Investigation on Additive Manufacturing with Conductive PLA Filament for Realisation of Low-loss Suspended Microstrip Microwave Circuits

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***Abstract*—In this paper we investigate the applicability of additive manufacturing with conductive Polylactic Acid (PLA) based filament for realization of low-loss suspended microstrip microwave circuits. Filament is used to 3D print case which serve three major functions: provides mechanical enclosure and support for the circuit, provides appropriate elevation of the thin laminate with circuit mosaic over the ground plane and can potentially serve as the ground plane. The influence of the bulk conductivity of the utilized filament on total losses within the structure has been studied. Moreover, an exemplary transmission line hosted in Fused Deposition Modelling (FDM) 3D printed case has been manufactured and measured. Graphene-enhanced PLA material having volume conductivity of ≈ 166 S/m has been used yielding total loss of ≈ 0.14 dB/cm/GHz while reference case with copper foil ground plane yields total loss of ≈ 0.04 dB/cm/GHz.**

Keywords—additive manufacturing; 3D printing; PLA; suspended microstrip transmission line.

I. Introduction

In recent years, an increased interest in utilization of different additive manufacturing techniques for realization of microwave circuit and systems is observed [1]-[10]. This is due to significant development of 3D printing machines providing high print resolution and possibility of deposition various types of non-conductive and conductive materials. Moreover, 3D printing allows for greater freedom of circuits geometry due to three-dimensional nature of the technology as in contrary to 2.5D for conventional techniques. Additionally, additive manufacturing allows for fast prototyping and evaluation of the microwave devices, as well as lowering the overall time and cost of production. Therefore, the novel manufacturing technologies have found their application for realization of e.g. waveguides [2], sensors' application [7] as well as antennas [1], [6] and other passive devices (filters, dividers, etc.,) [4], [8]-[10]. However, in many cases either the required printing equipment or appropriate materials can be very expensive. Moreover, some post-processing might be required such as metallization when core material is dielectric and conductive surface is required.

In this paper, we investigate the applicability of additive manufacturing with conductive PLA filament for realization of low-loss suspended microstrip microwave circuits. The PLA is a relatively inexpensive material, which is well suitable for Fused Deposition Modelling (FDM) 3D printers resulting in cost-effective circuit manufacturing. The filament is used to 3D print case, which can serve three major functions: to provide mechanical enclosure and support for the circuit, to provide appropriate elevation of the laminate over the ground plane and potentially can serve as the ground plane itself. Such an approach allows for simplification of the manufacturing process, since metallization of the case will no longer be required as in contrary to when case is manufactured using dielectric materials such as Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA) or Polymer based ones [8], [10]. However, applicability of the proposed approach strongly depends on conductivity of the utilized filament. The influence of filaments` volume conductivity on total losses within the circuit has been studied using EM calculation. Moreover, an exemplary transmission line hosted in 3D printed case using FDM method has been manufactured and measured. Material having volume conductivity of ≈ 166 S/m has been used yielding average total loss of ≈ 0.14 dB/cm/GHz.

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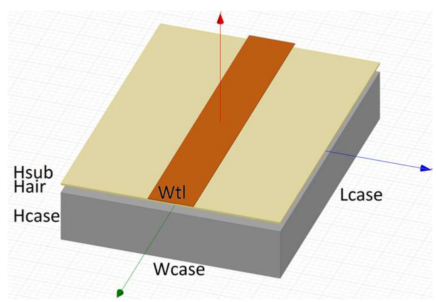

Fig. 1. Isometric view of the suspended microstrip structure under investigation. Thin laminate hosting transmission line is elevated over the ground plane. Ground plane is realized as solid block of conductive material.

II. Ground plane conductivity vs total loss of the suspended microstrip circuit

In order to verify the applicability of the additive manufacturing with conductive PLA filament for realization of low-loss suspended microstrip microwave circuits, at first a theoretical study has been conducted. For such purpose, a suspended microstrip line model shown in Fig. 1 has been used. The structure is composed of thin microwave laminate having thickness of h_{sub} hosting a transmission line section having width of w_{TL} being suspended at height of h_{air} over the ground plane. The ground plane is realized as a solid block of conductive material having dimensions of h_{case} by w_{case} by l_{case} and volume conductivity of σ. Since current commercially available conductive PLA filaments feature rather low volume conductivity ranging within hundreds of S/m, it has been assumed that conductivity of the ground conductor is the main contributor to the circuits` total loss (being a sum of conductor, dielectric and radiation losses).

