Design and Analysis of 3D Printed Slotted Waveguides for D-Band using Stereolithography and Electroless Silver Plating

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Abstract — This work demonstrates the feasibility of entirely additively manufactured slotted waveguides in combination with an electroless silver plating process for applications in the D-Band frequency range. Design rules are adjusted towards the requirements for 110-170 GHz and analyzed with respect to the limitations of conventional desktop SLA- and DLP printers. Measurements obtained in this work reach attenuation levels in the order of 20-35 dB/m, hence comparable to conventionally manufactured waveguides. Furthermore, it is shown, that the electrical behavior of slotted waveguides is similar to a conventional waveguide by comparison with simulation models.

Keywords — additive manufacturing, 3D printing, slotted waveguides, electroless plating

I. INTRODUCTION

The integration of passive components and distribution network circuitry is driven by the mass market compliant photolithographic printed circuit board (PCB) process which is limited to planar structures. However, the inevitable dielectric loss of PCB laminates scales linearly with frequency [1] and consequently becomes a dominant contribution to overall losses at mmWave and THz frequencies. In addition thereto, many passive components, such as couplers, filters, antennas [2], [3] and even entire waveguide circuits [4] can be realized with high performance as three-dimensional rather than planar structures. Yet, conventional manufacturing of such components typically involves complex and expensive micro-machining making it an option for the higher price segment. At this point, additive manufacturing (AM) offers new perspectives by combining the geometrical freedom of 3D printing with low fabrication cost for rapid prototyping and even commercial applications. Among a variety of different printing approaches, stereolithography (SLA) and digital light processing (DLP) printers provide the almost unique feature of fabricating structures with a surface roughness $R_q \leq 1 \mu m$ which is mandatory for mmWave frequencies and beyond [5]. However, it is typically limited to polymer materials which therefore, need to be metal coated for functionalization as waveguide components. In this work, the slotted waveguide approach [6] - introduced by additive manufacturing of slotted waveguide array antennas [7] - is used in combination with an electroless silver plating process as described in [8] and utilized in [9], [10] for waveguide components in E-Band. The requirements of D-Band are translated into the design rules of such type of waveguide and adjusted towards the limitations of conventional SLA- and DLP desktop printers. The proposed approach is compared with conventional manufacturing and different additive processes and finally, supported by simulation models.

II. DESIGN AND MANUFACTURING

For the design of slotted waveguides, the model described in [6] is reduced by the slots in the broad walls, so that only the slots in the narrow walls remain as shown in Fig. 1. These are characterized by their remaining post thickness $d$ and the gap $g$ between two such posts. The spacing $s = g + d$ describes the periodicity of the posts along the propagation direction. Although with $w = 1.65 \text{ mm}$ and $d = 0.825 \text{ mm}$ the dimensions of the waveguide cross section itself are still within the feasible dimension range of conventional desktop SLA and DLP printers, printing slotted waveguides for D-Band frequency range pushes the currently used printers to the limit of their restrictions. The sidewall posts must be placed with a periodicity $s \leq \lambda_w/4$ which results in $s \leq 500 \mu m$ for up to 170 GHz. As a consequence, the required minimum structure sizes reach an order of magnitude within 200-300 $\mu m$, which comes close to the typically proposed limitations towards minimum standalone structure sizes of such printing systems of approximately 250-300 $\mu m$ in order to provide reliable build results. Similar to minimum standalone structures, gap sizes also exhibit restrictions in SLA printing. Experience with typical desktop DLP and SLA printers shows, that distinct gaps should be larger than about 150-200 $\mu m$ in order to avoid clogging during the print. However, in this work, even smaller gaps are considered in order reach the printer limitations as close as possible. Hence, based on these considerations, Table 1 provides an overview of different gap and spacing
combinations for the targeted D-Band frequency range that are considered in this work. Parameter combinations that do not meet the minimum manufacturing requirements due to \( s = g + d \) are marked with a dash (“-”) in Table 1. Those marked with a ✓-symbol in Table 1 are fabricated and evaluated in this work. Samples A4 and A5 evaluate the possibility of printing at the limit of the restriction with standalone structures of 200 \( \mu \text{m} \). In case of sample D5, the minimum gap size is at the lower limit of the restrictions by the printer. In addition thereto, samples C6 and E7 are considered to experimentally analyze the effect of \( s \geq \lambda g/4 \).

After finishing the build process, the 3D printed polymer parts are subject to post processing and subsequent functionalization by metal plating. Post processing involves isopropanol alcohol for cleaning and curing in a UV post-processing chamber. After applying an initial conductive seed within a Palladium bath, the parts are silver plated by reduction of the Tollens’ reagent with glucose solution as described in [8], [9]. In combination with the slotted waveguide structure, this electroless silver plating process reduces geometrical restrictions since it nor requires complex placement of electrodes, neither controlled or pumped solvent flow. Although in [9] the silver plating was performed four times in order to deposit a metal layer that is thick enough, in this work, the process provides sufficient metal layer thickness already after two repetitions as shown by measurements presented in the following sections.

### III. Dimensional and Surface Analysis

The printed and silver plated specimen C5 is shown from side view in Fig. 2 with a total length of \( L = 30.3 \text{ mm} \) between both waveguide interfaces. The sidewall gaps of the two critically small posts A4 and A5 are shown in Fig. 3. It indicates an obvious damage in case of A5 and very unstable posts at A4 - where latter ones mechanically survived the processing due to the higher post-density of shorter periodicity \( s \). However, experience confirms significantly decreasing reliability when approaching the standalone structure size limitations of the printer. The close-ups on the sidewall gaps of specimens B5, C5 and D5 are shown in Fig. 4. Although modeled with the same \( s \), there are little variations in that geometrical parameter resulting from the build process. However, the post spacing is still close to 500 \( \mu \text{m} \). While B5 and C5 exhibit remaining gaps of about \( s \approx 300 \mu \text{m} \) and \( s \approx 240 \mu \text{m} \) respectively, most of the gaps in case of sample D5 are closed by silver plating although the printed model itself was not enclosed prior to silver plating.

