A copper pyramidal fractal antenna fabricated with green-laser powder bed fusion

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Abstract

Recent advances in additive manufacturing have enabled a new generation of electromagnetic applications to flourish. Complex geometries for dielectrics and conductors can now be simulated and rapidly fabricated from digital data. Powder bed fusion of metals is arguably the most widely adopted additive process by industry and can provide intricately-detailed structures in a wide range of high performance alloys. Copper and copper alloys have remained a challenge in this additive process, as the typical laser wavelength (approximately 1070 nm) used fails to provide sufficient absorption. Moreover, the high thermal conductivity of copper does not allow for the required heat generation for a stable melt pool. However, the recent commercial introduction of the green laser (515 nm wavelength) is enabling the printing of copper, which is particularly interesting for electrical and electromagnetic applications due to the high electrical conductivity and solderability. This paper describes the use of a green laser powder bed fusion system used to fabricate a complex fractal Sierpinski gasket ground structure with an isolated internal pyramid antenna built simultaneously—within and dielectrically isolated from the external ground element: a ship-in-the-bottle design paradigm. The electromagnetic performance, surface finish, dimensional compliance, and conductivity were measured and reported to inform the design of freestanding, geometrically-complex antennas.

Keywords Additive manufacturing · Green laser · Powder bed fusion · Fractal antennas · Copper · Sierpinski gasket

1 Introduction

Additive manufacturing (AM) originally enabled rapid prototyping of freeform structures but has more recently graduated to fabricating customized and complex end-use components from high-performance materials for a diverse array of industrial applications. One field that stands to benefit dramatically from AM is electromagnetics, in which unprecedented geometries are now feasible with 3D control of the placement of either conductive or dielectric materials or both together in new geometric topologies [1]. Yet, until recently, direct printing of materials with high electrical conductivity

has not been possible. Powder bed fusion (PBF) is one of the most widely embraced processes in the industry for customized metal fabrication; nevertheless, commercially-available metals have offered only a fraction of electrical conductivity as compared to traditional electrical manufacturing [2]. However, the introduction of the green laser in PBF is now enabling the fabrication of nearly full-density copper and copper alloy structures.

Antennas have been fabricated for years across many AM processes. Initially, 3D printed antennas largely featured conductive ink deposition on polymer substrates [3–13], enabling complex surface conduction for tunable electromagnetic (EM) characteristics; however, most applications only reached a fraction of the bulk conductivity based on limits on curing temperatures imposed by the polymeric substrates. Alternatively, exclusively polymer deposition (fused filament fabrication, material jetting and vat photopolymerization) have been employed for lensing elements that rely exclusively on dielectric materials, or with doped dielectrics containing conductive particles [14–17]. Building from polymer substrates has the advantages of weight savings and

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inexpensive material, but can come at the expense of performance, depending on the (EM) application [18]. For this reason, metallization of these parts by means of plating, painting and sputtering conductive material, either selectively or fully, can be effective, so long as the surface roughness of the components does not interfere with desired frequencies of interest [19–21]. Requirements of greater non-load-bearing mechanical stability and skin depth limitations motivate the need for fully metallic objects, which can improve components such as waveguides and free-standing antennas [22–25].

Combining both high thermal and electrical conductivity, copper remains one of the most favorable materials for fabricating EM products. Each of the seven methods of AM has been reported to fabricate or include copper alloy structures, surfaces or filaments. Copper wire has been embedded with selective heating in thermoplastics, conductors which retain bulk conductivity [26]. Surface metalization research has been achieved for antennas of all types (slot, fractal, horn, patch, reflectarray, etc.), with applications including radio frequency identification (RFID), thermal management of LEDs, telecommunications and snow-pack monitoring, and microwave waveguide lightweighting [18, 26–47].

Several additive processes are effective at fabricating complete copper structures. Highly precise Vat Photopolymerizable (VPP) metallic slurry-based methods have been developed by Admatec, which result in highly dense and smooth parts, but with the requirement of sintering which results in some shrinkage and porosity. Alternatively, binder jetting has been applied to a diversity of applications, but as studies suggest, these parts can be hampered in both conductivity and thermomechanical performance due to limited densification of green state parts [48, 49]. However, applications have been reported to have less-than-fully-dense foams which may benefit from porosity for lightweighting or impact energy management [50]. Recently, commercially-available systems provide material extrusion 3D printing of polymer filament, including suspended metal powder—enabling the fabrication of green parts that after further debinding and sintering, which can provide nearly-full dense structures. Although all of these processes can result in complex and nearly-full density copper structures, limitations remain in the debinding of thick bulky parts and shrinkage resulting from sintering [51–54].

