Characterization of a prototype batch of long polyimide cables designed for fast data transmission on ATLAS ITk strip staves

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ABSTRACT

The silicon-strip system in the ATLAS ITk detector has individual sensor modules mounted on staves to provide integrated solution for mechanical support, power, cooling, and data transmission. The data and power are transmitted to individual modules on polyimide tapes placed on thermo-mechanical stave cores. The 1.4 m long tapes transmit module data at the rate of 640 Mbps, along with providing several multi-drop clock and command links, and power lines. The first batch of 25 tapes has been produced. We characterized the line impedance and its variation across the batch, examined the tape cross-section, and assessed the variation between design and fabrication.

INTRODUCTION

This project studies the tradeoffs between optimization to satisfy the constraints from the rest of the experiment and signal integrity in data transmission. A previous investigation found that carbon fiber layer underneath the data traces results in dissipative effect and very long rise time, making the high speed data transmission impossible [1]. To remove this influence, a new generation of tapes has a layer of copper underneath the data traces, isolating the signals from the carbon fiber (Figure 1).

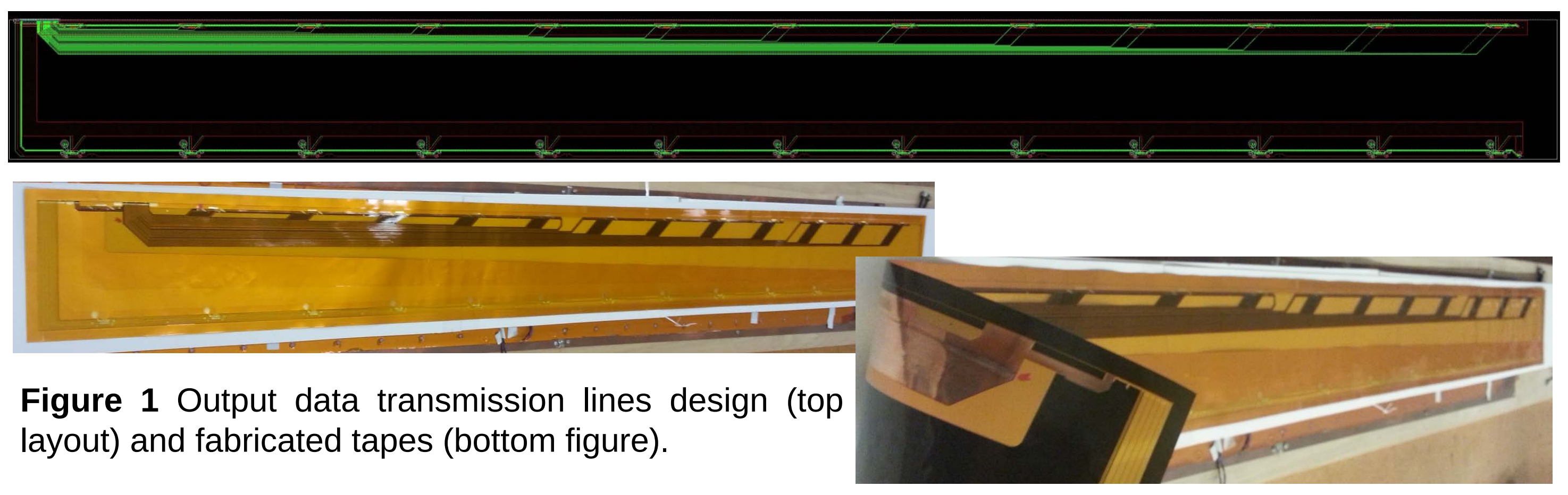


Figure 1 Output data transmission lines design (top layout) and fabricated tapes (bottom figure).

TRANSMISSION LINE THEORY

- First solve Laplace's equation → C and L, $Z_0 = \sqrt{(R + j\omega L)/(G + j\omega C)}$
- Needs 2D field solver (e.g. ANSYS HFSS)
- Main loss mechanisms [2]
  - Resistive (skin effect): $\exp(-R/2Z_0)$
  - Dielectric loss (loss tangent): $\exp[-\omega\varepsilon_r \tan\delta \, l/c]$
- Dispersion: $1/v = \sqrt{LC} + \frac{R}{2Z_0}\frac{1}{\sqrt{\omega\omega_0}}$

  R depends on skin depth and geometry. HFSS can predict loss and attenuation for line.
- Electric fields can be simulated.
- S-parameters:

  plot transmission and reflection properties.

