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Photonic Curing of mm-Wave Coplanar Waveguides for Conductor Loss Enhancement

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Abstract— **Additive manufacturing (AM) techniques for high-frequency electronics have evolved in the past decade to not only offer similar performance as traditional manufacturing, but to offer unprecedented design freedom. One of the main challenges of AM of radio-frequency devices is the losses associated with the printed conductive layers. Recent studies have shown that pulsed laser can enhance the conductivity of the conductive inks. In this work, the photonic curing process, or PulseForge®, is applied to AM coplanar waveguides (CPW) to measure its effect on the high-frequency electric conductivity. Dissipative losses are reduced by 2.58 dB, from -4.74 dB to -2.16 dB, at 40 GHz over a 10 mm long line, after photonic curing, when compared to thermally cured samples.**

Keywords—additive manufacturing, silver ink, coplanar waveguide, micro-dispensing, photonic curing.

I. Introduction

Over the last decade, additive manufacturing (AM) techniques have evolved to a level where it is possible to 3D print passive components and antennas with performance levels at the level of traditional manufacturing processes, with the capability of obtaining 3D and conformal geometries. AM provides an unprecedented design and manufacturing freedom to not only obtain geometries that are not possible to achieve by traditional means, but also engineered conductive and dielectric materials for specific applications.

AM of conductors typically involve the use of micro-particle or nanoparticles of copper or silver suspended in a resin, which is deposited and subsequently thermally cured. The electric conductivity of these thermally cured inks is typically two orders of magnitude lower than the bulk conductor, which directly impacts the losses of AM passive components. In [1] the concept of laser-enhanced direct print additive manufacturing (LE-DPAM) is introduced, showing that picosecond laser machining can improve effective electric conductivity of high-frequency coplanar waveguides (CPW) by a factor of over 100x. Further improvements on conductor loss by laser processing on grounded CPW (GCPW) and microstrip lines (ML), up to 30 GHz, are presented in [2]. In [3] the use of high-energy photonic curing is shown to improve the direct current (DC) electric conductivity of DPAM traces by up to a factor of 80x.

In this paper, improvements in high-frequency electric conductivity of printed silver conductors, up to mm-wave frequencies, is presented. CPWs are designed and manufactured using DPAM and milling to reduce surface roughness. The printed conductors are exposed to photonic curing with a peak power of 1700 W/cm^2, resulting in a reduction of their dissipative losses. The CPW showed a reduction in dissipative losses of 2.58 dB, from -4.74 dB to -2.16 dB, at 40 GHz.

II. Design and Fabrication

To test the effectiveness of photonic curing compared to thermal curing, coplanar waveguides are designed as test structures as shown in Fig. 1. Poly-ether-ether-ketone (PEEK) is selected as the dielectric due to its low high-frequency dielectric losses, mechanical properties, and compatibility with space environments [4]. The design properties of PEEK are: relative permittivity $\varepsilon_r = 3.2$ and loss tangent (tanδ) of 0.0046. NovaCentrix HPS-FG57b Ag paste is used to form the conductive ground planes and signal line of the CPW. This Ag paste has an average particle size of 4.5µm, making it ideal for dispensing fine features. The designed dimensions for the CPW are shown in Fig. 2. The substrate is additively manufactured using the fused deposition modeling (FDM) process and is printed with a 1mm thickness. To minimize the effects of surface roughness of the as-printed parts, a milling head (nScrypt nMill) is used to remove around 75 µm of material from the top layer of the substrate, yielding a surface with 0.8µm surface roughness, measured with a Mitutoyo SJ210 profilometer. The milling head is set to 20000 revolutions per minute, with a 3mm, four-flute endmill bit, and a feed rate of 50 mm/s.

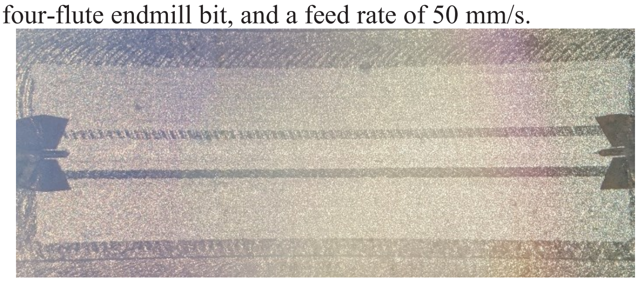
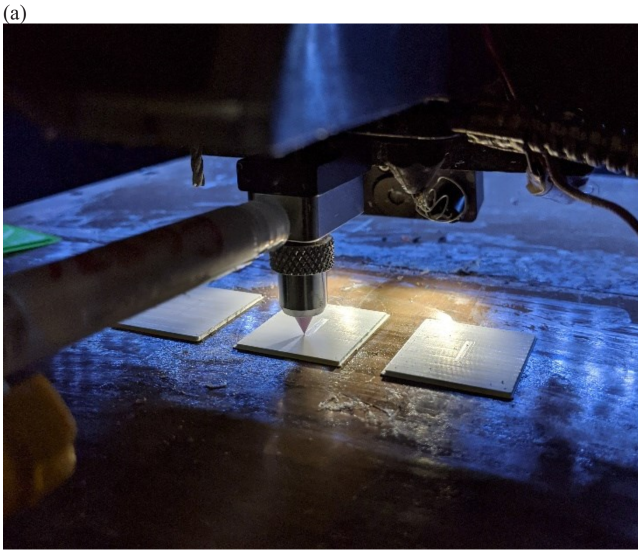


