursing staff. We can implant medical devices into human and animal body, therefore, certain diseases can be diagnosed, treated and prevented in real time. Implantable medical devices (IMDs) are one of the most recent developments of biomedical telemetry. For designing a implantable printed antennas, the basic requirement is that the antenna size should be small enough to be placed in the proper placement inside the body. Miniaturization of implantable microstrip antenna can be realized by employing substrate with a high dielectric constant and, thus, a large number of researches presented antennas with high permittivity substrate to reduce the implanted antenna size. At the same time, biocompatibility and flexibility are other two important factors to be considered when designing implantable microstrip antennas. The designed antennas must be coated with biocompatible materials, the substrate needs to be biocompatible in the natural.

Erderm Uras et al. proposed an implantable microstrip sandwiched antenna for dual-band biotelemetry communication [50]. The antenna use Rogers 3210 (ε_r = 10.2, tanδ = 0.0027) as substrates and placed into a part of arm (ε_s = 31.29). The proposed antenna has dimension of 10.6 × 10 × 1.27 mm^3 offers a dual band performance (VSWR<2) covering MICS and ISM bands having 50% and 29% bandwidths, respectively. (Figure 14)

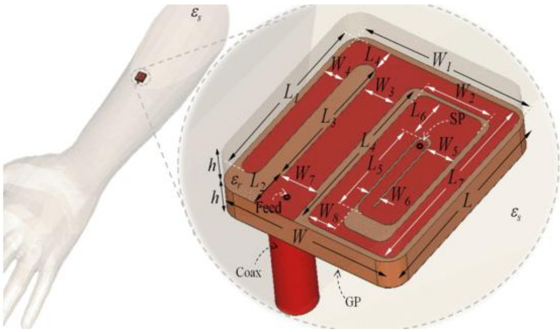


Figure 14. The proposed dual-band IMS antenna [50].

Implantable printed antennas have been investigated for the application of retinal prosthesis. We can design a retinal implant to replace the function of damaged photoreceptors. Bahrami proposed a intraocular microstrip patch antenna which enhance bandwidth at microwave frequency 2.45 GHz [51]. The antenna is designed with RT/doruid 6010 substrate (ε_r = 10.2, h = 25ml) and the dimensions less than 7 × 7 mm^2 to fit in human eye. (Figure 15)

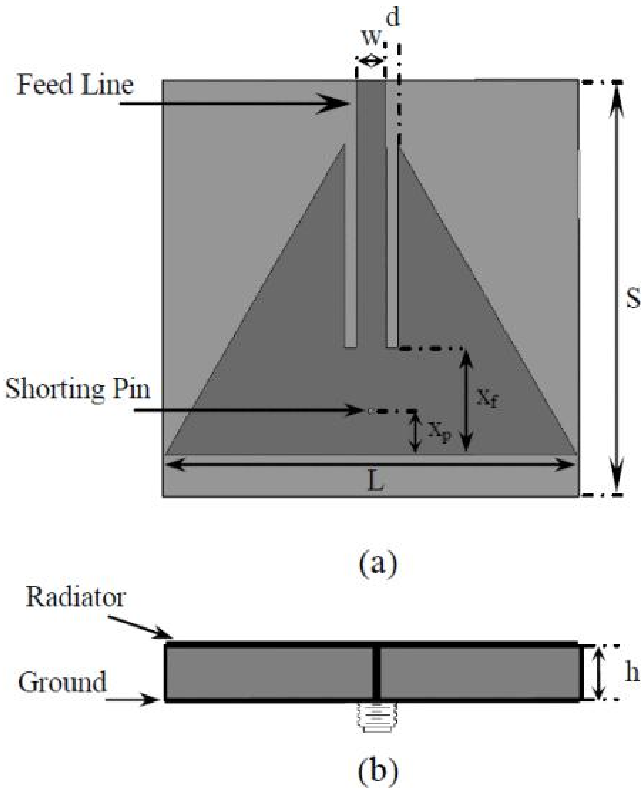


Figure 15. Intraocular microstrip patch antenna (a) Top view (b) Side view [51].

