Evaluation of a New Process for the Additive Manufacturing of Metal Antennas

Progress In Electromagnetics Research M, Vol. 117, 59–69, 2023

Evaluation of a New Process for the Additive Manufacturing of Metal Antennas

Germán A. Ramírez Arroyave[1, *], David L. Galindo Huertas[2], Daniel F. Garzón Cuervo[2], Manuel R. Pérez Cerquera[3], Liz K. Herrera Quintero[2], and Javier L. Araque Quijano[2]

Abstract—This paper presents a new process for additively manufacturing purely metallic antennas based on Fused Deposition Modeling (FDM), with a proprietary filament developed using a hot extrusion method and composed by a mix of rounded shape copper powders with particle sizes in the range from 20 to 80 μm embedded in a polymeric matrix, to accomplish the desired antenna shape; followed by a post-processing stage involving de-binding to remove the base polymer and a further sintering process for obtaining a purely metallic component. This new process is validated by means of a prototype antenna consisting on a modified tri-band cactus monopole that is manufactured and measured, exhibiting results in agreement with standard and alternative additive manufacturing techniques reported in the literature.

1. INTRODUCTION

Additive Manufacturing (AM), commonly used interchangeably with Rapid Prototyping (RP) or "3-D printing", is a term that comprises several manufacturing technologies in which the creation of complete parts is carried out by the aggregation of simpler units of raw material [1, 2]. The term "Additive" is used to emphasize the distinction with the traditional Subtractive Manufacturing (SM) processes where the final part is obtained by removing portions from a raw material slab, e.g., by handcrafting, molding, and Computer Numerical Control (CNC) machining.

Some distinctive differentiators of Additive Manufacturing (AM) against conventional manufacturing technologies [3, 4] are its design flexibility and customization that enable the construction of intricate geometries with a reduced number of attempts and almost exclusively using computational tools, hence affording lower prototyping cost and a faster move from design to production. Environmentally related advantages can also be associated with AM as parts can be built on-request, reducing the production and storage of unneeded inventory, with a lower generation of waste and pollution in the processes of manufacture and transport.

Additive manufacturing of metals [5–7] is particularly appealing in many industry sectors, such as dental and bio-medical prosthesis, and for the development of customized parts for aero-spatial and vehicular applications. However, the total cost of ownership of the equipment necessary for AM of metal parts (e.g., Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Laser Metal Deposition (LMD), among others) is elevated, which unavoidably increases production costs; accordingly, building prototypes or reduced batches of a sample product may not be afforded by many users.

For these reasons, in fields where electrical rather than mechanical characteristics of metals are desired, e.g., electromagnetic design in microwaves and antenna engineering, alternative paths such as

Received 21 December 2022, Accepted 13 May 2023, Scheduled 30 May 2023

* Corresponding author: Germán Augusto Ramírez Arroyave (german.ramirezarroyave@epfl.ch).

[1] École Polytechnique Fédérale de Lausanne — EPFL, Lausanne, Switzerland. [2] Universidad Nacional de Colombia, Bogotá, Colombia. [3] Pontificia Universidad Javieriana, Bogotá, Colombia.

the metal cladding of structures made by AM of plastic materials have proven promising results as in [8] and enable the realization of designs that were inconceivable or only theoretically possible in the recent past as for example [9].

Some milestones on 3-D-printed antennas have been reached recently: horn antennas were made through Stereolithography (SLA) followed by a copper electroplating on top of a conductive silver ink layer in [10, 11]; the fabrication of small antennas using a conductive ink for conformal printing on the surface of a 3D-shaped substrate introduced in [12]; a large reflector made by Nylon SLS and further coating with silver ink to achieve metallization presented in [13]; on the other hand we find the deployment of titanium and the later creation of a copper clad by vacuum sputtering of a selection of patch antennas produced by SLA presented in [14], and the variation presented in [15] with two steps metallization combining sputtering to create a thin copper (Cu) coating and a subsequent electroplating to attain a thick Cu layer.

Likewise, industrialization of AM techniques for antenna construction accomplished successful realizations as in [16], where a pair of "Ku"-band antennas were developed and tested in a cooperation between academy and industry, the commercial range of 3D printed antennas from [17], the collaboration in [18] where industrial partners combined efforts to assess manufacturing accuracy and repeatability of SLM for horn antennas, and the development of a 3D printed aluminum alloy antenna for space applications in [19]. An extensive review of 3-D printed antennas with current research challenges is presented in [20].

Although most of the additively manufactured antennas reported in the literature are based on conventional designs that could be undertaken utilizing traditional construction methods, those works are the foundation for establishing the viability of AM in antenna applications and enable the ulterior exploration of new shapes, plausible only by the additional design freedom opened up by arbitrary 3-D geometry. On the other hand, AM of antennas is still incipient compared to traditional technologies such as Printed Circuit Board (PCB) and SM; moreover, there remain issues on the deployment of AM-made antennas such as the ability to endure mechanical and thermal strain in demanding applications, the repeatability among production batches, and not less important, the time and cost required for prototyping and low-volume production.

