Suspended Microstrip Low-Pass Filter Realized Using FDM Type 3D Printing with Conductive Copper-Based Filament

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Abstract— **In this paper, the realization of microwave circuits in suspended microstrip structure with a 3D printed conductive enclosure is presented for the first time. An example of a low-pass filter with a cut-off frequency of 2.5 GHz was designed, manufactured and measured. A Fused Deposition Modeling (FDM) type 3D printing and a conductive copper-based filament recently developed by Multi 3D were employed to realize an enclosure serving both mechanical and electrical purposes. The influence of the ground plane conductivity on the total loss within the circuit was studied, and requirements for the conductive material properties were established. Moreover, the impact of the print parameters as well as the connection between microstrip line and SMA connectors was investigated. The obtained measurements proved that the proposed approach is of potential use for circuits and systems operating within low GHz frequency range.**

Keywords-3D printing; additive manufacturing; low-pass filter; low-loss; suspended microstrip.

I. INTRODUCTION

Three-dimensional (3-D) printing technology has gained in recent years an increased interest, especially for the realization of microwave circuit and systems [1]-[5]. Rapid development of the additive manufacturing process is caused by the significant development of 3D printing machines, which allows for high resolution printing as well as for deposition of various types of non-conductive [4], [6] and conductive [7] materials. It needs to be underlined, that additive manufacturing process can provide fast prototyping and evaluation of the microwave devices, lowering the overall time and cost of production at the same time. Due to this fact, the additive manufacturing process has found its application in the realization of many microwave circuits e.g. waveguides [3], filters [4], as well as antennas [6] and many others.

In this paper, we investigate the applicability of Fused Deposition Modeling (FDM) type 3D printing using a highly conductive filament for the realization of low-loss suspended microstrip microwave circuits for the first time to the best of our knowledge. A commercially available Electrifi filament by Multi3D was used to manufacture an enclosure that serves two purposes at once: electrical as a conductive ground plane, and mechanical as a structural support for the thin laminate hosting the circuit mosaic that is be elevated over the ground plane with an air layer in-between. Utilization of the conductive filament, which in this case consists of non-hazardous, proprietary metal-polymer composite that consists primarily of a biodegradable polyester and copper, allows for simplification and cost-reduction of the manufacturing process, since a metal milled enclosure or metallized 3D printed dielectric case is no longer required. An example of a stepped impedance low-pass filter with a cut-off frequency at 2.5 GHz was designed, manufactured and measured. The circuit layout was etched on a 12-mil thick RO4003 laminate and mounted in the 3D printed conductive enclosure which provides 1 mm of elevation over the ground plane. The 3D printed case also provides the access points to mount and secure the coaxial connectors. The obtained measurement results have shown, that even though the bulk resistivity of the Electrifi filament equals approx. 6 mΩ·cm as the manufacturer claims, it is sufficient to realize relatively low-loss microwave circuits. Total loss within the circuit equals 0.18 dB/cm/GHz while for frequencies higher than 7 GHz, more that quarter of power is lost for each centimeter of transmission line. It has also been shown that the total loss is not only influenced by the ground plane conductivity and its` roughens resulting from the printing parameters but also by the quality of contact between the grounding part of the coaxial connectors required for measurement and the enclosure itself. Different connection schemes were studied such as different mounting point designs, as well as provisions of a galvanic connection by pressing the connector against the 3D printed enclosure wall with and without an intermediate layer of silver epoxy which allows for better surface contact with a higher surface area.

II. DESIGN CONSIDERATION FOR SUSPENDED MICROSTRIP CIRCUITS REALISATION WITH 3D PRINTED CONDUCTIVE ENCLOUSURE

The Electrifi filament being a conductive 3D printed material is to be used to serve as a ground plane. Therefore, first the impact of its conductivity on the suspended circuit`s total loss was investigated and a minimal thickness of the conductive layer was established to minimize the sheet resistance. Additionally, the optimal print parameters were considered and their influence on the effective volume conductivity was discussed. Finally, the mechanical design of the enclosure was considered and two different SMA connector mounts were proposed.