Raed M. Shubair et al. [52] proposed an implantable miniaturized circular microstrip antenna. The antenna has two conducting patches and separated by a substrate with a radius of 2.5 mm and a height of 0.25 mm. The substrate material is alumina (ε_r = 9.4, tanδ = 0.006) which is a biocompatible dielectric. The volume of proposed antenna is reduced to only 14.73 mm^3. (Figure 16)

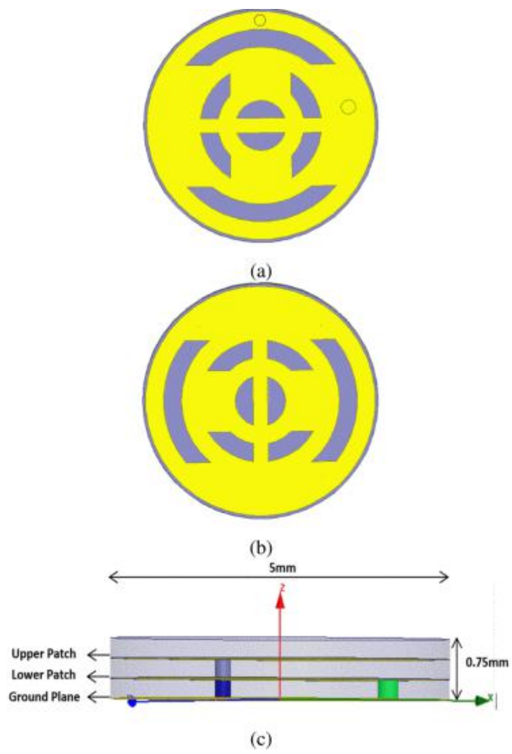


Figure 16. The proposed antenna: (a) Lower patch including shorting pin, (b) upper patch, and (c) side view [52].

6. Printed antennas for space applications

Antennas are expected to have lightweight, low cost, low volume, high gain and directivity when they are used in satellite communication systems. Both electrically and physically, the antennas must be suitable for structure of the object which they are used. Printed antennas are more appropriate because they can be manufactured using flexible PCB and easily mounted on non-flat surfaces.

For space antennas, we should not only consider the functionality but also take durability and reliability into account. So, environmental conditions are very important factors for antennas which designed for space applications. Materials of printed antennas to be used for space applications should meet requirements based on space qualifications and other two factors: launch phase and space environment [53]. Among the metal, polymer, ceramic and composite materials, currently more widely used in space antennas are polymer composites.

Volkan presented a very compact circularly polarized antenna. This small, printed antenna can be used on nanosatellite and CubeSat platforms [54]. The antenna structure as shown in Figure 17. The designer used two different substrates, Rogers® TMM6 (ε_r = 6) and Rogers® TMM10 (ε_r = 9.2) and 38 × 38 mm^2 and 30 × 30 mm^2 footprints are obtained, respectively, at operating frequency about 2.44 GHz.

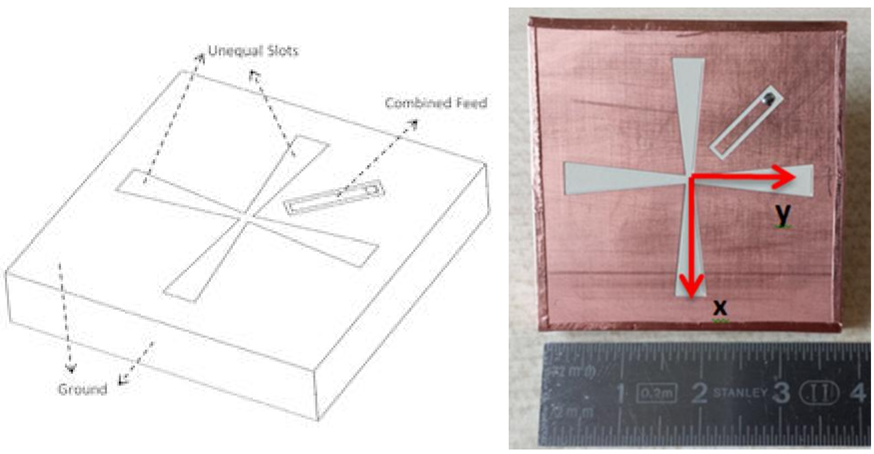


Figure 17. Cavity-backed antenna with tapered crossed-slot aperture and a combined feeding [54].