In this work, we present a new process for creating purely metallic structures from a blend of rounded-shape copper-powder particles embedded in a polymeric matrix, in the form of a filament as used in conventional Fused Deposition Modeling (FDM). The process mixes additive manufacturing based on FDM, followed by a de-binding process to remove the base polymer and further sintering for obtaining a purely metallic component, which provides the final antenna with excellent mechanical and thermal properties. In contrast to current alternatives for obtaining purely metallic pieces such as DMLS or SLM this process achieves similar performance with a very low cost.

In this regard, the estimated total cost per antenna can be disaggregated in: i) material \$3 USD, ii) printing \$2 USD, iii) sintering \$1.5–3 USD (Can be higher depending on the furnace loading), iv) postprocessing \$0 USD. It is worth mentioning that these are prototyping costs which could dramatically decrease at production.

As a way of summary, a qualitative comparison of our new manufacturing process with alternatives is presented in Table 1, where the advantages of cost, heat and power handling, and mechanical resistance stand out.

Accordingly, this method is proposed as an appealing alternative for manufacturing all-metallic structures with complex geometries, which will certainly break new ground in electromagnetics, microwaves, and antenna engineering applications.

In order to provide a common baseline in the validation of this novel manufacturing process, a conventional antenna design is used as case study. This antenna was conceived and developed to ascertain the performance of two alternate AM based processes, as already presented by the authors in [8] and summarized in the dissertation [21]. The results of the antenna manufactured with this new process are in accordance with those already reported and even with those obtainable using standard manufacturing techniques.

Table 1. Comparison of the proposed manufacturing method and existing alternatives.

	Ruggeddness	Accuracy	Electric conductivity	Heat and power handling	Cost
Subtractive manufacturing	High	High	High	High	High
Metal cladding of plastics	Medium	Medium	High	Low	Medium
Conductive coating of plastics	Medium	Medium	Medium	Low	Low
Powder Bed Fusion (PBF)*	High	Medium	High	High	High
Our method	Medium	Medium	High	High	Medium

* Also known as DMLS or SLM

2. ANTENNA DESIGN

The antenna chosen for validation purposes is a modified "cactus"-like monopole, whose electromagnetic performance can be accurately predicted using a commercial simulation package. Although PCB alternatives for building this kind of antennas have been documented, and conventional subtractive manufacturing approaches may be better suited for the shape herein considered. This geometry is chosen and tailored to validate the manufacturability of some complex 3D features such as cavities and the joints of vertical and horizontal walls which are pivotal in the manufacturing of intricate antenna geometries like the one in [9].

The antenna concept is inspired by the work in [22], where a planar "G"-shaped antenna with microstrip feed and dual-band operation is demonstrated and the work in [23], which introduces the term "cactus" antenna to describe a planar monopole loaded with one or two symmetrical sleeves, and the work in [24], in which a "fork"-shaped printed monopole for dual band operation is presented.

The operation principle of the proposed antenna is based on a parallel circuit equivalent where the input port is split to the "cactus" arms at the feeding point. Therefore, when one arm is at resonance, the remaining arms show a large impedance value to the common feed, attaining a multi-band functioning. As illustrated in Fig. 1, the three-arms design includes some additional concave

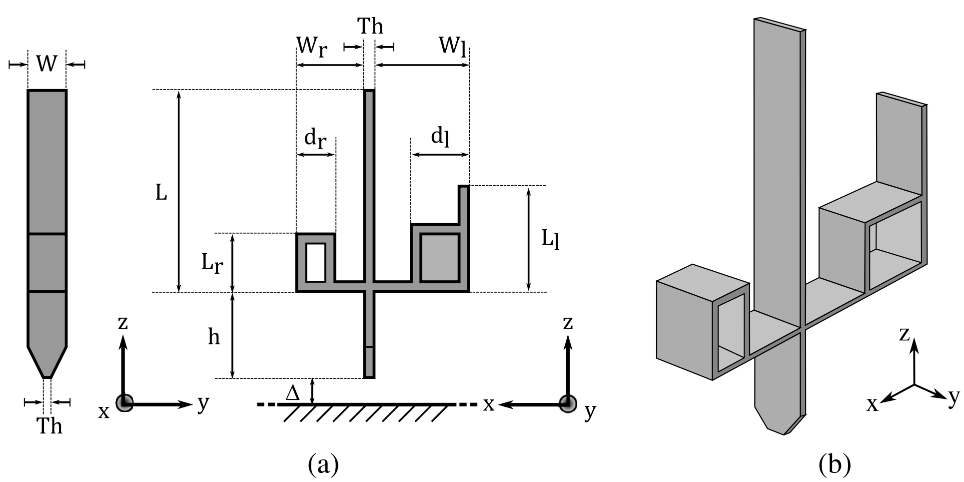


Figure 1. Projected and 3-D views of the modified tri-band cactus monopole. (a) Left "yz" plane. Right "'xz" plane. (b) 3-D view.

features (this modification is only aimed at evaluating the manufacturing of complex details and does not impact the impedance matching). The tapered transition from the main antenna body to the feed point is intended for reducing the capacitive interaction between the antenna and the ground plane, which is located under the antenna and coincides with the "xy" plane.