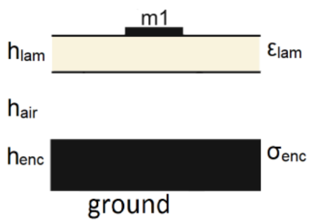


Figure 1. Cross-sectional view of the suspended microstrip structure under investigation, utilized for the design of a low-pass filter. The ground plane is realized as a solid block of conductive 3D printed material.

A. *Filament conductivity requirements for ground plane realization in suspended microstrip circuits*

In order to determine the requirements for the conductive filament to be useful for the realization of low-loss microwave circuits in terms of minimal volume conductivity, a theoretical study was conducted based on electromagnetic calculations. A suspended microstrip dielectric structure whose cross-sectional view is shown in Fig. 1 was considered. The structure is composed of a thin laminate having thickness of h_{lam} and relative permittivity ε_{lam} with metallization layer m1 on top, being suspended at height of h_{air} over the ground plane. The ground plane is a solid block of conductive material having thickness of h_{enc} and volume conductivity of σ_{enc}. It was assumed as a reference point that materials having volume conductivity in the range of 10^2 S/m and below are of no practical use, as it was experimentally verified in [7]. Since, a newly developed conductive filament by Multi3D was recently introduced to the mass market with claimed volume resistivity as low as 6 mΩ·cm that corresponds to a volume conductivity of $1.67 \cdot 10^4$ S/m, the investigation was conducted for σ_{enc} ranging from 10^3 to 10^5 S/m. Moreover, various air layer thicknesses were considered ranging from 1 to 2 mm. A test transmission line section being 8 mm wide by 5 cm long was modeled and EM analyzed in NI AWR Design Environment using AWR AXIEM solver. The line was realized out of 0.5 oz. copper on metal layer *m*1 on top of the $h_{lam} = 0.3$ mm thick microwave laminate having relative permittivity $\varepsilon_{sub} = 3.38$ and loss tangent $tan\delta = 0.003$. The obtained data expressed in terms of total loss per centimeter of length is shown in Fig. 2. The following can be stated based on the data analysis: first, the majority of power loss (being the sum of conductor, dielectric and radiation losses) can be attributed to the relatively low conductive ground plane; second, it is seen that the thicker the air layer the lower the power loss which can be explained by the current density reduction within the ground plane as the total height is increased. It has to be noted, however, that when the suspension height is increased, the circuit`s frequency of operation is decreased (line becomes too wide in respect to guided wavelength), since in order to maintain a given impedance the line must be wider. Finally, it can be observed that for the materials having conductivity in range of 10^4 S/m and higher, the resulting total loss within the circuit becomes acceptable making them potentially suitable for the realization of relatively low-loss circuits in the microwave band.