While all of these AM processes have their associated advantages for electromagnetics in terms of cost and office-friendly printing, PBF can provide complex metal parts with more than 99% density with minimal shrinkage, but copper has been a challenge, particularly for laser-based systems. PBF of metals subsumes two processes defined by the fusion source, including (1) electron beam- and (2) laser-based melting. Electron beam melting offers high energy and reliable melting under vacuum to avoid oxidation [55–57], but

requires larger powder size distribution, which impacts surface roughness and resolution. In contrast, early attempts to print copper components with laser powder bed fusion (LPBF) were less successful due to reflectivity and insufficient power. Traditional laser systems use red lasers, and while sufficient for metals of lower reflectivity and thermal conductivity, melt pool stability remains a challenge for copper. Increasing the laser power can result in increased spattering as well as energy reflected back toward the lasing system, and at high wavelengths, more contaminants can be incorporated in builds, which can reduce electrical conductivity [58–60]. Even with these shortcomings, researchers have been successful in developing prints in both high purity copper and alloyed components [2, 61–74]. Parts that are dependent on surface finish, like metamaterial latticing and high-frequency electromagnetic designs, have still met standards [75, 76]. Through these innovations, reasonable results have been obtained, although the introduction of blue and green wavelength lasers is advancing LPBF for structures with improved electrical and thermomechanical properties of printed copper parts [72, 73]. Recently, blue laser systems have begun to resolve the issue of power limitations [77]. New green laser systems, such as the Trumpf TruPrint 1000 Green Edition are well suited for copper and copper alloys.

The objective of this work is to demonstrate the utility of recently-available green laser processing in PBF to create a complex, novel and functional fractal antenna with a standing wave ratio of less than two and a discrepancy of less than 7 MHz between simulation to experimental resonances—all of which can be explained by post-processing assembly steps such as soldering, component alignment, and surface finishing. The 3D printed copper antenna was evaluated in terms of electromagnetic and dimensional performance, as well as manufacturability. All with the aim of informing antenna designers about the potential and limitations of this 3D printing process, capable of creating complex structures with copper and well suited for electromagnetic applications.

2 Materials and methods

The copper printing capabilities of the Trumpf TruPrint 1000 Green Edition with a 515 nm wavelength green laser (Fig. 1) were evaluated with typical figures of merit for electromagnetic evaluation. Surface roughness scans of finished parts were assessed. A desktop Wheatstone bridge setup was assembled for the determination of isotropic conductivity characteristics. A novel Sierpinski gasket antenna was designed with an internal conductor, allowing for the singular printing of the end-use part. The manufactured structure underwent an antenna simulation and was then evaluated for electromagnetic performance.

Fig. 1 Trumpf TruPrint 1000 green edition with green laser

2.1 TruPrint 1000 with green laser (515 nm)

The TruPrint 1000 Green Edition printer combines the capabilities of advanced lasers with PBF printing. The TruDisk 1020 is a high-power 515 nm continuous-wave industrial green lasers system based on a Yb:YAG thin-disk laser platform with intracavity frequency doubling, which delivers a maximum output power of 1 kW [78]. The system emits a beam with a brightness of 2 mm × mrad, transmitted by the beam delivery fiber, is collimated and deflected via a pair of galvanometer scanners, and focused by a f-theta lens to a spot size of 200 μm diameter with a top-hat intensity distribution before operating on the 7854 mm² TruPrint 1000 processing plane. This unique combination is well suited for LPBF printing of both copper and copper alloys. Copper, copper-based alloys, and other high thermal conductivity metals have higher energy absorption, based on molecular bandgap excitation within the metals, at green wavelengths than at the wavelengths associated with red diode lasers used in traditional PBF systems (see Fig. 2). The metal welding process can thus be stabilized with lower reflectivity, key-hole porosity, and balling [78].

The powder used in this study was Hoegenaes Cu OFCH powder 99.99% copper, with a particle size distribution of 15–53 microns. Conductivity measurements of up to 102% of the International Annealed Copper Standard (IACS) were obtained for the powder. It should be noted that the IACS was established over a century ago, and significant improvements in metallurgical processes have enabled modern manufacturers to exceed the conductivity thresholds established at that time. The system is capable of producing wall thicknesses in the 0.4–0.6 mm range when scan speed and power settings are controlled [78]. Table 1 provides the system process parameters that were used to build the antenna

Fig. 2 Comparative absorptivity plot of copper and other conductive metals by wavelength

prototype. This was a standard parameter set that will be optimized for further applications.