R. Di Bari [55] designed a novel dual-polarized broadband antenna which is composed of 6 × 2 microstrip antenna elements. The antenna structure as shown in Figure 18. The materials for this antenna are suitable for spacecraft. We can see the materials and thickness of the antenna used show in Table 6. Take the antenna top layer as an example, the antenna is printed on Kapton LF-9150 sheet and is mounted on a Rohacell foam substrate. The adhesive is a Redux 312 film.

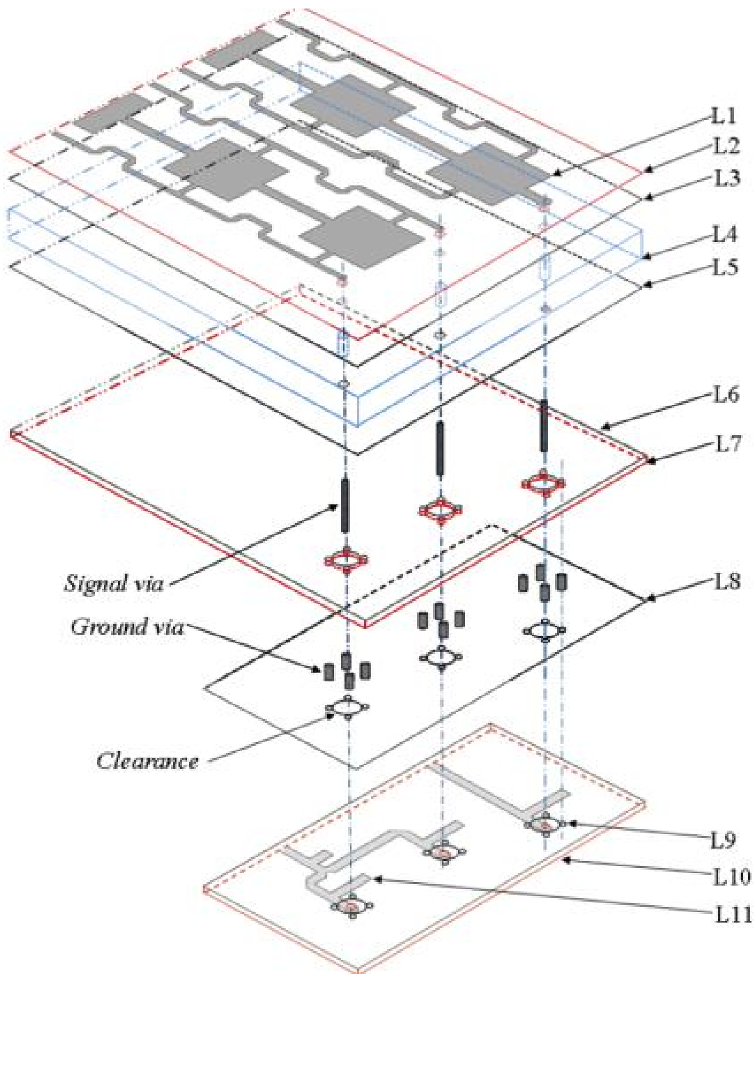


Figure 18. Exploded view of the antenna [55].

Table 6. Summary of the Materials and Thicknesses of the Antenna Layers [55].

Layer	Thickness [mm]	Material
L1	0.034	Copper (σ=5.8×10^7 S/m)
L 2	0.127	Kapton (ε_r=3.3, σ=0.08 S/m)
L 3	0.05	Adhesive (ε_r=3.1, σ=0.01 S/m)
L 4	6	Rohacell Foam (ε_r=1.048, σ=11×10^{-5} S/m)
L 5	0.05	Adhesive (ε_r=3.1, σ=0.01 S/m)
L 6	0.034	Copper (σ=5.8×10^7 S/m)
L 7	0.127	Kapton (ε_r=3.3, σ=0.08 S/m)
L 8	0.05	Adhesive (ε_r=3.1, σ=0.01 S/m)
L 9	0.017	Copper (σ=5.8×10^7 S/m)
L 10	1.6	Duroid (ε_r=2.3, σ=12×10^{-4} S/m)
L 11	0.017	Copper (σ=5.8×10^7 S/m)

Esfahlani et al. [56] designed a compact signal-layer dual-band microstrip antenna. The antenna has a broadside and symmetrical radiation patterns and can used for satellite application. The antenna used Rogers RT/duroid 5880 substrate with a relative permittivity of 2.2 and thickness of 1.58 mm. The final design as show in Figure 19.

