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Low-Loss LIGA-Micromachined Conductor-Backed Coplanar Waveguide

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Low-Loss LIGA-Micromachined Conductor-Backed Coplanar Waveguide

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Abstract

A mesoscale low-loss LIGA-micromachined conductor-backed coplanar waveguide is presented. The 517 μm lines are the tallest uniplanar LIGA-fabricated microwave transmission lines to date, as well as the first to be constructed of copper rather than nickel. The conductor-backed micromachined CPW on quartz achieves a measured attenuation of 0.064 dB/cm at 15.5 GHz.

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Introduction

Previous work in the field has taken advantage of the enhanced coupling provided by LIGA-micromachined transmission lines fabricated from thick metal to create microstrip filters [1], end-fire antennas [2], and high-Q resonant cavities for use in a klystrino [3]. This work extends the state of the art of LIGA-micromachined RF circuitry by building the tallest transmission-line structures to date, utilizing high-conductivity copper in place of the traditionally used nickel, and demonstrating a novel low-loss CPW.

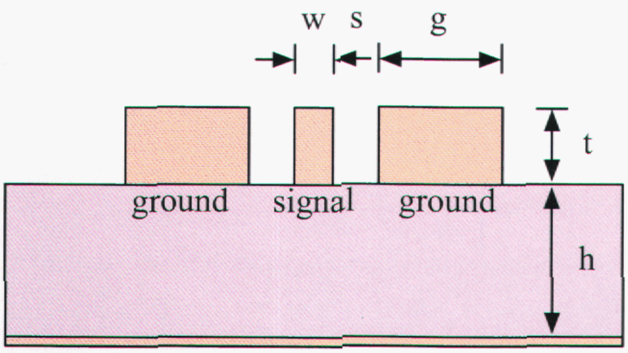
A conductor-backed coplanar waveguide (CPW) was fabricated using the LIGA-micromachining process. In the LIGA (*Lithographie, Galvanoformung, Abformung*) process, structures with near-vertical sidewalls are fabricated by means of deep X-ray lithography, electrodeposition of metal, and mechanical grinding. This process enables the creation of thick structures or molds with near-vertical sidewalls based on two-dimensional patterns. These structures can be between 10 μm and 1 mm in height with aspect ratios as high as 100:1 [4]. The variant of the LIGA-micromachining process, used to create the CPW presented in this paper, utilizes the intermediate metal structures and carrier substrate as the final microwave circuitry and dielectric. Due to the high sidewalls, the electric field is confined primarily to the space between the signal and ground lines. This geometry distributes the surface current over the full height of the metal, reducing ohmic losses, relative to standard CPW, while drawing the electric field out of the substrate, reducing dielectric loss. The reduced interaction between the fields and the substrate minimizes dispersion, radiation loss, and the excitation of substrate modes. Additionally, the ability to fabricate microwave structures with variable thickness adds an additional design parameter, increasing design flexibility.

Table 1. Comparison of microstrip and CPW

Feature	Microstrip	CPW
Dispersion	high	low
Losses	low	high
Coupling	high	low
Flexibility	low	high
Size	large	small
Backside	yes	no
Vias	yes	no

As can be seen in Table 1, CPW offers many advantages over microstrip transmission lines with the exception of loss. The works seeks to solve this deficiency while simultaneously increasing power-handling capacity, reducing dispersion, and and enabling the creation of high-Q CPW-based filters.