Table 1 Laser printing process parameters

Wavelength (nm)	515
Power (W)	485
Scan speed (mm/s)	600
Hatch distance (mm)	0.12
Layer thickness (mm)	0.03
Inert gas type	Argon

2.2 Dimensional compliance and surface roughness evaluation

To determine the overall dimensional accuracy of the antenna, the Faro Quantum S ScanArm 3D scans of the print were compared with the parent CAD model from the simulation to determine compliance [79]. Additionally, surface roughness measurements were conducted using the Keyence 3D Optical Profilometer–VR-5000 [80]. Such measurements serve to determine if the AM process is viable for high-frequency devices. For a specific frequency of interest, roughness on the order of approximately 1/10 of the wavelength is generally considered electromagnetically irrelevant. For example, the 2.4 GHz frequency used in many commercial radio applications has a wavelength of 6.5 cm and, therefore, spatial distortions less than 6.5 mm are considered immaterial. However, in the case of the antenna fabrication, dimensional compliance is paramount and it is most directly correlated with the resonance. Imperfections on a scale much smaller than the wavelength of interest generally will not impact antenna performance through the skin effect.

2.3 Antenna design and simulation

To demonstrate the utility of the green-laser PBF, an antenna geometry was selected that was both novel and complex, leading to the selection of the 3D ship-in-a-bottle Sierpinski gasket design. While other fractal designs, and Sierpinski designs for that matter, have been successfully printed before, this design nests a radiator within a gasket 3D ground plane [11, 23, 37, 38, 81, 82]. Previously, the Sierpinski gasket has been shown to have multiband and electrically small characteristics, with overall band congruence shown to have a dependence on the number of iterations in the fractalization design hierarchy: as the number of iterations approaches infinity, the bands become more mathematically similar [82]. Here, the internal component was positioned by non-conductive adapters on all four faces, strategically

maintaining the alignment of the ground plane pyramid symmetrically in the center of the radiating pyramid (see Fig. 3). The dielectric properties of the non-conductive supports were approximated to typical thermoset values in conjunction with the known values of the copper conductor parts in ANSYS HFSS simulations. A canting evaluation was conducted about the orthocenter of the internal pyramidal structure. Rotations about the x, y, and z axes were parameterized for low-angle deviations from perfect alignment to perform a misalignment sensitivity analysis. Common metrics of S_{11} and VSWR were taken to characterize antenna transmission.

2.4 Conductivity (DC) measurement and anisotropy

To determine the conductivity of the copper printed parts, a Fischer Sigmascope SMP350 was used to measure via the phase-sensitive eddy current method [78]. When properly welded, highly dense parts (> 99.5% density) result in an electrical conductivity of 5.8×10^7 S/m ($100 (\pm 2)\%$ IACS) and a thermal conductivity of approximately 400 W/(m*K). A Wheatstone bridge test was performed with the antenna treated as the unknown load. Multiple combinations of the terminal points on the antenna geometry were used to account for potential anisotropic conductivity behavior of the part—between layers and within a layer. Given that the antenna build orientation was in an upright position, the base vertices shared the same build layer, so measuring conductivity variations over multiple layers was not feasible in this case. This drove the need to test along all edges between vertices (Fig. 4).

2.5 Antenna evaluation

By measuring input impedance, radiation patterns, polarization, gain, specific absorption rate (SAR) and directivity of the antenna, the multiband behavior can be optimized to enhance many commercial applications, including multiband and frequency hopping. Complex input impedance

Fig. 3 Simulation body and picture of a nested Sierpinski gasket dipole with polymer standoffs (gray parts) and SMA connector included

Fig. 4 Conductivity readings were taken from the paired (same colored) points on every face. Every edge of the antenna was evaluated

measurements can provide information on the antenna's reflection characteristics, resonant frequency, radiation efficiency and the need for a matching network if used in the typical 50- Ω circuit [83]. S-parameters describe the input–output relationship between two terminals in an electrical system. Specifically, the S_{11} parameter represents how much power is reflected from the antenna back to the transmitter circuit. If the antenna complex impedance ($Z_L = Z_{\text{Real}} + jZ_{\text{Imaginary}}$) is equal to the complex conjugate of the line characteristic impedance (Z_0), then the transmission line is said to be “matched”. In this case, there is no loss to impedance mismatch reflections and all the power is transferred to the antenna. Qualitatively, the magnitude of the reflection coefficient is the ratio of power the antenna is absorbing and therefore radiating and/or losing to other ohmic losses such as heat dissipation. Direct measurement of the complex input impedance allows the design of the impedance matching network to maximize power delivery to the antenna. For the purposes of this study, antenna impedance was measured without the use of a matching network to give insight on the effects of the design and manufacturing processes on the finished product. Future work includes the design of a matching network, gain, directivity, and radiation pattern measurements to establish the prospective use of such a geometry, which can only be produced through manufacturing methods presented in this work. These elements are more related to the design rather than the manufacturing process.