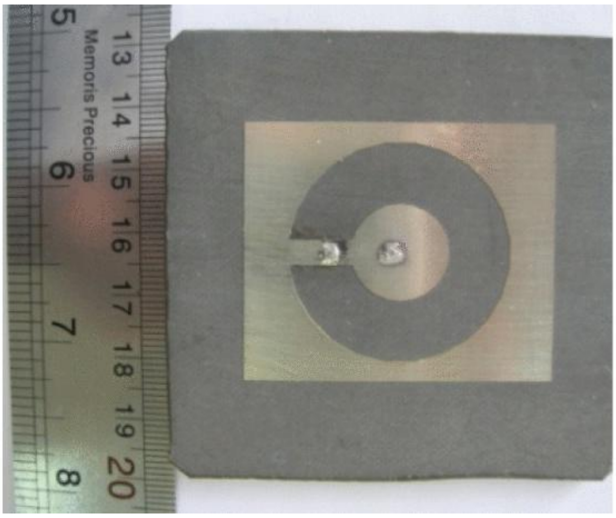


Figure 19. Final design of antenna [56].

7. The performance of most recently printed antenna

The performance of an antenna depends on various parameters such as the conductivity of the radiating element, the dielectric substrate and different design considerations. A highly conductive radiating element ensures excellent gain, efficiency and bandwidth of the antenna. Choosing a suitable dielectric material is critical to antenna performance. The higher the loss tangent of the dielectric substrate, the lower the efficiency and gain. In addition, dielectric permittivity affects the bandwidth and resonant frequency of the antenna. Increasing the dielectric permittivity can lead to miniaturization of the antenna, reduced impedance bandwidth and low radiation loss [57]. Substrate thickness is another factor that can affect efficiency, gain, bandwidth, and directivity. For printed antennas, the trade-offs of thickness, performance, and flexibility always have to be considered simultaneously when selecting the appropriate substrate. In addition to the above factors, antenna patch design, array configuration and power distribution transmission lines have a significant impact on the performance of the antenna. Patch shape affects polarization pattern, resonant frequency, return loss, gain and directivity.

Table 8 and Table 9 shows the performance comparison of different printed antennas in the most recently researches. Ahmad and Tlili [58] presented dual F-slot patch antenna at resonating frequency of 58.10 GHz (VBand) mmwave applications. At the same time, an Inverted U shape patch antenna is designed as a reference antenna to conduct comparative study of two microstrip patch antennas [60] (Figure 20). Double F-Slots patch antenna is designed which improve the Gain from 4.24 to 5.99 and efficiency from 46.73% to 69.83% (improvement of 49.43%) which is more efficient as compared to Inverted U shaped patch antenna (Figure 21). Yoon and Seo (2017) indicate the radiation pattern of all structures at the same frequency of 28 GHz to compare the gain [59]. The proposed structure has the highest gain. Comparing the conventional with the proposed structure, the proposed patch size is larger than the conventional one. However, it increases to around 1.8 times more than the conventional patch. The proposed structure has a wider bandwidth than and the highest gain among the three antennas with the same size.

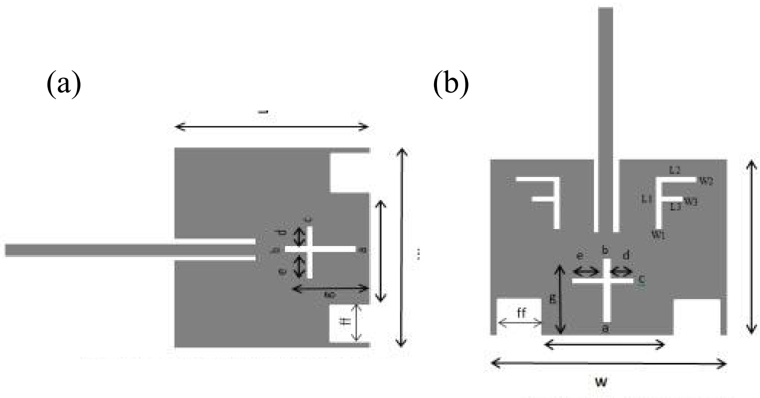


Figure 20. (a) Inverted U shape antennas, (b) Double F-slot patch [60].