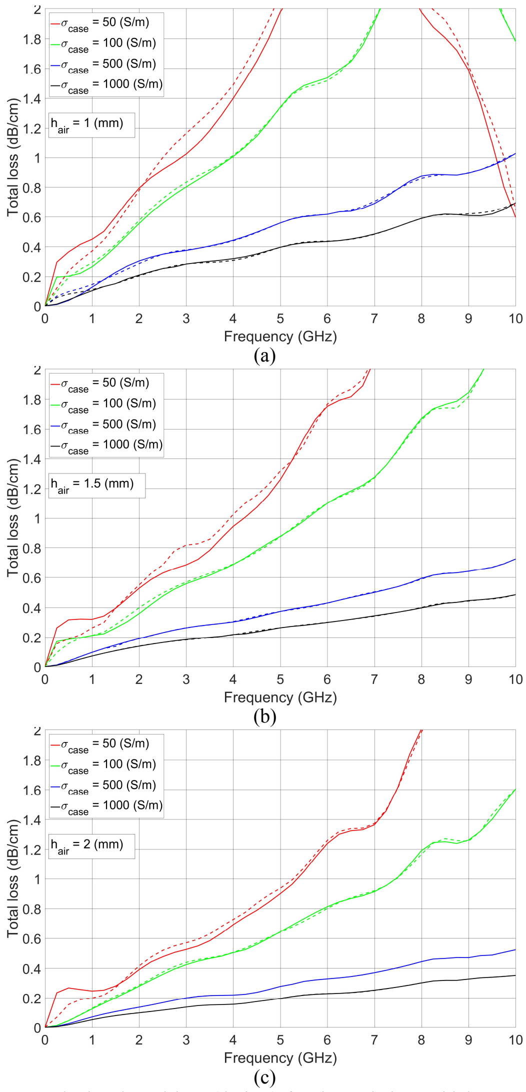

Fig. 2 Calculated total loss (dB/cm) for three air layer thickness: h_{air} = 1 mm (a), h_{air} = 1.5 mm (b) and h_{air} = 2 mm (c) and two case thicknesses: h_{case} = 2 mm (solid) and h_{case} = 5 mm (dashed). A perfect solid case is assumed having length l_{case} = 50 mm and width w_{case} = 28 mm (determined by *AWR AXIEM* simulator in *NI AWR Design Enviroment* for a given metal layer width). Transmission line width is set to w_{TL} = 8 mm.

Electromagnetic calculations have been performed for four different volume conductivities being order of magnitude apart (σ = 50, 100, 500, 100 S/m), two different case thicknesses (h_{case} = 2, 5 mm) as well as three different air layer thicknesses (h_{air} = 1, 1.5, 2 mm). Remaining case dimensions are fixed to be width w_{case} = 28 mm and l_{case} = 50 mm. Laminate having thickness h_{sub} = 0.3 mm, relative permittivity ε_{sub} = 3.38 and loss tangent $tan\delta$ = 0.003 which corresponds to parameters of a commercially available Arlon 25N material has been assumed. Moreover, section of transmission line on top of the laminate is w_{TL} = 8 mm wide and a 0.5 oz. copper is assumed as a conductor. The obtained data has been shown in Fig. 2. Following can be stated based on data analysis. Firstly, RF current skin depth is smaller than h_{case} = 2 mm since for all cases, except σ = 50 S/m, data for different thicknesses is in good agreement. Secondly, it can be observed that total loss is highly influenced by the thickness of the air layer. The higher the layer, the lower the loss. However, in order to maintain given characteristic impedance while increasing suspension height, the line width must be increased what decreases circuit frequency of operation (line becomes too wide in respect to guided wavelength). Finally, it can be observed that resulting total loss is relatively high, especially when low-loss circuits are considered what may discard the applicability of such conductive materials despite their promising advantages.

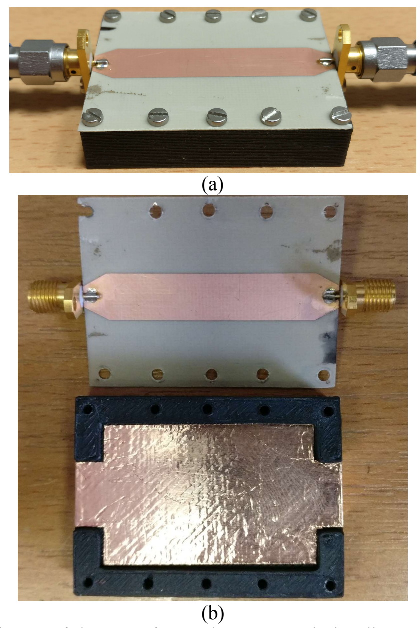

Fig. 15. Picture of the manufactured test transmission lines. Thin laminate hosting transmission line is suspended over 3D printed conductive case providing ground plane – circuit A (a) and suspended over 3D printed case with copper tape providing ground plane – circuit B (b).