3 Results and discussion

The antenna was reviewed for dimensional and surface abnormalities. While the dimensional accuracy and surface finish were acceptable, the surface roughness was slightly more coarse than traditional LPBF. Additionally, the antenna resonance was in near accordance with the expected simulation results. Lastly, the evaluation of conductive isotropy relative to build orientation showed minimal deviation along nonplanar edges of the conductive geometry.

3.1 Dimensional compliance and surface roughness

The antenna was printed successfully without any substantial defects, with support structures for the extreme overhangs preventing any sagging or noticeable warping. The part was shot-blasted with Al_2O_3 and glass beads but received no heat treatment, hot isostatic pressing (HIP), or similar post-processing steps. Additionally, printing resulted in minimal deviation from CAD measurements. A 3D surface scan of the part was taken, and analyzed the extent of surface deviation (Fig. 5) to be a maximum difference between intended and actual surface position of 0.222 mm.

Three dimensional optical profilometry was conducted on the part faces (Fig. 6). The arithmetic mean height (18.5 μm) and root mean square height (24.8 μm) are reasonable, and future optimization will bring this in line with conventional LPBF values associated with other metals processed with red wavelength lasers [22]. The surface roughness of the antenna has a minimal impact on the conductivity, however, it may change the surface current distributions especially in K, Ka, and other mm-wave frequency bands, where the surface roughness is comparable to the radio frequency (RF) wavelength. Antenna geometries were designed for optimal performance in the 5GHz range, and therefore, For the purpose of this evaluation, the radiation characteristics of this evaluation were constrained to the IEEE C band. Specifically, the frequency values from 4.0 to 6.5 GHz.

3.2 Antenna evaluation

For RF evaluation of the antenna, complex impedance measurements for the S_{11} parameter were taken using the Rigol™ RSA5065N, Real-Time Spectrum Analyzer with Vector Network Analysis (VNA) (Fig. 7). A 50-Ohm SMA connector was soldered to the antenna and connected directly to the VNA 50-Ohm port via the Mini-Circuits™ NM-SM50 + SMA to N adapter.

The S_{11} calculation from the complex impedance measurement revealed the antenna to be most resonant at 5.569 GHz, exhibiting a return loss of -9.323 dB

Fig. 5 3D scan—compliance to design intent

Fig. 6 A full surface 3D optical profilometry

(Fig. 8). This compared to the S_{11} minima of -2.963 dB at 5.579 GHz for the HFSS model suggested a 10 MHz delta in expected minimum resonance from design simulation to physical measurement. There were clear similarities in the frequency of minimum reflectance and overall shape between measured and simulated S_{11} parameters. Additionally, the S_{11} parameter of -9.323 dB translated to a voltage standing wave ratio (VSWR) of 2.039 . These measurements

encourage further study of the antenna's RF characteristics such as S_{21} parameters leading to efficiency, radiation pattern, directivity, and gain.

When converting S_{11} from dB to linear units, it can be seen that a fraction of the total signal is reflected. The measured return loss suggests that approximately 88% of the transmitted power is absorbed by the antenna when connected to a $50\text{-}\Omega$ termination. This does not imply however

Fig. 7 Direct connection of the antenna to the VNA

Fig. 8 Measured versus simulated S_{11} return loss

that ~880mW of 1 W transmitted power is radiated by this particular antenna. Ohmic losses must be taken into consideration when calculating the transmission efficiency of the antenna. As seen in the antenna Smith Chart (Fig. 9), there is an impedance mismatch in the antenna input and the VNA port. There is also a rotation between the simulated and measured impedances. Looking at the plot, it could be said that the measured data being less concentrated in the upper half-circle implies that the simulation predicted more

inductive behavior than was actually measured. The rotation itself implies that the behavior of the measured antenna is congruent to that of the predicted model but shifted in frequency. The direct connection to the VNA via RF adapter (only an adapter separating the antenna from the port: sans transmission line) may be affecting the results of the measured input impedance. Impedance mismatches can be remedied through the use of a matching network. Antenna impedance is a direct result of the design methodology and

Fig. 9 Measured versus simulated S parameter Smith Chart

geometry, material selection, manufacturing and assembly processes. Without the use of a matching network, antenna performance degradation is to be expected. However, it was decided not to employ a matching network in this study as not to influence the raw performance characteristic of the novel manufacturing process.

