Low-Cost Method for Internal Surface Roughness Reduction of Additively Manufactured All-Metal Waveguide Components

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***Abstract*— In this study, a novel low-cost polishing method for internal surface roughness reduction of additively manufactured components, developed for waveguide (WG) circuits operating in the millimeter frequency range is proposed. WG components fabricated using powder bed fusion (PBF) generally feature roughness of ten to fifty microns, which influences the increase of roughness-related conductor power losses having a major effect on the electrical performance of additively manufactured all-metal WGs. To improve and decrease the surface roughness of circuits fabricated using PBF, glass microbeads as an abrasive medium are proposed to be used in combination with a rotary tumbler. This technique allows the abrasive medium to efficiently penetrate internal long channels and cavities, having cross section dimensions in the range of sub- to a few millimeters. An experimental study was carried out on an example of WG sections and bandpass filters fabricated using PBF through selective laser melting (SLM), operating within the 8.2 to 40 GHz range. Polishing impact on both mechanical and electrical properties was studied showing surface roughness reduction by 18% and sixth order filter's insertion loss reduction at 23 GHz by 40% after 24 h of tumbling with 300–400 μm large glass microbeads.**

***Index Terms*— Additive manufacturing (AM), all-metal waveguide (WG), glass microbeads, mm-wave electronics, power losses, surface polishing, surface roughness, tumbling, WG.**

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I. Introduction

INCREASING demand for wireless communication systems throughput has been observed in recent years, which requires more efficient use of available resources [1], [2]. Extensive research efforts are directed toward the development of novel solutions and technologies allowing highly integrated and energy-efficient front-end production. A wide range of basic microwave building blocks such as: 1) filters [3], [4]; 2) power dividing/combining networks [5], [6]; 3) frequency multiplexers [7], [8]; and 4) antennas and antenna arrays' feeding networks [6], [9], and so on, are realized in strip transmission line and/or substrate integrated waveguide (SIW) techniques, all made with subtractive techniques. Despite many advantages, such circuits suffer from relatively high power loss being a combination of dielectric, conductor, and radiated losses. Low-loss passive devices are commonly produced with the all-metal waveguide (WG) technique [10], [11], where the wave propagates in lossless air, while attenuation is only due to the finite effective conductivity (combination of bulk conductivity, surface roughness, and frequency of operation) of the metallic walls. However, the main drawback of WG techniques relates to the physical production of such circuits, which requires expensive and precise machining. Moreover, the realization of complex structures is limited by subtractive manufacturing technologies such as computer numerical control (CNC) and electro discard machining (EDM). Such techniques also cannot be used for the realization of various high-frequency WG circuits in a single piece, which allows for avoiding power losses due to electrical contact issues among different parts [12].

To challenge the above issues additive manufacturing (AM) technologies have been proposed as an alternative for the production of various high-frequency electronic circuits [12], [13], [14], [15]. WG components in such a scheme can be printed out of nonconductive material using, e.g., stereolithography process (SLA) [16], [17], [18], fused filament deposition (FFD) [19], [20], and polyjet printing [21], [22], [23]. Nevertheless, such approaches require an additional fabrication step, during which the 3-D-printed plastic components are metal coated. An alternative solution is direct 3-D printing out of metallic materials [14] such as stainless steel, aluminum, titanium, nickel, or copper using powder bed fusion (PBF) technologies such as binder jetting (BJ) [24], [25], metal selective laser melting (SLM) [26], [27] and direct metal sintering (DMS) [28], [29]. In the context of RF/microwaves, SLM represents one of the most promising AM techniques, as complex geometries with internal features and channels can be easily realized.

One of the most significant issues related to WG circuit production through SLM technology, in comparison with subtractive technologies, is the high surface roughness [30], [31] on manufactured components. Roughness influences the insertion losses of fabricated circuits, especially visible at higher frequencies [32], [33], [34], [35], [36], [37]. In literature, many solutions for smoothing additively manufactured surfaces are presented, but most of them are used on plastic components [38], [39], [40]. For metal parts, on the other hand, mechanical polishing techniques are commonly used where vibration, tumbling, or rotation action forces the abrasive medium against the surface [41]. With these methods, outer surfaces are easily processed, while inner walls are challenging, especially for parts with fine internal features, since usually, the abrasive medium is too large to fit inside or too aggressive. An alternative is the electropolishing process [41], where the current-assisted reverse plating process in an electrolyte bath is used for smoothing the surface. It is well suited for the discussed application as the liquid could easily penetrate the interior. However, chemicals are required, making the process more expensive.

In this article, a novel low-cost polishing method for metal additively manufactured components is presented. This method is applied to WG components operating in the millimeter frequency range. In this regime, a wall roughness of tens of microns is hardly acceptable. Rough internal surfaces impact the electrical performance of components as it results in lower effective conductivity of walls as compared to bulk value. This is of importance since conductor-related losses are the only source of attenuation within the circuits, while in many cases metal type, composition, or bulk conductivity, is technology specific and cannot be altered to some extent. To overcome the challenge of the abrasive medium efficiently penetrating internals with long channels and/or (multiple) cavities having cross section dimensions in the range sub- to a few millimeters, a rotary tumbler is proposed to be used in combination with micro glass beads. An experimental study is carried out on a set of additively manufactured WG sections and bandpass filters operating within cm- and mm-wave frequency range, produced through SLM technology. Polishing impact on both mechanical and electrical properties was studied, showing surface roughness reduction by 18% and sixth order filter‘s insertion loss reduction at 23 GHz by 40%, after 24 h of tumbling with 300–400 μm large microbeads, hence validating the superior performance and applicability of the proposed method.

II. Additively Manufactured All-Metal WGs

In this section, the conductor and surface properties of additively manufactured all-metal WGs are studied. The impact of effective conductivity (influenced by metal conductivity), frequency of operation, and surface roughness on total power loss (TPL) (which is the key electrical performance metric for metal WG circuits), is elaborated. A low-cost surface polishing method for additively manufactured printed WG components postprocessing is introduced. Finally, test vehicles for experimental assessment of the method's performance are developed.

