A Model for 3D-Printed Microstrip Transmission Lines using Conductive Electrifi Filament

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***Abstract*—New research on wearable electronics, domotics, flexible circuits, and RF applications on conformal surfaces have used the advancements of material science and additive manufacturing technology. Parallelly, the limited design specifications of industrially available PCB substrates (i.e., flat substrates) has stimulated a *de novo* exploration for more complex electronic circuits with versatile geometries. In this paper, the development of a microstrip transmission line using additive manufacturing technology and Electrifi conductive filament is reported for the first time. The simulated and measured transmission properties of the design are also compared and presented.**

I. Introduction

Lately, there has been an increasing demand in using additive manufacturing technology to cater the need of low-profile, low-cost, flexible electronic circuits. Compared to the traditional photolithography process, conductive traces can now be manufactured in a relatively simpler and economic way using this incipient technology. Additionally, these printed transmission lines can be less vulnerable to cracking and breaking compared to the industry manufactured regular transmission lines (TLs) made of copper. Recently, the uses of various liquid conductive mediums, such as Carbon Black ink, Silver ink, Nanoparticle ink, and Metallograph ink to print simple RF circuits have been reported [1]. However, these techniques require complex and extensive manufacturing procedures and further developments on the issues of connections and measurements are needed.

The objective of this paper is to use additive manufacturing (i.e., 3-D printing) with Electrifi [2] conductive filament, instead of copper, to create and model the top conducting layer of microstrip TLs for antenna applications. A model of the proposed Electrifi-based 3D-printed TL including all the connections, as shown in Fig. 1, is presented for the first time here, followed by a detail comparison analysis using measurement and full-wave simulation. Finally, it was shown that this new type of conductive filament can be used as an alternative to regular copper TLs.

II. Methodology and fabrication of prototypes

All reported TLs in this paper were 51 mm long and evaluated on a 62 mil Rogers TMM4 [3] substrate (ϵ_r = 4.5, $\tan\delta$ = 0.002) with 35 μm copper cladding on the bottom (i.e., grounded substrate).

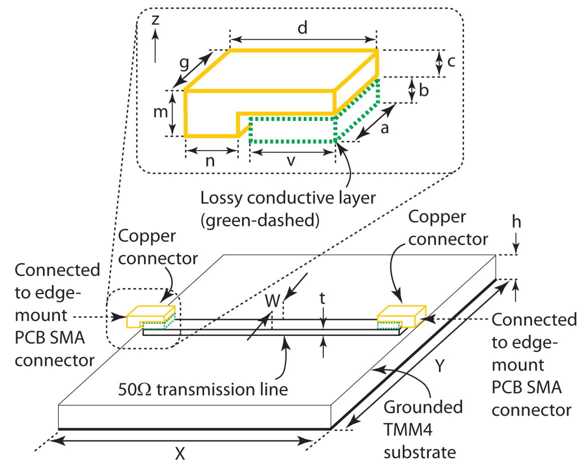

Fig. 1. Model of the printed TLs (Dimensions: a = g = 0.898, b = 0.15, c = 0.213, d = 4, h = 1.57, m = 1.113, n = 1, t_{Copper} = 0.035, $t_{Electrifi}$ = 1, v = 2.5, W = 2.71, X = Y = 53, all in mm).

A. Copper-based Regular Microstrip Transmission Line

Initially, for validation, the top layer of the 50Ω microstrip TL in Fig. 1 was fabricated with copper. As the benchmark, the phase of the transmission coefficient S_{21} of this prototype was measured and compared with a full-wave model designed in Ansys Electronics Desktop [4]. As illustrated in Fig. 2, a good match between the simulation and measurement is shown for the copper TL, confirming the full-wave model design and measurements. It should be noted here that all resulting phases due to the intermediate SMA connectors during measurements have been considered in the full-wave simulation.

B. Electrifi-based 3-D Printed Microstrip Transmission Line

Next, the top conducting layer of the 50Ω TL in Fig. 1 was manufactured using a 3-D printer and Electrifi conductive filament, instead of copper, on the same TMM4 substrate. The bottom conducting layer remained copper. To do so, a MakerBot Replicator [5] 3-D printer was set to a temperature of 145°C, a print speed of 10 mm/sec and was fed the new conductive Electrifi filament to 3-D print a 2.71 mm wide, 51 mm long, and 1 mm thick trace with 100% infill. Finally, the manufactured trace was carefully placed on the side of the TMM4 board without the copper and connected to SMA connectors using industrial silver epoxy (CAT. NO. 8330-

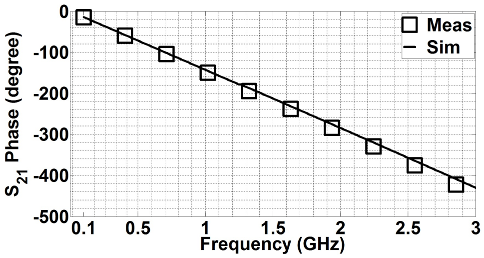

Fig. 2. Simulated and Measured S_{21} phase of the 50Ω copper TL.