The antenna width and thickness were set to suitable values for 3-D printing using FDM of $W = 7\,\text{mm}$ and $th = 0.7\,\text{mm}$, respectively, and this choice has the additional advantage of reducing the number of design variables. Likewise, the feeding port gap is fixed during all the design stages to $\Delta = 1\,\text{mm}$. The frequencies chosen for operation are: $f_1 = 1.7\,\text{GHz}$, $f_2 = 2.45\,\text{GHz}$, $f_3 = 3.5\,\text{GHz}$, which are widely used for the operation of wireless services.

The starting estimates of the arm lengths are obtained assuming the existence of three uncoupled monopoles at the three operating frequencies f_i as

$$L_{fi} = Kc/f_i - W/2\pi \quad (1)$$

with $K = 0.24$, $c = 3 \times 10^8\,\text{m/s}$, $W = 7\,\text{mm}$. The calculated lengths are: $L + h + \Delta = L_{f1} = 40.6\,\text{mm}$, $W_l + L_l = L_{f2} = 28.2\,\text{mm}$, $W_r + L_r = L_{f3} = 19.7\,\text{mm}$. Full-wave electromagnetic simulation performed with the Integral Solver of CST Microwave Studio was used for the refinement of these lengths.

From a sweep of the antenna's geometrical parameters, aimed at fine-tuning the desired matching frequencies, it was noticed that the separation between the antenna arms and the ground plane has a large impact on the input impedance match: for the case in which the arms are relatively close to the ground plane, this can be partly explained by a large coupling of the portions of the antenna parallel to the ground plane and the latter, thus the monopoles arms effectively become a transmission line, and therefore, the impedance seen from the splitting point is a transformed version of the radiation impedance, whereas for the situation of high h the feed is split in a lower current position, i.e., at location having a higher impedance, thus leading to a performance that is not well described by operation principle described above. In that case, the impedance at the splitting point should be obtained by a de-embedding procedure, which enables proper matching at the input port.

Once the initial arm lengths are defined, their modification allows a somewhat independent control of the corresponding resonances. The final parameter values are summarized in Table 2.

Table 2. Antenna parameters (all values are in mm).

Parameter	L	h	W_r	L_r	W_l	L_l	d_r	d_l
Value	31.7	8.0	10.35	7.7	17.35	15.7	5.0	9.2

3. MANUFACTURING PROCESS

The manufacturing process in this work aims at the creation of completely metallic antennas, which, in contrast to the metal cladding of AM plastic shapes, translates in superior endurance to heat, which is a useful feature for antenna soldering, as well as for high-power operation or deployment in hot environments.

The manufacturing process involves the extrusion of a blend which is 90% composed of rounded-shape copper-powders, with particle size smaller than 80 µm and larger than 20 µm, embedded in a filament-shaped polymeric matrix totalling the remaining 10% of the mixture (the composite material can be observed in Fig. 2(a)). The filament is currently being developed using a hot extrusion method in the Foundry and Powder Metallurgy Laboratory in Universidad Nacional de Colombia [25].

The extrusion is made using Fused Deposition Modeling (FDM) with a conventional Creality Ender-3 3-D printer, using the Ultimaker Cura software to control the processing parameters such as printing speed, temperature of extrusion, "z-axis" resolution, and other parameters, which are set to the standard values used in FDM of plastic materials such as Acrylonitrile Butadiene Styrene (ABS). After this printing stage is completed, and a "green part" is obtained as the one shown in Fig. 3(a), which corresponds to the part shape desired with the copper powders still immersed on the polymeric matrix.