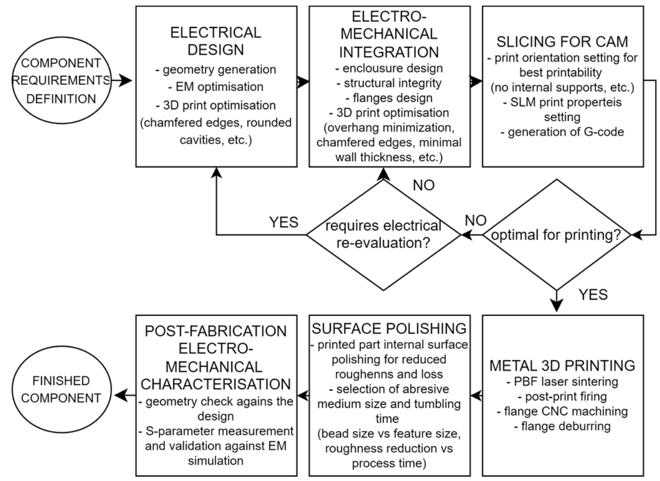


Fig. 1. Flowchart of the design to fabricate the process of microwave components using the proposed approach.

A general flowchart of the employed design to fabricate process is depicted in Fig. 1 where two domains are visible: digital preparation and physical fabrication. First, the component type and related requirements are defined. This is followed by an electrical design where the components' geometry is determined by means of full-wave electromagnetic (EM) simulations and optimization using computer aided desing (CAD) software. At this stage, the geometry optimization may already take advantage of the properties of the intended fabrication technology, i.e., 3-D printing which provides true 3-D flexibility. In addition, features that are helpful for better printability may already be accounted for such as edge chamfering or rounded corners. This is followed by electro-mechanical integration using yet another type of CAD software where mechanical features ensuring structural integrity such as wall thickness, coupling flanges, mounting holes, sub-component integration, and 3-D printing requirements adjustment are done. The next step is file preparation for computer aided manufacturing (CAM) using slicing software. Parameters such as part placement and print orientation are set and the software slices the model into layers and generates the G-code for CAM. It provides a report with potential print issues such as print instability, overhands, internal supports, too-thin walls, and so on. If any problem is indicated, either one or two earlier steps must be re-revisited depending on whether mechanical fixes may or may not affect the electrical performance. Otherwise, the part fabrication begins starting with 3-D printing using the SLM technology out of metal powder. Then the part is cut out of the built platform and if necessary, CNC machined to, e.g., flatten/surface flanges. Finally, the proposed post-processing method is applied to reduce the surface roughness of the print where glass beads are used as a polishing medium to tumble along with the part leading to reduced roughness and thus reduced power losses. The finished part is then characterized in terms of mechanical (geometry accuracy) and electrical (fulfillment of design requirements). If the objectives are fulfilled then the part is ready, if not the data can be fed back to the design loop and corrected for in the next iteration.

A. Surface Roughness Impact on WG Propagation Characteristics

To investigate the fabrication method's effect on WG components, we first consider wave propagation properties through a section of an air-filled rectangular WG operating in the fundamental TE_{10} mode. Signal transmission through a matched ($S_{11} = S_{22} = 0$) transmission line section is expressed in terms of scattering parameters (S-parameters) as follows:

$$S_{21} = S_{12} = e^{-\gamma l} = e^{-(\alpha + j\beta)l} \tag{1}$$

where l is the physical length of the lines, while γ is the complex propagation constant, and α and β are, respectively, the attenuation and propagation constants. As provided in [42], the complex propagation constant of the TE10 mode is

$$\gamma = \sqrt{(R' + j\omega L')\left(\frac{1}{R'' + j\omega L''} + G' + j\omega C'\right)} \tag{2}$$

and can be expressed in terms of per- and times-unit-length model resistance R (conductor-related losses), inductance L, conductance G (dielectric-related losses), and capacitance C. Conductivity and surface roughness of the guide‘s conductor has a significant impact on parameters representing the interaction of magnetic fields with conductive media, namely R' and R'', and partially L' and L''. In the case of an ideally smooth surface that represents the abrupt transition from dielectric into conductive media, the skin effect occurs, and thus, the current skin depth can be defined as follows [43]:

$$\delta = \frac{1}{\sqrt{\pi \mu_0 \mu_r \sigma_{dc} f}} \tag{3}$$

where μ_0 and μ_r are the vacuum and relative permeability, σ_{dc} is the conductivity, and f is the frequency. Nevertheless, it needs to be underlined, when the skin depth decreases to a similar range as the variation in surface profile due to roughness (as a reference, skin depth at 30 GHz for copper (60 MS/m) $\approx$ 0.38 μm, while for stainless steel (1.5 MS/m) $\approx$ 2.38 μm) [42], then (3) is no longer valid. In such a case, the conductivity is a variable parameter continuously depending on the spatial coordinates. It can be determined using, e.g., the Gradient Model [44] that requires only the rms roughness value R_q if the surface roughness follows the normal distribution. The impact of surface roughness is transferred into effective, frequency-dependent material parameters σ_{eff} (lower than σ_{dc}), and $\mu_{r,\text{eff}}$ (higher than μ_r). Then, the skin depths in rough surfaces for current densities δ_c and magnetic fields δ_m can be derived [42], to finally obtain R and L. The ohmic loss R mainly affects the attenuation coefficient, while the inner inductance L is related to the phase coefficient. Moreover, it is necessary to differentiate between the frequency region close to the cutoff frequency f_c and the usually used transmission region of a WG from $1.25 f_c$ to $1.9 f_c$, since rough surfaces affect the propagation properties with different orders of magnitude. On the one hand, the cutoff frequency decreases with increasing R_q due to an increase in both R and L, but on the other hand, increasing R_q imposes a severe increase of attenuation constant α in the typical frequency range. When R_q is much higher than the skin depth, b is increased at least twofold [42]. The impact of increased L is especially reflected in the phase coefficient β in the frequency region around f_c. Like α, the responses in β also exhibit a shift toward lower frequencies with increasing R_q. In addition, the slope reduces during the transition from attenuation to transmission region. However, in the typical frequency range of the WG, β is relatively insensitive to variations in R_q.

The previous study can be extended to resonators, which are basic building blocks for many circuits such as filters. The quality factor Q of a resonator describes its ability to store energy, and the unloaded quality factor Q_U is the maximum quality factor of the system. When there are only conductor losses, the Q_U value is inversely proportional to α and thus decreases when R_q increases. High Q_U is especially important when high selectivity filters operating at high frequency with low in-band insertion losses IL are to be realized, since [45]

$$\text{IL}(f_0) = 4.343 \frac{N}{Q_U \frac{\Delta f}{f_0}} \tag{4}$$

where N is the filter‘s order, while $\Delta f / f_0$ and f_0 are the fractional bandwidth and midband frequency, respectively. The impact of conductor properties (including surface roughness) becomes more pronounced as the number of resonators increases. The passband of a filter is also affected since R_q affects the propagation constant and in turn the resonant frequency. However, as indicated earlier within the WG's typical frequency range, this impact is relatively low and is more visible for highly selective filters.