Design

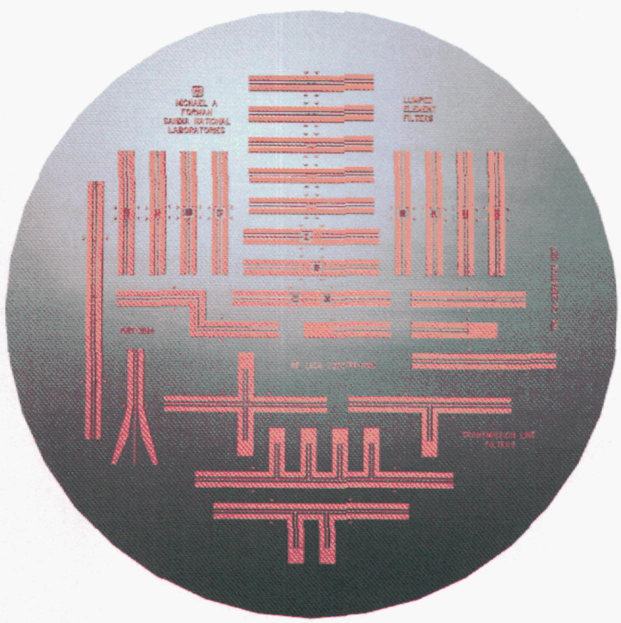


(a)

CPW Dimensions		Parameters (20 GHz)	
w	250 µm	ε_{eff}	1.614
s	300 µm	λ_g	18.9 mm
g	850 µm	Z_0	52 Ω
t	500 µm		

(b)

Figure 1. A cross section of the CPW (a) shown with designed dimensions (b).



(a)

CPW Dimensions		Substrate Values	
w	238±5 µm	ε_r	3.75
s	318±5 µm	$\tan\delta$	0.0004
g	835±5 µm	h	1 mm
t	517±10 µm	d	100 mm

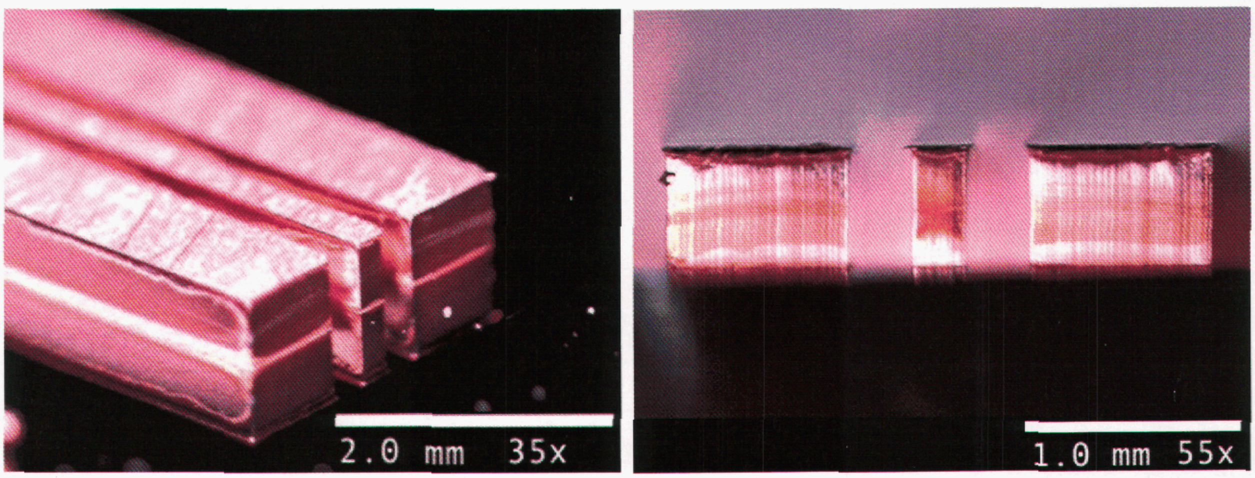
(b)

Figure 2. Schematic of quartz wafer with copper CPW transmission lines and filters (a) with measured CPW dimensions (b).