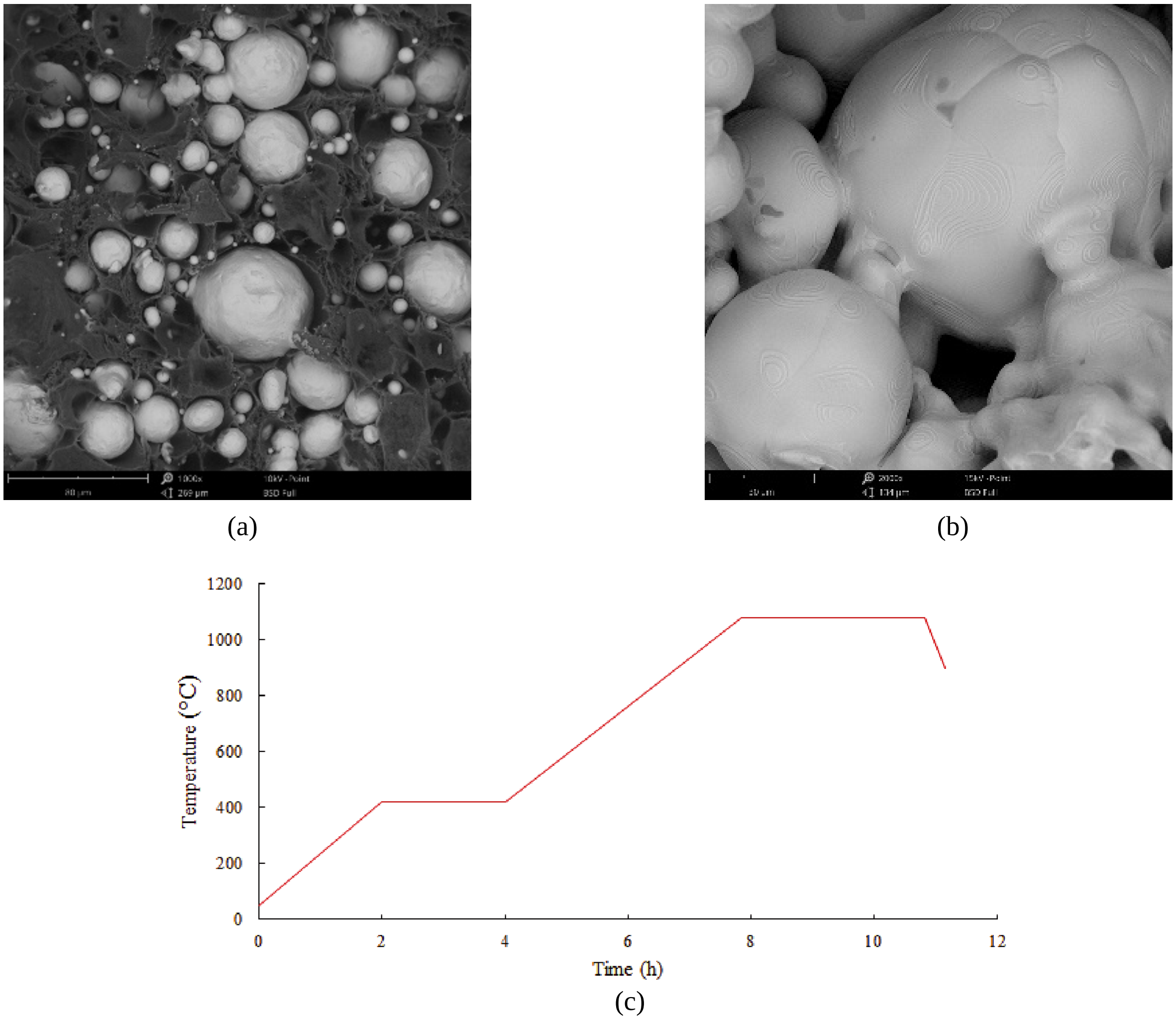


Figure 2. Manufacturing process observed by scanning electron microscopy. (a) Composite material. (b) Neck growing and coalescence of copper particles. (c) Temperature profile.

A purely metallic component with the optimal electrical properties results from the subsequent processes of de-binding and sintering, which are very sensitive to temperature and time. The temperature profile of the whole process is summarized in Fig. 2(c). In the de-binding stage, the polymer is thermally removed by heating the structure with a heating rate of 3°C/min, reaching a temperature between 300 and 400°C and keeping it for 2 hours. Afterwards, during the sintering, the component is exposed to a high temperature just below the copper melting point (1083°C) for another 3 hours. At this temperature, the mass transport phenomenon takes place due to the atomic diffusion of the copper atoms, giving rise to neck growing and the coalescence of the copper particles as can be seen in Fig. 2(b)). As the atomic diffusion is time-dependent, the sintering time may affect the electrical properties of the final component.

In sintering processes it is common to observe porosity in the final material; using microscopy images, the air content of our final prototype was estimated to be in the range 25–30% of total antenna volume and is distributed uniformly regardless of the FDM printing axis. After de-binding and sintering are accomplished, no further processing is performed (the final antenna prototype is presented in Fig. 3(b)). Finally, the monopole antenna is carefully soldered to the inner conductor of an SMA connector centrally mounted on a square ground plane with 20 cm side length.