In summary, the overall power losses in WG circuits depend on the frequency range of operation, bulk conductivity, surface roughness, and WG geometry. Therefore, it is crucial for a given fabrication technology and material to provide the smoothest inner surfaces where current flows and magnetic fields propagate, to minimize power losses.

B. Test Vehicles

The analysis presented in Section II-A suggests that two types of circuits might benefit differently from low surface roughness, namely: broadband sections of transmission lines where the attenuation constant is minimized, and narrowband-like filters where the unloaded quality factor is maximized. Therefore, a set of test vehicles was designed to include both types to operate in the cm/mm-wave frequency range.

First, rectangular WGs in various geometries were considered.

1) A 150 mm long straight section in WR-90 geometry (cross section of 22.86 $\times$ 10.16 mm, recommended band between 8.2 and 12.4 GHz).

2) A 100 mm long 90° twisted (five wavelengths) section in WR-42 geometry (cross section of 10.67 × 4.32 mm, recommended band between 18 and 26.5 GHz).

3) A 100 mm long straight section in WR-28 geometry (cross section of 7.11 × 3.56 mm, recommended band between 26.5 and 40 GHz).

Each guide was equipped with a flange for mating with the measurement equipment. On top of loss reduction, the usability of the method for complicated internal walls such as spiraled or rotated ones was benchmarked with the WG twist. Relatively long sections were realized to maximize the γl term change due to attenuation factor change since the measurement of low losses is limited by measurement system uncertainty. The full-wave models were simulated in *Ansys HFSS* software assuming metal properties and surface finish provided in Section II-C (Groisse model for roughness used). The predicted losses are 0.013 dB/cm for WR-90 at $f_{0\_\mathrm{WR}-90} = 10.5$ GHz, 0.048 dB/cm for WR-42 at $f_{0\_\mathrm{WR}-42} = 22.25$ GHz, and 0.073 dB/cm for WR-28 at $f_{0\_\mathrm{WR}-28} = 33.25$ GHz. Considering the EM-calculated losses of the WG, the unloaded quality factor can be established to be ~328 at $f_{0\mathrm{WR}-42}$.

Second, narrowband filters of different orders and bandwidths were developed.

1) A semi 3-D printing optimized second order bandpass filter, namely BPF2_42 in WR-42 geometry operating at the center frequency of 24 GHz with a relative bandwidth of ~8% for which the (4) yields $\mathrm{IL}_{\min}$ of 0.265 dB. The minimal dimension of the resonator cavity is ~5.5 mm; the minimal iris opening is ~4.4 mm.

2) A fully 3-D printing optimized sixth order bandpass filter, namely BPF6_42 in WR-42 geometry operating at the center frequency of 23 GHz with a relative bandwidth of ~10% for which the (4) yields $\mathrm{IL}_{\min}$ of 0.678 dB. The minimal dimension of the resonator cavity is ~10.6 mm; the minimal iris opening is ~4.4 mm.

3) A downscaled to WR-28 geometry version of the BPF6_42, namely BPF6_28 operating at the center frequency of 38 GHz. The minimal dimension of the resonator cavity is ~5.6 mm, while the minimal iris opening is ~3 mm.

Advanced layout optimization for AM [27], [46] was applied within a dedicated tool in *InventSim* software [47]. The final layout of both filters is provided in Fig. 2. BPF2 has a filter length of 20.6 mm, BPF6_42 of 73.3 mm, and BPF_28 of 39 mm. Adding the WG sections, the overall component length sums up to 50, 100, and 100 mm, respectively.

C. AM Process

In PBF, the physical and chemical properties of powder particles affect the final quality of additively manufactured components [48]. Fine particles enable high-density parts with good surface quality, while the spherical shape improves flowability and, as a result, mechanical properties. Irregular powder particles can lead to poor surface finish, low density, and increased defects.

In this article, PBF based on SM was adopted, namely the printer [49] was used to 3-D print the test vehicles out of

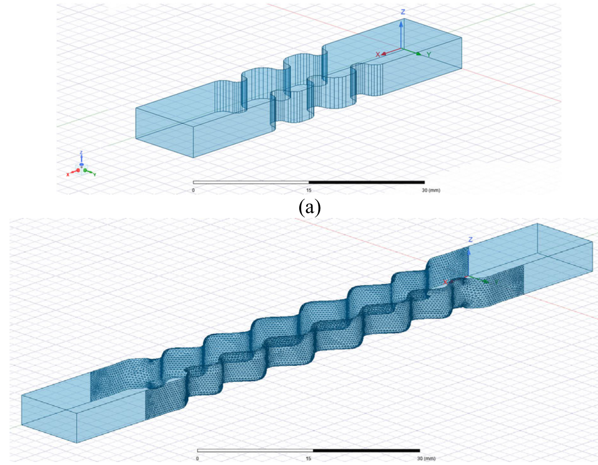


Fig. 2. Layout of the developed (a) second and (b) sixth order bandpass filters in WR-42 geometry featuring 3-D printing optimized geometry.

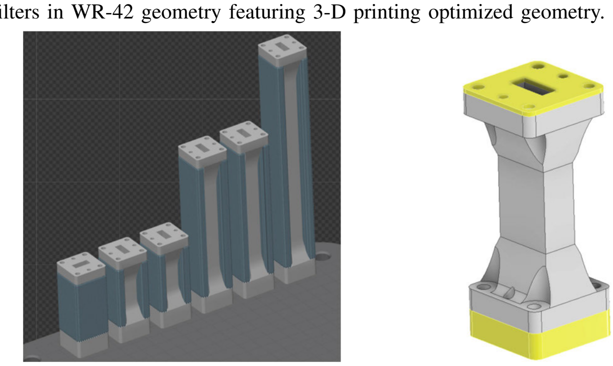


Fig. 3. Test vehicle orientation on the print bed with supports added (a) is set in the slicing software. Exemplary test vehicle view where yellow color indicates stock in the flange region that is removed and machined with CNC after detachment from building plate (b).

