IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 15, 2020, accepted September 21, 2020, date of publication September 28, 2020, date of current version October 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3027383

Antenna Design Using Modern Additive Manufacturing Technology: A Review

DIOGO HELENA[1], (Member, IEEE), AMÉLIA RAMOS[1,2], (Member, IEEE), TIAGO VARUM[1], (Member, IEEE), AND JOÃO NUNO MATOS[1,2], (Member, IEEE)

[1]Instituto de Telecomunicações at Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
[2]Departamento de Eletrónica, Telecomunicações e Informática, Universidade de Aveiro, 3810-193 Aveiro, Portugal

Corresponding authors: Diogo Helena (diogo.helena@ua.pt), Amélia Ramos (ameliaramos@ua.pt), Tiago Varum (tiago.varum@ua.pt), and João Nuno Matos (matos@ua.pt)

This work was supported in part by the Fundação para Ciência e Tecnologia/Ministério da Ciência, Tecnologia e Ensino Superior (FCT/MCTES) through national funds, in part by EU funds under Project UIDB/50008/2020-UIDP/50008/2020, in part by the European Regional Development Fund through the Competitiveness and Internationalization Operational Program, in part by the Regional Operational Program of Lisbon, in part by the Regional Operational Program of the Algarve, in component European Regional Development Fund (FEDER), and in part by the Foundation for Science and Technology, through the Reflectometry Technologies to Enhance the Future Internet of Things and Cyber-Physical Systems (RETIOT) Project, under Grant POCI-01-0145-FEDER-016432.

ABSTRACT Three-dimensional (3D) printing technology is an area of research that has received great attention in the last decade and it is pointed out by many as the future of manufacturing. 3D printing can be described as an additive process that creates a physical object from a digital model, depositing materials layer by layer. The ability to quickly produce complex structures at a reduced cost and without wasting materials is the main reason why this additive manufacturing technique is increasingly being used instead of conventional manufacturing processes. 3D printing has been applied in several scenarios, including automotive, maritime and construction industry, healthcare, as well as in the antenna research field. This paper reviews the current state-of-the-art of 3D printed antennas. Firstly, an overview of 3D printing technology is presented and then a vast number of 3D printed antennas, categorized by their construction process, are described. Finally, the main advantages and some of the limitations of using 3D printing technology in the construction of Radio Frequency (RF) structures are presented.

INDEX TERMS 3D printing, additive manufacturing, antennas.

I. INTRODUCTION

Wireless communications is among the greatest technological contributions to humanity [1], being defined as the transmission of information at a certain distance, without the need of cables, wires or any other electrical conductors. An antenna plays a fundamental role in a wireless communication system and can be used both for transmitting and receiving a Radio Frequency (RF) signal [2].

The antenna history dates back to the days of James Maxwell, Heinrich Hertz, and Guglielmo Marconi. Maxwell explored the theory of electricity and magnetism, being the first physicist to estimate the propagation velocity of electromagnetic waves through mathematical calculations. He achieved this thanks to his well-known Maxwell's equations. In 1886, Hertz validated the first wireless electromagnetic communications system, becoming the first person to send and receive radio waves. Some years later, Marconi was able to send signals across the Atlantic Ocean (1902) [3]. These achievements contributed to the first steps in the world of wireless communications.

Since then, wireless communications have changed significantly, being nowadays intrinsic in people's lives. The advent of the new generation of mobile communications (5G) will allow an increase of transmission rates, coverage, and number of connections, and the Internet of Things (IoT) concept will become a reality, connecting everything and everyone [4]. Several devices will interact with the environment, leading to an exponential increase of the number of objects with integrated sensors.

As such, the main challenge for the RF engineer is to develop high-performance systems, including antennas, without compromising the user's comfort, whether it concerns an increase in the devices' dimensions or a higher cost.

The associate editor coordinating the review of this manuscript and approving it for publication was Lu Guo.

Additive manufacturing, also known as three-dimensional (3D) printing, is a technology with potential to accomplish these demands, since it allows easy and fast prototyping. 3D printing consists of the additive construction of a solid object based on a digital model [5], as shown in Fig. 1. This technology has the advantage of being capable to produce structures with different levels of complexity, with various shapes, a great flexibility, and with low manufacturing cost, when compared to other traditional techniques [5].

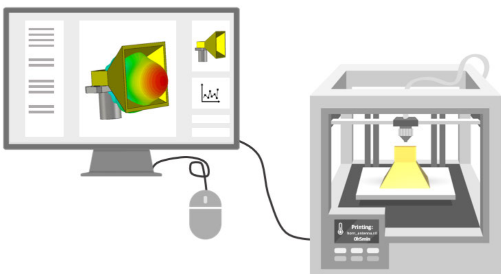

FIGURE 1. **3D printing technology.**

Three-dimensional printing has received great attention in the development of RF devices, such as antenna elements [6]. Although additive manufacturing provides significant flexibility in the production of antenna structures, an effort is currently being made to investigate different techniques and diverse materials to produce an antenna.

In this work, the fabrication of antennas with 3D printing technology is evaluated, analyzing numerous and recent structures, for different frequencies, and produced with various materials and diverse techniques. The main advantages of 3D printing are also discussed throughout the article, as well as the challenges associated with this technology in the RF devices production.

This paper is organized into five sections, in which the present section intends to contextualize the work developed and its importance in the scope of radio frequency systems. An overview on the 3D printing technology is provided in Section II, with a review of the history of 3D printing, a brief description of the main techniques and some applications of this technology. Section III reports some of the major works found in the literature concerning the topic under review. The main potentials and challenges associated with the production of 3D printed antennas are presented in Section IV, ending the paper with Section V, where main conclusions are made.

II. OVERVIEW OF 3D PRINTING TECHNOLOGY

3D printing has been a concept widely discussed for the past decade. However, the initial stages of this technology were taken in the early 1980s, when Hideo Kodama started the first attempts at rapid prototyping, having been the first to describe the production of an object, layer by layer [8].

However, it was only in 1986 that the first 3D printing technique, Stereolithography (SLA), was patented. The author of this achievement was Charles Hull, founder of 3D Systems Corporation and responsible for the first commercial 3D printing product: the SLA-1 printer [9].

In 1988, Selective Laser Sintering (SLS) technology joined SLA as one of the patented 3D printing techniques. This technique was developed by Carl Deckard [9].

A year later, Scott Crump patented the Fused Deposition Modeling (FDM) technology [10]. With this, it can be said that, in less than 10 years, 3D printing was born.

Throughout the years, the evolution of 3D printing techniques has been tremendous, with several additive manufacturing technologies being used nowadays. Some examples of these techniques are: Material Jetting (MJ) [11], Binder Jetting [12], Direct Metal Laser Sintering (DMLS) [13], Selective Laser Melting (SLM) [14], Electron Beam Melting (EBM) [15], among others. Even today, three of the most used techniques are the ones first invented: SLA, SLS and FDM. A brief description of how these three 3D printing techniques work is presented below.

- **SLA**: this method uses a liquid resin, usually called a photopolymer, which solidifies when exposed to a beam of light, and an ultraviolet laser beam is generally used [5].
- **SLS**: this technique also uses a laser beam to fuse. However, the material used is a powder substance. The printer uses the laser selectively, as the name implies, on the printing platform and the powder particles are melted transforming the material into a solid object [5].
- **FDM**: in this technique the process used is the extrusion of the material, meaning that the so-called filament is melted through an extrusion nozzle and it is deposited in layers to create the desired object [5].

One of the key decisions when dealing with 3D printing is the choice of material that will be used for each object's construction. There is a wide variety of materials with distinct properties (elastic, waterproof, resistant to impact, or high temperatures, among others), including polymers, ceramics, metals, and concrete [16]. The choice of the most adequate material will always depend on the type of application.

In recent years, 3D printing has grown significantly and has undergone some changes, with a growing interest of the industry in this technology.

In the automotive industry, several companies have already been using 3D printing technology [17]–[19], where they started by printing new components for recent cars or to reproduce parts that are no longer manufactured [20].

This technology has also revolutionized products used in the medical sector [21]–[23], especially concerning prostheses. This production technique allows to create prosthetic models at a reduced cost, and at the same time customizing the product to each of the patient's needs [24].

Aviation is another example where 3D printing is used [25], [26], [28], for instance, the new Boeing 787, has some of its parts produced with this technology [29], which clearly revokes any doubts regarding robustness.

In the construction industry, it is possible to use 3D printing to produce some large building components [30]–[34], such as doors, walls, bridges, or even to 'print' an entire building. As mentioned in [20]: "3D printing is what many believe the future of construction.".

Following this trend of 3D printing exploration, mobile communications are not an exception, and in fact, many radiating structures have already been tested with 3D printing construction methods. The diverse processes of this technology are already used in the production of numerous antenna systems [35].

III. 3D PRINTED ANTENNAS: STATE-OF-THE-ART

Generally, 3D printed antennas can be divided into three main categories in terms of used materials in manufacture: 1) those printed with dielectric materials and subsequently metallized, 2) those that are produced directly with conductive materials and 3) dielectric antennas [36]–[44], those that are merely printed with dielectric materials. The production of dielectric antennas using 3D printing technology is considerably natural given the high precision of some 3D printers and the characteristics of the polymer materials normally used in 3D printing. In this way, it is possible to create dielectric components that require fine details and high precision, such as gradient index lenses [45]–[49], dielectric rod antennas [50]–[52], and electromagnetic crystals [53], [54].

However, the focus of this work is devoted on antennas that are conventionally built with metal, that is, antennas printed with dielectric materials that require later metallization processes, or antennas printed directly with conductive materials. Tables 1, 2, 3, 4, 5 and 6 summarize the current state-of-the-art of 3D printed antennas with respect to the antennas' construction process, used materials, Publication Year (PY) and operating band.

A. WITH METALLIZATION PROCESS

1) L, S, C AND X BAND (1-12 GHz)

Table 1 condenses the current state-of-the-art of 3D printed antennas with metallization process in the frequency range of 1 GHz to 12 GHz.

The development of microstrip patch antennas for the L-band with 3D printing technology is common due to the structural simplicity of this antenna type and its quite easy application. A tunable circularly polarized (CP) microstrip patch antenna operating at 1.84 GHz was proposed in [55], and its substrate was printed in Acrylonitrile Butadiene Styrene (ABS) using the FDM technique. This material has a dielectric constant (ϵ_r) of 2.7 and a loss tangent ($tan\ \delta$) of 0.005. The use of 3D printing technology for the construction of this antenna allowed the vertical integration of the varactors in the 3D printed substrate, which would not be possible with traditional manufacturing techniques using commercially available substrates. In this 3D printed structure, an additional metallization process with an aluminum tape was used to create the conductive parts of the antenna.

Some antennas are manufactured by combining two additive processes [56]. The SLA technique was used to print the antenna substrate, which has a ϵ_r of 2.83 and a $tan\ \delta$ of 0.038, and inkjet printing was applied to deposit the metallic layers of silver ink, creating the radiating element. It was possible to confirm that the greater the number of layers, the lower the electrical resistance. The inkjet process used led to an irregular surface, with the printed patch having a measured surface roughness of 7183 nm. Nevertheless, this value did not significantly affect the obtained results. The proposed antenna operates in the GPS L1 frequency band and has a directivity of 7 dB at 1.6 GHz.

The production of antennas for low frequencies might be a challenge, due to the large dimensions of their structures, as in the case of the antenna manufactured in [57]. This antenna has a non-planar substrate of very large dimensions (1.128 m of curvature radius, 1.219 m of arc length, and 18.034 cm of width) to be generated on a standard 3D printer at once. Its substrate was produced with the ABS-M30 filament using the FDM technique, and the circular patch antenna elements were copper plated. Although there is a discontinuity in the manufacturing process (due to the production limitations mentioned), the results obtained with the produced prototype are in compliance with those obtained in simulation, with the antenna operating at a central frequency of 1.24 GHz and with a maximum gain of 4.7 dBi.

Attaching a SMA connector to a 3D printed antenna has to be done carefully and using a suitable method. Since most of the structures are printed on plastic-based materials, traditional welding methods are not advisable due to the high temperatures associated [55]. An alternative and commonly used technique for attaching connectors to 3D printed antennas is using conductive silver epoxy, as demonstrated in [55] − [57].

One of the main challenges associated with antennas printed on dielectric materials is the correct choice of the metallization process. A method that is commonly used is the copper electroplating process. The use of this coating technique in [58] resulted in good electrical conductivity and satisfactory measured results. However, the antenna manufacturing process requires additional effort, since the structure had to be divided into 3 sub-arrays due to the limited size of the utilized SLA printer. This 3D printing technique was also used to develop a Yagi-Uda Loop antenna operating at 2.45 GHz [59]. The material used was a resin (FormLabs Durable [60]) with a dielectric constant of 2.78 and a loss tangent of 0.06. The antenna was submitted to a surface treatment process and later the structure was metallized with a liquid metal alloy.