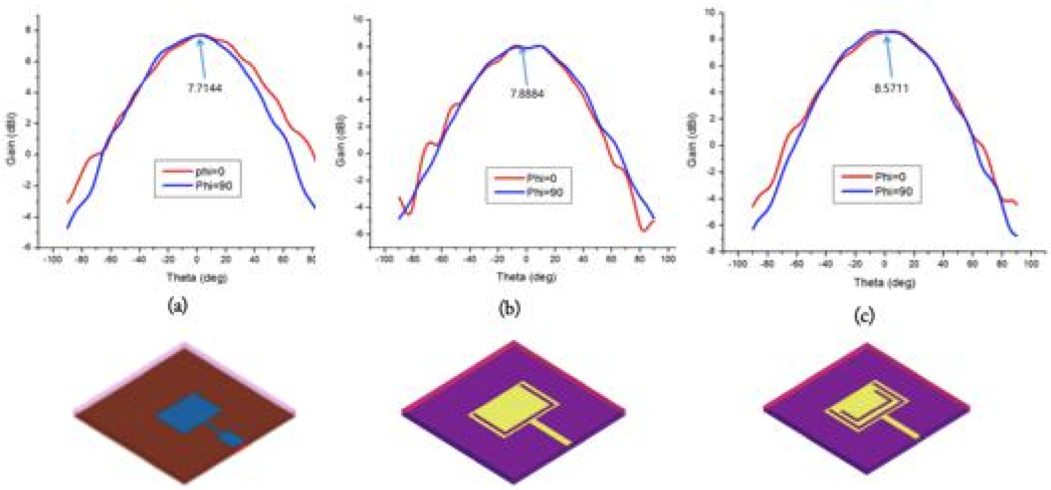


Figure 21. Simulation result of the single-patch antenna (radiation pattern): (a) conventional, (b) one-U-slot, and (c) two U-slots [60].

Novacentrix Metalon® B25HV silver nanoparticle ink (25% Ag by weight) suspended in aqueous medium with particle size distribution of 60-80 nm on 140 ± 12 μm thick silicon coated PET substrate (Novacentrix Novele™ IJ-220). The average conductivity of printed ink was measured at 1.49 × 10^6 S/m. The dielectric constants of the substrate and aluminum foil adhesive were not available. With simulation and experimental trails, the relative permittivity of the system was concluded to be 3.2 with dielectric loss tangent of 0.01. The antenna was designed for 25.6 GHz resonance frequency with conductor conductivity of 1.42 × 107 S/m (100-mW laser power) at the thickness of 1.5 μm using ANSYS™ HFSS. F. Air-cured printed antenna showed resonance frequency response of 25.62 ± 0.012 GHz with return loss less than -10 dB (Figure 17). The 50, 150 and 500 mW laser sintered printed antenna showed resonance frequencies of 26.26 ± 0.116, 25.84 ± 0.104, 26.02 ± 0.284 GHz, respectively [61].

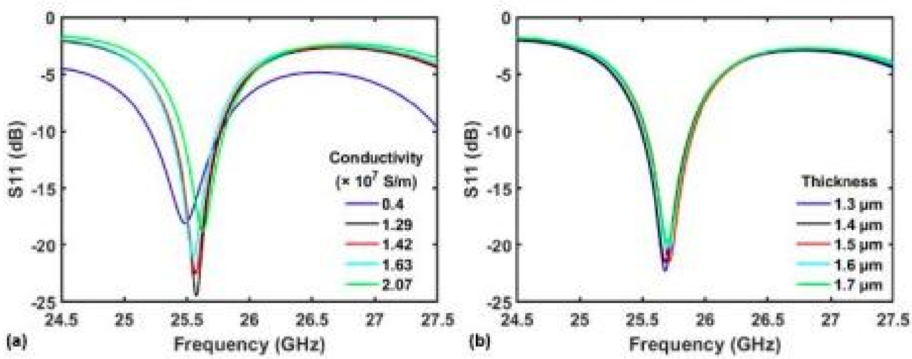


Figure 22. ANSYS™ HFSS S_{11}measurement of simulated antenna design as function of (a)different conductivity with thickness of 1.5 μm, (b) different thickness with conductivity of 1.42 × 10^7 S/m [61].