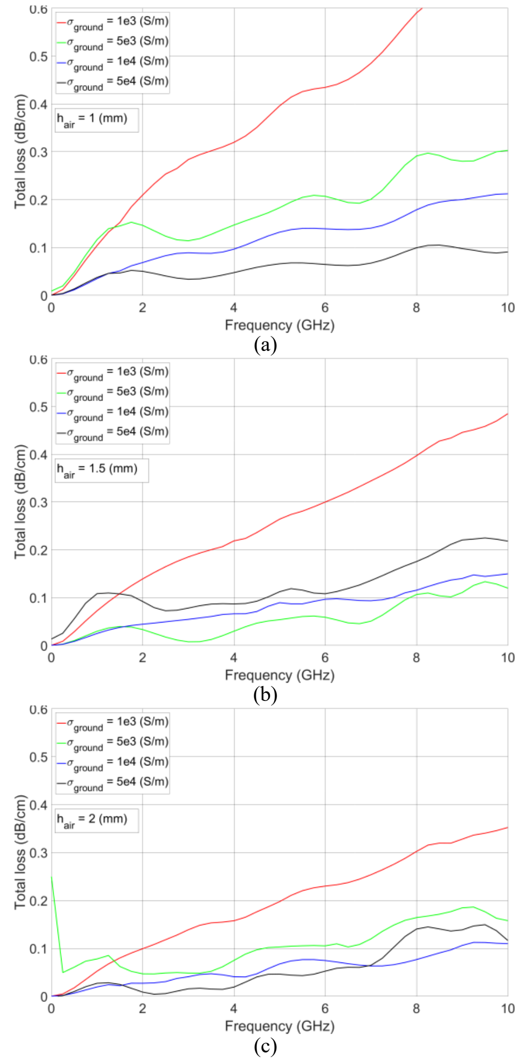


Figure 2. Total loss per cm of length for a 8 mm wide transmission line on *m*1 metal layer in suspended microstrip structure shown in Fig. 1 assuming a $h_{lam} = 0.3$ mm thick laminate having relative permittivity $\varepsilon_{lam} = 3.38$ and loss tangent $tan\delta_{lam} = 0.001$, being suspended over an h_{air} thick air layer while the ground plane is a solid block of conductor having volume conductivity of σ_{enc}. Results of EM simulations in *NI AWR Design Environment* using *AWR AXIEM* solver.

B. *Minimal thickness of the ground plane and 3D printing parameters*

Following, the ground plane thickness was considered to establish the minimal thickness requirements. For this purpose, the depth of penetration of a plane electromagnetic wave into the conductive material was analyzed within the specified - in the previous subsection- range of volume conductivities. A theoretical skin depth for a bulk material was provided in Fig. 3 together with the resulting effective square resistance. It is seen that the thickness h_{enc} of the ground conductor needs to be chosen accordingly to the designed circuit`s frequency of operation; however, for materials having conductivity in the range of 10^4 S/m and higher a minimal thickness in the range of 0.5 to 1 mm is sufficient. It has to be noted, however, that the study considers only electrical properties of the 3D printed enclosure and from a mechanical integrity stand point such thicknesses might not be sufficient.

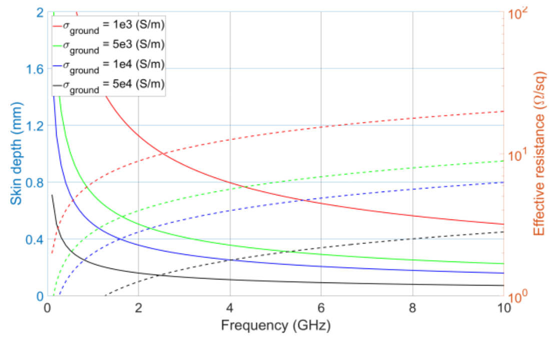


Figure 3. Calculated theoretical electromagnetic wave penetration into the material expressed in terms of skin depth (solid lines) and effective conductivity (dashed lines) for a given bulk conductivity of metal.

The above provided analysis is conducted under the assumption that a bulk material having uniform volume conductivity and a perfectly flat surface is provided. Due to the specification of 3D printing technology, particularly the FDM type, in which a continuous filament of a thermoplastic material is used, the substrate must be considered in terms of an effective volume conductivity rather that bulk volume conductivity. The print head temperature, as well as the printing pattern and material infill settings lead to a less effective bonding of adjacent strings of the extruded material with variable size and shape of air gaps which influences the surface roughness and results in an effective conductivity being lower or equal than bulk material value. A detailed study is provided e.g., in [9] where variables, such as the details of the printed line (shell thickness, infill pattern, etc.) and the direction of resistivity measurement (between printed layers, along a line, etc.) were investigated for their influence of the resulting object resistivity printed out of the Electrifi filament. It was shown that the resistivity of a vertically printed tower is much higher than for horizontal traces (85 mΩ·cm vs. 12 mΩ·cm) with both the traces and tower being printed at a temperature of 140 °C, speed of 15 mm/s, a nozzle size of 0.8 mm, and a wall thickness of 0.7 mm. Moreover, the optimal flow rate, infill pattern, and shell thickness were studied. Test traces were printed at a print speed of 15 mm/s and a print temp of 150 °C with a nozzle size of 0.4 mm and a layer height of 0.2 mm. It was observed that a flow rate ensuring the object being 100% filled is of importance for minimizing the effective resistivity. Moreover, the parallel pattern provides better continuity and fill along the line than a zig-zag pattern. Finally, the influence of the layer height was studied showing that a lower resistivity is obtained for greater layer heights (85 mΩ·cm for 0.4 nozzle and 0.2 mm layer height vs. 12 mΩ·cm for 0.8 nozzle and 0.5 mm layer height).