Antenna structures are quite complex and costly to produce with traditional manufacturing methods, which is one of the main reasons why 3D printing has drawn so much attention. One example is the antenna proposed in [61], a compact dual-polarized unidirectional wideband antenna (1.7 − 2.9 GHz) that has a very complex structure. The authors choose to print this structure with PC-ABS material and applied the

TABLE 1. **3D printed antennas with metallization process in L, S, C and X band.**

[Ref.] (PY)	Antenna Type	Manufacturing process	Frequency band	Contribution
[55] (2019)	Tunable CP microstrip patch	FDM (ABS) and covered with aluminum tape	L	Presents the benefits of 3D printing technology to produce a tunable CP microstrip patch antenna, employing an L-slot in a square patch, that was not doable by traditional manufacturing techniques.
[56] (2016)	CP patch	SLA and Inkjet printing	L	Demonstrates the use of alternative and inexpensive machines for the manufacturing of a 3D printed patch operating in the 1.575 GHz GPS frequency band.
[57] (2016)	Conformal array	FDM (ABS) and copper plating	L	Proposes a conformal array antenna using a combination of 3D printing and copper plating techniques. The structure had to be printed in two different parts due to its large size.
[58] (2018)	6-element linear array	SLA and copper electroplating process	S	A lightweight, low-cost, and high-performance non-planar linear array antenna was proposed for multi-mission applications. The antenna was printed in three different sub-arrays due to the limited size of the printer, which increases the complexity of the construction process.
[59] (2019)	Yagi-Uda Loop	SLA (FormLabs Durable) and coated with a liquid metal alloy	S	Proposes a low-cost 3D printed deployable Yagi-Uda loop antenna operating at 2.45 GHz. The printed structure underwent a treatment process before being metallized.
[61] (2017)	Dual-polarized unidirectional wideband	Laser Sintering (PC-ABS) and copper electroplating process	S	Reports a novel low profile dual-polarized antenna based on ME dipole antenna. The printed structure has a complex design, a reduced fabrication cost, and a total weight of only 105 g. A granular finish was observed due to 3D printing process.
[62] (2017)	Dual-band zigzag and helical	SLA (liquid metal alloy EGaIn)	Multi-band	Presents a proof-of-concept of two "tree" antennas using merely 3D printing technology. Both structures were quickly manufactured, have a low cost and can be applied in several scenarios.
[64] (2018)	Dual-band and Dual CP patch	SLA and aluminum and copper plate	Multi-band	Investigate the effects of 3D printed inhomogeneous substrate and superstrate on the operation of patch antenna. With the use of 3D printing it was possible to obtain a prototype with a low profile, lightweight, reduced cost, and operating in dual-band.
[66] (2017)	Sierpinski triangle 3D fractal and Voronoi tessellated	SLA and electroless deposition of copper	C	Presents a novel surface modification technique combined with SLA 3D printing to create structures that are difficult to fabricate with conventional processes.
[67] (2017)	Half-Width Microstrip Leaky-Wave (HWMLWA)	Polyjet (VeroWhitePlus), sputter deposition with Ti and Cu, and then electroplated with copper	C	The HWMLWA produced demonstrates that 3D printing technology can be adopted for the manufacture of antennas with complex geometries and that allows rapid prototyping.
[69] (2017)	Waveguide corrugated horn	FDM (PC-ABS) and coated with a conductive silver ink	C	The process of manufacturing and metallizing a triple mode circular waveguide horn antenna with corrugated chokes is presented in detail.
[71] (2018)	Waveguide array	Polyjet (VeroWhitePlus) and electroplated with copper	C	Proposes a slotted waveguide antenna array that is fabricated in three separate pieces and assembled using a Lego-like process. Both the print resolution and the surface roughness in the 3D printed antenna structure were verified.
[72] (2017)	Pyramidal horn	FDM (PLA) and metallic coating process	X	A pyramid horn antenna was presented for military purposes. The structure was printed with a dielectric material and divided into two parts to facilitate the metallization process.
[73] (2019)	Pyramidal horn	SLA (liquid photosensitive resin) and metallized using a conductive ink	X	The dielectric structure took less than 3 hours to print and was later coated with a metallic spray.
[74] (2017)	Helical antenna with integrated lens	3D printing (VeroBlackPlus) and 2D Inkjet printing (commercial silver nanoparticle-based ink)	X	Proposes a combination of 3D and 2D inkjet printing of dielectric and metallic inks, respectively, to fabricate a helical antenna monolithically integrated with a lens.
[76] (2018)	Horn array	FDM (PLA) and coated with a carbon conductive material	X	A CP horn array antenna for CP-SAR sensor was developed. Although the material used to metalize the antenna does not have good electrical conductivity, the structure presents a low weight and a reduced waste of material in its construction.
[86] (2016)	Waveguide slot array	SLA and metal plated	X	The performance of three waveguide slot array antennas was demonstrated. All prototypes presented a lightweight structure and much lower manufacturing costs in comparison with traditional metal structures.

TABLE 2. 3D printed antennas with metallization process in Ku, K and Ka band.

[Ref.] (PY)	Antenna Type	Manufacturing process	Frequency band	Contribution
[78] (2018)	Several antennas and components	SLA with an additional metallization process	Ku	Presents several satellite communications horn antennas and components produced with 3D printing technology and latter copper platted. The results obtained show higher losses than the metallic prototypes due to the surface roughness.
[80] (2016)	Ring-focus dual-reflector and spline-profiled smooth horn	SLA and copper plating	Ku	Two different compact medium to high-gain antennas were designed, manufactured with 3D printing, and coated with copper and were subsequently tested.
[81] (2017)	Vivaldi	Polyjet (VeroWhitePlus), sputter deposited with Ti and Cu and followed by electroplating with copper	Ku	Demonstrates a Vivaldi antenna printed in two pieces and later metallized. The 3D printed antenna shows a high gain and a large bandwidth of 20 GHz.
[82] (2019)	Phased-array	Combination of Polyjet (VeroWhite) with FDM (ABS) and electroplating	Ku	Presents the potential of using a combination of 3D printing technologies for manufacturing antennas with complex geometric features.
[83] (2014)	Corrugated conical horn	FDM (ABS) and spray coated with conductive ink	Ku	Reports a novel way to rapidly prototype a low-cost and lightweight corrugated conical horn antenna for the Ku-band.
[86] (2016)	Waveguide slot array	SLA and metal plated	Ku and K	The performance of three waveguide slot array antennas has been demonstrated. All prototypes presented a lightweight structure and much lower manufacturing costs in comparison with traditional metal structures.
[87] (2017)	Waveguide-fed horn array (8x8)	Hybrid process: SLA and electroless metal plating combined with aluminum CNC	K	A waveguide array antenna for mobile SATCOM applications was fabricated with a hybrid process, including 3D printing and conventional machining.
[88] (2017)	Quasi-Yagi Uda	Polyjet printing (VeroWhitePlus) combined with Aerosol Jet printing (conductive silver ink)	K	Presents a compact, low-profile, and low-cost quasi Yagi-Uda antenna operating at 24 GHz. The structure was manufactured with a combination of Aerosol Jet printing and Polyjet printing techniques.
[89] (2018)	Conical horn	FDM (ABS) and copper plating	K	Proposes a 3D printed circular waveguide antenna with central frequency at 24 GHz for police radar gun. The structure has a total weight of only 18 g.
[90] (2018)	Pyramidal horn	FDM (PLA) and three different metallization approaches	K	Evaluates different techniques to coat a horn antenna manufactured with FDM.
[91] (2018)	Leaky-Wave Antenna (LWA)	SLA (polymer) and copper plating	K	Presents a new geometry of a LWA using the SLA technology and a metal-coating process.
[92] (2015)	Dual-band offset stepped-reflector	SLS and conductive spray paint	Multi-band	Describes the design, implementation, and manufacturing of a dual-band CP offset stepped-reflector antenna for K and Ka bands.
[94] (2017)	Pyramidal horn	FDM (ABS) and copper plating (with copper tape and conductive copper ink)	Ka	Demonstrates the feasibility of manufacturing Ka-band horn antennas using low-cost 3D printing and metallization. Two prototypes were fabricated and compared with a reference antenna.
[95] (2020)	Pyramidal horn	FDM (PLA) and copper metallization (with copper tape and conductive paint)	Ka	Presents the simplicity and low-cost fabrication of a horn structure combined with the good antenna performance.
[97] (2018)	Radiating slot surrounded by a rectangular cavity and corrugations	Polyjet (transparent polyethylene) and conductive spray	Ka	Two compact, light, rigid and low-cost antennas operating at 28 GHz were developed. The structures were fabricated with the FDM 3D printing technique and latter coated with a conductive spray.
[98] (2019)	Waveguide	SLA and subsequent metallization	Ka	Reports several metal-coated 3D printed waveguide devices manufactured with distinct materials and metallization techniques.
[99] (2020)	Corrugated horn	Polyjet and two different metallization processes (jet metal and electrolube silver conductive paint)	Ka	Offers the proposed antennas as a potential alternative for lightweight and low-cost millimeter-wave applications. The 3D printed proposed antennas have high gain and wide bandwidth.
[101] (2019)	Microstrip patch	FDM (PLA) and copper metallization	Multi-band	Proposes a simple and low-cost microstrip patch antenna operating in dual-band for mm-Wave 5G applications.

Laser Sintering technique. The antenna was subsequently electroplated with copper. Due to the construction process, the antenna structure has a total weight of only 105 g. However, the produced piece has a granular finish.

Through recent developments in flexible 3D printing technologies, it is possible to create prototypes of foldable and compressible antennas, such as the Zigzag and the Helical antenna presented in [62]. These prototypes

TABLE 3. 3D printed antennas with metallization process in V, W band and above.

[Ref.] (PY)	Antenna Type	Manufacturing process	Frequency band	Contribution
[102] (2016)	Reflect array	Polyjet printing and RF magnetic sputtering	V	Provides a rapid prototyping approach to manufacture a reflectarray antenna operating at 60 GHz. The 3D printed antenna achieved a measured gain of 23.8 dBi.
[105] (2018)	Pyramidal horn	SLA with jet metal process	W	Presents a comparison of a 3D printed horn antenna metallized with the JMT process with standard copper horn antennas and 3D printed electroplated horn antennas at mm-Wave frequencies.
[107] (2016)	Corrugated horn antenna	Polyjet and coated in gold	W	Evaluates the performance of a 3D printed corrugated horn antenna.
[108] (2018)	Slotted waveguide array	SLA and electroless copper plating	W	Reports a slotted waveguide array antenna with 12 radiating elements and a differential feed design fabricated with 3D printing technology and with metallization process.
[110] (2016)	Multi-flare angle horn	EBM and followed by metallization	W	Presents the performance of a W-band horn antenna fabricated with 3D printing. The surface roughness and the metallization of the polymer are mentioned as the main challenges in the production.
[111] (2020)	Compact antenna based on the resonant cavity antenna (RCA) concept	MJ (dielectric material) and copper plated	Above 110 GHz	Proposes an antenna prototype fabricated using a printed dielectric with copper metallization applied latter. In the measurements, an inaccuracy was observed in the 3D printing method.
[113] (2019)	Corrugated pyramidal horn	SLM (tin bronze powder) and gold-plated	Above 110 GHz	A 3D printed horn antenna operating at 300 GHz was proposed. The gold-plating process proved to be a possibility in the construction of 3D antennas since promising results were obtained.

TABLE 4. 3D printed antennas without metallization process in L, S, C and X band.

[Ref.] (PY)	Antenna Type	Manufacturing process	Frequency band	Contribution
[116] (2019)	Radio frequency Identification (RFID) flexible tag antennas	FDM (Electrifi)	L	Demonstrates that 3D printing technology can be used successfully to quickly and easily produce an electromagnetic structure.
[117] (2013)	V-shaped meander line dipole	FDM (integrated process with PLA printing and a custom conductive ink)	L	Presents an environmentally friendly integrated process that consists on the combination of printed electronics using conductive ink together with 3D printing.
[114] (2018)	Fractal bow-tie	FDM (conductive PLA)	S	Three antenna structures were designed and produced using different additive manufacturing approaches.
[119] (2017)	Dipole	FDM (with double extruder: Nylon and a conductive filament based on graphene)	S	An embedded dipole antenna was designed, simulated, and fabricated with the 3D printing technology using bio-compatible dielectric and conductive materials.
[122] (2018)	Patch	FDM (PLA and Black-Magic 3D)	C	Proposes the manufacturing of a 3D-patch antenna using commercially available dielectric and conductive filaments.
[125] (2017)	Dual-band Sierpinski gasket	DMLS (titanium alloy)	Multi-band	Demonstrates that 3D printing technology offers an easy and efficient method to fabricate complex geometries, as is the case of the Sierpinski gasket antenna manufactured with a DMLS 3D metal printer.
[127] (2016)	Pyramidal horn	DMLS (aluminum AlSi10Mg)	X	Proposes a weight-reduction technique to manufacture lightweight waveguide components and antennas. A horn antenna was produced with the help of 3D metal printing technology and a metal-sheet perforation technique was used to reduce the weight of the horn.
[128] (2019)	Pyramidal horn	SLM (aluminum AlSi10Mg)	X	A 3D printed aluminum horn antenna for satellite communications was presented. The manufactured prototype has a good build quality and has advantages over antennas fabricated with conventional techniques.

were manufactured with liquid metal alloy EGaIn (Sigma-Aldrich, 495425 [63]) using the SLA printing technique. This alloy has great potential to be used in antenna systems since it has high-conductivity and stretchable properties.

As can be seen in Table 1, a lightweight and low-profile dual-band and dual-circularly polarized patch antenna was developed at a reduced cost using the SLA printing technique [64]. The antenna structure was printed with a transparent color dielectric material, WaterShed XC 11122 [65], which has a permittivity of 3.11 and a loss tangent of 0.0253. The radiating element was produced with two thin slices of copper with a conductivity of 5.7×10^7 S/m. The fabricated prototype operates at 2.75 GHz and 3.2 GHz frequencies, and obtained a gain of 6.7 dBi and 7.3 dBi, respectively.

TABLE 5. 3D printed antennas without metallization process in Ku, K and Ka band.

[Ref.] (PY)	Antenna Type	Manufacturing process	Frequency band	Contribution
[129] (2016)	Slotted Waveguide Antenna Array (SWAA)	DMLS (aluminum AlSi10Mg)	Ku	Proposes an evaluation of the manufacturing capacities of the DMLS technique to produce a complex antenna design.
[130] (2018)	Feed horn	SLM (aluminum AlSi10Mg)	Ku	Demonstrates the ability of the SLM process to fabricate a high-performance feed horn operating at Ku-band.
[132] (2019)	Feed horn array	SLM (aluminum)	K	Emphasizes the advantage of the metallic 3-D printing to rapidly manufacture geometrically complex structures.
[132] (2018)	Double-ridged square horn	SLM (aluminum / copper)	K	Presents 3D printing technology as a simple and low-cost process for manufacturing antennas, since the metallic horn antennas were printed in one run.
[133] (2016)	Pyramidal horn	Binder Jetting	Ka	A Ka-band pyramidal horn antenna was manufactured to evaluate the performance of the metal 3D printing technique: Binder Jetting.
[134] (2020)	Axial corrugated conical horn	DMLS	Ka	Describes the design, implementation, and manufacturing of a 3D metal printed low cost axial corrugated horn antenna operating in the Ka-band.