Stainless Steel 316L [50]. The average surface roughness (R_a) of SS316L additively manufactured components is commonly 11 ± 2 μm (JIS B 0601-2001 -ISO 97) after bead blasting (assuming Gaussian probability density function (PDF) $R_q = 1.25$, $R_a = 13.75 \pm 2.5$ μm). All test vehicles (having a general form of a long rectangular tube) were oriented on the building plate with flanges parallel to the print bed as shown in Fig. 3. Such orientation results in support only on the outside of the WG to carry the load of the top flange contour, while there are no supports inside the WG cross section. Each printed test piece has the same surface finish with the same lay, i.e., parallel deposited metal layers oriented perpendicular to the direction of wave propagation. Finally, to reduce the number of variables affecting the measured power losses, both flanges were CNC-milled postfabrication so that very good electrical contact is ensured between the measurement instrument's WG flanges and device-under test WG flanges. The fabricated test vehicle set is presented in Fig. 4.

D. Surface Polishing

Additively manufactured metal parts usually have a poor surface finish in comparison to milled and turned components. Many post-processing techniques can ensure that additively manufactured metal parts meet dimensional requirements, performance characteristics, and even esthetic

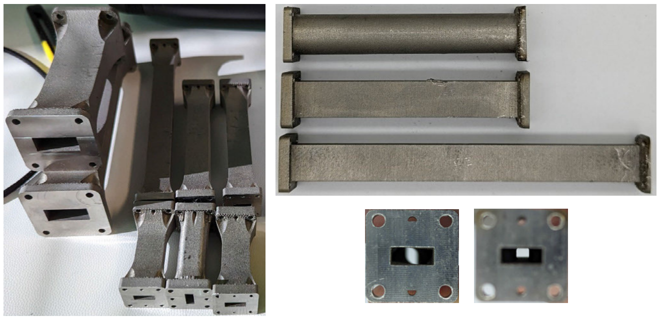
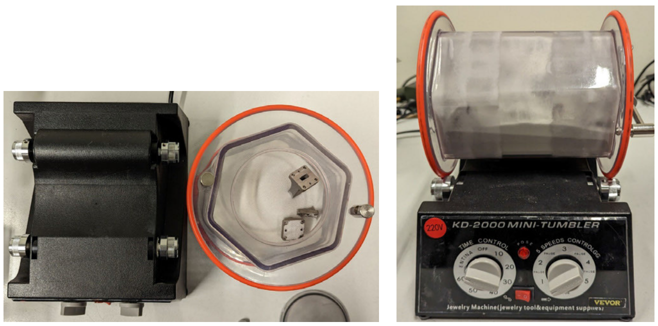


Fig. 4. Photographs of the fabricated test vehicles.



(a) (b)

Fig. 5. Photograph of the setup used for polishing of parts. (a) Barrel loaded with glass microbeads. (b) Running machine during polishing cycle.

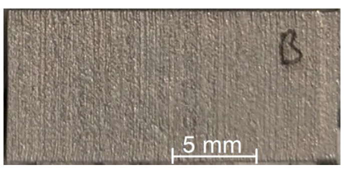


Fig. 6. Photograph of the fabricated sample for mechanical properties analysis. Layers orientation is clearly visible and thus the resulting roughness is orientation dependent. The sample area equals 20 × 10 mm.

guidelines. These processes include green sanding, media blasting, tumble finishing, pin finishing, vibratory finishing, and electropolishing. The WG components present internal channels, therefore, one of the most promising surface post-processing treatments is electropolishing [51], sometimes referred to as "reverse plating" as it utilizes a phosphoric-based electrolyte bath and rectified current to remove surface material. Electropolishing eliminates micro-peaks (high points within the microscopic surface) to reduce surface roughness to a higher level of smoothness than other finishing methods. Moreover, the electropolishing solution can reach every part of the component surface. This can include internal gaps and cavities that other finishing methods cannot reach. A smoother surface means fewer places for corrosive elements to take hold and thus extend part lifetime. Finally, electropolishing generally delivers a more consistent finish across the entire part surface. In contrast to that, many other polishing systems can leave marks or patterns on the surface. A large drawback of the method is its relatively high cost and careful handling as chemical bath is needed.

In this study, a mechanical barrel-based surface polishing method is introduced and validated. This method presents the advantages of electropolishing in combination with microbead-blasting Barrel polishing [41] is a surface-improving operation in which a mixture of parts, media, and compounds are placed in a six- or eight-sided barrel and rotated at a predetermined speed to round corners, deburr, grinding, descaling, deflashing, improving surface finish, burnishing, polishing, and radiusing parts in bulk. Tumbling parts are placed in a rotating barrel, and an abrasive media is introduced inside the barrel. Producing good surface finishes depends on the right selection of tumblers, abrasives, lubricating agents, carrying agents, and polishing agents. Very little handling is required for the process and many metal parts can be processed at once while the process can be finished in a tumbling barrel overnight, or in an hour or less in a high-energy machine. Barrel speeds in dry tumbling are generally kept at 28–32 r/min. On the other hand, in the microbead-blasting process, a very fine abrasive media and a miniature nozzle are used to produce a controllable abrasive jet that can target and remove microns of material. The result is a reliable and repeatable method for deburring, texturing, cleaning, stripping, etching, or milling part surfaces. The abrasive medium is easily available in a gamut in hardness (from soft compounds like sodium bicarbonate to hard ceramics like silicon carbide), that suits different materials to be processed as well in different shapes from spherical to blocky or pointy and sizes ranging from a couple of microns to hundreds of microns. Despite advantages, the process itself uses a directed jet of medium and thus internal cavities and channels of additive manufactured components parts cannot be reached.

In this study, the dry tumbling method using the Vevor KD-2000 jewelry grade mini rotary tumbler (5 kg max load, 4.5 l barrel dimensions of 190 × 180 mm, opening diameter of 90 cm), in combination with 300–400 μm large glass microbeads was employed. Such a combination ensures that the container size is large enough to fit a few parts while the medium size is small enough to easily penetrate the insides of the parts even having openings in the range of single millimeters. Glass microbeads are well suited for processing stainless steel and due to their structure leave the surface a bit satin, uniform, and smooth. The larger the beads the more effective they are and shinier, hence smoother, the surface. For example, 40–70 μm leads to a matte finish whereas 300–400 μm returns very shiny surfaces. On the other hand, too-large beads will not penetrate chambers with small openings and will not affect areas in proximity to sharp corners. An additional benefit of using microbeads in the dry tumbling process is that they provide an extraordinary amount of surface area to carry the dirty residue, thus avoiding having the residue embedded into the surface of the parts. A photograph of the polishing setup is presented in Fig. 5. The tumbler is filled with beads up to roughly three quarters of its volume.