C. *Microstrip to coaxial transition and SMA connector mounting scheme for low-resistance connection*

The design of the transition from the microstrip to a coaxial transmission line was considered in terms of the electrical contact quality between the 3D printed enclosure and the metal SMA connectors. It was shown in [9] that a low-resistance contact can be obtained when using an intermediate layer of silver paste between the SMA and the printed material to even out the materials` roughness and provide a large contact area or using screw terminals to apply pressure (11 mΩ·cm vs. 14 mΩ·cm, respectively). Taking the above into account together with the previous considerations, two different mounting schemes shown in Fig. 4 were proposed, namely mount A (Fig. 4a-b) and mount B (Fig. 4c-d). Mount A allows for a larger contact surface area and provides screw terminals, however, an additional relatively narrow vertical wall is required which may lead to increased current density in the contact area. On the other hand, for the mount B either pressure or screw contact is possible while it provides a more direct current path from the outer coaxial conductor to the ground plane at the expense of a smaller surface area. For both mounts, a layer of conductive epoxy can be added to improve both electrical and mechanical reliability.

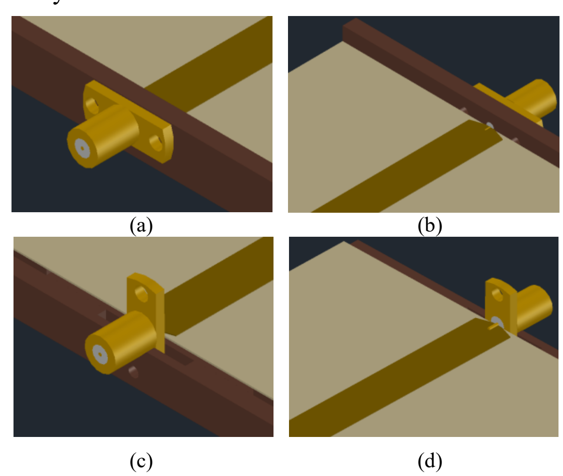


Figure 4. Two different SMA connector mounting styles: mount A - a vertical wall is added on top of the ground slab and the connector is screw mounted (a), (b); mount B - a cavity is added in an extended ground slab and the connector is inserted and screw mounted (c), (d).

III. Circuit`s Design and Manufacturing using a Combination of Laminate and FDM-Type 3D printing Technologies

To experimentally verify the proposed suspended microstrip circuits' realization approach, a low-pass filter was designed, manufactured and measured. A combination of laminate and FDM-type 3D printing technologies were used. The circuit pattern was etched on a 0.3 mm thick Rogers RO4003C microwave laminate having a permittivity of 3.38 and a loss tangent equal to 0.002 (parameter as for the theoretical study), while the enclosure was printed using a low-cost, consumer market grade MakerBot Replicator 2 3D printer out of Multi3D Electrifi conductive copper-based filament.

A. Low-Pass Filter Design

The suspended microstrip dielectric stack-up shown in Fig. 1 with the laminate being suspended 1 mm above the ground plane was used for the design of a low-pass filter. A 3rd order low-pass filter in stepped impedance topology shown in Fig. 5 having a cut-off frequency of $f_T = 2.5$ GHz was designed. The Chebyshev transfer function was used to approximate the filter response to provide maximum stop-band attenuation for a given filter degree, assuming 0.1 dB ripple in the pass-band of the filter. Such a design requires two high impedance transmission lines having an impedance of $Z_1 = 120\ \Omega$ and 20° of electrical length at f_T, separated by a low impedance transmission line having $Z_2 = 20\ \Omega$ and 22° of electrical length. The frequency response of such an ideal-element directional filter is shown in Fig. 6. The final layout of the circuit was designed using *NI AWR Design Environment* software and is shown in Fig. 7 along with annotated dimensions.