TABLE 6. 3D printed antennas without metallization process in V, W band and above.

[Ref.] (PY)	Antenna Type	Manufacturing process	Frequency band	Contribution
[135] (2015)	Conical and pyramidal horn	SLS (316L stainless steel)	V	Proves the great potential of 3D printing technology compared with traditional milling and injection moulding to fabricate antennas for mm-Wave applications.
[137] (2018)	Open-ended waveguide antenna (OEWGA)	DMLS (stainless steel)	V	An open-ended waveguide antenna operating at 60 GHz was fabricated using the additive manufacturing technology. The prototype was printed with the stainless-steel material.
[138] (2019)	Dual CP horn	DMLS (aluminum AlSi10Mg)	V	Presents the feasibility of aluminum AlSi10Mg material in the fabrication of three-dimensional antennas using additive manufacturing method.
[111] (2020)	Compact antenna based on the resonant cavity antenna (RCA) concept	DMLS (stainless steel and aluminum)	Above 110 GHz	Demonstrates the design and fabrication of a novel low-profile all-metal antenna with resonant cavity configurations.
[113] (2019)	Corrugated pyramidal horn	SLM (tin bronze powder)	Above 110 GHz	A metallic 3D printed corrugated horn antenna operating at 300 GHz was produced with the SLM technique using a tin bronze powder.
[136] (2016)	Conical horn	SLM (Cu-15Sn) with manual polishing	Above 110 GHz	Presents a study of different metallic 3D printing technologies and materials for millimeter and submillimeter applications.

Three-dimensional printing is a very versatile technology, as it can quickly produce not only simple objects but also more complex structures. It can be said that the creation of an object with 3D printing is only limited to the designer's imagination since the drawing is done in digital format and does not need a mold like other techniques. In this way, designers have freedom in the process of building the object, as in [66], where the authors proposed two complex antenna structures: a Sierpinski triangle 3D fractal antenna and a Voronoi tessellated antenna. A SLA printer was used to print the structures on a dielectric material and electroless deposition of copper was used to metallize the antennas. The structures were immersed in an ethanol-based saturated palladium chloride solution and then incubated with a homemade copper electroless deposition bath. Although satisfactory results have been obtained, three-dimensional printing technology had to be supported with various post-printing processes to create the desired antenna.

The authors of [67] used the Polyjet technique to print a Half-Width Microstrip Leaky-Wave Antenna (HWMLWA). The antenna has a simple structure and it was printed in the dielectric material VeroWhitePlus 3D [68]. The printed structure was metallized using sputter deposition and then it was electroplating with copper. It was possible to confirm a measured gain of 6.8 dBi at 6 GHz and, in general, the measured results are in agreement with those obtained in simulation. The authors justify that a small discrepancy in results is due to small deviations in the dimensions of the printed antenna and in the losses associated with the silver epoxy used to attach the SMA connector to the ground plane.

In order to simplify the printing and coating process, the structure of the triple mode circular waveguide antenna with corrugated chokes presented in [69] was printed in two halves. The antenna was manufactured with a dielectric filament (PC-ABS) and coated with Novacentrix silver conductive ink [70]. With the objective of obtaining a sufficient conductor thickness, it was necessary to apply several layers of silver paint. The fabricated prototype operates correctly in the frequency band from 7.5 GHz to 7.90 GHz. Another alternative to simplify the metallization process is presented in [71], where a slotted antenna array was printed in three different pieces using a polyjet printing process. The material used was the VeroWhitePlus [68] polymer and the structure was submitted to a cleaning and polishing process. Then, the designed antenna was metallized and electroplated with copper. Finally, a silver epoxy and a Lego-like process were used to assemble all parts. The manufactured prototype has a measured gain of 15.86 dBi at 7.7 GHz. Although the results obtained are in according with the simulated ones, there are some small discrepancies that are justified by the tolerance of printing resolution and by the surface roughness of the printed material.

The X-band is typically used for military and civil radar applications, such as traffic control and climate monitoring. Horn antennas are widely used in these frequency bands due to their versatility, ease of construction, wide bandwidth and high gain [2]. In order to evaluate the 3D printing technology in the construction of an antenna for military purposes, a horn antenna was designed to operate at a central frequency of 10 GHz [72]. The structure was printed with a common Polylactic Acid (PLA) filament and sliced into two parts to facilitate the metal coating process. In the measurement, a reflection coefficient of less than -18 dB and a gain of more than 12 dBi was observed in the entire operating band $(8 - 12$ GHz).

Xuyi Zhu and Bing Zhang also reported in [73] a 3D printed horn antenna for X-band applications. The antenna was developed using the SLA technique and printed with a liquid photosensitive resin. This material has the following properties: relative permittivity of 2.54 and loss tangent of 0.04. The metallization of the structure was realized with a conductive paint of resistivity $6.0 \times 10^{-5}\ \Omega.cm$. It was verified that the manufactured antenna operates correctly in the entire X-band with a gain greater than 14 dBi. Another important aspect is that the printing process was completed in less than 3 hours, thus highlighting one of the main characteristics of 3D printing which is the rapid prototyping. The authors of [74] also mention that one of the main advantages of this technology is to quickly produce complex structures, although the proposed antenna requires several steps to be manufactured. A combination of 3D and 2D inkjet printing process was used to produce a helical antenna. The materials used were a photosensitive polymer (VeroBlackPlus) and a commercial silver nanoparticle-based ink from Sigma Aldrich [75]. The antenna underwent a surface treatment process and, then, ten layers of silver ink were printed, which resulted in a conductivity of $3.8 \times 10^5\ S/m$. The total antenna manufacturing process took less than 6 hours. In the results obtained, small discrepancies were observed between the measured values and those obtained in the simulation, something which is justified by the roughness of the inkjet printed metal surface.

Also for the X-band, it was developed a PLA-based 3D printed CP horn array antenna [76], where the structure was printed with PLA and coated with a carbon conductive material. There is a slight variation between the values obtained in simulation and those measured due to the low conductivity of the carbon material used in the antenna's coating.

2) KU, K AND KA BAND (12-40 GHz)

Table 2 reveals the information from the 3D printed antennas with metallization process for the Ku, K and Ka bands.

The Ku-band is typically used for satellite services. As mentioned in [77], nowadays, satellites need to be flexible, easy to produce and yet at a reduced cost. In this sense, some research works have been developed in the Space and Telecommunications area with the use of three-dimensional printing technology [78]. A wide variety of components were produced and tested, such as waveguides, filters, and horn antennas. The structures were manufactured with a high precision SLA 3D printer using Somos PerFORM resin [79] which allows a suitable detail resolution. It was necessary to use a metallization process and the printed components were coated with a layer of copper between 100-150 μm thick. All the designed prototypes operate properly in the Ku-band. Although the horn antenna obtained a satisfactory radiation diagram, the authors refer to the surface roughness of the structure as the main reason to justify the losses found in the measured gain.

The SLA technique was also used to manufacture two different compact antennas: a ring-focus dual-reflector antenna and a spline-profiled smooth horn antenna [80]. This technique is a strong candidate for the production of RF structures, as it offers high resolution and good surface properties when compared to other additive methods. The two antennas were designed to have a high gain both in the transmission and reception bands. Their structures were printed on plastic and later were copper plated. Despite a small discrepancy found in both prototypes due to measurement inaccuracies, a good matching was observed between the expected and measured results.

Also, for the Ku-band, the design, production and measurements of an Ultra-Wideband (UWB) Vivaldi antenna were presented in [81]. The antenna's structure was printed with the material VeroWhitePlus [68], sputter-deposited with Ti and Cu, and followed by electroplating with copper to reduce conductor losses. The structure was divided in two parts so that the interior sections could be easily metallized and were subsequently assembled using a Lego-like process and silver conductive epoxy. Promising results were obtained, with a measured bandwidth of 20 GHz and a maximum gain of 10.3 dBi.

In some researches a combination of different 3D printing technologies is used to manufacture an antenna, as is the case of the phased-array antenna presented in [82]. In this work, an industrial-level Polyjet printer and an entry-level FDM printer were used. The main body of the antenna was printed in two parts to simplify the cleaning and metallizing process. The structure was metallized with a commercial copper-electroplating process. In the measurements, the antenna exhibited a good agreement with the results obtained in simulation, both in terms of return loss and radiation patterns.

The 3D printed and electroplated antenna weighs 522 g, which is relatively lower when compared to the weights of a conventional aluminum and copper antenna, which weigh 1026 g and 3397 g respectively. Once again, it was possible to manufacture a complex structure with high resolution, low weight, and good performance characteristics.

The research performed in [83] used the metallic spray coating to produce a corrugated conical horn antenna. The structure was printed in two parts on a Fortus 250 MC 3D printer [84] using an ABS filament ($\epsilon_r \approx 2.8$ and $tan\ \delta \approx 0.005$). The total printing time was approximately 8 hours. The interior of the printed parts was covered with three layers of Super Shield 841 [85] and later the antenna was joined with acrylic and metal fasteners. Using this coating method, it is not possible to effectively control the uniformity of the metallization layer thickness, as well as the surface roughness, since a manual process was realized. However, it was possible to obtain a maximum measured gain of 19.61 dBi at 16 GHz, verifying the feasibility of 3D printing technology in the rapid prototyping of RF components.

Three customized waveguide slot array antennas were developed in [86] for three different frequencies: 10.7 GHz, 12.5 GHz, and 21.7 GHz. The structures were produced in plastic with the Stereolithography 3D printing technology and were later copper plated. The antennas revealed an excellent agreement between the simulated performance and the measurements, presenting simulated antenna efficiency values of 100%, 83.4%, and 95%, and measured gains of 15.1 dBi, 24.6 dBi, and 29.5 dBi, respectively for the 10.7 GHz antenna, 12.5 GHz antenna and 21.7 GHz antenna. The authors highlighted that one of the main advantages of 3D printing compared to conventional metal manufacturing is to provide the customization of components without any additional cost since the 3D printing cost is essentially based on the volume of plastic used. In this way, it was possible to manufacture the three antennas with a total cost of less than 1900 USD, which is much lower when compared to commercial customized slot arrays that typically have costs in the order of 10k USD [86].

Sometimes it is difficult to choose only one production method for an antenna, and that is the case of the 8-by-8 antenna array produced in [87]. The antenna was divided into two subsystems and a hybrid process was selected for its fabrication. The upper part consists of horn elements and septum polarizers and was printed in a single block with the 3D SLA printing technique. Subsequently, the structure was submitted to an electroless metal plating. The lower subsystem consists of the horizontal signal distribution networks and it was produced in aluminum using the conventional Computer Numerical Control (CNC) technique. In this way, the authors took advantage of each of these techniques to produce the antenna. The total weight of the prototype is 36% lighter than if it was all made of aluminum. The array was designed to operate at 20 GHz and has a measured efficiency of approximately 80%.

In [88] it was demonstrated the combination of two techniques to manufacture an antenna. In this structure, the Aerosol Jet printing technology was combined with the 3D Polyjet printing technique to produce a Quasi-Yagi Uda antenna. The substrate was printed with a photopolymer resin (VeroWhitePlus [68]) and a layer of copper was sputtered on the backside. The design pattern of the antenna was produced using an Aerosol Jet printer. After the antenna was printed, it was submitted to a baking and curing process. The silver ink used can achieve a conductivity around 10% of solid silver. A slight deviation was verified in the minimum value of the reflection coefficient, denoting an undesired inaccuracy in the antenna's manufacturing process since it is known that the resonance is very sensitive to its dimensions. However, the authors state that the main advantage of the fabrication technique used is that the entire process is carried out in a single step and without wasting materials, thus reducing the overall cost when compared to conventional techniques.

When the operating frequency increases, the proper manufacture of an antenna with 3D printing technology can become a very complex and time-consuming process, as described in [89]. A circular waveguide antenna for K-band applications was printed with an ABS filament, and then it was covered with copper. The structure printed in ABS was submitted to a brief smooth bath to improve the surface of the antenna. The copper coating method was developed with chemical baths and had five sub-processes to prepare the 3D object before the electrolytic plating. The produced antenna obtained a measured gain of 20.5 dBi at 24 GHz. This complex process used resulted in the production of a low-profile prototype, weighing only 18 g, and showing some promising results.

In [90], three different techniques to coat a horn antenna were studied. The manufacture of the antennas was based on a two-stage process: the structure was first printed with FDM technology using a PLA filament and later a conductive material was deposited. In a first approach, the metallization was performed with a highly conductive shielding lacquer, referred to as EMC-spray, where a copper-based solvent was used. The second technique consisted of galvanic electroplating on PLA. Finally, a Neotech AMT Piezo Jet system with a highly conductive silver paste was used for covering the inner surfaces of the plastic structure. Regarding the surface roughness, the prototypes built have values between 5 and 10 μm, slightly higher when compared to the reference antenna that has only 1.5 μm of surface roughness. However, the overall performance of all the 3D printed antennas is comparable to common all-metal reference antennas. It should also be noted that these antennas have a weight between 5-8 g (much lower weight than the metallic reference - 33 g), stating the ability of 3D printing technology to produce lightweight RF structures.

Also for the K-band, a novel topology of a dual-polarized leaky-wave antenna (LWA) was developed with the support of 3D printing technology [91]. The antenna structure consists of a modulated triple-ridge square waveguide perforated on its top wall and the authors chose to print the antenna with the SLA technique due to its high precision and low roughness (tolerance of the manufacturing process of 40 μm and approximately 250 nm of surface roughness [91]). The structure was 3D printed using a nonconductive UV-photosensitive polymer and subsequently metallized using a chemical plating process with copper. The good antenna performance proved the potential of the additive manufacturing technique for the fabrication of complex antenna geometries.