With the primary goal being the creation of a low-loss transmission line, the conductor and substrate were selected to minimize loss. The selected metal is copper with a conductivity of $\sigma = 5.8 \times 10^7$ S/m, which is higher than the traditionally used nickel with a conductivity of $\sigma = 1.0 \times 10^7$ S/m. The selected dielectric is a clear, fused quartz wafer with a relative permittivity of

$\varepsilon_r = 3.75$, a loss tangent of $\tan\delta = 0.0004$, a height of $h = 1.0$ mm, and a diameter of $d = 100$ mm. The cross section of the designed CPW is shown in Figure 1 (a). Ansoft *HFSS* [5], is used to simulate the CPW. The height of the transmission line is set at $t = 500\,\mu$m, in order to achieve a novel metallic thickness, while ensuring that the structure is not so tall, that it can not be reliably fabricated. The gap between conductors is $s = 300\,\mu$m, to reduce the likelihood of long beams of acrylic polymethyl-methacrylate (PMMA) buckling due to expansion during the processing. The CPW is designed with a center-conductor width of $w = 250\,\mu$m, a signal-ground separation of $s = 300\,\mu$m, and a ground-conductor width of $g = 850\,\mu$m. The line has a simulated characteristic impedance of $Z_0 = 52\,\Omega$, an effective relative permittivity of $\varepsilon_e = 1.614$, and a guided wavelength of $\lambda_g = 18.9$ mm at 20 GHz.

Fabrication

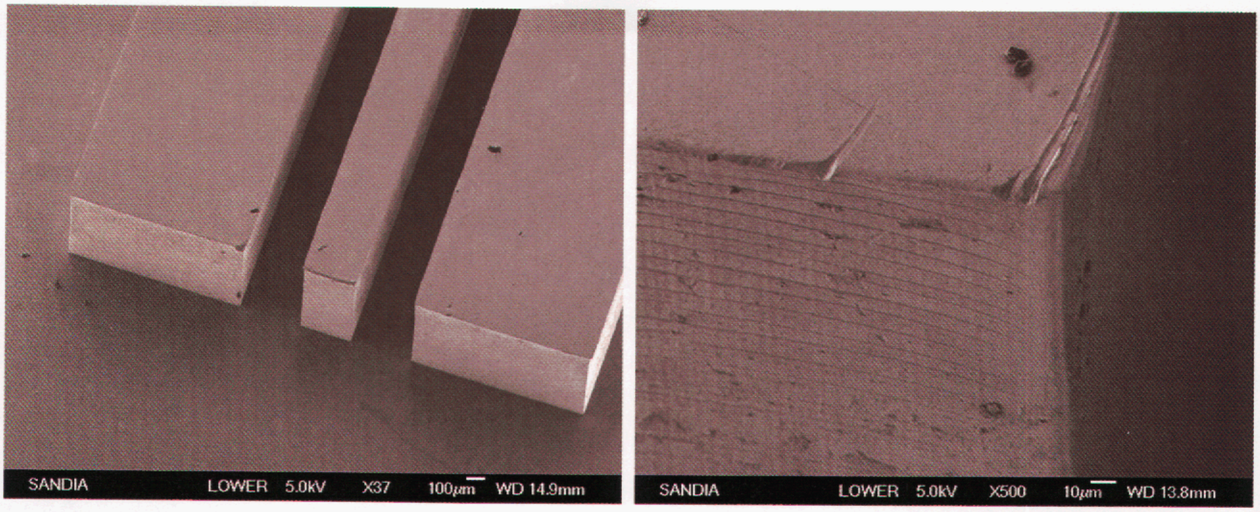


(a) (b)

Figure 3. Optical photographs of fabricated prototype CPW.

The LIGA-micromachining process is similar to a standard photolithographic and electroplating process with a few key differences. Standard photoresist is replace by a solid PMMA that may be several millimeters thick and the ultraviolet (UV) light source is replaced with a synchrotron, a high energy X-ray source. A special membrane mask, which does not attenuate the X-rays, is used in the patterning process.

The circuitry is fabricated by means of deep X-ray lithography (DXRL). Thick PMMA resist is exposed to X-ray synchrotron radiation through a patterned gold absorber mask. The exposed resist is developed and removed, yielding a mold that is then filled by electrodeposition, forming the metal transmission lines. Overplating and excess PMMA are removed in a series of grinding steps, to achieve the desired height, followed by the removal of the PMMA. Unplated portions of the metallic seed layer, present for electrodeposition, are etched from the surface of the quartz



(a) (b)

Figure 4. Images of the fabricated prototype CPW taken by SEM.