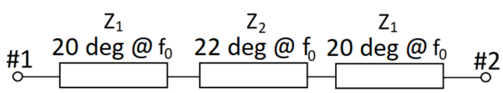


Figure 5. General schematic of a stepped-impedance low-pass filter.

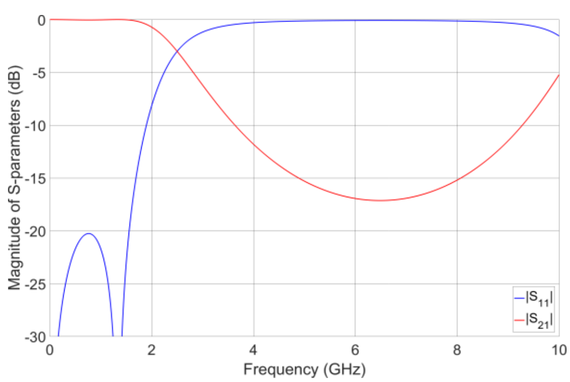


Figure 6. Frequency response of a 3rd order low-pass filter calculated for ideal-element circuit shown in Fig. 5 realizing equal-ripple Chebyshev transfer function with in-band ripples of 0.1 dB.

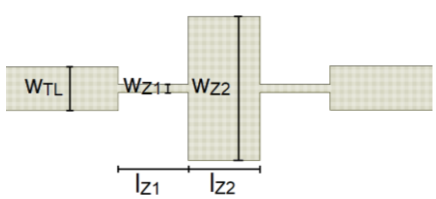
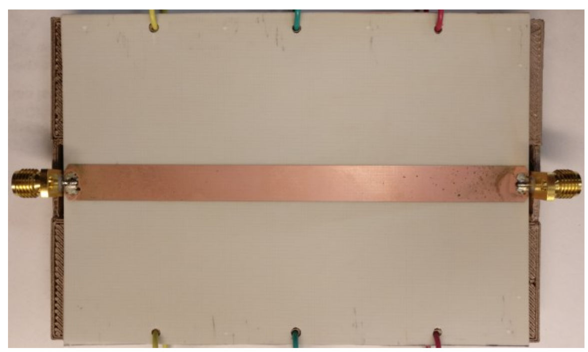


Figure 7. Layout of the designed 3rd order low-pass filter: $w_{Z1} = 1$ mm, $l_{Z1} = 8.7$ mm, $w_{Z2} = 18$ mm, $l_{Z2} = 9$ mm, $w_{TL} = 5.45$ mm.

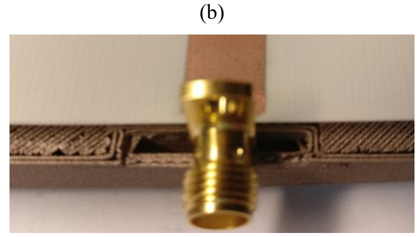
B. Test Transmission Line Section Manufacturing

A 50Ω test transmission line was designed beforehand to test-run the proposed manufacturing scheme and to fine-tune the filament print parameters for the utilized 3D printer. The 7.75 mm wide by 10 cm long test transmission line section was etched on a 12-mil thick RO4003C laminate and suspended 1.5 mm above the ground plane. The enclosure was designed accordingly to provide appropriate support and elevation of the laminate as well as thick enough conductive surface. Moreover, type B mounts were designed to attach the SMA connectors resulting in a final enclosure volume of 106.4 mm x 70 mm x 7 mm. Photographs of the circuit before and after assembly are shown in Fig. 8. A 0.4 mm nozzle was used to print at 0.2 mm layer height. The first four layers on the top and bottom were printed solid with a rectilinear infill at 45° with respect to the transmission line orientation. The material requires proper print parameter selection otherwise the print can be slightly under-extruded as seen in this case.