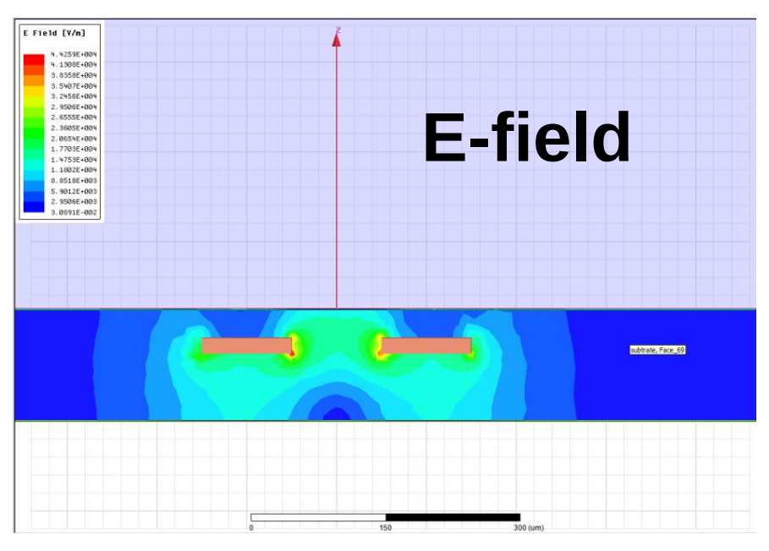


Figure 2 Electric field for microstrip lines.

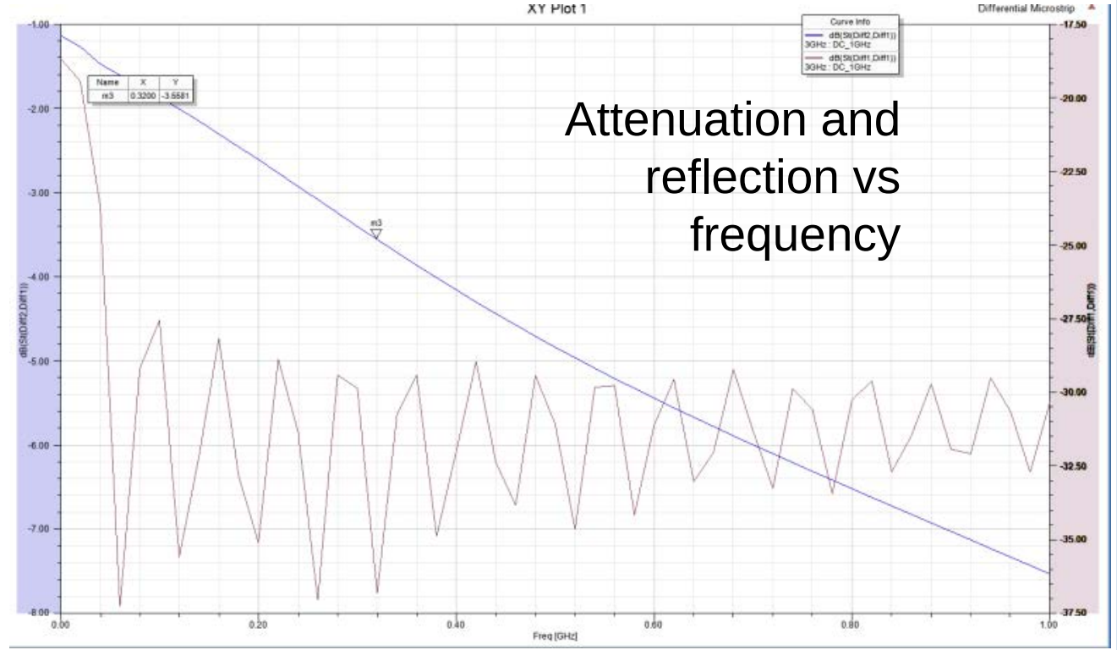


Figure 3 Simulated S-Parameters

FABRICATED GEOMETRY

Examination of the bus tape stackup proved to be non-trivial. The initial attempts of cross-sectional imaging after polishing lead to variable results. Metal layer thickness was in the range of 20-25 μm, depending on the polishing method and direction (Figure 4).