In [92] a 3D printed antenna was developed using the SLS technique. This antenna has a parabolic structure and was designed for dual-band operation (20 and 30 GHz). This report confirms that three-dimensional printing is a viable solution to build high frequency and medium-size antennas. Despite presenting an adequate gain and good efficiency, its construction process is relatively complex. The manufacture of the antenna took a total of 72 hours and it was still necessary to apply a conductive spray paint to make the structure reflective.

Frequency bands are being allocated in the millimeter-wave region for future 5G/IoT systems, as they enable high data transmission rates [93]. The 28 GHz band is pointed out as an operating frequency for these systems and numerous works have been developed in this band. The study of antenna production with 3D printing technology is no exception. As shown in Table 2, there are several antenna structures using different feeding and metallization methods for this band. In [94] two identical pyramidal horn antennas were reported for the frequency of 28 GHz. These antennas were printed with ABS material and later metallized with copper. Two approaches were adopted for the structure's coating: one with conductive paint and the other using copper tape. The first prototype was completely painted, both inside and outside, with copper spray, while the second one was covered with copper tape on the outside surface. This finishing difference between both prototypes led to a significant result on their gains, whereas the antenna coated with the conductive paint obtained 18.6 dBi, and the antenna covered with copper tape reached 9.4 dBi, nearly half. It is proved that, when working with very small dimensions, it becomes hard to execute the post-printing metallized structures printed in dielectric materials.

A similar study was developed in [95], where several prototypes were built using a common PLA filament and two different metallization techniques: with copper tape and with conductive paint (RS EMI/RFI Shielding Aerosol [96]). In the last metallization approach, the influence of the number of sprayed layers applied to the structure was also studied. The horn antenna was designed to operate at 28 GHz with a gain value of 12 dBi. The simulated horn antenna presents a maximum total efficiency of 95.6% at 28 GHz. In the construction of all prototypes, the metallization layer was applied in the outer surface of the 3D printed structure. All prototypes exhibited a good correlation between the simulated and measured results and proper matching of the antenna at the desired frequency, 28 GHz. In terms of measured gain, the antenna using copper-tape obtained a value of 11.23 dBi while the measured value of the antenna metallized with conductive ink was 10.79 dBi. In the case of the spray-coated antenna, it was also proven that the greater the number of conductive paint layers, the better the antenna performance. It is also important to note, once again, the ability of 3D printing technology to manufacture structures at a reduced cost, since the copper tape antenna has a total material cost higher than the one coated with four layers of paint.

The authors of [97] developed two compact and lightweight antennas, with a rigid and low-cost structure. The antennas were designed for 28 GHz, being the first antenna fed by a waveguide and the second using a microstrip line. To improve their performance, a new structure consisted by a resonant slot surrounded by a rectangular cavity and two corrugations was tested. The material used was a transparent polyethylene that allows the production of a solid, rigid, and light prototype. Once again, the antenna's structure had to be submitted to post-printing treatment with a conductive spray. The authors state that this coating method allows to reduce the cost of producing the antenna when compared to other conventional metallization processes. However, this technique has a negative feature, as it is not possible to guarantee uniform thickness throughout the structure. Despite this problem, both antennas perform well.

The selected material and metallization technique are two of the most important aspects to be considered when building an RF structure with 3D printing technology. In this sense, an impressive research was developed in [98], where different materials and metallization techniques were analyzed to produce waveguide devices. A total of six prototypes were manufactured using four different materials (Nanotool, Accura SL 5530, Material D, VisiJet SL Clear [98]) and three different metallization processes (electroplating, electroless, and vacuum coating technology). In general, the results are positive and similar to the simulation, with only a significant degradation being observed in the measurement of the transmission coefficient of the prototype that was vacuum-coating. This result is due to the fact that the thickness of the metallic layer of this prototype (in the order of nanometers) is much inferior to that recommended to obtain a good metallic performance. It is advised that the thickness of the metal layer should be seven times greater than the metal skin depth at the operating frequency, being these values between 0.33 and 0.40 μm for copper at the Ka-band. Thus, the authors emphasize the importance of the metallization process of the plastic structures.

Also for the Ka-band, two corrugated horn antennas were manufactured using 3D printing technology and compared to one produced in aluminum using the traditional CNC technique [99]. The Stratasys Object30 Prime printer [100] was used to print the antenna structures which were later metallized. While the first 3D printed prototype was coated by jet metal (JMT) metallization process, the second was metallized using electrolube silver conductive paint (SCP). This last metallization technique is very attractive since the 3D structure does not need any treatment process before and after printing. In the measurements, all prototypes have bandwidths greater than 6 GHz. Regarding the maximum gain, the aluminum antenna has a value of 18.9 dBi at 30 GHz, while the 3D printed antennas have values of 16.2 dBi and 18.5 dBi, respectively for the 3D printed JMT antenna and the 3D printed SCP antenna. The main reason that deteriorates the gain of the 3D printed JMT antenna is the existence of the air gap between layers. In the case of the 3D printed SCP antenna, the slight difference observed in the gain is due to the metallization process that was performed manually, which produces a non-uniform layer of paint. The authors report that the roughness of the 3D printed antenna is unlikely to be responsible for gain losses since the printer used provides objects printed with a smooth surface and with low surface roughness. These particular 3D antennas have a manufacturing cost lower than 8 USD and a weight of approximately 10 g.

In [101], a simple, low-cost and dual-band microstrip patch antenna was developed. The structure was designed to operate in the 28 GHz and 38 GHz frequencies. In the antenna manufacture, the substrate was first 3D printed using a PLA filament, which has a relative dielectric constant (ϵ_r) of 2.75 and a loss tangent ($tan\,\delta$) of 0.01, and the metallization process consisted of pasting a strip of copper on the 3D printed substrate. The proposed antenna provides impedance bandwidth from 28.35 GHz to 29.9 GHz and from 36.89 GHz to 39 GHz, considering the $S_{11} < -10\ dB$ criteria. The satisfactory gain of around 5dBi for both frequencies proved that the proposed antenna is a suitable candidate for future mm-Wave 5G applications.

3) V, W BAND AND ABOVE (ABOVE 40 GHz)

Table 3 summarizes the gathered information about 3D printed metallized antennas in this frequency region.

It is necessary to take into consideration the metallization process used in the production of 3D antennas with dielectric materials, mainly for high-frequency applications, since the characteristics of the metallic layer will have a significant impact on the antenna performance. In this sense, the authors of [102] decided to replace the electroless plating technique with RF magnetic sputtering to coat a thin seed copper film on the 3D printed surface. The structure was printed with VeroBlue RGD240 material and the Stratasys Object30 [103] system was used. Before metallizing the antenna, a surface treatment process was realized to clean and improve the adhesion between the polymer surface and the metal film surface. Subsequently, the metallic deposition process was applied, where the deposition time was taken into account due to heating, thus avoiding the deformation of the plastic structure. A 3D printed reflect-array antenna was designed to operate at 60 GHz with a maximum gain value of 25 dBi. In the measurements, a maximum gain of 23.8 dBi was obtained and this marginal difference may be due to the misalignment of the open-ended waveguide feed. The weight of the measurement cable can cause bending of the 3D printed support, as it is not as rigid as the metallic one, thus causing misalignment. However, the 1.2 dBi gain difference does not significantly affect the antenna performance, validating the feasibility of using this metallic coating method for high frequency applications.

The resolution of the 3D printer used in the antenna fabrication process can influence its design, as it is the case of the rod antenna with constant gain based on spoof surface plasmon polaritons (SPPs) presented in [104]. The radiating number of SPPs unit cell had to be chosen with a tapering step of 25 μm, the maximum resolution of that 3D printer. Regarding the construction process, the structure was 3D printed and later coated with a 10 μm metallic layer, which allows good conductivity and does not affect the SPPs antenna size. In a laboratory environment, it was possible to measure a gain between 12.9 and 16.5 dBi in the $50 - 70$ GHz operating band. The small discrepancies noticed between the simulated and measured results are due to manufacturing tolerances. However, the authors reported that 3D manufacturing has advantages when compared to conventional techniques since it allows the direct integration of the feeding network and rod radiating element, eliminating the misalignment effect.

A horn antenna was designed to 77 GHz [105], in a band which is typically used for automotive radar applications [106]. The antenna was 3D printed and metallized with silver ink using the JMT process. The paint used has good electrical conductivity, approaching the value of metallic silver when it has a 2.5-3 μm thick layer. The manufactured antenna has S_{11} values below -20 dB in the 75-90 GHz band. Regarding the gain, a difference of only 0.6 dB was observed between measurements and simulations. This difference is justified either by the possible misalignment of the antennas in the measurement process or by the antenna manufacturing tolerances or even by the surface roughness, since this parameter was not considered in a simulation environment.

Also for the W-band, a corrugated horn antenna was fabricated with the Polyjet process and coated in gold [107]. The structure was 3D printed in two different split blocks and, after that, it was gold plated. In a simulation environment was obtained a radiation efficiency of 99% due to the high conductivity of gold. In the measurements, it was observed a difference between the simulated and measured reflection coefficients mainly due to the non-uniformity of the metallization process and the surface roughness.

A 3D printed slotted waveguide array antenna has also been made for automotive radar applications [108]. The antenna body was manufactured with polymer material Accura SL 5530 [109] on a SLA printer. Subsequently, the structure was covered with a copper layer by electroless plating. In the measurements, despite showing the tendency of the simulations, the results denoted a minor absolute shift, both in the reflection coefficient and in the gain. This deviation is related to the surface roughness and manufacturing tolerances since the antenna design considered a slot length of 1.87 mm and the fabricated prototype exhibited a value of 1.91 mm. In [110] the deviations in the dimensions of the manufactured horn antennas were analyzed and confirmed. In addition, it was also observed under the microscope that some small areas of the antenna were not correctly metallized, leading to a non-uniform surface that affects the antenna performance.

THz antennas tend to have delicate geometry details due to their short wavelength, which implies more attention in the manufacturing methods used [111]. Regarding this, the authors decided to use a commercial 3D printer, a Stratasys J750 industrial-grade 3D printer [112], since it is possible to achieve better print resolution values. This printer works based on the Material Jetting principle and the material VeroPureWhite RGD837 was used. For the structure's metallization, an initial conductive layer was deposited using PVD (Physical Vapor Deposition) followed by a layer of 10 μm of copper. The manufactured prototype revealed a maximum gain of 12.1 dBi at 146 GHz, with a gain reduction of about 4 dB and a deviation in frequency concerning the value obtained in simulation. These differences can be caused by the metallic coating, since it is likely that the internal surfaces of the structure are not fully coated, and by the imprecision of the 3D printing process, respectively.

In [113] the influence of gold coating on 300 GHz corrugated horn antennas was studied. The antenna was first 3D printed in bronze with the SLM technique and its characteristics were analyzed and, later, it was gold-plated in order to study the influence of this plating process on the antenna performance. The prototype that was merely printed on metal is described later in sub-section III-B3 of this work. The antenna that was gold-plated exhibited a measured gain of 24.83 dBi, more 1.91 dB than the antenna that was not subjected to any post printing process, and it was also possible to improve the antenna's efficiency by 15% with this process. These results are intuitive since the conductivity of gold is superior to that of bronze. Despite the authors state that the main drawback of this method is the roughness of the printed surfaces, especially in the high-frequency bands, the antenna performance was improved with the gold-plating process.

B. WITHOUT METALLIZATION PROCESS

1) L, S, C AND X BAND (1-12 GHz)

The current state-of-the-art on 3D printed antennas without metallization process, for the L, S, C, and X band is listed in Table 4.

The advances in three-dimensional printing have led to the advent of new materials that can be used in antenna systems, such as conductive filaments. In [114] two PLA filaments are characterized, one dielectric and another conductive, with dielectric constants of 2.53 and 9.35, respectively. Three different structures were constructed using these materials. Although the conductive filament is promising for the manufacture of RF devices, the results obtained from the antennas produced with this material were by far worse than those obtained from the antennas printed with the dielectric PLA and coated with copper. Regarding conductive filaments, Electrifi is considered to be the most conductive filament available on the market [115]. This material is specified with a conductivity of 1.67×10^4 S/m at zero Hertz (DC), depending on some printing properties, such as printing speed and temperature [115]. The Electrifi material was characterized and studied in [116], where it was concluded that the conductive properties of the antenna produced with this material are inferior to those of the antennas made with other techniques. However, the antenna manufactured with Electrifi is the one with the best relation in terms of production cost and time consumption, since the studied structure can be printed in a few minutes and its material cost is less than 2€.

An integrated three-dimensional printing process was also studied, which consists on the combination of a dielectric material together with conductive nanoparticle ink [117]. A total of 72 conductive paint samples were tested to realize which one is most suitable for the respective application. The ink that showed the best performance was 4.5 gr/ml SSX ink cured at 85°C for 15 minutes, since it has good adhesion to the surface and a resistivity of only 6.6×10^{-7} $\Omega.cm$. As a dielectric substrate, a common PLA filament was used. The antenna was designed to operate at 1 GHz and regarding the results obtained with this process, it was observed a good matching between the measurements and the simulation.

In [119] a dipole antenna was designed for the central frequency of 3.2 GHz. The authors decided to print the antenna exclusively using FDM technique, so a 3D printer with double extruder was used, allowing to use two different materials in the same printed prototype. The nylon material was used as a substrate, and a conductive graphene-based filament was employed to the conductive part of the antenna. The printed prototype reveals a reasonable matching between the measured and simulated reflection coefficient, thus demonstrating that graphene can be a possible solution for the antennas' conductive parts production. However, the measured cross-polarization levels were higher than the simulated ones, being the rough surface of 3D printed antenna one possible reason for this issue.

Following the conductive filaments, two possible solutions available on the market are the Protopasta filament [120], a conductive PLA with a conductivity of $\sigma \approx 6.67$ S/m, and the BlackMagic 3D graphene-enhanced PLA filament [121], with a conductivity of $\sigma \approx 166$ S/m. The authors in [122] selected the Black Magic 3D filament to manufacture a 5.8 GHz patch antenna due to its higher conductivity compared with Protopasta. To build the antenna, a Lulzbot Taz 5 dual print head 3D printer with a printing resolution of 0.1 mm, [123], was used in order to simultaneously print the substrate in PLA and the conductive patch and ground plane of the antenna in BlackMagic. In the experimental results, a consistency with the simulated results was witnessed. However, there was a significant reduction in the gain values due to the meaningful losses observed in the conductive material.