III. Experimental Results

The proposed surface polishing method was experimentally validated within the postprocessing of test vehicles (broadband and resonant ones) operating within the cm/mm-wave frequency range. The impact of polishing on the resulting mechanical and electrical properties of circuits is provided and discussed in detail. Each test vehicle was measured before

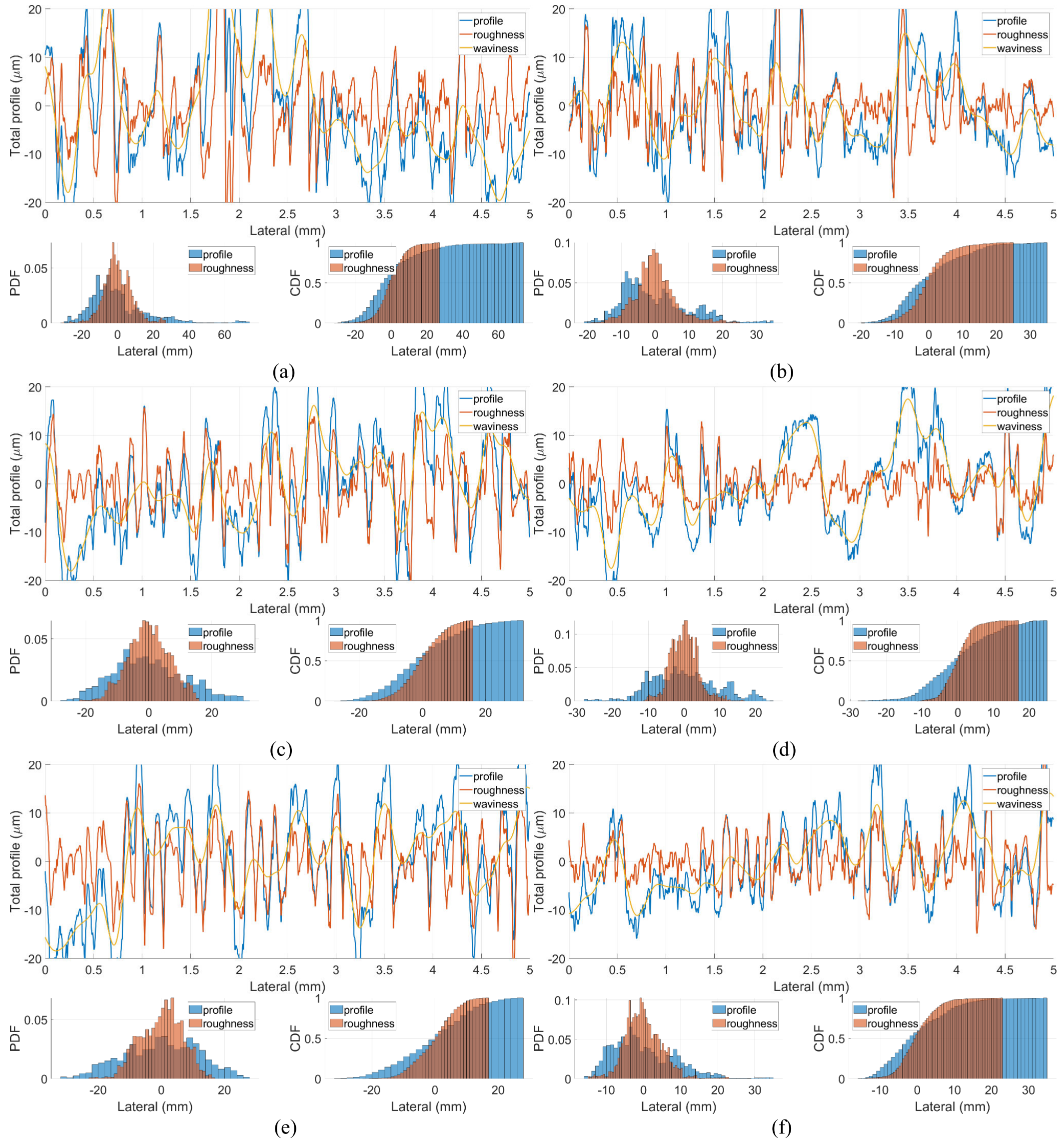


Fig. 7. Measured surface profiles of the printed specimen. (a) and (b) No polishing applied, (c) and (d) after 24 h of polishing, and (e) and (f) after 48 h of polishing. Profiles at orthogonal directions (orientation parallel (a), (c), and (e) and perpendicular (b), (d), and (f) to layer arrangement).

polishing and then after one and two cycles of polishing. Each 24-h (12-h) polishing cycle was carried out at 50 rotation-per-minute speed (to avoid microbeads sticking to internal surfaces due to centrifugal force instead of tumbling).

A. Mechanical Performance

First, the mechanical properties of additively manufactured test vehicles were assessed. Dimensions of the parts shown in Fig. 4 were measured using a digital caliper (10 μm least significant digit) in two different spots and averaged to assess the fabrication tolerance including post-heat treatment shrinkage. The results are summarized in Table I: the internal cross section of WG components shrunk after all processing steps. Dimension reduction is in the range of 1%–3%.

In the next step, the Bruker Dektak XT stylus profilometer was used to evaluate surface roughness: 1) before polishing; 2) after 24 h of polishing; and 3) after 48 h of polishing. Two parameters were used for comparison purposes, i.e., rms roughness value R_q and the average surface roughness R_a. Since the internal surface profile of test vehicles could not be nondestructively measured between tumbling cycles, a dedicated 20 × 10 × 3 mm specimen shown in Fig. 6 was fabricated and processed in the same way. At every step, an optical inspection was carried out as well, and a 5 mm long surface profile was captured in two orthogonal directions. The resulting roughness and waviness profiles are provided in Fig. 7, the optical images are shown in Fig. 8, while the average and rms roughness values are summarized in Table II.