Fig. 1. Geometry of the coplanar waveguide (CPW).

Fig. 2. CPW designed dimensions, in mm.

Both sets of CPW samples are thermally cured in the oven at 160°C for 5 minutes. One set of samples is then processed with a NovaCentrix PulseForge photonic curing system. The photonically cured samples are placed on the printing bed, and exposed to the photonic lamp for 500 µs, with a peak power of 1700 W/cm^2.

(a)



(b)

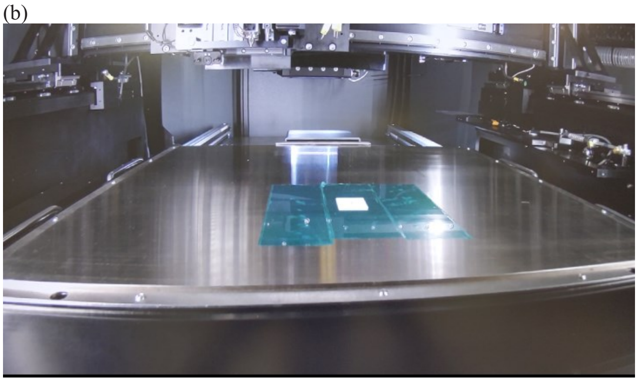


Fig. 3. (a) nScrypt system fabricating CPWs (b) CPW prepared for photonic curing

III. Results

The S-parameters of the thermally cured and photonically cured samples are measured using an RF probing station, using a pair of ground-signal-ground GGB 40A-GSG-600-DP probes, as shown in Fig. 4. which are calibrated with a CS-9 GGB calibration substrate. The S-parameters are extracted using an E8361A vector network analyzer up to 40 GHz.

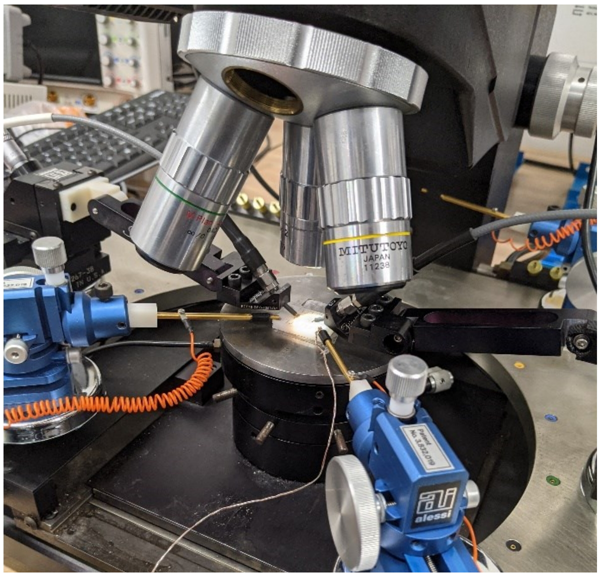


Fig. 4. RF probe station.

Fig. 5(a) shows the comparison between the measured insertion loss and return loss, for both the thermally cured and photonically cured samples. The dissipative loss (DL) in the transmission line is calculated with the equation: $DL = S_{21}{}^2/(1-S_{11}{}^2)$, where all the parameters are in linear scale. Fig. 6 shows the comparison between the thermally cured and photonically cured samples.

The top surface of the thermally cured and photonically cured conductors is inspected using a scanning electron microscope. Fig. 7(a) and 7(b) show the top view of the ink after thermal curing, and after photonic curing, respectively.