The research in [124] intends to study the flexibility of the materials used in 3D printing. A bow-tie antenna was proposed and two materials were used to produce the antenna: a flexible PLA as a dielectric complemented by a conductive ABS where needed. The antenna has a compact size, lightweight and a flexible structure. Although the studied antenna has good bandwidth, its structure is quite fragile.

As can be seen from Tables 4, 5, and 6, the DMLS technique is widely used to produce 3D metallic antennas, as it is one of the few technologies that allow the direct creation of metallic parts from a 3D digital model [13]. A 3D metal printed Sierpinski gasket antenna was fabricated with this technique and a Titanium alloy was used [125]. The structure is 1 mm thick and has a multi-band performance. The connector was attached to the antenna with the help of a conductive silver epoxy adhesive. In the measurements, a difference of 1 dB and 2.19 dB was observed when compared to the simulated model, respectively for the frequencies of 4.2 GHz and 8.4 GHz. This difference is due to the surface roughness and no additional treatment was applied to reduce this effect.

The same authors evaluated the influence that surface roughness has on the antenna performance [126]. For this, the authors gradually reduced the surface roughness of the 3D metal printed Sierpinski multi-band antenna produced in [125] and previously presented. The post-printing process of surface treatment consisted of several steps, using techniques such as wet blasting and polishing. The achieved results showed that it was possible to improve the antenna performance by reducing the surface roughness of the structure. Regarding the measured gain of the antenna without treatment, the values were 4.07 dB and 4.45 dB, compared with the measured gain values of the antenna after being wet blasting and polishing, an improvement of values was verified: 4.89 dB and 6.19 dB, respectively for 4.2 GHz and 8.4 GHz. It was possible to prove that the surface roughness of an antenna has an impact on its performance. From the results obtained, it was possible to observe that the antenna gain reduces with the increase of the surface roughness.

The DMLS technique has the advantage of being able to use both metal alloys or pure metals, but either way their respective material properties are not affected [13]. This technology was used to manufacture a horn antenna for the X-band [127]. A metal-sheet perforation technique was applied to reduce the total weight of the antenna. The material used was an aluminum alloy (AlSi10Mg) which has good properties in terms of resistance and electrical conductivity. Also, for the X-band and using this aluminum alloy, a horn antenna was manufactured with the SLM printing technique [128]. The antenna was designed to have a directivity of 18 dBi at 7.9 GHz and a thickness of 1 mm. The measured results are quite satisfactory since there is a clear matching with simulations. However, authors recommend a more robust structure, with a thickness of at least 1.5 mm, and a post-printing treatment to prevent oxidation and dirt from the antenna.

2) KU, K AND KA BAND (12-40 GHz)

Table 5 presents an overview of the state-of-the-art on 3D printed antennas produced without any metallization process for the frequency range of 12 to 40 GHz.

For the Ku-band, the combination of the DMLS technique with the AlSi10Mg material was also used to manufacture a slotted waveguide antenna array (SWAA) [129]. This aluminum alloy, previously mentioned, has an electrical conductivity of 2.3×10^7 S/m [129]. The manufactured prototype presents an impedance mismatch observed by the minimum value of the reflection coefficient, this fact naturally leads not only to a lower efficiency at the operating frequency, but also to a consequent lower performance of the antenna. This discrepancy may be due to the roughness of the structural surface, especially relating to the 0.3 mm differences observed in the prototype dimensions. On the other hand, the feed horn manufactured in [130] revealed a remarkable agreement between the measured and simulated results, which confirm the quality of the manufactured antenna. The antenna structure was printed with 3D printing SLM technology using the aluminum alloy AlSi10Mg material and with a manufacturing process consisting of several steps, that lasted approximately 24 hours. In this approach, a treatment process (shot-peening) was used to reduce the roughness of the antenna surface and the discrepancies observed in the structure dimensions are in the order of 0.07 ± 0.01 mm, values well under of those reported in [129].

Horn antennas are typically used as a feed source for lens antennas. In [131], a feed composed of a horn array with a nonuniform aperture was proposed to feed a lens antenna. The feed horn array was manufactured with SLM technology using aluminum. Although the outside of the structure has not undergone any treatment, the inner surface has been subjected to a polishing process to minimize the ohmic losses and the cross-polarization. Even so, there was a slight reduction in the feed horn gain caused by the surface roughness. However, this manufacturing process is less time-consuming than traditional milling and molding processes. Moreover, the manufacture of complex antenna geometry is practically impossible using conventional techniques. The proposed horn array feed highlights the flexibility of 3D printing technology to implement geometrically complex structures over conventional manufacturing techniques, as well as the simplicity of the manufacturing process and the physical robustness over 3D printed antennas with dielectric materials.

Taking advantage of the 3D printing technology, two double-ridged square horn antennas were proposed in [132]: one was made with aluminum alloy and the other using copper. The printing technique used was SLM, and the structures were printed in one run, requiring no coating or additional assembly process, which is clearly an advantage in the production time, when compared to other antennas printed on dielectric materials. The external surface of the antennas has undergone a polishing process, while the internal surface has not been subjected to any improvement. Both prototypes obtained an S_{11} value $< -10\ dB$ in the entire K-band (18 to 26 GHz). The aluminum alloy antenna obtained a maximum measured gain of 13.23 dBi at 25 GHz and the copper antenna achieved a value of 13.5 dBi at 24 GHz. These slight variations are due to the differences in the conductivity of the materials used or because of the surface roughness, being that the aluminum alloy antenna has a rougher finish. The satisfactory results of these two prototypes combined with their simplicity of construction, confirms the 3D printing as a promising technology to produce RF devices.

It can also be observed from Table 5 that a pyramidal horn antenna was fabricated for the Ka-band using the Binder Jetting technique [133]. The material chosen was 420 stainless steel metal powder with copper infiltration, which has a DC electrical conductivity of $3.73 \times 10^6\ S/m$ and a surface roughness value of 6.26 μm. The produced antenna operates across the entire Ka-band (26-40 GHz), with good results. In [134] a 3D metal printed axial corrugated horn antenna was proposed using AlSi10Mg material, with the DMLS printing technique. The manufacturing tolerances of the printer used have the following values: $\pm$ 150 μm and $\pm$ 50 μm on the z-axis and x-y plane, respectively. The manufactured horn has a gain over 12 dBi across the Ka-band. The observed differences between simulated and measured results can be associated with manufacturing and measurement errors.

3) V, W BAND AND ABOVE (ABOVE 40 GHz)

3D printed metal antennas for frequencies above 40 GHz are summarized in Table 6.

With the innovation that three-dimensional printing technology brought to wireless communication systems, the authors of [135] studied the design of horn antennas in the V-band ($50 - 75$ GHz). There, both a conical and a pyramidal horn antennas were developed using the SLS technique. The biggest contribution in this study is the fact that the radiating structures do not require any post-printing metallization process, being printed on 316L stainless steel. Despite this attempt, the measured results of the reflection coefficient of the two horns reveal clear divergences in comparison with those obtained in simulation. This disparity is justified by the surface roughness of the antennas.

Concerning the surface roughness of a metallic structure, an comprehensive work was developed in [136], where two different 3D printing technologies with distinct materials were analyzed. The first technique consists of printing 316L stainless steel using binder jetting and sintering, while the second uses SLM technology and a Cu-15Sn powder. In addition, three post-printing surface treatment processes were studied: manual polishing, gold electroplating, and micromachined process (MMP). Regarding the two materials used, Cu-15Sn is slightly softer than 316L stainless steel and, therefore, easier to polish. Comparing the three treatment processes, the one that obtained a smoother surface was the MMP treated antenna, however, with higher cost. Consequently, the authors refer that the manual polishing process is an appropriate choice considering a compromise between cost and performance. According to this study, the authors manufactured three conical horn antennas with manually polished Cu-15Sn for E-band ($60 - 90$ GHz), D-band ($110 - 170$ GHz), and H-band ($220 - 325$ GHz). A good agreement was witnessed between the simulated and measured results, with all the prototypes obtaining a gain greater than 21.5 dBi.

Furthermore, it can also be observed from Table 6 that two antennas were fabricated with the DMLS technique for the V-band: an open-ended waveguide antenna (OEWGA) [137] and a dual CP horn antenna [138]. The OEWGA was printed with stainless steel and operates in the 57 to 64 GHz frequency band. In the measurements, a gain of 10.8 dBi was found, with a deviation from the theoretical value of approximately 0.6 dB. This slight disparity is due to experimental imperfections. On the other hand, the dual CP horn antenna was printed with the aluminum alloy AlSi10Mg. In this work, an important change is proposed since the surface roughness was considered in simulation environment and it was found that the values for the S-parameter change approximately 1 dB when the surface roughness varies between 0 and 100 μm. The prototype has a measured bandwidth from 50 to 52.69 GHz and a gain of 12.70 dBi. The differences between the measured and simulated results are related to the manufacturing of the antenna structure, where the surface roughness is much higher than that which was considered before the manufacture of the antenna.

It can be said that the most attractive feature of 3D printing on metal is the ability to produce structures that do not require any post-printing treatment, saving time and labor [111]. In this way, two antennas were manufactured using the DMLS printing method: one printed with aluminum (AlSi10Mg) and the other with Stainless Steel (316L) [111]. The reflection coefficients of both antennas present a good correlation with the simulated results, where a bandwidth range from 126 GHz to 170 GHz was verified. The maximum measured gain is 15.5 dBi at 135 GHz, 1 dB less than the simulated gain due to metal losses. There was also a slight shift in the frequency that can be attributed to the tolerances of the 3D printing process. The manufactured structures have a surface roughness of $12 \pm 2\ \mu$m and $16 \pm 2\ \mu$m, respectively for the material aluminum and stainless steel.

Moving up in frequency, a 300 GHz corrugated horn antenna was produced using the SLM printing process [113]. The material used was a bronze tin powder ($CuSn_{10}$). This structure was subsequently subjected to a metallization process using a thin layer of gold. However, the characterization of this antenna has been described previously in section III-A3 and, here, only an analysis is made of the antenna merely printed on metal. In the measurements, the untreated horn antenna presented a Half Power Beam Width (HPBW) of 8.05° corresponding to a gain of 22.92 dBi. Although this technique has relatively high surface roughness and printing

TABLE 7. Typical material options in the construction of 3D printed antennas.

Material	Type	Properties	Refs
ABS	Dielectric	$\epsilon_r = 2.69$ $tan\ \delta = 0.012$ @ 1 MHz [139]	[55], [57], [82], [83], [89], [94]
PLA	Dielectric	$\epsilon_r = 2.7$ $tan\ \delta = 0.008$ @ 1 MHz [140]	[72], [76], [90], [95], [101], [122]
Vero White	Dielectric	$\epsilon_r = 2.97$ $tan\ \delta = 0.0285$ @ 1.5 GHz [141]	[67], [71], [81], [82], [88]
Black Magic 3D	Conductive filament	$\sigma \approx 167\ S/m$ [121]	[122]
Electrifi	Conductive filament	$\sigma \approx 1.67 \times 10^4\ S/m$ [115]	[116], [118]
Stainless Steel 316L	Conductive	$\sigma \approx 1.35 \times 10^6\ S/m$ [142]	[111], [135]
Aluminum AlSi10Mg	Conductive	$\sigma \approx 2.3 \times 10^7\ S/m$ [129]	[127], [128], [129], [130], [138]

tolerances, the results obtained are good, considering that these antennas operate at very high frequencies.

IV. THE CHALLENGES AND POTENTIALS OF 3D PRINTING

3D printing technology is pointed out as the future of manufacturing due to its ability to quickly produce complex structures [35]. Recently, a great effort has been made towards maximizing the usage of 3D printing technology. However, there are still some challenges to be overcome for this technology to be used on a large scale in antenna industry.

One of the main limitations of three-dimensional printing technology is the challenge of creating metallic/conductive elements. As noted, most of the work developed in the antenna research field requires metallization after the printing process, adding some complexity to its construction. For its metallization, different processes have been reported, from covering with copper tape, coating with conductive spray paint or even using chemical baths. The complexity of plating the structures, as well as the performance of the antennas, depends on the process used and the antenna's design.

There are antenna structures that are printed in different parts, either because the printer used has printing area limitations or because inside's structure metallization process is easier, as observed in [57] and [72], respectively. In both cases, there is a discontinuity in the printing process, which not only increases the complexity in the antenna construction but can also affect its performance, since an assembly process has to be realized to reunite the different printed parts.

In the antenna design, it is essential to consider the material used to build the structure. Regarding the properties of the chosen material, electrical conductivity is one of the main parameters to be considered. The low conductivity of some materials, such as some of the available conductive filaments, can significantly affect the performance of the antenna. In this sense, in the construction of a 3D printed antenna, it is advisable to use a material with high electrical conductivity, but this is as important as the material's strength and robustness after printing.

Bearing this in mind, it is important to highlight the materials most oftenly used in the construction of 3D printed antennas. Table 7 summarizes the main materials used in the antennas described throughout this paper, and they were divided in two major categories: dielectric and conductive materials. The main material properties are also listed, as well as some of the works that use these same elements. Regarding the properties of the materials, typical values were considered, and these can differ according to individual conditions, such as frequency and printing temperature.

The surface roughness of a 3D printed structure is one of the main drawbacks in the antenna production, both in those printed with dielectric material and subsequently metallized or in those printed directly with conductive materials. This factor is due to the materials used in 3D printing. In this sense, it is advisable to take into consideration the choice of 3D printing technology when manufacturing an RF component, since the surface roughness differs depending on the technique used. Therefore, considering the surface roughness, the optimum choices are SLA and SLM techniques, respectively for dielectric and metallic 3D printing [143]. To improve the quality of the surface, the main technique used is polishing the structure, often done with manual processes. However, there is also mechanical or chemical polishing that can be more uniform than manual, but with higher costs. These techniques allow to smooth the surface of the structure, which translates into better antenna performance.