TABLE I

MEASURED DIMENSIONS OF THE FABRICATED PROTOTYPES AND CALCULATED DEVIATION Δ FROM THE DESIGN VALUES

	a (mm)	Δa	b (mm)	Δb
WR-90 section	22.68	-0.8%	10.07	-0.9%
WR-42 twist	10.59	-0.8%	4.23	-2.2%
WR-28 section	6.99	-1.8%	3.43	-3.7%
WR-42 BPF2_42	10.61	-0.6%	4.24	-2.0%
WR-42 BPF6_42	10.60	-0.7%	4.24	-2.0%
WR-28 BPF6_28	7.01	-1.5%	3.45	-3.2%

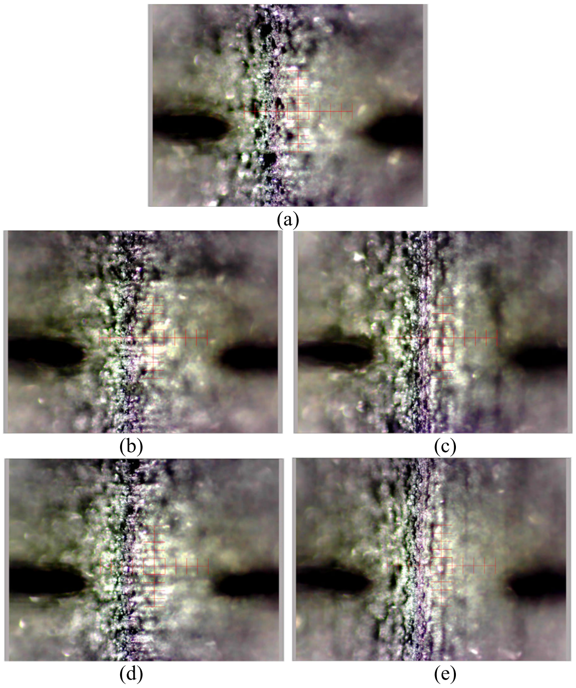


Fig. 8. Optical image of the printed specimen's surface. (a) No polishing applied, (b) and (c) after 24 h, and (d) and (e) after 48 h of polishing. The total picture width and height is 2.25 mm (1× zoom). Photographs at orthogonal directions [(b) and (d) orientation parallel and (c) and (e) perpendicular to layer arrangement]. The layered print pattern is clearly visible.

TABLE II

ESTABLISHED ROUGHNESS OF THE SLM PRINTED SPECIMEN FROM A 5 MM LONG PATH IN TWO ORTHOGONAL DIRECTIONS

Orientation	perpendicular to layer arrangement			
Profile	primary		roughness	
Metrics	R_a (µm)	R_q (µm)	R_a (µm)	R_q (µm)
Prior polishing	12.05	16.63	6.00	7.85
After 24h	9.23	11.38	5.19	6.47
Improvement	23.4%	31.6%	13.5%	17.6%
After 48h	9.73	11.82	5.37	6.58
Improvement	-	-	-	-
Orientation	parallel to layer arrangement			
Profile	primary		roughness	
Metrics	R_a (µm)	R_q (µm)	R_a (µm)	R_q (µm)
Prior polishing	8.07	9.99	4.48	6.12
After 24h	7.60	9.46	2.99	3.87
Improvement	5.8%	5.3%	33.3%	36.8%
After 48h	6.83	8.45	3.81	4.95
Improvement	-	-	-	-

Both the optical and the surface analysis reveal the typical characteristics of part made by SM: irregularities, larger melted grain clusters, and relatively large waviness. The collected profiles must be considered random and as just a local representation of the surface. Nevertheless, they allow us to assess the polishing technique performance to a certain degree.

The highest roughness is found in the planes parallel to the printing plate, while along the direction orthogonal to the printing plate a lower roughness is observed. In both directions, the PDF for roughness is close to the Gaussian distribution. Finally, it is clearly seen that the specimen surface is smoother after 24 h of polishing while an extra 24 h makes no significant difference. Roughness R_q reduction by 17% and 37% are obtained for orientations perpendicular and parallel to layer arrangement, respectively. Considering the above, various polishing times were applied to the fabricated WG demonstrators for a better assessment of polishing time versus loss reduction assessment.

TABLE III

MEASURED IMPACT OF POLISHING ON WG ATTENUATION CONSTANT (EXPRESSED THROUGH TPL METRICS). POSITIVE DIFFERENCE Δ MEANS VALUE REDUCTION WITH RESPECT TO THE BASE ONE

		α @ f_0 (dB)	$\Delta\alpha$ (%)	α @ f_0 (dB/cm)
WR-90	Pre	0.186		0.0124
	After 24h	0.164	11.9	0.0109
	After 48h	0.195	-2.9	0.0130
WR-42 twisted	Pre	0.615		0.0615
	After 12h	0.506	17.7	0.0506
	After 24h	0.499	19.0	0.0490
WR-28	Pre	0.475		0.0475
	After 12h	0.450	5.2	0.0450
	After 24h	0.430	9.5	0.0430

TABLE IV

MEASURED IMPACT OF POLISHING ON BANDPASS FILTER IN-BAND INSERTION LOSS AND EXTRACTED UNLOADED QUALITY FACTOR. POSITIVE DIFFERENCE Δ MEANS VALUE IMPROVEMENT WITH RESPECT TO PRE-POLISHING

		f_0 (GHz)	BW (GHz)	IL @ f_0 (dB)	ΔIL @ f_0 (%)	Q_U @ f_0 (Eq. 4)	ΔQ_U (%)
BPF2_42	EM	23.93	1.95				
	Pre	24.8	1.69	0.67		190.2	
	24h			0.65	9.5	196.1	3.1
	48h			0.62	15.4	205.6	8.1
BPF6_42	EM	23.05	2.4				
	Pre	22.97	2.07	2.02		142.8	
	24h			1.27	39.7	227.4	59.2
	48h			1.24	38.3	233.7	63.6
BPF6_28	EM	38.13	4.35				
	Pre	38.46	4.04	1.42		160.8	
	12h			1.27	10.5	195.3	21.4
	24h			1.2	15.5	207.2	28.8