Li et al. [62] propose a triband slot microstrip patch antenna for ink-printing fabrication. Figure 18 show the structure layout of the antennas and Table 6 is the dimensional parameters of proposed antenna. The antenna operates at 5.73 GHz, 6.16 GHz and 8.34 GHz respectively. The substrate material chosen for this design is flexible polyethylene terephthalate (PET) film. The antenna is optimized to operate at three resonant frequency bands with optimal return loss values. The antenna is fed by a 50-Ω microstrip line. The patch and ground layer are designed to be inkjet-printed with Metalon JS-B25P silver particle based ink, which has a sheet resistance of 60-70 mΩ/square, viscosity of 3-5 cP and weight percentage of 25%. The substrate is Novele IJ-220 PET printing film with dielectric constant ε_r = 3.66 and a size of 40 × 40 × 0.98 mm^3. The return loss and antenna gain illustrated in Figure 19 show that the antenna operates at three frequency bands (S11 < -10 dB), i.e., 5.73 GHz, 6.15 GHz and 8.34 GHz; bandwidths are 91 MHz, 10 MHz and 65 MHz respectively; the corresponding antenna gain at these operating frequencies are 6.23 dBi, 4.62 dBi and 5.43 dBi.

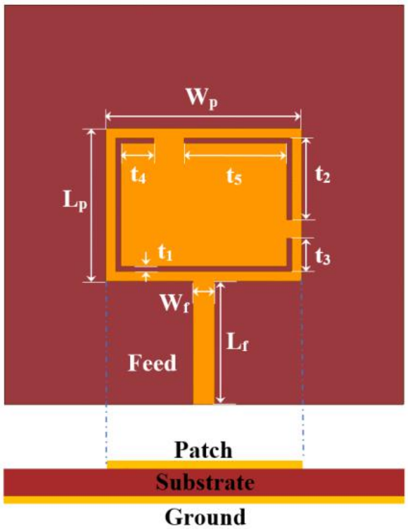


Figure 23. the structure layout of the antennas [62].

Table 7. The Dimensional parameters of proposed antenna.(unit:mm) [62].

Para.	Value	Para.	Value	Para.	Value
L_p	15.37	W_p	19.64	L_f	12.32
W_f	2.15	t_1	0.504	t_2	8.192
t_3	3.282	t_4	3.808	t_5	10.74

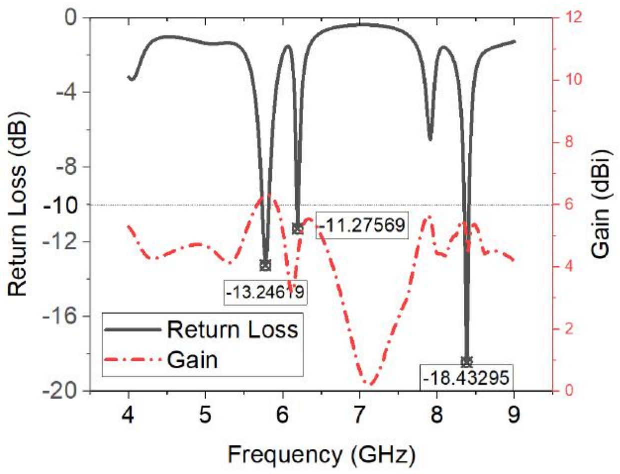


Figure 24. The return loss and antenna gain illustrated [62].

Table 8. The performance of different printed antennas in the most recently researches

Reference	MPAs Configuration	Resonating frequency (GHz)	Material	Thickness	ε_r	Area (mm^2)	BW (GHz)	Gain (dBi)	Return loss(dB)
[63]	Magneto Electric Dipole Leaky-wave Antenna	28	Rogers RT5880 substrate	0.127 mm	2.2	N/A	N/A	16.55	-25
[64]	Pharaonic Ankh-key Broadband Antenna	28	Rogers RT5880 substrate	0.127 mm	2.2	7.5 * 7.5	N/A	8.4	-20.2
[65]	New Gridded Parasitic Patch Stacked Microstrip Antenna.	60	Arlon CuClad/ Taconic TLY substrate	0.0762 mm /0.127 mm/	2.2	N/A	15.6	8.6	-10
[66]	Single Band Antenna Low-profile	59.93	Rogers RT5880 substrate	0.0002mm	2.2	8 * 8	4.028	5.48	-40
[58]	Double F Slot Patch antenna Low-profile	58.10	Silicon substrate	0.275 mm	11.9	0.984 * 0.62	N/A	5.99	-32.5
[67]	Dual Band Antenna Low-profile	28.25/38	Rogers RT5880 substrate	0.127 mm	2.2	4.9 *7.6	1.5 - 2	5.5/4.5	-40