The discrepancies between simulated and measured reflection coefficient magnitudes at ~ 5.57 GHz has yet to be determined. However, it is hypothesized that the main radiation mechanism is from fringing fields—with orthogonal lines between the inner and outer pyramid [84]. Through simulation analysis, it was found that any canting or off-alignment of the two pyramids can have a direct impact on radiation characteristics and therefore the perceived input impedance. Separation measurements between the pyramidal bases were made on the antenna (Fig. 10) and replicated in the HFSS model. These iterations lead to a stronger correlation of measurement parameters displayed in this work.

3.3 Conductivity

In evaluation of the potential for anisotropic effects on conductivity, a Wheatstone bridge test was performed on the antenna. Statistical data from the Wheatstone bridge was recorded for the assessment of the hypothesis that conductivity did not depend on the building orientation of this anisotropic manufactured structure. At the time of the test, the dipoles were disconnected, but an SMA connector had

Fig. 10 Separation between lower surfaces of inner and outer triangles in millimeters

been soldered to form the coaxial junction. Measurements for resistance were taken along four edges in the manner illustrated by Fig. 3, where shared edges were denoted by subscripts (Table 2). A single factor ANOVA evaluation proved that the test voltages found each edge resistance value measured for the bulk component to be reliable (Table 3). The implication being that the build orientation has minimal effects on the isotropic nature of the conductivity. For new geometries, antenna designers can ignore the influence of layer direction at least in terms of conductivity. However, surface roughness and stair stepping are features that may still need to be considered in terms of conductivity in these novel 3D printed antennas.

4 Conclusions

A nested Sierpinski gasket antenna was successfully printed using the Trumpf TruPrint 1000 Green Edition L-PBF system. Greater capabilities exist with systems of smaller build volumes, but a geometrically similar Sierpinski antenna of the necessary size would radiate beyond the capabilities of available testing equipment. Soldering of the RF feed components may have caused a frequency shift of the antenna, as copper thermal conductivity requires a high heat soldering environment and properly matched flux to avoid oxidation. Future work involving matching components will be tested for increasing antenna resonance. High conductivity copper components will be fabricated to further develop freeform electromagnetic and thermal management capabilities. A

Table 2 Wheatstone ANOVA approximated antenna resistance

Wheatstone ANOVA voltage readings (grand mean = 1.019×10^{-7}) $R_1 = 7.5 \text{ k}\Omega$; $R_2 = 75 \text{ m}\Omega$						
Edge Under Test	<i>N</i>	Mean detector voltage (μV)	Std. dev	Std. error	R_3 (Ω)	R_{antenna} ($\text{m}\Omega$)
Edge ₂₃	76	− 80.902	0.0002239736446	0.00002569153903	122.4	1.224
Edge ₁₂	74	37.175	0.0001827358052	0.00002124260587	111.2	1.112
Edge ₁₁	187	− 56.365	0.0002330991522	0.00001704589821	113.8	1.138
Edge ₂₂	83	37.679	0.0002149101348	0.00002358945191	116	1.160
Edge ₃₃	354	86.835	0.0002445523742	0.00001299781204	113	1.130
Edge ₁₃	82	62.804	0.0002638087767	0.00002913280581	112.9	1.129

Table 3 Single Factor ANOVA test for resistance variance demonstrating isotropic behavior

ANOVA resistance test summary ($\alpha = 0.001$)						
Source	DF	Sum of squares SS	MS	<i>F</i> -stat	<i>P</i> -value	<i>F</i> crit
Between groups	5	3.57E-06	7.14E-07	12.95071	3.67E-12	4.145531
Within groups	850	4.68E-05	5.51E-08			
Total	855	5.04E-05				

more rigorous follow-up evaluation is required for parts of lower complexity, however, statistical evaluations show a high confidence in the isotropic behavior of conductivity.

- The fabrication of a geometrically-complex and functional antenna was demonstrated with a green LPBF system.
- Preliminary evaluation shows good simulation-to-measurement agreement to validate the use of sophisticated 3D electromagnetic simulations for exploring the enhanced design space afforded by additive manufacturing—particularly of highly-conductive metals.
- Although the surface roughness was greater than previously printed components on the system, for the sake of the evaluated antenna frequency band, minimal effects on resonance were found.
- Ultimately, evaluations concluded that conductivity is not build-orientation dependent and is isotropic, as small differences in measured resistances were the result of measurement precision rather than actual regional surface roughness. Antenna designers can ignore conductivity effects based on how the part is oriented during fabrication.
- Surface roughness was not highly dependent on the build orientation, but stair-stepping could require consideration for frequencies at or greater than the K_a band (26.5 GHz and above). Future work will endeavor to optimize printing parameters.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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