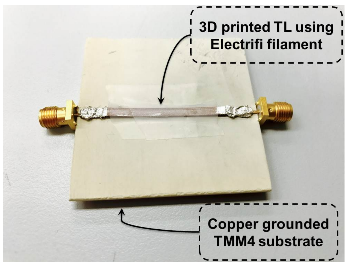

Fig. 3. Printed 50 Ω microstrip TL using Electrifi filament on TMM4.

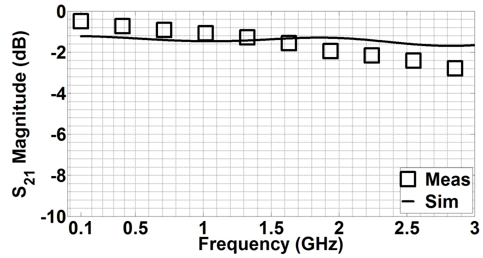

Fig. 4. S_{21} Magnitude of printed 50 Ω microstrip TL using Electrifi filament.

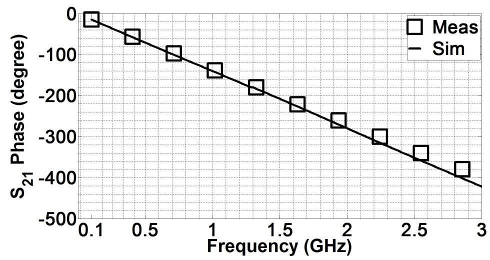

Fig. 5. S_{21} Phase of printed 50 Ω microstrip TL using Electrifi filament.

19G) with a cure time of 24 hours at room temperature. The top layer of this new 50Ω microstrip TL is shown in Fig. 3. Next, the reflection coefficient S_{11} was measured from 100MHz to 3GHz and $|S_{11}| < -20$ dB for the entire band. Also, the magnitude and phase responses of the transmission coefficient S_{21} were measured and are shown in Figs. 4 and 5, respectively.

Then, the Electrifi-based TL was modeled in HFSS. Two key aspects of this full-wave model are the losses in the 3-D printed trace and the losses in the bond between the 3-D printed trace and the edge mount SMA connectors. To determine these losses, as noticed in the Fig. 4 with a magnitude of 1-2 dB, the net dc resistance R_{net} was measured between the center pins of the two SMA connectors and can be written as

$$R_{\text{net}} = R_{\text{trace}} + R_{\text{connectors}} \tag{1}$$

where R_{trace} is the resistance due to the trace and $R_{\text{connectors}}$ is the resistance due to the bond between the trace and the connection with the silver epoxy on each connector. Now, considering the resistivity of the trace made of the Electrifi filament to be 61 $m\Omega$-mm, provided by the manufacturer [2], the resistance due to only the trace was calculated from the dimensions using the following equation:

$$R_{\text{trace}} = 61 \times \frac{50}{2.71 \times 1} m\Omega = 1.125\Omega. \tag{2}$$

To find R_{net}, three identical microstrip TLs made of Electrifi conductive trace were manufactured and their individual resistivities were measured across the pair of connectors. An average value for the net dc resistance R_{net} was measured to be 7.5Ω. Hence, the dc resistance due to only the connectors on the either side of the Electrifi filament TL was found using equation (1) to be $R_{\text{connectors}}$=6.375Ω. Assuming negligible dc resistivity of the SMA connector itself, the resistance $R_{\text{connectors}}$ was determined to be due to the bond between the silver epoxy and the trace made of Electrifi filament. To model this bond, a lossy conductive layer (σ) was inserted between the SMA pin and the Electrify-based TL and simulated in HFSS. A complete geometry of this model is shown in Fig. 1. The value of the conductivity σ of the bond was evaluated from the geometry of the bond and $R_{\text{connectors}}$ using following equation:

$$\sigma = \frac{b}{\text{a} \times \text{v}} \times \frac{1}{R_{\text{connectors}}} \approx 10(S/m). \tag{3}$$

Overall, a very good agreement between the simulation and the measurement in Figs. 4 and 5 established the validity of this newly reported full-wave model.

III. Conclusion

The development of a novel 3D-printed 50Ω microstrip TL was reported here. The comparison analysis between the full-wave simulations and the measurements were presented using a new full-wave TL model. Altogether, it can be concluded that 3D-printed TLs using Electrifi filament can be used as an alternative to regular copper TLs for antenna applications up to 3.0 GHz.

References

[1] Ahmadloo, M. and Mousavi, P., "A novel integrated dielectric-and-conductive ink 3D printing technique for fabrication of microwave devices", *2013 IEEE Int. Microwave Symposium*, pp. 1-3, June 2013.
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