(a)



(b)

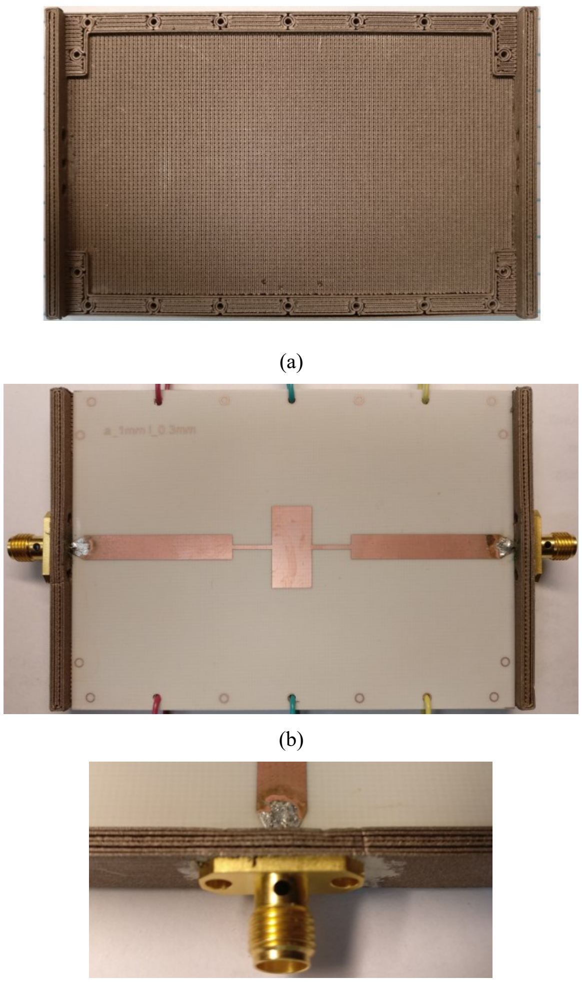


(c)

Figure 8. Photographs of the 3D conductive enclosure (a) and assembled test transmission line (b) with close-up on the mount A (c).

C. Low-Pass Filter Manufacturing

After successfully manufacturing the test transmission line, the designed low pass filter was manufactured. A dedicated enclosure was designed to provide the appropriate support and elevation of the laminate as well as thick enough conductive surface. In this case, type A mounts were design to attach the SMA connectors. The overall enclosure volume is 106.4 mm x 70 mm x 5 mm. Photographs of the circuit before and after assembly are shown in Fig. 9. Similarly, a 0.4 mm nozzle was used to print at 0.2 mm layer height. The first four layers on the top and bottom were printed solid with rectilinear infill at 0º with respect to the transmission line orientation. The surface roughness is reduced and the material fill is improved compared to the enclosure shown in Fig. 8.



(a)

(b)

(c)

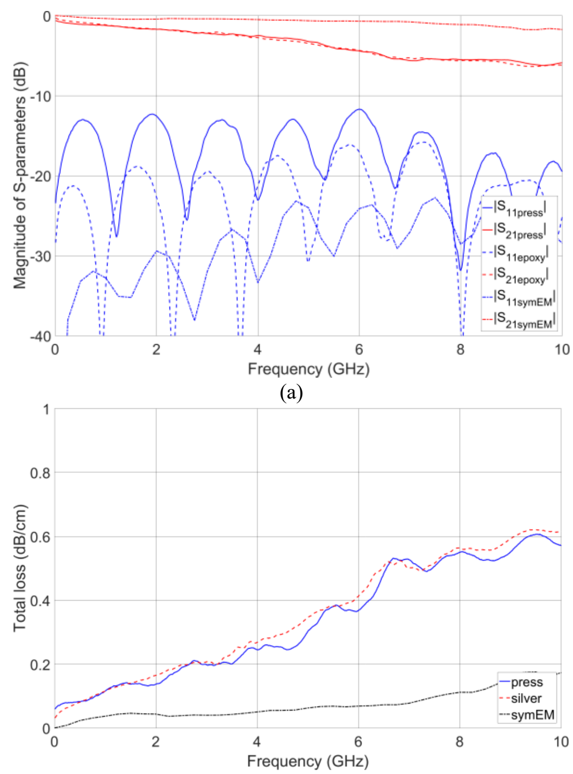
Figure 9. Photographs of the 3D conductive enclosure (a) and assembled exemplary low-pass filter (b) with close-up on the mount B (c).