At this point it is interesting to mention that we carried out initial experiments with thinner

(a) (b)

Figure 3. Manufactured antenna. (a) Composite material. (b) Sintered.

structures which did not remain attached at the final stage, hence the thickness chosen for the prototype presented here. Furthermore, a refinement of the computer-aided design (CAD) representation of the prototype was required to maintain structural integrity; specifically, fillets were introduced throughout the wedges of the original structure to avoid cracking.

4. EXPERIMENTAL RESULTS

Validation is performed by comparing the antenna attained with the process described in this work with simulation results and with our previously reported set of 3-D "cactus" antennas realized by either vacuum Aluminum (Al) deposition or Copper (Cu) electroplating of an Acrylonitrile Butadiene Styrene (ABS) base structure. The check includes input impedance and both radiation pattern and realized gain; the latter is essential in this work, as we did not have any reference on the conductivity of the material that resulted from our process at the operation frequencies.

We validated the performance of our design experimentally in an anechoic chamber. The measurements were carried out in the facilities at Pontificia Universidad Javeriana, and the setup is illustrated in Fig. 4.

We have compared the measured performance of our design with measurements of a copper clad ABS 3-D printed antenna presented in [8] and for reference, with simulated results of an identical Perfect

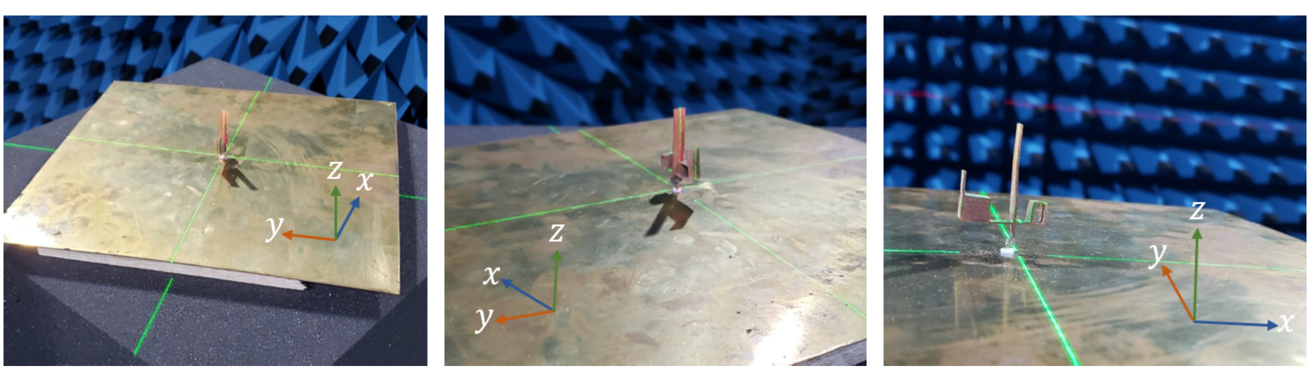
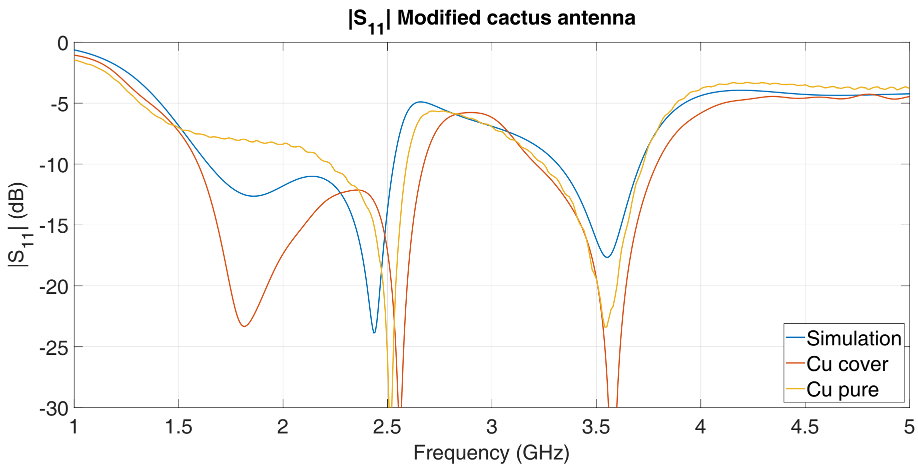
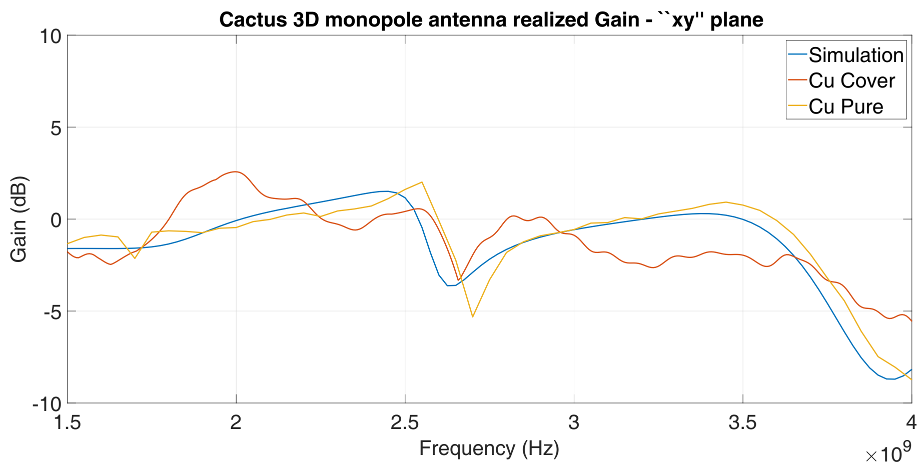