Surface quality in DLP- and SLA printing differs depending on the orientation in the build volume. The best quality is obtained on surfaces that touch the bottom film of the resin tray since they are related to the surface roughness of the film itself. The opposite plane however, which is realized as an overhanging element, exhibits significantly
higher surface roughness and so does the plane parallel to the build direction as well. Latter one reveals a periodic structure resulting from the vertical printer axis movement which can be observed at the layered shape of the posts. Fig. 5 compares the smooth and rough surfaces after silver plating under a 50X microscope. These two surfaces which are most relevant to the waveguide (broad wall surfaces) are both measured with a laser-scanning microscope. The RMS surface roughness of both surfaces yields \( R_q \approx 300 \text{ nm} \) for the smooth and \( R_q \approx 1.5 \text{ µm} \) for the rough sides respectively, which can be introduced into modeling as described in [5], [11] either numerically or by full wave simulation with CST - Microwave Studio which is compared to measurements in the following section.

### IV. ELECTRICAL CHARACTERIZATION AND ANALYSIS

The manufactured specimens were measured with D-Band (WR06) frequency converters in the range between 110-170 GHz where the reference plane was calibrated to the interface of the test-port adapters by a TOSM algorithm with known waveguide standards. Figs. 6 and 7 show the measured reflection \( |S_{11}| \) and transmission coefficients \( |S_{21}| \) of the undamaged manufactured slotted waveguides (A5 was not measured due to damage). The length of the samples was about \( L = 30.3 \text{ mm} \) with a variation of 200 µm depending on the post diameter \( d \) in order to provide a solid interface at the flange. Due to dimensional mismatch within the waveguide cross section, matching is not ideal. However, for most of the measured waveguides, a matching of \( |S_{11}| \leq -10 \text{ dB} \) can be achieved over the entire D-Band and even around \(-15 \text{ dB} \) for most of the specimens. The measured insertion loss \( |S_{21}| \) is minimal for sample D5. All other samples exhibit significantly higher loss. However, it is not samples C6 and E7 revealing highest attenuation, but rater A4, although the criterion for the spacing dimension \( s < \lambda_g/4 \) as described above is violated by C6 and E7. The reason for the significant attenuation in case of A4 might be within mechanical instability, which in turn may introduce small cracks in the metal coating on the posts.

The attenuation coefficients of the best performing fabricated slotted waveguides are derived according to [12], [13]:

\[
\alpha = -\frac{10}{T} \log_{10} \left( \frac{|S_{21}|^2}{1 - |S_{11}|^2} \right)
\]

and shown in Fig. 8 with a comparison to a conventionally manufactured reference waveguide from extruded copper pipe. Fig. 9 compares the best slotted waveguide sample (D5) with simulations of continuous wall waveguides with a width of 1.8 mm and different values for surface roughness \( R_q = 300, 600 \text{ and } 1500 \text{ nm} \) in order to include the range of measured surface roughness values into the modeling consideration. The bulk conductivity of the electroless silver coating is assumed as \( \sigma_{DC} \approx 10 \text{ MS/m} \). However, at D-Band frequencies, already little surface roughness \( R_q \geq 200 \text{ nm} \) dominates the overall conductor losses [11]. The responses for measured minimum
and maximum roughness $R_q = 300 \text{ nm}$ and $R_q = 1.5 \mu m$ completely enclose the measured $\alpha$ of the successful slotted waveguide D5. As shown in Fig. 9, the attenuation of D5 follows the model for $R_q \approx 600 \text{ nm}$. Hence, the effective surface roughness of the slotted waveguide, as a mixture of top and bottom broad walls, is closer to the smooth surface than it is to the rough one on the overhanging surface. Compared with planar and PCB bounded transmission surface than it is to the rough one on the overhanging surface roughness of the slotted waveguide, as a mixture of top and bottom broad walls, is closer to the smooth surface than it is to the rough one on the overhanging surface. Printed continuous wall polymer waveguides with electroless copper plating are proposed by [16] where an overall attenuation of 23-26 dB/m is reported for D-Band, which is comparable to the results obtained in this work with slotted waveguides. Even lower attenuation is reported in [17] by selective laser melting of copper powder. However, with increasing system complexity, as e.g. demonstrated in [9] for E-Band, the slotted waveguide benefits of better metal plating properties when compared to metal plated conventional waveguides. Also, powder-based approaches are limited towards complexity, since removing remaining powder from the prototypes becomes tedious work.

V. CONCLUSION

This work provides a design and analysis study of the slotted waveguide approach in combination with electroless silver plating for applications in D-Band. Different possible combinations of geometrical parameters are adjusted to the requirements at 110-170 GHz and the limitations of the conventional desktop SLA/DLP printing machinery. Measured attenuation levels of 20-35 dB/m can be achieved over the entire frequency band while being on par with conventional hollow waveguides due to particularly high surface quality. Model based analysis suggests an effective surface roughness of $R_q \approx 600 \text{ nm}$ without explicit surface smoothing measures. As a consequence of the close relation between measurement and simulation, the slotted waveguide may well be modeled as a continuous wall waveguide with sufficient precision and therefore, reduce model complexity and thus, simulation time. Moreover, as an inherent benefit of the slotted waveguide approach, structures with higher complexity, such as 3D waveguide paths [9] or couplers [10] can be realized and still metal plated at acceptable effort.

REFERENCES