B. Electrical Performance

Finally, the electrical properties of the additively manufactured test vehicles were assessed. The dc conductivity of the specimen was measured using the Hioki 3522-50 LCR meter to be 0.96 MS/m which is 71% of the bulk value for the SS316L. This was followed by measuring the scattering parameters of the test vehicles using the Agilent PNA N5224A vector network analyzer at an IF bandwidth of 1 kHz. The calibrated reference plane is set at the WG flange, using WR-90, WR-42, and WR-28 Thru-Reflect-Line cal-kits. Measurements were taken before polishing, and once after each 24 h (12 h) polishing run. Since very low loss differences were to be measured, the S_{21} measurement uncertainty of the VNA being 0.02 dB [52] cannot be overlooked, and thus a strict protocol was followed. To ensure repeatable results, each time all the screws that force mating the WG flanges were tightened with the same torque force. Moreover, after calibration, the cables connecting VNA with the coax-to-WG adapters were kept in the same position. The measured frequency response of the pre-polished circuits is provided for the WG section in Fig. 9, while for bandpass filters in

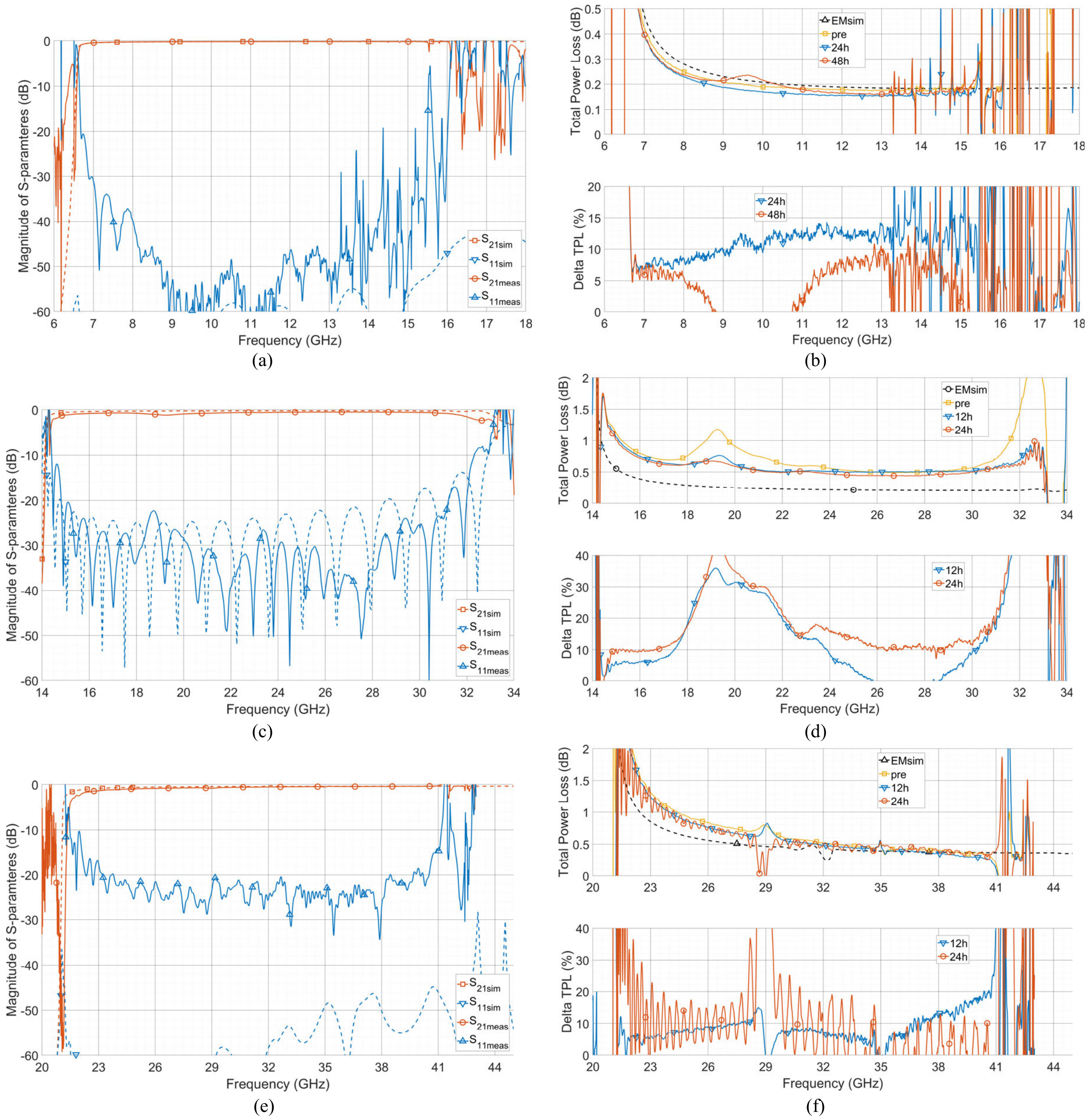


Fig. 9. Measured (solid lines) pre-polishing S-parameters of the SLM-fabricated (a) WR-90, twisted (c) WR-42, and (e) WR-28 sized WG sections along with EM simulated ones overlayed (dashed lines). Measured impact of polishing on TPL of (b) WR-90, (d) WR-42, and twisted (f) WR-28 sized WG sections: pre-polishing, after one and two rounds of polishing. Delta TPL referenced to pre-polishing TPL.

Fig. 10. Moreover, the attenuation constant expressed through the TPL is defined as TPL $= 1 - \left(|S_{21}|^2 + |S_{11}|^2\right)$ for both WG sections and BPFs is confronted with the full-wave simulated EM to assess the polishing effectiveness on the power loss. Finally, the percentage improvement after each round of polishing is determined. The results are also summarized in Table III for WGs and in Table IV for BPFs. From the above results, the following conclusions can be drawn. First, the VNA measurement uncertainty has a visible impact on the experimental results which manifests itself in, e.g., erroneous percentage improvement as the in-process TPL values are relatively small. Second, it is seen that a slight dimension reduction is observed due to metal printed part shrinkage. This can be easily counteracted by slightly scaling up the model before printing. Third, for the proposed process, the polishing time is selected as a tradeoff between potential roughness reduction and the time required. It is seen that even after only 12 h of polishing a dozen percent improvement is seen with longer times the gain being less and less significant. Fourth, glass bead size must be selected considering feature size since the medium must freely penetrate cavities.

The difference is seen, e.g., between loss improvement for WR-42 geometry (even in a twist configuration) versus WR-28. In addition, in BPF6_28 the minimal iris is only an order of magnitude larger than the bead radius. For higher bands smaller beads (e.g., 150–200 μm radius) could yield better results. Fifth, since a rough surface is inevitably bounded by the fabrication technique, the use of different base materials such as aluminum (roughly 30 times better conductivity) powder in combination with the proposed post-processing method would provide a very low loss metal 3-D printed mm-wave components.