III. Experimental Results

In order to experimentally verify the results of theoretical study, two exemplary suspended microstrip transmission lines hosted in 3D printed case has been designed, manufactured and measured. For one, namely A, the ground plane is provided by the conductive case itself while for the reference one, namely B, the ground plane is realized using copper foil. Two potentially suitable low-cost filaments have been found available on the market: conductive, carbon black enhanced PLA filament by Proto-pasta [11] and conductive, graphene enhanced PLA filament by Black Magic 3D [12]. For the experimental investigation, the latter filament has been used. The material is advertised to feature superior conductivity and improved mechanical properties in respect to other PLA filaments, which is valuable from electrical as well as mechanical perspective for the resulting circuits. According to datasheet [12] material features volume resistivity of 0.6 Ω-cm, which translates into volume conductivity of σ ≈ 166 S/m while the considered counterpart features volume resistivity of as much as 30 Ω-cm (σ ≈ 3.3 S/m) [11]. The utilized filament is well suitable for additive manufacturing using FDM technique and manufacturer provides optimal parameters for this type of processing. Three important aspects of the printing process can be distinguished which will influence the effective conductivity of the printed case, hence circuit total losses. First is minimal case thickness as it has been investigated in previous Section that ensures RF current flowing within full skin depth. Second is optimal printing pattern that provides flat surface with minimal roughness at least within several layers of the print starting from air layer-conductive filament interface. Third is material infill within the print. As a result, the effective volume conductivity is going to be less or equal to materials` volume conductivity.

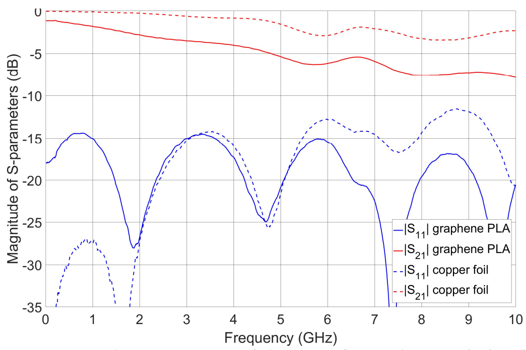

Fig. 16. Measured S-parameters of the manufactured transmission line for case when conductive graphene-enhanced PLA material serves as a ground plane (solid) in comparison to case where copper foil serves as ground line (dashed).

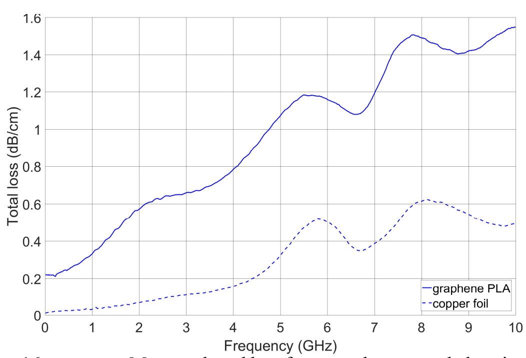

Fig. 16. Measured total loss for case when ground plane is realized using conductive graphene based PLA material (solid line) and when ground plane is realized using solid copper tape (dashed line).

The experimental transmission line is realized as follows: Arlon 25N laminate having parameters as assumed for theoretical study hosting w_{TL} = 8.5 mm wide transmission line has been suspended over the ground plane by h_{air} = 1.4 mm. The manufactured cases use an inter-layer rectilinear pattern; angled 45° in respect to the transmission line direction. A 0.4 mm layer height has been used and 40% infill after three solid layers on top, bottom and sides of the case. Case dimensions are h_{case} = 8.6 mm, w_{case} = 28 mm and l_{case} = 50 mm. Extra 5 mm wide material layer around edges is added to support and suspend the laminate. Moreover, slight tapper at both ends of the transmission line has been added to accept SMA connectors. A picture of the manufactured circuits is shown in Fig. 3 while measured S-parameters are shown in Fig. 4. Moreover, total loss calculated as a difference between power delivered to the port and sum of reflected and transmitted power from that port is shown in Fig. 5. The mean total loss per cm per GHz calculated as slope of linear approximation of the measured data equals ≈ 0.14 dB/cm/GHz for transmission line with ground plane being graphene-enhanced PLA filament while reference transmission line with copper foil ground plane yields total loss of ≈ 0.04 dB/cm/GHz.

IV. Conclusion

The applicability of additive manufacturing with conductive PLA filament for realization of low-loss suspended microstrip microwave circuits has been investigated. The 3D printed conductive case can serve as a mechanical structure, and potentially, as well as electrical ground plane. The influence of filament volume conductivity on total losses within the suspended structure has been studied using EM calculations. Moreover, an exemplary transmission line hosted in 3D printed case has been manufactured and measured. Recently developed graphene-enhanced PLA material having volume conductivity of ≈ 166 S/m has been used yielding total loss of ≈ 0.14 dB/cm/GHz. The proposed approach has potential for application, however the state-of-the-art conductive PLA materials does not provide sufficient conductivity for practical uses.

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