IV. Experimental Results

Both of the manufactured circuits, i.e., the test transmission line section and the 3rd order low-pass filters were measured and the obtained results are discussed. The Keysight PNA Network Analyzer N5227A calibrated using SOLT standards with the reference plane set at the SMA connector plane was used. The measured frequency response along with mean total power loss per cm of length (calculated as a difference between power delivered to the port and sum of reflected and transmitted powers) is provided in each case. Moreover, both circuits were measured for two cases: (i) SMA connectors mounted using screws to provide a pressure galvanic contact, and (ii) SMA connectors mounted using screws and additional silver epoxy to provide a galvanic contact.

A. *Transmission Line Section*

First, the manufactured section of transmission line was measured and respective data is provided in Fig. 10 for both contact cases along with results of electromagnetic (EM) simulations using the *NI AWR Design Environment* software taking into account the parameters of each material used. As seen, the addition of silver epoxy improves the reflection coefficient, however slight or no improvement is visible on the total loss. The mean total loss per cm per GHz calculated as a slope of linear approximation of the measured data equals ≈ 0.08 dB/cm/GHz. Moreover, the effective conductivity of the manufactured enclosure falls between 1-5·10^3 S/m as compared to data shown in Fig. 2b.



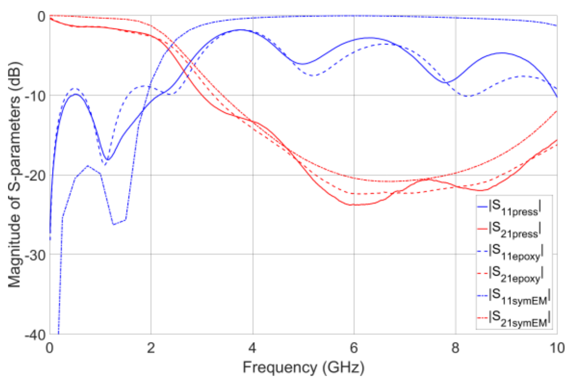
(a)

(b)

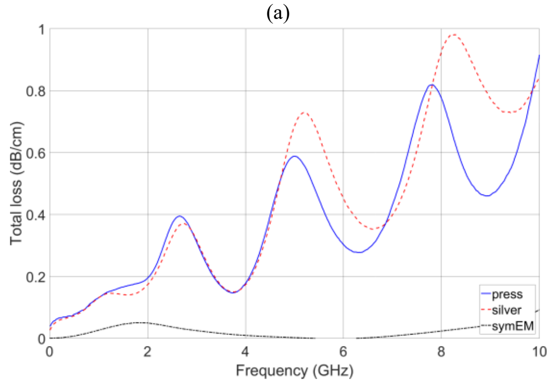
Figure 10. Measured S-parameters of the manufactured test transmission line section for a case when SMA connectors are attached and held by pressure (solid lines), and with addition of silver epoxy (dashed lines) in comparison with EM simulated data (dash-dot lines) (a). Calculated total loss per cm of length for each of the above described cases (b).

B. *Third-Order Low-Pass Filter*

Finally, the manufactured low-pass filter was measured and the measurement results are provided in Fig. 11 for both contact cases along with results of EM simulations. Little or no improvement is observed for the addition of silver epoxy which can be interpreted that the proposed mounting style provides reliable connection. The mean total loss per cm per GHz equals ≈ 0.93 dB/cm/GHz leading to the same conclusion as for the previous circuit with respect to the effective conductivity of the manufactured enclosure. The predicted total loss at 1.25 GHz, i.e. at the center of the passband equals ≈ 0.059 dB/cm while measurements show ≈ 0.145 dB/cm. The discrepancy between the manufactured circuit response and the design is most likely a result of different than assumed air layer thickness and print resolution in Z-axis. Moreover, the circuit behavior above cut-off frequency where equidistant ripples are observed can be attributed to the particular print pattern and geometrical dimensions of the enclosure.