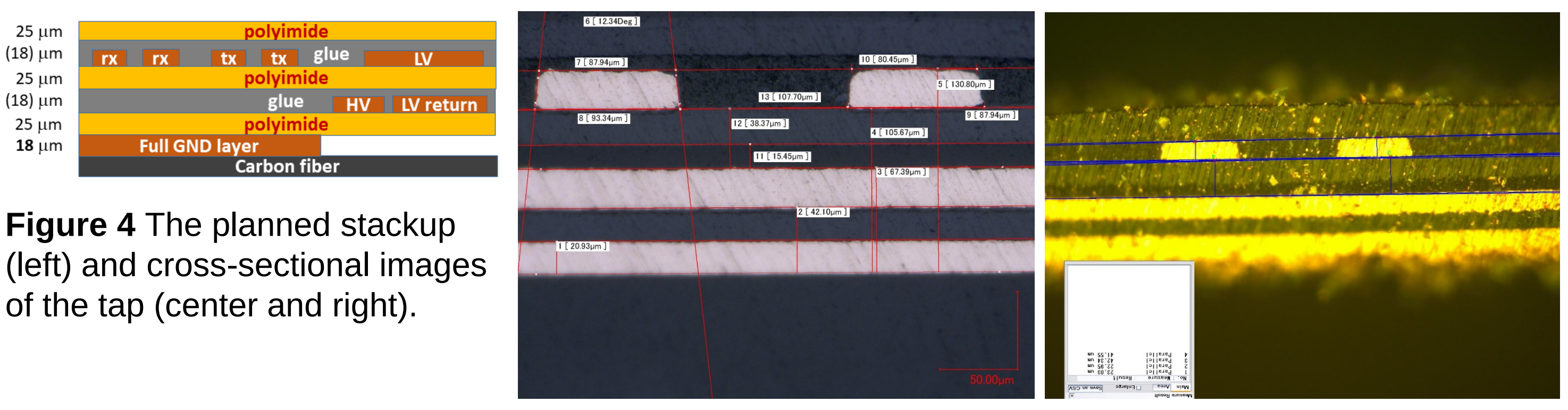


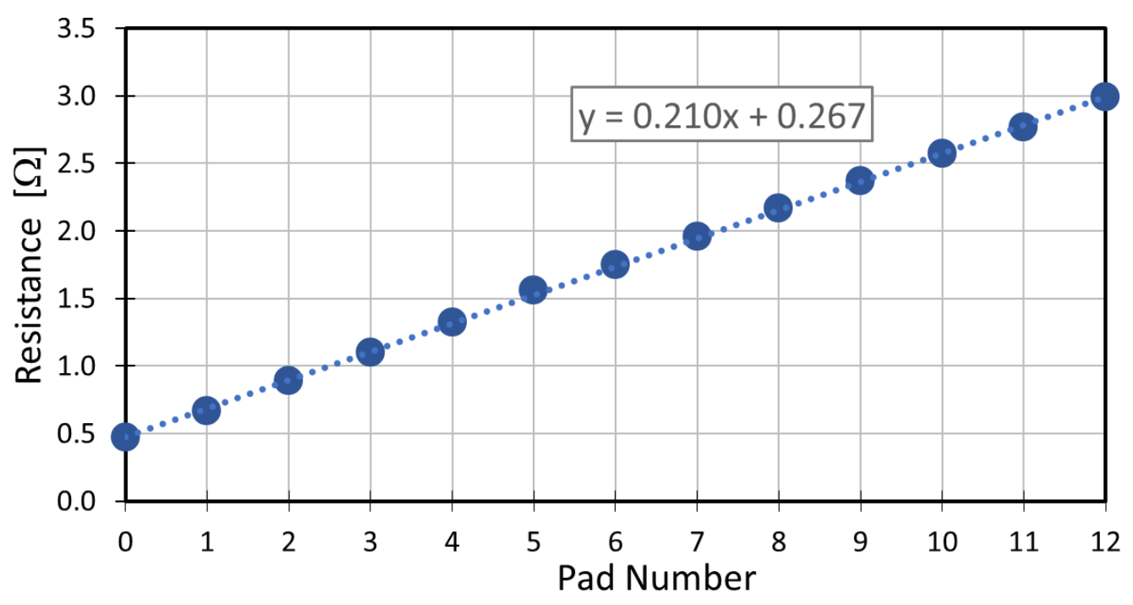
Figure 4 The planned stackup (left) and cross-sectional images of the tap (center and right).