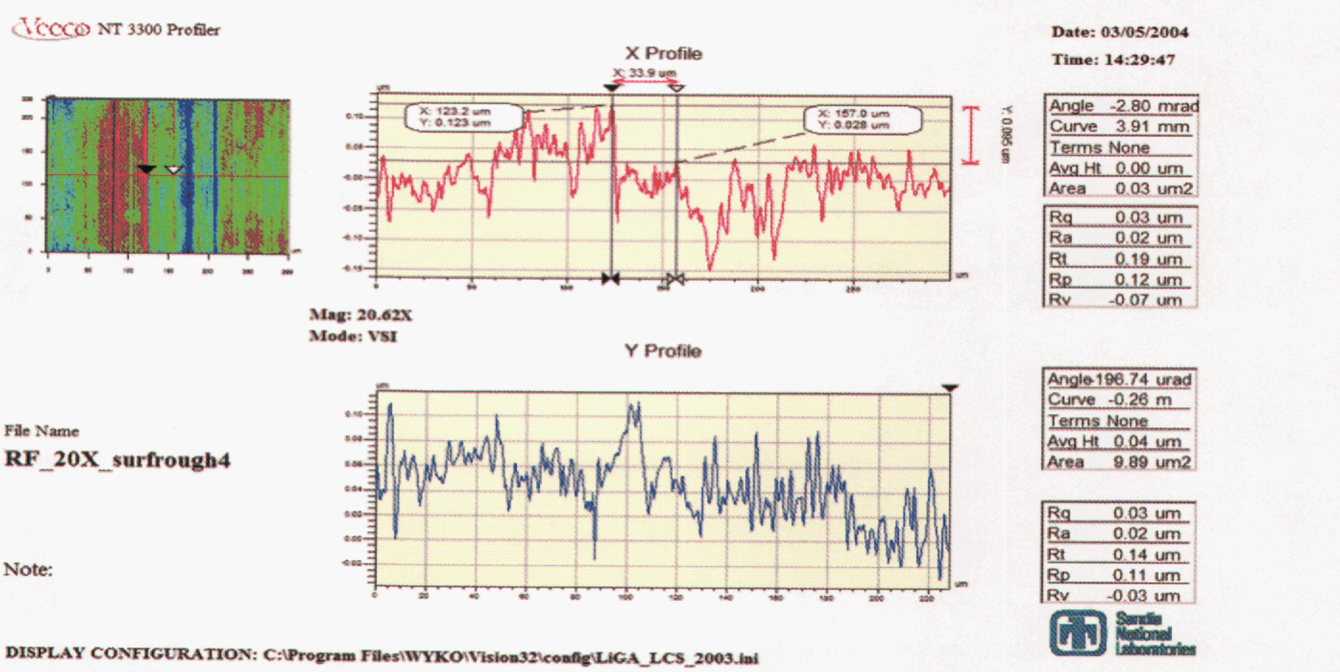


Figure 5. Measured surface roughness of new CPW prototypes. The RMS surface roughness is 62 nm with a standard deviation of 21 nm.

wafer. Finally, an application of electroless gold plating is applied to the surface of the copper to prevent oxidization before circuit characterization. The designed wafer and measured dimensions of the fabricated circuitry are given in Figure 2.

Conductor height averages $517 \pm 10\,\mu$m over the face of the wafer. CPW dimensions are approximately $15\,\mu$m smaller than designed as a result of overetching. Due to impurities in the copper-plating bath, slight irregularities with an approximate periodicity of $350\,\mu$m exist on the conductor sidewalls of the circuits characterized in this paper.

A second round of prototype CPW circuits with significantly smoother sides were fabricated on silicon (shown in Figure 3 and 4) but as of yet have not been characterized at microwave frequencies due to the use of the incompatible and lossy silicon substrate. Measurements of surface roughness on the prototype circuitry, summarized in Figure 5, show an RMS roughness of $\Delta =$ 62 nm with a standard deviation of $\sigma = 21$ nm, implying low loss at frequencies in the hundreds of gigahertz.