Table 9. The performance of different printed antennas in the most recently researches

Reference	Configuration	Resonating frequency (GHz)	Material	Thickness(mm)	ε_r	loss tangent, tan δ	Area (mm²)	Technique Applied	BW@ (−10dB) (GHz)	Gain (dBi)
[68]	2 x 2 U-shaped Patch Array Antenna	28	-	-	2.2			Inserted slot	3.35	12
[69]	8-Elements Helix Phase Array Antenna	28	Rogers RT5880 substrate	1	1		60 *120	Inserted slot	7	5
[70]	A Compact Parasitic Element MSA	28	FR4 substrate	0.8	4.4		11.2*8.75	Coplanar slot	1.55	6.7289
[71]	Patch Phase Array Antenna	28	FR4 substrate	1.6	4.4	-	5 *5	Inserted	1.4	8.64
[72]	A Compact MPA Slot	28.2	Rogers RT5880 substrate	0.508	3	0.0009	20 *16.5	Inserted slot	1.38	9.0
[73]	Yagi-Uda antenna	28	Rogers RO4350 B substrate	0.762	3.48	0.0037		Inserted slot	2	N/A

8. The perspectives of the materials for the printed antennas of 6G communication

At present, there is not much difference in the proportion of lateral diffusion metal oxide semiconductor (LDMOS), gallium arsenide (GaAs) and gallium nitride (GaN) in the field of telecom base station, and from the perspective of future development trend, 5G communication frequency can reach up to 85GHz, which is the frequency band where GaN plays an advantage, so GaN is expected to be one of the key materials for 5G base station construction. In addition, as the GaN body single crystal substrate research technology becomes mature, the next development direction is large size, high integrity, low defect density and self-supporting substrate material.

The sixth generation (6G) mobile communication systems have become a promising area for academia and industry. Compared with 5G, 6G can achieve faster access rates (10 to 100 times more), lower access latency, wider and deeper communication coverage, and better energy and spectral efficiency, making the antenna and radio frequency (RF) system materials, processes, technologies and forms continue to evolve. Many types of microstrip antennas are developed, such as single-band, T-type, dual-band. But, since the substrate of the microstrip antennas is very thin and sensitive to frequency, the current research on THz microstrip antennas is concentrated at the low frequency range of THz (0.1-1 THz).

M. Khulbe et al. [74] designed a T-type dual-frequency microstrip antenna which based on a T-shaped patch on an epoxy resin(FR-4) substrate. This THz microstrip antenna can be used in biomedical applications and radar, secure data transmission and so on. In 2017, Muhammad Saqib Rabbani et al. [75] used liquid crystal polymers as substrate, this antenna can be fabricated on a simple printed circuit board (PCB) and is suitable to applications in medicine, which includescancer detection by THz spectroscopy and vital signs detection by Doppler radar or vitro technology. Table 10 shown performance comparison of several THz printed antennas.

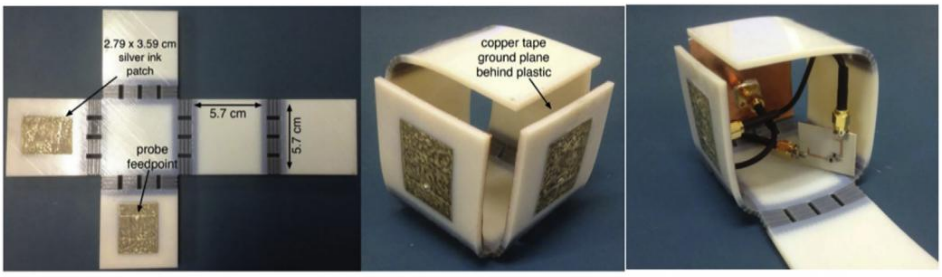
Table 10. Performance comparison of several THz printed antennas [76].