Two other methods were used to find out the metal thickness:

- **Weighting measurement** : Weigh cut-outs of small sections of tape with one, two or no Cu layers. Measure area and calculate the copper thicknesses:
  - Top layer: 17.7 μm
  - Bottom layer: 17.2 μm
  - The nominal thickness is 17.4 μm
- **Resistance measurement** : Choose a wide metal line to limit the influence of over- and under-etching. Then probe its resistance at 12 locations along the tape.

Figure 5 Resistance measurements of a wide trace along the tape to determine the metal layer thickness.

R(one segment)	0.21	Ω
ρ(Cu)	1.68E-08	Ω-m
Width	480	μm
Length (segment)	10.05	cm
Thickness	16.74	μm



Feature size: Top-side imaging of the tape indicates the trace dimensions. The nominal track and gap were designed to be 100 μm. After etching, the track plus gap is 200 μm, but the widths of the tracks is less than 100 μm. There is likely a tapering effect present, with the track width being slightly wider at the bottom than the top.

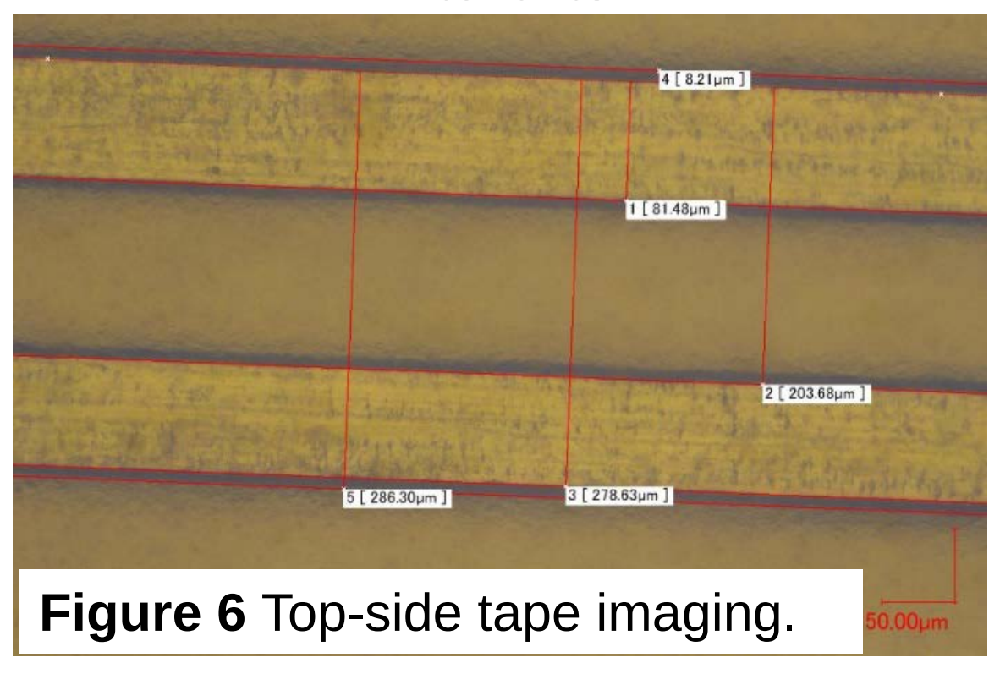


Figure 6 Top-side tape imaging.

References

1) J. Dopke et al, "Lessons learned in high frequency data transmission design: ATLAS strips bus tape", 2017 *JINST* **12** C01019

2) Johnson, H. Graham, M. (06 Mar. 2003) "High-Speed Signal Propagation: Advanced Black Magic". *Print*. Ed. Upper Saddle River, NJ: Prentice Hall.