Measurements

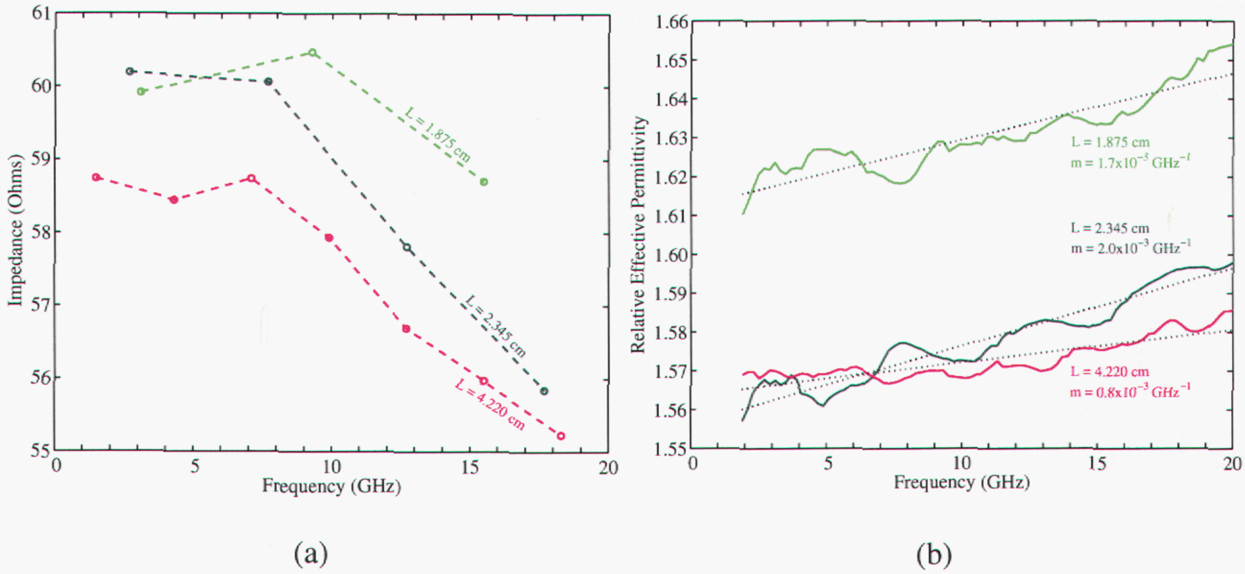


Figure 6. Measured characteristic impedance (a) and relative effective permittivity (b) as a function of frequency for three lines with lengths 1.875 cm, 2.345 cm, and 4.220 cm. Variations in relative effective permittivity are believed to be due to variations in fabricated line dimensions as a result of nonuniform etching and grinding.

Characterization was performed on three transmission lines with lengths of 1.875 cm, 2.345 cm, and 4.220 cm on an Agilent 8510C network analyzer using a Cascade Microtech probe station with