Figure 4. Measurement setup.



(a)



(b)

Figure 5. Comparison of simulated antenna behavior considering PEC material with measurements of two 3-D printed structures: a copper clad design presented previously in [8] (Cu cover), and the purely metallic FDM structure presented in this work (Cu pure). (a) $|S_{11}|$. (b) Realized gain.

Electric Conductor (PEC) antenna (including material thickness). These results are presented in Figs. 5 and 6.

Concerning results in Fig. 5(a), there is a good correspondence between all the curves; nevertheless, the first resonance, occurring around 1.5 GHz, has a faint behavior for the structure presented in this work, which we traced back to the real part of the impedance being lower than the port impedance.

The realized gain G of our prototype is compared in Fig. 5(b) to simulation and the reference structure mentioned previously. Variations within 1 dB from those predicted by the simulation demonstrate the high efficiency of the conducting material resulting from the manufacture process proposed.

Relevant cuts of the radiation pattern at the frequencies of resonance are illustrated in Fig. 6. In this case also, a very good agreement with simulation and the copper cladded prototype results is observed. As expected, the radiation pattern at the lowest frequency resembles that of a monopole antenna, whereas in the second and third resonant frequencies the field is mostly directed towards the active arm. This behavior can be explained by observing the antenna structure where the central monopole becomes a reflector for the waves generated by the lateral arms.