3) The TDR measurements procedure is described in this note: S. Sullivan, "S-Parameter measurement Instructions," 2016. [Online]. Available: https://twiki.ppe.gla.ac.uk/bin/view/ATLAS/PUUKA/ServicesAndIntegration. [Accessed 08 Sept 2017].

IMPEDANCE MEASUREMENTS

Impedance measurements of differential lines were done with TDR scope[3]. Test traces on the periphery of the tapes were assessed. These traces have ground layer closer than intended: the dielectric gap with the data lines was 50 μm instead of 75 μm. Observations show that the impedance measured on the first batch of these tapes (Figure 7) is well within the specification of 90-120 Ω. HFSS Simulations with narrower traces and reduced distance to the ground plane indicate a similar impedance value of 93 Ω.

Figure 7 TDR waveform (left) and a histogram of impedance measurements for the first batch of tapes (right).

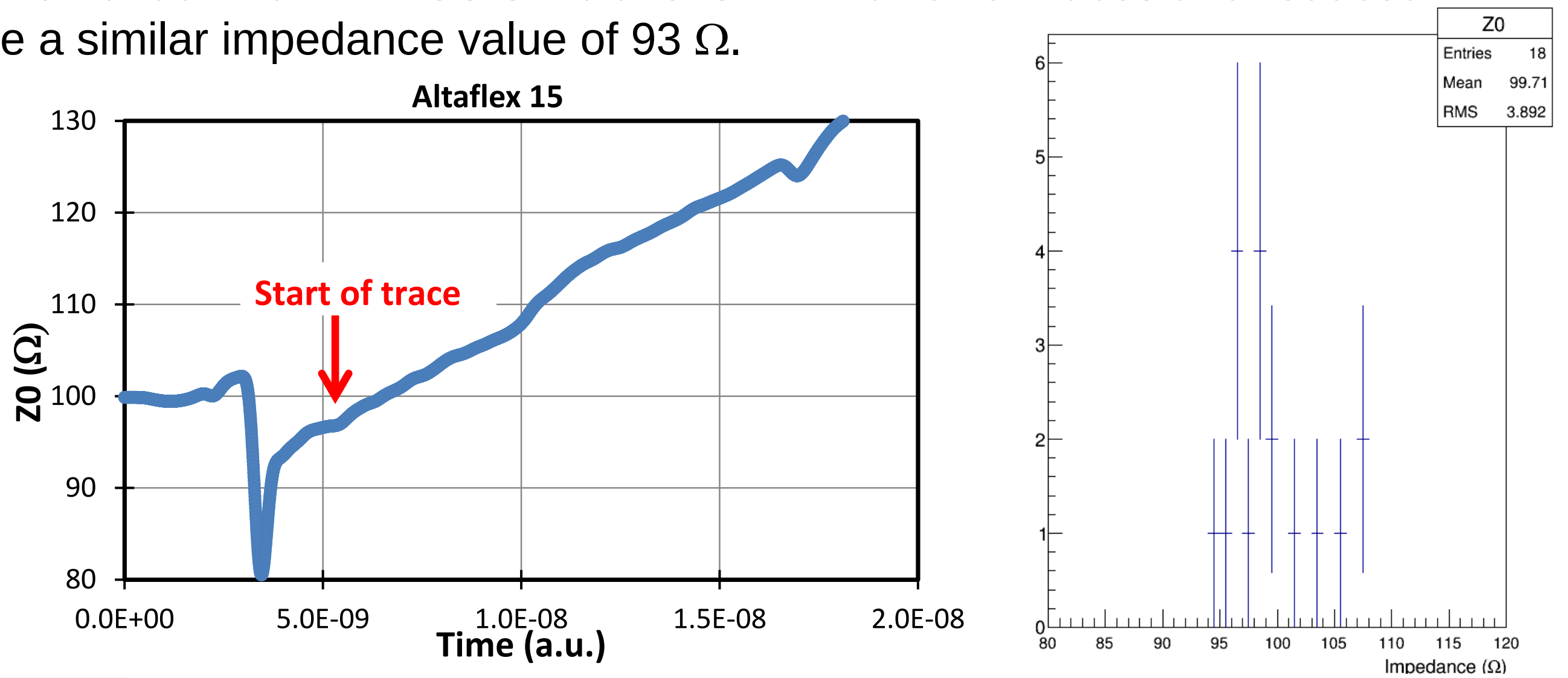
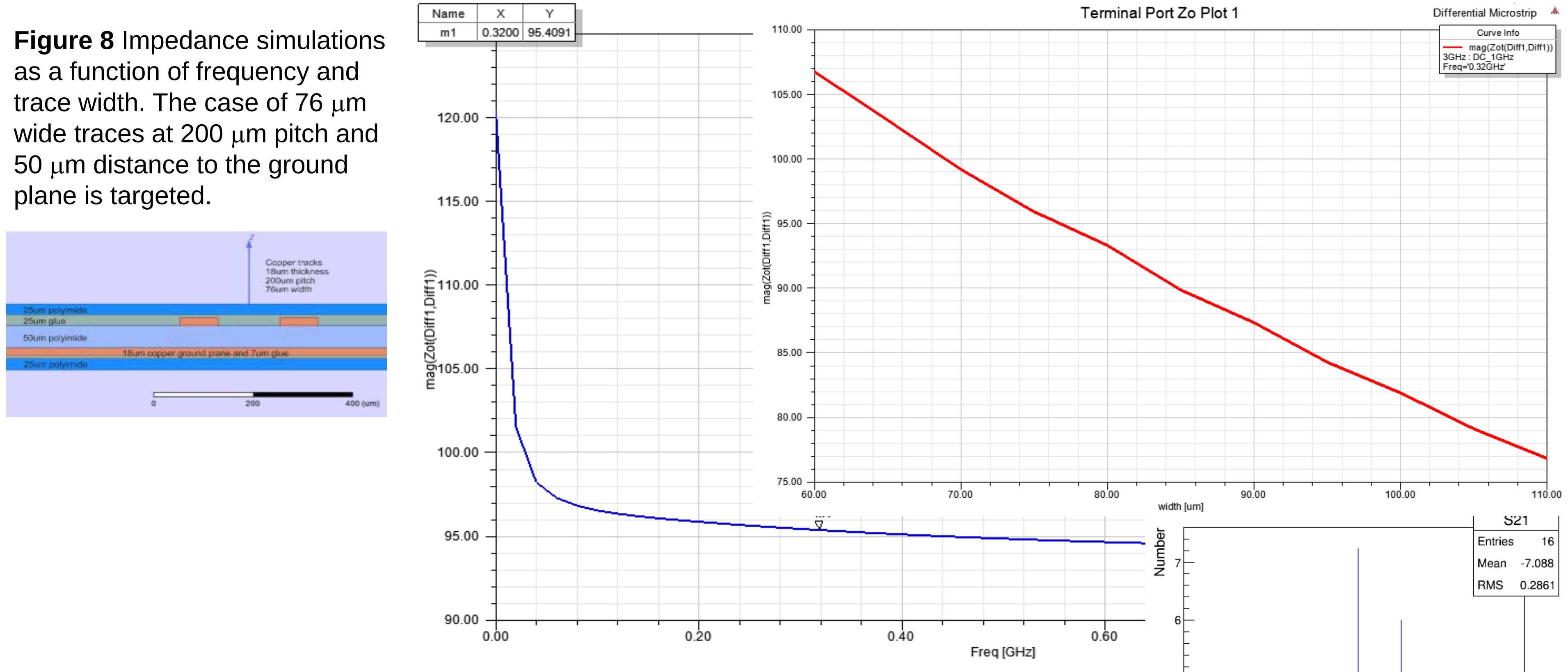