Another challenge associated with the production of antennas with 3D printing technology is the influence of manufacturing precision. Since the resonance frequency depends on the antenna's structure, small inaccuracies in its manufacture will have a significant impact on its performance. This is a problem that worsens with the increase of the operating frequency since it conducts to a structure with very small dimensions. In this sense, the resolution of the 3D printer used is an important aspect to consider in the production of RF devices, mainly for higher frequencies. One possible solution for this problem is to use 3D printers with high resolution quality, however, these machines have a high cost.

Despite these issues, the creation of an antenna with 3D printing technology has its advantages when compared to conventional techniques. Rapid prototyping is one of the defining characteristics of 3D printing. The process of printing small structures can take a few minutes to be complete and the entire process of building an object, from the design to the construction of the prototype, can be finished in a few hours.

As the object to be printed is based on a digital model, the limitation in the structure design is restricted to each creator's creativity, being possible to print structures with high complexity. In this way, 3D printing technology is very flexible, as it allows the conception of several structures that can be applied in numerous scenarios.

The construction simplicity of 3D printing is another reason why this technology is so sought after today. With the use of this technology, it is not necessary to create molds to produce a particular object, as it is required with other conventional manufacturing techniques. For this reason, the process of producing an object with 3D printing becomes simple, with just a 'click' to transform a digital model into a three-dimensional piece.

Increasingly, the reduction of the ecological footprint becomes a decisive factor in the selection of a method of producing objects. 3D printing, unlike many other manufacturing techniques, uses only the material needed to build the desired prototype. In this way, three-dimensional printing is considered as an eco-friendly technology since the waste of material is almost zero. For this same reason, there is also a cost reduction in the production of an object.

Bearing in mind what was mentioned earlier, 3D printing is a potential solution for the antennas production, since it allows the rapid development of compact, robust and lightweight objects at a low cost that can be implemented in sensors for monitoring the everyday life.

V. CONCLUSION

3D printing is considered to be one of the technologies of the future. However, it is already present in many daily realities. Recently, 3D printing has taken a giant leap due to its potential and it is becoming increasingly popular, a trend which can be explained by the numerous applications in which it is used.

This article reviews the current state-of-the-art of the 3D printed antennas, revealing that this technology is suitable for rapid prototyping of low-cost radiating structures. In this paper, a detailed study has been performed on the recent antenna structures produced with the additive manufacturing method. The 3D printed antennas have been presented in a structured and organized form, taking advantage of two main categories regarding their construction technique: with and without post-printing metallization process.

Within the context of this work, it was considered that, in general, the antennas created with this technology performed adequately, either in reflection coefficient, bandwidth, or maximum gain values. Regarding the construction method, the manufacturing complexity of the prototypes depends always on the antenna structure and its respective application.

There are still some circumstantial challenges that need to be overcome for the antenna structures to be completely fabricated using three-dimensional printing technology. It can be said that the two main challenges associated with this technology in the production of radiating structures are the surface roughness and the limited dimensional tolerance. These problems can significantly affect the performance of an antenna, especially for high frequencies. However, the existing researches in higher resolution printers will certainly lead to a new paradigm of 3D printed antennas.

The structures analyzed in this article show promising results and point out three-dimensional printing as a viable option to be used in mobile communications, in order to provide an excellent quality-cost ratio for commercial applications.

REFERENCES

[1] R. Mary. *Wireless Communication and Types*. Engineers Garage. Accessed: Jan. 30, 2019. [Online]. Available: https://www.engineersgarage.com/article_page/wireless-communication-and-types/
[2] C. A. Balanis, "Antenna theory: A review," *Proc. IEEE*, vol. 80, no. 1, pp. 7–23, Jan. 1992.
[3] *Maxwell, Hertz and Marconi*. Sounds in Communication. Accessed: Jan. 29, 2019. [Online]. Available: https://katrinasiron21.wordpress.com/contributors-to-the-development-of-telephone/maxwell-hertz-and-marconi/
[4] (2016). *Making 5G NR a Reality | Qualcomm*. Qualcomm. Accessed: Oct. 17, 2019. [Online]. Available: https://www.qualcomm.com/documents/making-5g-nr-reality
[5] B. Redwood, F. Schoöffer and B. Garret, *The 3D Printing Handbook*. Amsterdam, The Netherlands: 3D Hubs, 2017.
[6] Y. Mandke and R. Henry, "Review of additive manufacturing 3D printed microwave components for rapid prototyping," *Int. Sci. Press*, vol. 10, no. 29, pp. 11–14, 2017.
[7] D. Helena, A. Ramos, T. Varum, and J. N. Matos, "Evaluation of different materials to design 3D printed horn antennas for Ku-band," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Nov. 2019, pp. 1–3.
[8] H. Bensoussan. (2016). *The History of 3D Printing: From the 80s to Today*. 3D Printing Blog: Tutorials, News, Trends and Resources–Sculpteo. Accessed: Feb. 7, 2019. [Online]. Available: https://www.sculpteo.com/blog/2016/12/14/the-history-of-3D-printing-3D-printing-technologies-from-the-80s-to-today/
[9] (2018). *History of 3D Printing—When Was 3D Printing Invented?—All3DP*. All3DP. Accessed: Feb. 7, 2019. [Online]. Available: https://all3dp.com/2/history-of-3d-printing-when-was-3d-printing-invented/
[10] (2017). *Inventor of FDM 3D Printing and Co-Founder of Stratasys, Scott Crump, Inducted in to the TCT Hall of Fame | Stratasys*. Stratasys. Accessed: Mar. 25, 2019. [Online]. Available: http://investors.stratasys.com/news-releases/news-release-details/inventor-fdm-3d-printing-and-co-founder-stratasys-scott-crump
[11] (2019). *What Is Material Jetting?—3D Printing Simply Explained | All3DP*. All3DP. Accessed: May 14, 2020. [Online]. Available: https://all3dp.com/2/what-is-material-jetting-3d-printing-simply-explained/
[12] (2019). *What Is Binder Jetting?—3D Printing Simply Explained | All3DP*. All3DP. Accessed: May 14, 2020. [Online]. Available: https://all3dp.com/2/what-is-binder-jetting-3d-printing-simply-explained/
[13] (2019). *Direct Metal Laser Sintering (DMLS)—Simply Explained | All3DP*. All3DP. Accessed: May 10, 2020. [Online]. Available: https://all3dp.com/2/direct-metal-laser-sintering-dmls-simply-explained/
[14] (2019). *Selective Laser Melting (SLM)—3D Printing Simply Explained | All3DP*. All3DP. Accessed: May 14, 2020. [Online]. Available: https://all3dp.com/2/selective-laser-melting-slm-3d-printing-simply-explained/
[15] (2019). *Electron Beam Melting (EBM)—3D Printing Simply Explained | All3DP*. All3DP. Accessed: May 14, 2020. [Online]. Available: https://all3dp.com/2/electron-beam-melting-ebm-3d-printing-simply-explained/
[16] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," *Compos. B, Eng.*, vol. 143, pp. 172–196, Jun. 2018.

[17] T. Lecklider, "3D printing drives automotive innovation," *EE, Eval. Eng.*, vol. 56, no. 1, pp. 16–19, 2017.
[18] *Five Ways 3D Printing Is Transforming the Automotive Industry*. Stratasys. Accessed: Sep. 9, 2020. [Online]. Available: http://www.stratasys.com/-/media/files/white-papers-new/wp_du_fivewaysauto.pdf
[19] M. R. Nichols, "How does the automotive industry benefit from 3D metal printing?" *Metal Powder Rep.*, vol. 74, no. 5, pp. 257–258, Sep. 2019.
[20] *What is 3D Printing? How Does a 3D Printer Work? Learn 3D Printing*. 3D Printing. Accessed: Sep. 10, 2020. [Online]. Available: https://3dprinting.com/what-is-3d-printing/
[21] M. N. Nadagouda, V. Rastogi, and M. Ginn, "A review on 3D printing techniques for medical applications," *Current Opinion Chem. Eng.*, vol. 28, pp. 152–157, Jun. 2020.
[22] R. J. Morrison, K. N. Kashlan, C. L. Flanangan, J. K. Wright, G. E. Green, S. J. Hollister, and K. J. Weatherwax, "Regulatory considerations in the design and manufacturing of implantable 3D-printed medical devices," *Clin. Transl. Sci.*, vol. 8, no. 5, pp. 594–600, Oct. 2015.
[23] M. Di Prima, J. Coburn, D. Hwang, J. Kelly, A. Khairuzzaman, and L. Ricles, "Additively manufactured medical products—The FDA perspective," *3D Printing Med.*, vol. 2, no. 1, pp. 1–6, Dec. 2016.
[24] F. Mashambanhaka. (2019). *3D Printing in Medicine: The Best Applications in 2019—All3DP*. All3DP. Accessed: Oct. 21, 2019. [Online]. Available: https://all3dp.com/2/3d-printing-in-medicine-the-best-applications/
[25] A. Gisario, M. Kazarian, F. Martina, and M. Mehrpouya, "Metal additive manufacturing in the commercial aviation industry: A review," *J. Manuf. Syst.*, vol. 53, pp. 124–149, Oct. 2019.
[26] (2017). *Boeing Talks 3D Printing for Aerospace*. Engineering.com. Accessed: Sep. 9, 2020. [Online]. Available: https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/15475/Boeing-Talks-3D-Printing-for-Aerospace.aspx
[27] (2017). *Norsk Titanium to Deliver the World's First FAA-Approved, 3D-Printed, Structural Titanium Components to Boeing*. Norsk Titanium. Accessed: Sep. 9, 2020. [Online]. Available: https://www.norsktitanium.com/media/press/norsk-titanium-to-deliver-the-worlds-first-faa-approved-3d-printed-structural-titanium-components-to-boeing
[28] M. Kalender, Y. Bozkurt, S. Ersoy, and S. Salman, "Product development by additive manufacturing and 3D printer technology in aerospace industry," *J. Aeronaut. Space Technol.*, vol. 13, no. 1, pp. 129–138, Jan. 2020.
[29] (2018). *Making 3D-Printed Parts for Boeing 787s | Aerospace America*. Aerospace America. Accessed: Oct. 21, 2019. [Online]. Available: https://aerospaceamerica.aiaa.org/departments/making-3d-printed-parts-for-boeing-787s/
[30] P. Wu, J. Wang, and X. Wang, "A critical review of the use of 3-D printing in the construction industry," *Autom. Construct.*, vol. 68, pp. 21–31, Aug. 2016.
[31] B. Furet, P. Poullain, and S. Garnier, "3D printing for construction based on a complex wall of polymer-foam and concrete," *Additive Manuf.*, vol. 28, pp. 58–64, Aug. 2019.
[32] H. Alhumayani, M. Gomaa, V. Soebarto, and W. Jabi, "Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete," *J. Cleaner Prod.*, vol. 270, Oct. 2020, Art. no. 122463.
[33] M. Sakin and Y. C. Kiroglu, "3D printing of buildings: Construction of the sustainable houses of the future by BIM," *Energy Procedia*, vol. 134, pp. 702–711, Oct. 2017.
[34] C. Buchanan and L. Gardner, "Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges," *Eng. Struct.*, vol. 180, pp. 332–348, Feb. 2019.
[35] M. Liang, J. Wu, X. Yu, and H. Xin, "3D printing technology for RF and THz antennas," in *Proc. Int. Symp. Antennas Propag. (ISAP)*, Okinawa, Japan, Oct. 2016, pp. 536–537.
[36] B. T. Malik, V. Doychinov, S. A. R. Zaidi, I. D. Robertson, and N. Somjit, "Antenna gain enhancement by using low-infill 3D-printed dielectric lens antennas," *IEEE Access*, vol. 7, pp. 102467–102476, 2019.
[37] H. Giddens and Y. Hao, "Communication multi-beam graded dielectric lens antenna from multi-material 3D printing," *IEEE Trans. Antennas Propag.*, vol. 68, no. 9, pp. 6832–6837, Sep. 2020.
[38] C. Ballesteros, M. Maestre, M. C. Santos, J. Romeu, and L. Jofre, "A 3D printed lens antenna for 5G applications," in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting*, Jul. 2019, pp. 1985–1986.
[39] Z.-X. Xia, K. W. Leung, and K. Lu, "3-D-Printed wideband multi-ring dielectric resonator antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 10, pp. 2110–2114, Oct. 2019.
[40] E.-S. Jo and D. Kim, "3-D printer based lens design method for integrated lens antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 11, pp. 2090–2093, Nov. 2018.
[41] Y.-X. Zhang, Y.-C. Jiao, and S.-B. Liu, "3-D-Printed comb mushroom-like dielectric lens for stable gain enhancement of printed log-periodic dipole array," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 11, pp. 2099–2103, Nov. 2018.
[42] G. Wu, Y. Zeng, K. F. Chan, S. Qu, and C. H. Chan, "3-D printed circularly polarized modified fresnel lens operating at Terahertz frequencies," *IEEE Trans. Antennas Propag.*, vol. 67, no. 7, pp. 4429–4437, Jul. 2019.
[43] P. Kumar, S. Dwari, Utkarsh, S. Singh, and J. Kumar, "Investigation and development of 3D printed biodegradable PLA as compact antenna for broadband applications," *IETE J. Res.*, vol. 66, no. 1, pp. 53–64, Jan. 2020.
[44] P. Mahouti, M. A. Belen, F. Güneş, and R. Yurt, "Design and realization of multilayered cylindrical dielectric lens antenna using 3D printing technology," *Microw. Opt. Technol. Lett.*, vol. 61, no. 5, pp. 1400–1403, May 2019.
[45] C. Wang, J. Wu, and Y. Guo, "A 3-D-printed multibeam dual circularly polarized Luneburg lens antenna based on quasi-icosahedron models for Ka-band wireless applications," *IEEE Trans. Antennas Propag.*, vol. 68, no. 8, pp. 5807–5815, Aug. 2020.
[46] K. V. Hoel, M. Ignatenko, S. Kristoffersen, E. Lier, and D. S. Filipovic, "3-D printed monolithic GRIN dielectric-loaded double-ridged horn antennas," *IEEE Trans. Antennas Propag.*, vol. 68, no. 1, pp. 533–539, Jan. 2020.
[47] H. Saghlatoon, M. M. Honari, S. Aslanzadeh, and R. Mirzavand, "Electrically-small luneburg lens for antenna gain enhancement using new 3D printing filling technique," *AEU - Int. J. Electron. Commun.*, vol. 124, Sep. 2020, Art. no. 153352.
[48] C. Wang, J. Wu, and Y.-X. Guo, "A 3-D-Printed wideband circularly polarized parallel-plate luneburg lens antenna," *IEEE Trans. Antennas Propag.*, vol. 68, no. 6, pp. 4944–4949, Jun. 2020.
[49] P. Liu, X. Zhu, Y. Zhang, J. Li, and Z. Jiang, "3D-printed cylindrical Luneburg lens antenna for millimeter-wave applications," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 30, no. 1, 2019, Art. no. e21994.
[50] J. Huang, S. J. Chen, Z. Xue, W. Withayachumnankul, and C. Fumeaux, "Wideband circularly polarized 3-D printed dielectric rod antenna," *IEEE Trans. Antennas Propag.*, vol. 68, no. 2, pp. 745–753, Feb. 2020.
[51] D. C. Lugo, R. A. Ramirez, J. Castro, J. Wang, and T. M. Weller, "3D printed multilayer mm-wave dielectric rod antenna with enhanced gain," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 1247–1248.
[52] J. Wen, Y. Jiao, Y. Zhang, Z. Weng, and C. Zhang, "Low-cost and easy manufactured dielectric rod antennas based on 3D printing technology," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 29, no. 12, Dec. 2019, Art. no. e21954.
[53] Z. Wu, W.-R. Ng, M. E. Gehm, and H. Xin, "Terahertz electromagnetic crystal waveguide fabricated by polymer jetting rapid prototyping," *Opt. Express*, vol. 19, no. 5, pp. 3962–3972, Feb. 2011.
[54] M. Liang and H. Xin, "3D printed microwave and THz components," in *Proc. Asia–Pacific Microw. Conf. (APMC)*, Dec. 2015, pp. 1–3.
[55] M. F. Farooqui and A. Kishk, "3-D-Printed tunable circularly polarized microstrip patch antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 7, pp. 1429–1432, Jul. 2019.
[56] J. Heirons, S. Jun, A. Shastri, B. Sanz-Izquierdo, D. Bird, L. Winchester, L. Evans, and A. McClelland, "Inkjet printed GPS antenna on a 3D printed substrate using low-cost machines," in *Proc. Loughborough Antennas Propag. Conf. (LAPC)*, Nov. 2016, pp. 1–4.
[57] A. J. Fenn, D. J. Pippin, C. M. Lamb, F. G. Willwerth, H. M. Aumann, and J. P. Doane, "3D printed conformal array antenna: Simulations and measurements," in *Proc. IEEE Int. Symp. Phased Array Syst. Technol. (PAST)*, Oct. 2016, pp. 1–4.
[58] M. Mirmozafari, S. Saeedi, H. Saeidi-Manesh, G. Zhang, and H. H. Sigmarsson, "Direct 3-D printing of nonplanar Linear-Dipole-Phased array antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 11, pp. 2137–2140, Nov. 2018.
[59] A. O. Adeyeye, R. A. Bahr, and M. M. Tentzeris, "3D printed 2.45 GHz yagi-uda loop antenna utilizing microfluidic channels and liquid metal," in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting*, Jul. 2019, pp. 1983–1984.
[60] *Material Data Sheet—Durable*. FormLabs. Accessed: Jun. 30, 2020. [Online]. Available: https://formlabs-media.formlabs.com/datasheets/Durable_Resin_Technical.pdf