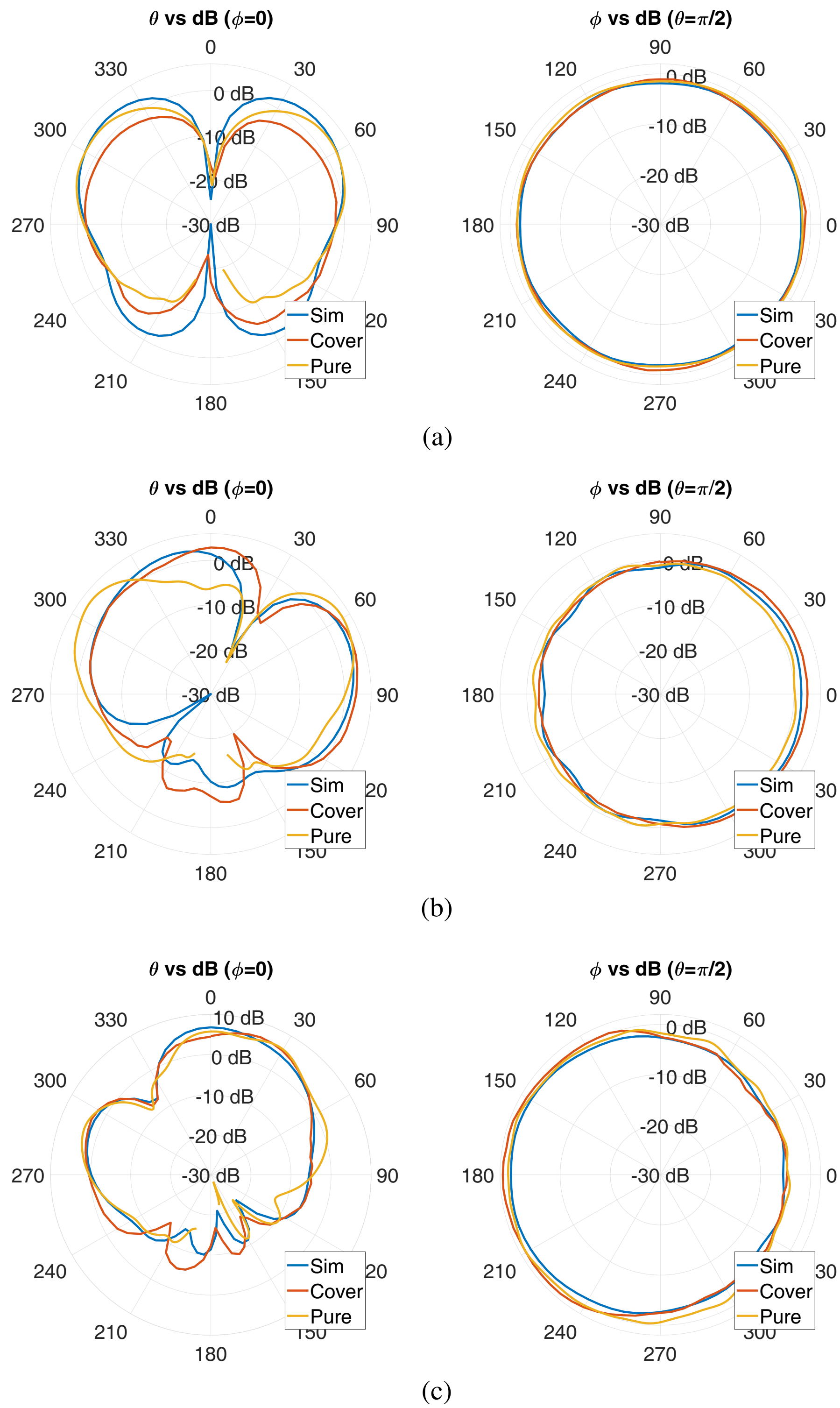


Figure 6. Comparison of radiation pattern cuts for the simulated antenna considering PEC material, with measurements of two 3-D printed structures: a copper clad design presented previously in [8] (Cover), and the purely metallic FDM structure presented in this work (Pure). (Left $\phi = 0$). (Right $\theta = \pi/2$). (a) $f = 1.7\,\text{GHz}$. (b) $f = 2.45\,\text{GHz}$. (c) $f = 3.5\,\text{GHz}$.

5. CONCLUSIONS AND FUTURE WORK

It was demonstrated that the use of the FDM of all-copper antennas is technically feasible, supporting the applicability of the manufacture process for the production of components with different geometries and sizes for electronics applications.

The manufacturing process presented in this work entails no significant loss in antenna performance, including efficiency, with respect to additive prototyping techniques previously validated by the authors and even simulation results, and overall provides a cost-effective method for the production of metal-only antennas.

Due to high de-binding/sintering time required in this process, for industrial scaling purposes, it would be needed to process a large number of pieces at the same time. Nevertheless, further research efforts are due in order to determine the microstructural influence of the de-binding/sintering for large production batches.

The porosity displayed by the metal parts at the end of the process (about 30%) does not seem to impact the electromagnetic behavior of the antennas manufactured with this process; this indeed could be of interest to reduce the final weight or reduce air drag. On the other hand, it should be noted that the material resulting from our manufacture process is not very robust mechanically speaking, as it required careful handling to avoid warping or breaking.

A basic guideline for better results is that the geometrical design avoids thin surfaces and sharp edges, which usually involves some CAD refinement of the original design. Further research is required to fine tune the geometrical and processing parameters to ensure mechanical robustness. For future work, we aim at manufacturing complex antenna structures that take advantage of the flexibility afforded by 3-D printing.

ACKNOWLEDGMENT

The authors thank the Powder Metallurgy and Electrical Laboratories of Universidad Nacional de Colombia Sede Bogotá, for the logistical, technical, human and financial support of the project.

REFERENCES

1. Gibson, I., D. W. Rosen, and B. Stucker, *Additive Manufacturing Technologies*, Springer-Verlag, New York, 2015.
2. Gao, W., Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C. B. Williams, C. C. Wang, Y. C. Shin, S. Zhang, and P. D. Zavattieri, "The status, challenges, and future of additive manufacturing in engineering," *Computer-Aided Design*, Vol. 69, 65–89, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0010448515000469.
3. Attaran, M., "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing," *Business Horizons*, Vol. 60, No. 5, 677–688, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0007681317300897.
4. Tofail, S. A., E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, and C. Charitidis, "Additive manufacturing: Scientific and technological challenges, market uptake and opportunities," *Materials Today*, Vol. 21, No. 1, 22–37, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1369702117301773.
5. DebRoy, T., H. Wei, J. Zuback, T. Mukherjee, J. Elmer, J. Milewski, A. Beese, A. Wilson-Heid, A. De, and W. Zhang, "Additive manufacturing of metallic components — Process, structure and properties," *Progress in Materials Science*, Vol. 92, 112–224, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0079642517301172.
6. Frazier, W. E., "Metal additive manufacturing: A review," *Journal of Materials Engineering and Performance*, Vol. 23, No. 6, 1917–1928, Jun. 2014. [Online]. Available: https://doi.org/10.1007/s11665-014-0958-z.