Finally, results obtained in this study for narrowband filters were compared with the state-of-the-art. A summary is provided in Table V from which it can be noted that the

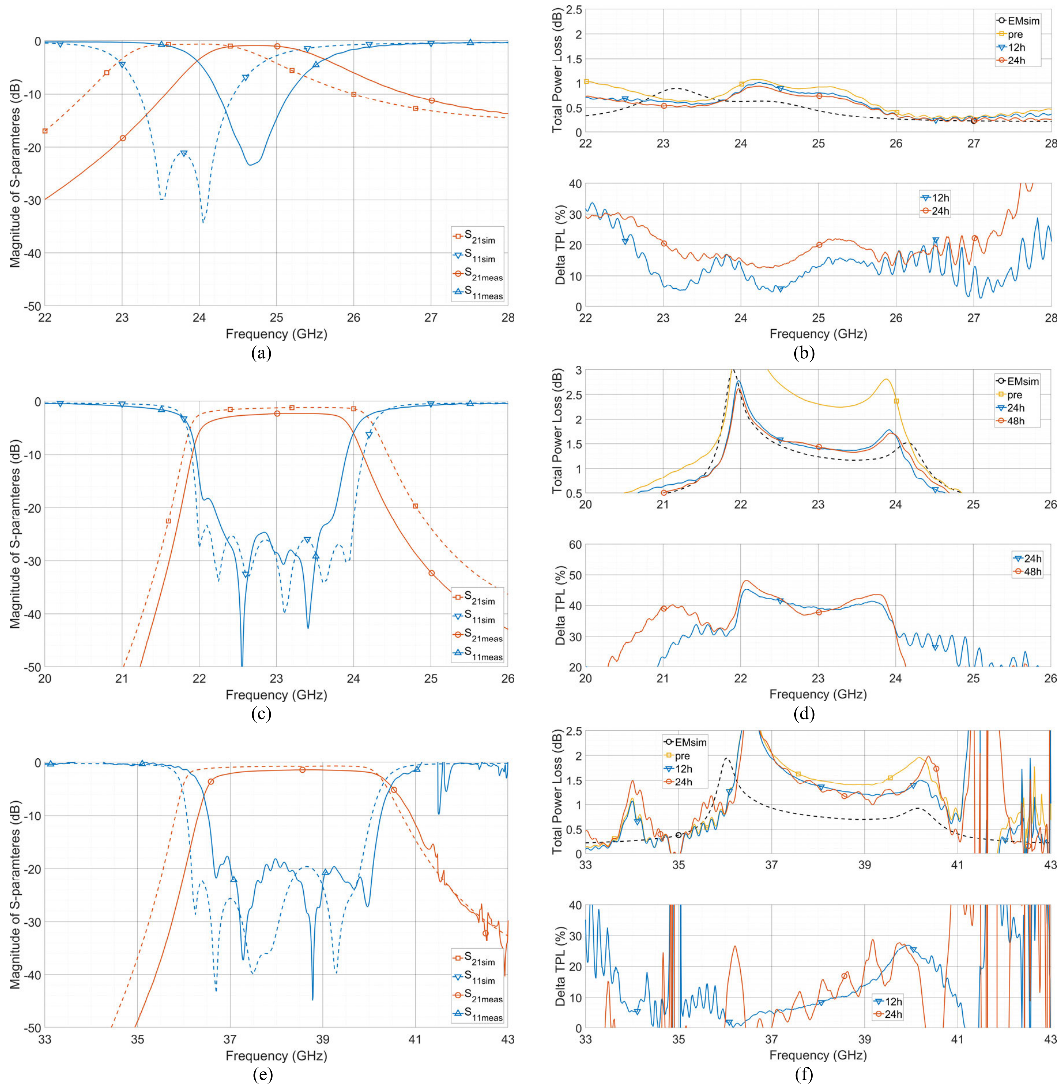


Fig. 10. Measured (solid lines) pre-polishing S-parameters of the SLM-fabricated (a) BPF2_42, (c) BPF6_42, and (e) BPF6_28 filters along with EM simulated ones overlayed (dashed lines). Measured impact of polishing on TPL of (b) BPF2_42, (d) BPF6_42, and (f) BPF6_28 sized WG sections: pre-polishing, after one and two rounds of polishing.

TABLE V

State-of-the-Art Additively Manufactured Filters Versus Proposed Fabrication Scheme

	Filter Order/Geometry	3D Technology	f_0 (GHz)	BW (%)	*IL* @ f_0 (dB)
[52]	4th -order filter/groove gap waveguide	PolyJet electroplated	35.65	1.4	~0.5
[53]	5th -order filter/ rectangular waveguide cavities	SLA# copper plated	87.5	11.5	~0.5
[54]	9th-order filter with shaped resonators	SLM Scalmalloy	~12	~5	~1.3
[55]	5th-order H-plane filter with irises	MLS* stainless steel	88	12	~2
This	6th-order filter with shaped resonators	Polished SLM stainless steel	23	9	~1.2
This	6th-order filter with shaped resonators	polished SLM stainless steel	38.45	10.5	~1.2

#SLA – Stereolitography, *MLS – Micro Laser Sintering.

proposed fabrication and processing approach provides a very good insertion loss performance even when using a relatively low conductivity metal.

IV. Conclusion

A low-cost polishing method dedicated to all-at-once fabricated WG circuits that employ mechanical barrel tumbling of metal additively manufactured parts, using glass microbeads as an abrasive medium, was introduced, and experimentally validated. In contrast to electropolishing, neither chemicals nor sophisticated equipment is necessary, while similar benefits of good internal cavities and channel penetration and polishing are still provided. A set of test vehicles was fabricated in SS316L using the SLM technique. Both mechanical and electrical properties were assessed before polishing and after one and two polishing rounds. In practice, electropolishing reduces a part's R_a by 10%–30% depending on the starting finish. In the case of the proposed method, improvement is in the range of 6%–23% in terms of surface finish and 14%–33% in terms of roughness. The proposed method's results are comparable to those of industry-standard high-cost high-performance techniques. The obtained results translate into a 10%–20% loss reduction within tested WG geometries and finally between 10% and 40% loss reduction for the tested second- and sixth-order filters. Therefore, the experimental results certified the performance and applicability of the proposed metal 3-D printed WG components post-processing method that the AM technology is well suited for cm- and mm-wave component fabrication.

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