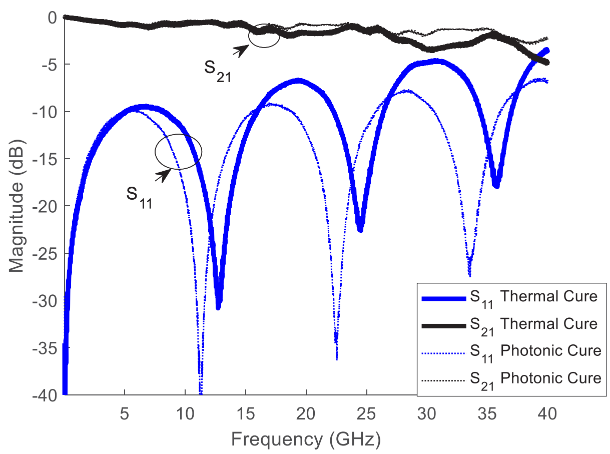


Fig. 5. (a) Magnitude of measured S-parameters.

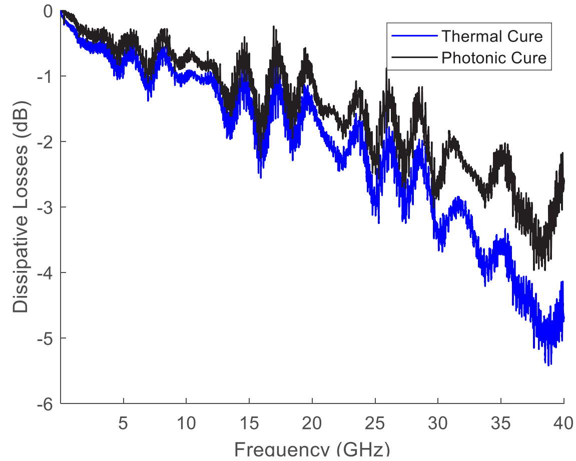
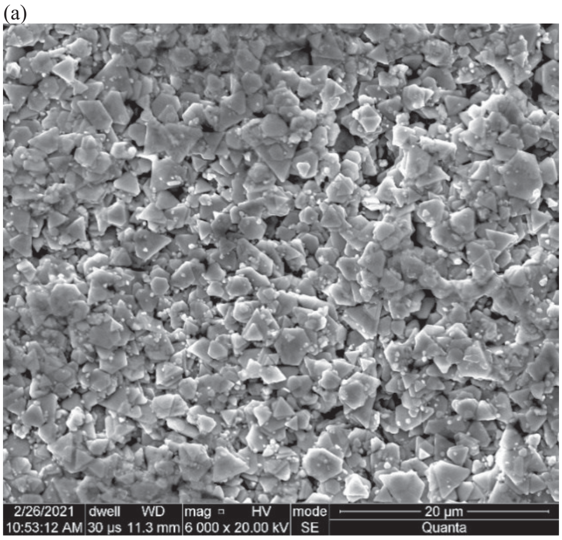


Fig. 6. Dissipative loss on the CPW extracted from the measured S-parameters.

IV. Conclusion

The measured S-parameters of the CPW suggest a reduction of 2.58 dB in dissipative loss, from -4.74 dB to -2.16 dB, at 40 GHz, after the samples are photonically cured. This notable reduction in loss suggests improvements on the effective electric conducticity after photonic curing, when compared to thermally cured samples. The SEM micrographs (Fig. 7) show that the boundaries of the silver particles are better defined after photonic curing, when compared to the thermally cured samples; indicating potential removal of the ink's resin, hence, an improvement on electric conductivity. Future work includes the characterizaiton of the CPW loss reduction for different photonic curing parameters, such as power and duration, as well as inspecting cross setions of the conductive layer to detect any potential solidification of the deposited silver ink layer.

(a)



(b)

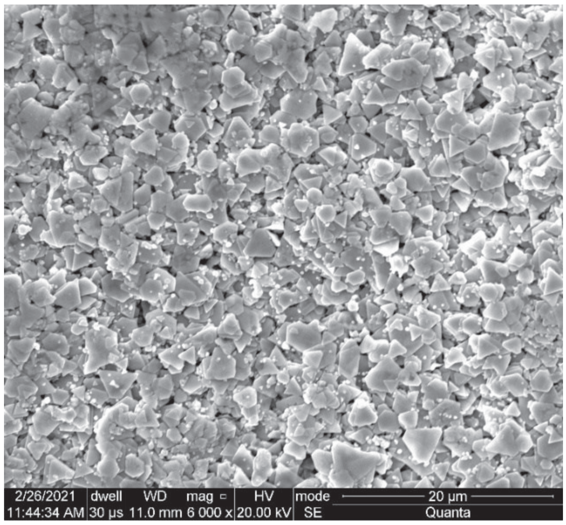


Fig. 7. Scanning electron microscope micrographs of top surface of the printed conductor. Images (a) and (b) are for the thermally cured and photonically cured conductors, respectively.

V. Aknowledgements

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