7. Herzog, D., V. Seyda, E. Wycisk, and C. Emmelmann, "Additive manufacturing of metals," *Acta Materialia*, Vol. 117, 371–392, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1359645416305158.
8. Ramirez Arroyave, G. A. and J. L. Araque Quijano, "Evaluation of additive manufacturing processes for 3-D multiband antennas," *2018 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, 589–592, Sept. 2018.
9. Ramírez Arroyave, G. A. and J. L. Araque Quijano, "Optimization and additive manufacture of a miniature 3-D pixel antenna for dual-band operation," *Progress In Electromagnetics Research B*, Vol. 85, 163–180, 2019.
10. Huang, Y., X. Gong, S. Hajela, and W. J. Chappell, "Layer-by-layer stereolithography of three-dimensional antennas," *2005 IEEE Antennas and Propagation Society International Symposium*, Vol. 1A, 276–279, Jul. 2005.
11. Maas, J., B. Liu, S. Hajela, Y. Huang, X. Gong, and W. J. Chappell, "Laser-based layer-by-layer polymer stereolithography for high-frequency applications," *Proceedings of the IEEE*, Vol. 105, No. 4, 645–654, Apr. 2017.
12. Adams, J. J., E. B. Duoss, T. F. Malkowski, M. J. Motala, B. Y. Ahn, R. G. Nuzzo, J. T. Bernhard, and J. A. Lewis, "Conformal printing of electrically small antennas on three-dimensional surfaces," *Advanced Materials*, Vol. 23, No. 11, 1335–1340, 2011. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201003734.
13. Menéndez, L. G., O. S. Kim, F. Persson, M. Nielsen, and O. Breinbjerg, "3D printed 20/30-GHz dual-band offset stepped-reflector antenna," *2015 9th European Conference on Antennas and Propagation (EuCAP)*, 1–2, Apr. 2015.
14. Ghazali, M. I. M., E. Gutierrez, J. C. Myers, A. Kaur, B. Wright, and P. Chahal, "Affordable 3D printed microwave antennas," *2015 IEEE 65th Electronic Components and Technology Conference (ECTC)*, 240–246, May 2015.
15. Gjokaj, V., P. Chahal, J. Papapolymerou, and J. D. Albrecht, "A novel 3D printed Vivaldi antenna utilizing a substrate integrated waveguide transition," *2017 IEEE International Symposium on Antennas and Propagation USNC/URSI National Radio Science Meeting*, 1253–1254, Jul. 2017.
16. Van der Vorst, M. and J. Gumpinger, "Applicability of 3D printing techniques for compact Ku-band medium/high-gain antennas," *2016 10th European Conference on Antennas and Propagation (EuCAP)*, 1–4, Apr. 2016.
17. O. Tech., "Metal 3D printed custom antennas," 2018. [Online]. Available: https://www.optisys.tech/.
18. Foged, L. J., A. Giacomini, R. Morbidini, F. Saccardi, V. Schirosi, M. Boumans, B. Gerg, and D. Melachrinos, "Investigation of additive manufacturing for broadband choked horns at X/Ku band," *IEEE Antennas and Wireless Propagation Letters*, Vol. 17, No. 11, 2003–2007, Nov. 2018.
19. SENER, "Sener aeroespacial and catec develop a 3D-printed metal antenna for the European Space Agency's Proba-3 space mission," 2019. [Online]. Available: https://www.group.sener/press-releases/sener-aeroespacial-and-catec-develop-a-3d-printed-metal-antenna-for-the-european-space-agencys-proba-3-space-mission/.
20. Helena, D., A. Ramos, T. Varum, and J. N. Matos, "Antenna design using modern additive manufacturing technology: A review," *IEEE Access*, Vol. 8, 177 064–177 083, 2020.
21. Ramírez Arroyave, G. A., "Design of a multiport frequency reconfigurable antenna suitable for IMT-advanced communications systems," Ph.D. dissertation, National University of Colombia, Ciudad Universitaria, Bogotá, 2020. [Online]. Available: https://repositorio.unal.edu.co/handle/unal/78517.
22. Pan, C., C. Huang, and T. Horng, "A new printed G-shaped monopole antenna for dual-band WLAN applications," *Microwave and Optical Technology Letters*, Vol. 45, No. 4, 295–297, 2005. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/mop.20800.
23. Zachou, V., C. G. Christodoulou, M. T. Chryssomallis, D. Anagnostou, and S. Barbin, "Planar monopole antenna with attached sleeves," *IEEE Antennas and Wireless Propagation Letters*, Vol. 5, 286–289, 2006.

24. Mishra, S. K., R. K. Gupta, A. Vaidya, and J. Mukherjee, "A compact dual-band fork-shaped monopole antenna for bluetooth and UWB applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 627–630, 2011.
25. Garzón Cuervo, D. F., L. López Kleine, and L. K. Herrera Quintero, "Ingeniería de fabricación rápida en la industria 4.0: Estudio de propiedades mecánicas y eléctricas de piezas metálicas fabricadas mediante manufactura aditiva," Tech. Rep., Universidad Nacional de Colombia, 2020.