[61] A. S. Kaddour, S. Bories, A. Bellion, and C. Delaveaud, "3D printed compact dual-polarized wideband antenna," in *Proc. 11th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2017, pp. 3441–3443.
[62] W. Su, S. A. Nauroze, B. Ryan, and M. M. Tentzeris, "Novel 3D printed liquid-metal-alloy microfluidics-based zigzag and helical antennas for origami reconfigurable antenna 'trees,'" in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2017, pp. 1579–1582.
[63] *Gallium–Indium Eutectic*. Sigma Aldrich. Accessed: Jun. 30, 2020. [Online]. Available: https://www.sigmaaldrich.com/catalog/product/aldrich/495425?lang=pt&region=PT
[64] S. Wang, L. Zhu, and W. Wu, "3-D printed inhomogeneous substrate and superstrate for application in dual-band and dual-CP stacked patch antenna," *IEEE Trans. Antennas Propag.*, vol. 66, no. 5, pp. 2236–2244, May 2018.
[65] *SOMOS Watershed XC 11122*. DSM. Accessed: Jun. 30, 2020. [Online]. Available: https://www.dsm.com/content/dam/dsm/additive-manufacturing/en_US/documents/dsm_lmt_productleaflet_somos-watershed-xc-11122.pdf
[66] R. A. Bahr, Y. Fang, W. Su, B. Tehrani, V. Palazzi, and M. M. Tentzeris, "Novel uniquely 3D printed intricate Voronoi and fractal 3D antennas," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2017, pp. 1583–1586.
[67] V. Gjokaj, P. Chahal, L. Kempel, and E. Rothwell, "A novel 3D printed half-width microstrip leaky-wave antenna," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 1249–1250.
[68] *VeroWhitePlus*. Stratasys. Accessed: Jun. 30, 2020. [Online]. Available: https://www.stratasysdirect.com/-/media/files/direct/material-datasheets/polyjet/polyjet_verowhiteplus_material_specifications.pdf?la=en&hash=5D5417297933FEC3A514CCFC19A5CD2293D2DD08
[69] A. T. Castro and S. K. Sharma, "A triple mode waveguide corrugated horn antenna using 3D printing technology," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 1235–1236.
[70] *Metalon Conductive Inks*. Novacentrix. Accessed: Jun. 30, 2020. [Online]. Available: https://www.novacentrix.com/products/metalon-conductive-inks
[71] M. I. M. Ghazali and P. Chahal, "A 3D printed cavity backed 2×4 slotted waveguide antenna array," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2018, pp. 1435–1436.
[72] Y. C. Toy, P. Mahouti, F. Gunes, and M. A. Belen, "Design and manufactering of an X-band horn antenna using 3-D printing technology," in *Proc. 8th Int. Conf. Recent Adv. Space Technol. (RAST)*, Jun. 2017, pp. 195–198.
[73] X. Zhu and B. Zhang, "A low-cost stereolithography printed X-band antenna with metallic-plated surface," in *Proc. Int. Conf. Microw. Millim. Wave Technol. (ICMMT)*, May 2019, pp. 1–3.
[74] M. F. Farooqui and A. Shamim, "3-D inkjet-printed helical antenna with integrated lens," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 800–803, 2017.
[75] *Silver Nanoparticle Ink*. Sigma Aldrich. Accessed: Jun. 29, 2020. [Online]. Available: https://www.sigmaaldrich.com/catalog/product/aldrich/719048?lang=pt&region=PT
[76] A. H. Wahyudi, J. T. S. Sumantyo, S. Wijaya, and A. Munir, "PLA-based 3D printed circularly polarized X-band horn array antenna for CP-SAR sensor," in *Proc. Int. Workshop Antenna Technol. (iWAT)*, Mar. 2018, pp. 1–4.
[77] S. Gao, Y. Rahmat-Samii, R. E. Hodges, and X.-X. Yang, "Advanced antennas for small satellites," *Proc. IEEE*, vol. 106, no. 3, pp. 391–403, Mar. 2018.
[78] J. Teniente, J. C. Iriarte, R. Caballero, D. Valcazar, M. Goni, and A. Martinez, "3-D printed horn antennas and components performance for space and telecommunications," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 11, pp. 2070–2074, Nov. 2018.
[79] *Product Data Sheet—SOMOS PerFORM*. DSM. Accessed: Jun. 29, 2020. [Online]. Available: https://uniontech3d.de/wp-content/uploads/2019/07/Somos-PerFORM-Datasheet.pdf
[80] M. van der Vorst and J. Gumpinger, "Applicability of 3D printing techniques for compact ku-band medium/high-gain antennas," in *Proc. 10th Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2016, pp. 1–4.
[81] V. Gjokaj, P. Chahal, J. Papapolymerou, and J. D. Albrecht, "A novel 3D printed vivaldi antenna utilizing a substrate integrated waveguide transition," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 1253–1254.
[82] S.-H. Shin, D. F. Alyasiri, M. D'Auria, W. J. Otter, C. W. Myant, D. Stokes, Z. Tian, N. M. Ridler, and S. Lucyszyn, "Polymer-based 3-D printed ku-band steerable phased-array antenna subsystem," *IEEE Access*, vol. 7, pp. 106662–106673, 2019.
[83] J.-C.-S. Chieh, B. Dick, S. Loui, and J. D. Rockway, "Development of a ku-band corrugated conical horn using 3-D print technology," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 201–204, 2014.
[84] *Fortus 250mc*. Stratasys. Accessed: Jun. 30, 2020. [Online]. Available: https://support.stratasys.com/en/products/fdm-platforms/fortus-250mc
[85] *841—Super Shield Nickel Conductive Coating*. MG Chemicals. Accessed: Jun. 29, 2020. [Online]. Available: https://www.mgchemicals.com/products/emi-and-rfi-shielding/acrylic-conductive-coatings-original-series/super-shield-nickel-841
[86] G. P. Le Sage, "3D printed waveguide slot array antennas," *IEEE Access*, vol. 4, pp. 1258–1265, 2016.
[87] F. Bongard, M. Gimersky, S. Doherty, X. Aubry, and M. Krummen, "3D-printed ka-band waveguide array antenna for mobile SATCOM applications," in *Proc. 11th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2017, pp. 579–583.
[88] Y. He, C. Oakley, P. Chahal, J. Albrecht, and J. Papapolymerou, "Aerosol jet printed 24 GHz end-fire quasi-Yagi-Uda antenna on a 3-D printed cavity substrate," in *Proc. Int. Workshop Antenna Technol., Small Antennas, Innov. Struct., Appl. (iWAT)*, 2017, pp. 179–182.
[89] H. J. Martinez Odiaga, M. A. Yarleque Medina, and S. A. Navarro, "An implemented 3D printed circular waveguide antenna for k band applications," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Dec. 2018, pp. 1–3.
[90] K. Lomakin, T. Pavlenko, M. Ankenbrand, M. Sippel, J. Ringel, M. Scheetz, T. Klemm, D. Graf, K. Helmreich, J. Franke, and G. Gold, "Evaluation and characterization of 3-D printed pyramid horn antennas utilizing different deposition techniques for conductive material," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 8, no. 11, pp. 1998–2006, Nov. 2018.
[91] A. Dorle, R. Gillard, E. Menargues, M. Van Der Vorst, E. De Rijk, P. Martin-Iglesias, and M. Garcia-Vigueras, "Additive manufacturing of modulated triple-ridge leaky-wave antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 11, pp. 2123–2127, Nov. 2018.
[92] L. G. Menéndez, O. S. Kim, F. Persson, M. Nielsen, and O. Breinbjerg, "3D printed 20/30-GHz dual-band offset stepped-reflector antenna," in *Proc. 9th Eur. Conf. Antennas Propag. (EuCAP)*, Lisbon, Portugal, Apr. 2015, pp. 1–2.
[93] (2015). *5G Vision | Networks Insights | Samsung Business Global*. Samsung Global_nw. Accessed: Oct. 17, 2019. [Online]. Available: https://www.samsung.com/global/business/networks/insights/white-paper/5g-vision/
[94] H. Yao, S. Sharma, R. Henderson, S. Ashrafi, and D. MacFarlane, "Ka band 3D printed horn antennas," in *Proc. Texas Symp. Wireless Microw. Circuits Syst. (WMCS)*, Mar. 2017, pp. 1–4.
[95] D. Helena, A. Ramos, T. Varum, and J. N. Matos, "Inexpensive 3D-printed radiating horns for customary things in IoT scenarios," in *Proc. 14th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2020, pp. 1–4.
[96] *EMI/RFI Shielding Aerosol With Bronze colour 400mL*. RS Components. Accessed: Sep. 8, 2020. [Online]. Available: https://uk.rs-online.com/web/p/products/2474251
[97] S. Alkaraki, A. S. Andy, Y. Gao, K.-F. Tong, Z. Ying, R. Donnan, and C. Parini, "Compact and low-cost 3-D printed antennas metalized using spray-coating technology for 5G mm-wave communication systems," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 11, pp. 2051–2055, Nov. 2018.
[98] A. Tamayo-Dominguez, J.-M. Fernandez-Gonzalez, and M. Sierra-Perez, "Metal-coated 3D-printed waveguide devices for mm-wave applications [application notes]," *IEEE Microw. Mag.*, vol. 20, no. 9, pp. 18–31, Sep. 2019.
[99] S. Alkaraki, Y. Gao, S. Stremsdoerfer, E. Gayets, and C. G. Parini, "3D printed corrugated plate antennas with high aperture efficiency and high gain at X-Band and ka-band," *IEEE Access*, vol. 8, pp. 30643–30654, 2020.
[100] *Objet30 Prime*. Stratasys. Accessed: Jun. 30, 2020. [Online]. Available: https://www.stratasys.com/-/media/files/printer-spec-sheets/pss_pj_objet30prime.pdf
[101] G. Shivani, K. G. S, D. Santhoshi, D. R. Krishna, and S. K. Koul, "Low cost 3D printed dual band antenna for mm wave 5G applications," in *Proc. IEEE Indian Conf. Antennas Propogation (InCAP)*, Dec. 2019, pp. 1–4.