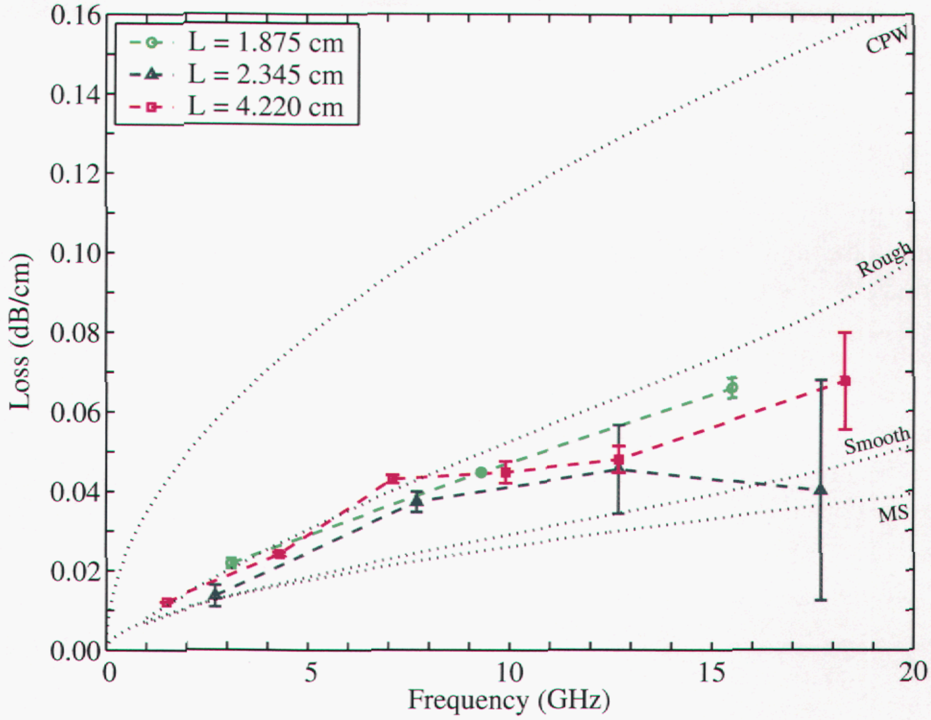


Figure 7. Measured attenuation as a function of frequency for three lines with lengths 1.875 cm, 2.345 cm, and 4.220 cm. Simulated loss for microstrip and standard CPW are shown for reference. Simulations of a perfectly smooth line (Smooth) and the fabricated line (Rough) are shown for reference.

ACP40-A GSG probes. Two-port S-parameters were measured from 1 to 20 GHz and line parameters were extracted from S-parameters using previously published techniques [6]. The measured characteristic impedance of the three lines is approximately 55 Ω at 20 GHz and is within 3 Ω or 5.7% of the simulated value. Characteristic impedance as a function of frequency varies between lines by 3 Ω at most (Figure 6 (a)). The measured relative effective permittivity for the three lines is between 1.585 and 1.655 at 20 GHz and is within 0.04 or 2.5% of the simulated value of 1.614. Relative effective permittivity as a function of frequency varies between the lines at most by 0.070 (Figure 6 (b)). Variation in measurements between lines is believed to be due to variations in fabricated dimensions due to nonuniform etching and grinding as well as randomly distributed defects in the sidewalls. Measured attenuation as a function of frequency is shown in Figure 7. Attenuation is extracted from measured S-parameters, using two independent methods, one which employs a transmission-line lumped-element model [6] and another which employs an ABCD-matrix conversion [7]. The difference in values for each method is used to generate ranges for the points plotted on the graph. Measured attenuation is 0.050 dB/cm at 10 GHz and 0.064 dB/cm at 15.5 GHz. Measured data agrees within ±0.01 dB/cm of simulations that include the measured sidewall irregularities (Figure 7 (Rough)). Data from surface measurements (Figure 5) are used in conjunction with Equation 1, to estimate loss due to roughness.

$$\alpha_r = \alpha \left[1 + \frac{2}{\pi} \tan^{-1} \left(1.4 \left(\frac{\Delta}{\delta} \right)^2 \right) \right] \tag{1}$$

Recent electroplating experiments have eliminated sidewall irregularities and it is believed that the second iteration of the circuitry will achieve the simulated ideal loss levels, yielding CPW with loss on the order of comparable microstrip transmission lines.

Conclusions

A mesoscale low-loss LIGA-micromachined conductor-backed coplanar waveguide is presented. The 517 μm lines are the tallest uniplanar LIGA-fabricated microwave transmission lines to date, as well as the first to be constructed of copper rather than nickel. The conductor-backed micromachined CPW on quartz are the among the lowest-loss CPW ever fabricated with an attenuation of 0.064 dB/cm at 15.5 GHz. These structures show excellent promise for use in high-power, low-loss, low-dispersion uniplanar microwave circuitry. Possible uses include high-Q filters and radar front ends.

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