(a)



(b)

Figure 11. Measured S-parameters of the manufactured low-pass filter for a case when SMA connectors are attached and hold by pressure (solid lines) and with addition of silver epoxy (dashed lines) in comparison with EM simulated data (dash-dot lines) (a). Calculated mean value of total loss per cm of length for each of the above described cases (b) where LPF is 26.4 mm long while connecting lines are 36.8 mm long on each side.

Based on the above presented measurement results we conclude that the proposed manufacturing process and material choice is of potential use for realization of circuits operating in the low GHz frequency range. To improve the circuits' performance, especially in terms of total power loss, a material featuring higher conductivity is required or further optimization of the 3D printing process parameters is of need since the effective permittivity of the manufactured enclosures is of one order of magnitude lower than the bulk conductivity of the utilized conductive filament.

V. Conclusion

In this paper, the realization of microwave circuits in suspended microstrip structure with a 3D printed conductive enclosure was presented for the first time. A low-pass filter with a cut-off frequency of 2.5 GHz together with a test transmission line section were designed, manufactured and measured. A Fuse Deposition Modeling (FDM) type 3D printing and a recently developed by Multi 3D conductive copper-based filament were employed to realize an enclosure serving both mechanical and electrical purposes. 3D printing related design aspects were considered and an optimal parameter selection was discussed. The manufactured circuits exhibit an average of approximately 0.8 - 0.93 dB/cm/GHz total loss meaning that the effective conductivity is only roughly 10% of the material`s bulk conductivity. However, the obtained results show that the proposed approach is of potential use for circuits and systems operating in the low GHz frequency range.

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References

[1] X. Jiao et al., "Designing a 3-D Printing-Based Channel Emulator With Printable Electromagnetic Materials," *IEEE Transactions on Electromagnetic Compatibility*, vol. 57, no. 4, pp. 868-876, Aug. 2015.

[2] M. Mirzaee and S. Noghanian, "High frequency characterisatio of wood-filled PLA for antenna additive manufactuirng application," *Electronics Letters*, vol. 52, no. 20, pp. 1655-1658, Sep. 2016.

[3] S. Khan, N. Vahabisani and M. Daneshmand, "A Fully 3-D Printed Waveguide and Its Application as Microfluidically Controlled Waveguide Switch," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 7, no. 1, pp. 70-80, Jan. 2017.

[4] J. A. Byford, M. I. M. Ghazali, S. Karuppuswami, B. L. Wright and P. Chahal, "Demonstration of RF and Microwave Passive Circuits Through 3-D Printing and Selective Metalization," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 7, no. 3, pp. 463-471, Mar. 2017.

[5] F. Cai, Y. H. Chang, K. Wang, C. Zhang, B. Wang, and J. Papapolymerou, "Low-Loss 3-D Multilayer Transmission Lines and Interconnects Fabricated by Additive Manufacturing Technologies," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 10, pp. 3208–3216, 2016.

[6] M. I. M. Ghazali, E. Gutierrez, J. C. Myers, A. Kaur, B. Wright, and P. Chahal, "Affordable 3D printed microwave antennas," *in Proc. 65th IEEE Electron. Compon. Technol. Conf.*, May 2015, pp. 240–246.

[7] J. Sorocki, S. Koryciak, I. Piekarz, S. Gruszczynski, K. Wincza, "Investigation on Additive Manufacturing with Conductive PLA Filament for Realisation of Lowloss Suspended Microstrip Microwave Circuits," in Proc. *International Conference on Electrical, Electronics*

and System Engineering (ICEESE 2017), pp. 48-51, 09-10.11.2017, Kanazawa, Japan.

[8] A. Rida, L. Yang, R. Vyas, and M. M. Tentzeris, "Conductive inkjetprinted antennas on flexible low-cost paper-based substrates for RFID and WSN applications," *IEEE Antennas Propag. Mag*., vol. 51, no. 3, pp. 13–23, Jun. 2009

[9] Multi3D, "Electrifi Conductive 3D Printing Filament," Electricaly Conductive Filament FAQ page, [Online]. Available: https://www.multi3dllc.com/faqs/. [Accessed Feb. 12, 2018]