[102] B. Chen, H. Yi, K. B. Ng, S. Qu, and C. H. Chan, "3D printed reflectarray antenna at 60 GHz," in *Proc. Int. Symp. Antennas Propag. (ISAP)*, Okinawa, Gurugram, Oct. 2016, pp. 92–93.

[103] *Objet30*. Stratasys. Accessed: Jun. 30, 2020. [Online]. Available: http://www.stratasys.com/-/media/files/printer-spec-sheets/pss_pj_objet30.pdf

[104] Q.-L. Zhang, B.-J. Chen, and C.-H. Chan, "3D printed V-band rod antenna with constant gain based on spoof surface plasmon polaritons," in *Proc. 11th Global Symp. Millim. Waves (GSMM)*, May 2018, pp. 1–4.

[105] A. Jammes, E. des Gayets, K. Staelens, R. Feger, T. Lampersberger, and A. Stelzer, "Silver metallization of 77 GHz 3D printed horn antennas," in *Proc. 12th Eur. Conf. Antennas Propag. (EuCAP)*, 2018, pp. 1–4.

[106] J. Hasch, E. Topak, R. Schnabel, T. Zwick, R. Weigel, and C. Waldschmidt, "Millimeter-wave technology for automotive radar sensors in the 77 GHz frequency band," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 3, pp. 845–860, Mar. 2012.

[107] E. Decrossas, T. Reck, C. Lee, C. Jung-Kubiak, I. Mehdi, and G. Chattopadhyay, "Evaluation of 3D printing technology for corrugated horn antenna manufacturing," in *Proc. IEEE Int. Symp. Electromagn. Compat. (EMC)*, Jul. 2016, pp. 251–255.

[108] K. Lomakin, D. Simon, M. Sippel, K. Helmreich, E. Seler, Z. Tong, R. Reuter, and G. Gold, "3D printed slotted waveguide array antenna for automotive radar applications in W-Band," in *Proc. 15th Eur. Radar Conf. (EuRAD)*, Sep. 2018, pp. 389–392.

[109] *Accura SL 5530 (SLA)*. 3D Systems. Accessed: Jun. 30, 2020. [Online]. Available: https://www.3dsystems.com/materials/accura-sl-5530

[110] E. Decrossas, T. Reck, C. Lee, C. Jung-Kubiak, I. Mehdi, and G. Chattopadhyay, "Development of W-band horn antennas using 3D printing technologies," in *Proc. IEEE Int. Symp. Antennas Propag. (APSURSI)*, Jun. 2016, pp. 1181–1182.

[111] C. Gu, S. Gao, V. Fusco, G. Gibbons, B. Sanz-Izquierdo, A. Standaert, P. Reynaert, W. Bösch, M. Gadringer, R. Xu, and X. Yang, "A D-band 3D-printed antenna," *IEEE Trans. Terahertz Sci. Technol.*, vol. 10, no. 5, pp. 433–442, Sep. 2020.

[112] *Stratasys J750*. Stratasys. Accessed: Jun. 30, 2020. [Online]. Available: http://www.stratasys.com/-/media/files/printer-spec-sheets/pss_pj_stratasysj750_1017b.pdf

[113] A. Reinhardt, M. Mobius-Labinski, C. Asmus, A. Bauereiss, and M. Hoft, "Additive manufacturing of 300 GHz corrugated horn antennas," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jul. 2019, pp. 40–42.

[114] J. Bjorgaard, M. Hoyack, E. Huber, M. Mirzaee, Y.-H. Chang, and S. Noghanian, "Design and fabrication of antennas using 3D printing," *Prog. Electromagn. Res. C*, vol. 84, pp. 119–134, 2018.

[115] *Electrifi Conductive Filament*. Multi3D. Accessed: May 5, 2020. [Online]. Available: https://www.multi3dllc.com/product/electrifi/

[116] R. Colella, F. P. Chietera, L. Catarinucci, J. F. Salmeron, A. Rivadeneyra, M. A. Carvajal, A. J. Palma, and L. F. Capitan-Vallvey, "Fully 3D-printed RFID tags based on printable metallic filament: Performance comparison with other fabrication techniques," in *Proc. IEEE-APS Topical Conf. Antennas Propag. Wireless Commun. (APWC)*, Sep. 2019, pp. 253–257.

[117] M. Ahmadloo and P. Mousavi, "A novel integrated dielectric-and-conductive ink 3D printing technique for fabrication of microwave devices," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2013, pp. 1–3.

[118] S. Roy, M. B. Qureshi, S. Asif, and B. D. Braaten, "A model for 3D-printed microstrip transmission lines using conductive electrifi filament," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 1099–1100.

[119] M. Mirzaee and S. Noghanian, "3D printed antenna using biocompatible dielectric material and graphene," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 2543–2544.

[120] *Conductive PLA—ProtoPlant, Makers of Proto-Pasta*. Protopasta. Accessed: Sep. 8, 2020. [Online]. Available: https://www.proto-pasta.com/pages/conductive-pla

[121] *Conductive Graphene PLA Filament 100g*. Black Magic 3D. Accessed: Jun. 22, 2020. [Online]. Available: https://www.blackmagic3d.com/Conductive-p/grphn-pla.htm

[122] U. Hasni, R. Green, A. V. Filippas, and E. Topsakal, "One-step 3D-printing process for microwave patch antenna via conductive and dielectric filaments," *Microw. Opt. Technol. Lett.*, vol. 61, no. 3, pp. 734–740, Mar. 2019.

[123] *Lulzbot 3D Printers*. Lulzbot. Accessed: Sep. 8, 2020. [Online]. Available: https://www.lulzbot.com/lulzbot-3d-printers

[124] M. Mirzaee, S. Noghanian, L. Wiest, and I. Chang, "Developing flexible 3D printed antenna using conductive ABS materials," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2015, pp. 1308–1309.

[125] D. Shamvedi, O. J. McCarthy, E. O'Donoghue, P. O'Leary, and R. Raghavendra, "3D metal printed sierpinski gasket antenna," in *Proc. Int. Conf. Electromagn. Adv. Appl. (ICEAA)*, Sep. 2017, pp. 633–636.

[126] D. Shamvedi, O. J. McCarthy, E. O'Donoghue, P. O'Leary, and R. Raghavendra, "Improved performance of 3D metal printed antenna through gradual reduction in surface roughness," in *Proc. Int. Conf. Electromagn. Adv. Appl. (ICEAA)*, Sep. 2017, pp. 669–672.

[127] G.-L. Huang, S.-G. Zhou, and T.-H. Chio, "Lightweight perforated horn antenna enabled by 3-D metal-direct-printing," in *Proc. IEEE Int. Symp. Antennas Propag. (APSURSI)*, Jun. 2016, pp. 481–482.

[128] K. Kotze and J. Gilmore, "SLM 3D-printed horn antenna for satellite communications at X-band," in *Proc. IEEE-APS Topical Conf. Antennas Propag. Wireless Commun. (APWC)*, Sep. 2019, pp. 148–153.

[129] A. Guennou-Martin, Y. Quere, E. Rius, L. Fourtinon, C. Person, G. Lesueur, and T. Merlet, "Design and manufacturing of a 3-D conformal slotted waveguide antenna array in ku-band based on direct metal laser sintering," in *Proc. IEEE Conf. Antenna Meas. Appl. (CAMA)*, Oct. 2016, pp. 1–4.

[130] G. Addamo, O. A. Peverini, F. Calignano, D. Manfredi, F. Paonessa, G. Virone, and G. Dassano, "3-D printing of high-performance feed horns from Ku- to V-bands," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 11, pp. 2036–2040, Nov. 2018.

[131] B. Zhang, L. Wu, Y. Zhou, Y. Yang, H. Zhu, F. Cheng, Q. Chen, and K. Huang, "A K-band 3-D printed focal-shifted two-dimensional beam-scanning lens antenna with nonuniform feed," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 12, pp. 2721–2725, Dec. 2019.

[132] B. Zhang, Y.-X. Guo, H. Sun, and Y. Wu, "Metallic, 3D-printed, K-band-stepped, double-ridged square horn antennas," *Appl. Sci.*, vol. 8, no. 1, p. 33, Dec. 2017.

[133] E. A. Rojas-Nastrucci, J. Nussbaum, T. M. Weller, and N. B. Crane, "Metallic 3D printed ka-band pyramidal horn using binder jetting," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Dec. 2016, pp. 1–3.

[134] I. Agnihotri and S. K. Sharma, "Design of a 3D metal printed axial corrugated horn antenna covering full ka-band," *IEEE Antennas Wireless Propag. Lett.*, vol. 19, no. 4, pp. 522–526, Apr. 2020.

[135] B. Zhang, P. Linner, C. Karnfelt, P. L. Tarn, U. Sodervall, and H. Zirath, "Attempt of the metallic 3D printing technology for millimeter-wave antenna implementations," in *Proc. Asia–Pacific Microw. Conf. (APMC)*, Dec. 2015, pp. 1–3.

[136] B. Zhang, Z. Zhan, Y. Cao, H. Gulan, P. Linnér, J. Sun, T. Zwick, and H. Zirath, "Metallic 3-D printed antennas for Millimeter- and submillimeter wave applications," *IEEE Trans. THz Sci. Technol.*, vol. 6, no. 4, pp. 592–600, Jul. 2016.

[137] J. Ren and K. W. Leung, "3D-printed open-ended waveguide antenna for 60 GHz applications," in *Proc. IEEE Asia–Pacific Conf. Antennas Propag. (APCAP)*, Aug. 2018, pp. 52–53.

[138] N. Luo, G. Mishra, S. K. Sharma, and X. Yu, "Experimental verification of 3D metal printed dual circular-polarized horn antenna at V-band," in *Proc. Antenna Meas. Techn. Assoc. Symp. (AMTA)*, Oct. 2019, pp. 1–6.

[139] *Technical Data Sheet ABS*. Ultimaker. Accessed: Jun. 22, 2020. [Online]. Available: https://ultimaker.com/download/74640/UM180821%20TDS%20ABS%20RB%20V11.pdf

[140] *Technical Data Sheet PLA*. Ultimaker. Accessed: Jun. 22, 2020. [Online]. Available: https://ultimaker.com/download/74599/UM180821%20TDS%20PLA%20RB%20V10.pdf

[141] R. L. Dumene, P. Kennedy, C. B. Williams, D. Sweeney, and G. Earle, "Creating embedded radiofrequency structures using polyjet material jetting," in *Proc. Int. Solid Freeform Fabr. Symp.*, 2015, pp. 1–19.

[142] *Stainless 316, 316L, 317, 317L*. United Performance Metals. Accessed: Jun. 22, 2020. [Online]. Available: https://www.upmet.com/sites/default/files/datasheets/316-316l.pdf

[143] B. Zhang, Y.-X. Guo, H. Zirath, and Y. P. Zhang, "Investigation on 3-D-printing technologies for millimeter- wave and terahertz applications," *Proc. IEEE*, vol. 105, no. 4, pp. 723–736, Apr. 2017.

DIOGO HELENA (Member, IEEE) was born in Vila Nova de Gaia, Portugal, in April 1995. He received the M.Sc. degree in electronics and telecommunications engineering from the Universidade de Aveiro, Aveiro, Portugal, in 2019.

He joined the Instituto de Telecomunicações at Campus Universitário de Santiago, in February 2020. He is currently working on 3D-printed antennas for mm-wave applications. He wrote and presented a publication in a conference.

AMÉLIA RAMOS (Member, IEEE) was born in Aveiro, Portugal, in October 1994. She received the M.Sc. degree in electronics and telecommunications engineering from the Universidade de Aveiro, Aveiro, Portugal, in 2018.

She joined the Instituto de Telecomunicações at Campus Universitário de Santiago in January 2019. She has authored or coauthored several conference papers, and she is the main author of one journal article. She is currently working in smart antennas for mm-wave applications, with an emphasis on phased arrays, antennas for satellite communication systems, and multi-band radiating structures.

TIAGO VARUM (Member, IEEE) was born in Estarreja, Portugal, in 1987. He received the M.Sc. degree in electronics and telecommunications engineering and the Ph.D. degree in electrical engineering from the Universidade de Aveiro, Aveiro, Portugal, in 2010 and 2016, respectively. He is currently a Research Assistant with the Instituto de Telecomunicações at Campus Universitário de Santiago, Aveiro. His main research interests include antenna design, reconfigurable antennas, 3D-printed antennas, non-uniform antenna arrays, beamforming, and smart/adaptive antennas, for mmWave applications such as radars, 5G, or SATCOM. He has participated in some projects, published several papers in this field, and in conference proceedings and journals, and has been a Reviewer for several journals and international conferences. He is a member of the IEEE Antennas and Propagation Society.

JOÃO NUNO MATOS (Member, IEEE) was born in Oliveira de Azeméis, Portugal, in 1959. He received the degree in electronics and telecommunications engineering from the Universidade de Aveiro, Portugal, in 1982, the master's degree in electrical science from the University of Coimbra, Portugal, in 1989, and the Ph.D. degree in electrical engineering from the Universidade de Aveiro, in 1995.

He worked twice in the industry Portugal Telecom Innovation, Aveiro, Portugal, from 1982 to 1983, and Ensa Electronic, Madrid, Spain, in 1990. From 1998 to 2000, he was the Head of the Department of Electronics and Telecommunications, Universidade de Aveiro. He is currently an Associate Professor with the Universidade de Aveiro and a Senior Researcher with the Telecommunications Institute. He has authored or coauthored over 100 international conference papers and journal articles. With the Telecommunications Institute, he participated or led dozens of research's projects in RF/microwave (MW) circuits, system design, and system integration. His research interests include satellite communications and radars with a special focus on front-end and smart antennas, and engineering education. He is a member of several scientific committees of conferences and journals as well as professional organizations and is currently on the Executive Committee of the IEEE Portugal Education Chapter that received the IEEE Education Society Chapter Achievement Award in 2019.