Type	f(THz)	Bandwidth(GHz)	Gain(dBi)	Return loss(dB)	Substrate materials
T-type dual-frequence microstrip antenna	0.632and0.8702	50~80	Peak gain 8.2	N/A	FR-4
Microstrip antenna array	0.1	2.24	15.7	-26.04	Liquid crystal ploymer
Double T-tytpe slot micristrip antenna	0.3 and 0.76	12 and 31	7.31 and 3.71	-29and-40	Arlon Cuclad
Slotted patch RMPA	0.703	26.4	5.235	-50.945	PBG and DGS
Stacked microstrip antenna	8.2	0.36	6.48	-38.85	FR-4
Slotted rectangular micristrip antenna	4.952	0.4445	4.254	-55.31	FR-4

Much has been achieved in the research of microstrip antennas at the low frequency range of THz, but the research of terahertz microstrip antennas for high frequency bands is still in the development stage. The more serious characteristics are related to the choice of substrate which has a great influence on the radiation performance of the antenna. One of the most important research directions for future terahertz microstrip antennas is performance optimization

Metamaterials are combinations of metallic and/or dielectric materials with properties not easily found in naturally occurring materials. Therefore, metamaterial structures are often loaded on/near the patch, embedded into the substrate, loaded/cut in from the ground plane, or placed as a stack to increase bandwidth and gain and miniaturize the size of conventional patch antennas. The need for wide bandwidth, high gain and compact antennas has been highly emphasized in recent wireless communication research. Although patch antennas are lightweight, easy to fabricate, have small profiles, and are easy to integrate, their performance is limited by their narrow bandwidth, low gain, large size, and low power handling capability. To solve these problems, metamaterial-based antennas have gained great interest. The status of extensive research reports on the application of metamaterials for patch antenna performance enhancement is underreported in the literature.

Origami technology is a cutting-edge technique for developing nanoscale antennas that work in microwave and terahertz systems. Figure 20 shows the special hinge shape in the origami antenna material, a structure that prevents the material from breaking during the folding process. Four-dimensional (4D) printing technology enables the fabrication of self-driven reconfigurable origami antennas. Three-dimensional multi-material polymer printers can utilize thermoset shape memory polymers, where epoxy slurries are used to create conductive patterns. A combination of inkjet and 3D printing hybrid printing techniques is used to provide a 3D format by thermal folding, which in turn creates an origami cube. Origami antennas offer several advantages over conventional antennas in terms of mobility and accessibility deployment applications, including easy and stable functional conversion. Origami can easily miniaturize antenna sizes, making them more transportable and easier to deploy in their desired locations [77][78], Therefore, origami technology offers a very good and low-cost option for designing flexible and deployable antennas. Currently, deployable antennas have been developed using glass fiber reinforced epoxy resin embedded in copper alloy conductors [79], and high gain tetrahedral [80] and circularly polarized origami antennas [81] have been proposed for military applications. Moreover, in terms of future trends, deployable origami antennas in the microwave frequency range can be a very suitable option for military communications. In addition, reconfigurable origami antennas are very suitable for CubeSat applications.



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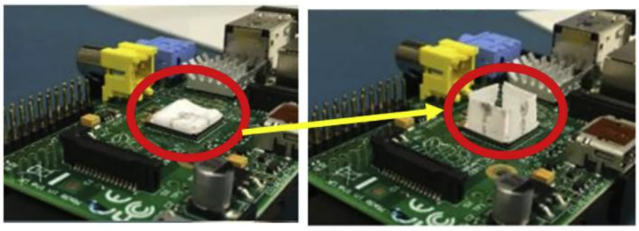

b

Figure 25. Shape memory polymer based deployable origami antenna (a) unfolded and folded cube and origami packaging for harvester electronics, (b) implementation of monopole foldable array in temporary and permanent state [82].

9. Conclusion

Printed antennas are one of the key components for the realization of terminal electronics. Printed antennas are ideal for current and future wireless communication and sensing applications, primarily due to their light weight, small form factor, low manufacturing cost, and ability to accommodate a variety of surfaces. Highly conductive materials such as silver nanoparticle inks, copper tape or copper cladding, conductive polymers, PDMS embedded conductive fibers, and graphene-based materials are commonly used to achieve conductive patterns for antennas. Substrate materials need to have minimal dielectric loss, low relative permittivity, low thermal expansion coefficient and high thermal conductivity, among which commonly used materials are FR4, polydimethylsiloxane (PDMS) substrates, textile substrates, paper and plastic. Overall, the choice of antenna fabrication materials is based on application preferences such as environment, seamless integration with rigid and non-rigid devices, cost, and mass manufacturing aspects of the fabrication process.

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