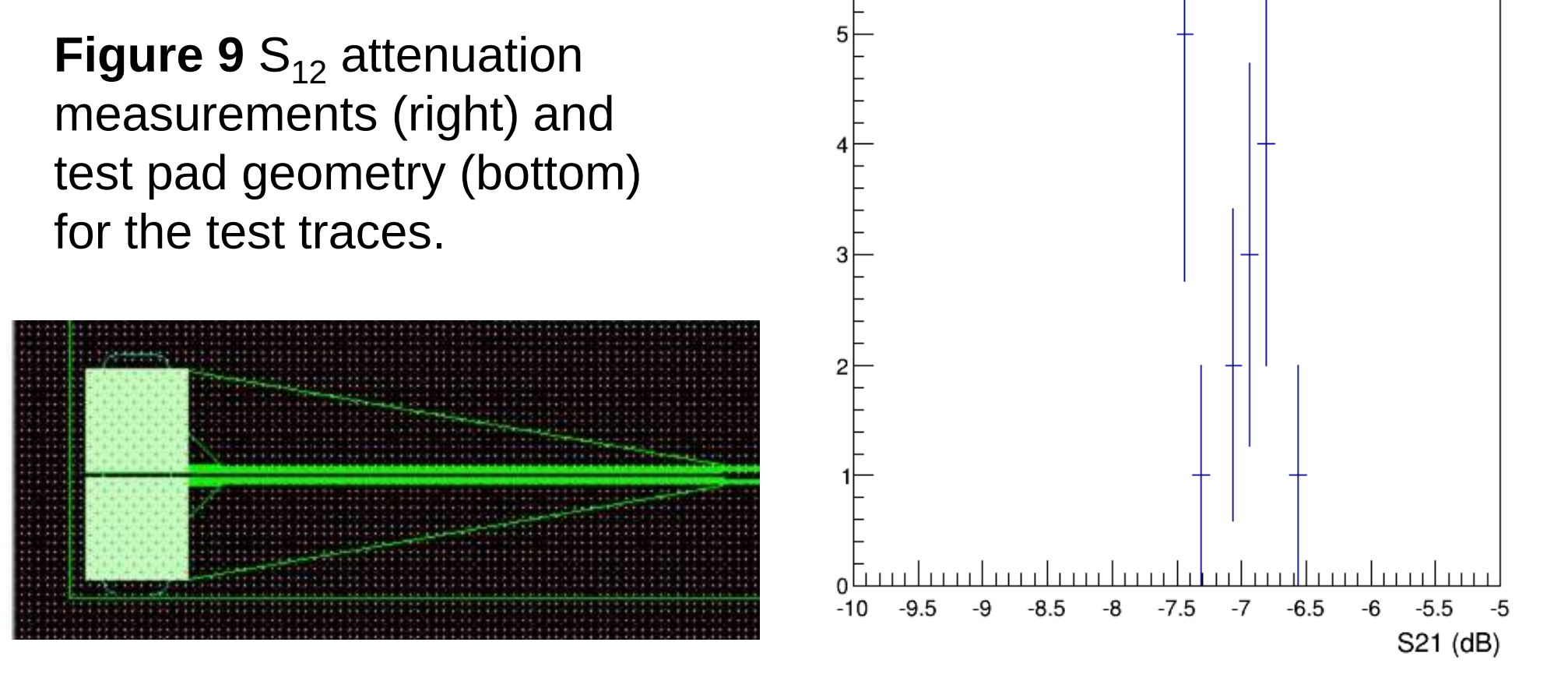
Figure 8 Impedance simulations as a function of frequency and trace width. The case of 76 μm wide traces at 200 μm pitch and 50 μm distance to the ground plane is targeted.



The test traces have built-in test pads allowing straightforward measurements of attenuation using hand-held probes. The derived S_{12} attenuation is much better than specified limit of 15 dB at 1 GHz.

Measurements for some of the tape designs were affected by too large pads. We will fix this in new designs.

Figure 9 S_{12} attenuation measurements (right) and test pad geometry (bottom) for the test traces.



QUALITY ASSURANCE

The measured impedance strongly correlates with the DC resistance of the signal traces. This indicates that the trace width is the likely cause of the variation and that the resistance measurements can serve as a proxy for impedance while performing QC monitoring during the tape production.

Furthermore, there is a strong correlation between the resistance of the long "snake" of the test trace and signal traces (Figure 11). We conclude that this is due to etching influence which is fairly uniform across the tape. The correlation bodes well for using the test trace as the QC assessment vehicle. It has a much larger resistance, which is easier to measure, along with larger test pads which are easier to probe.

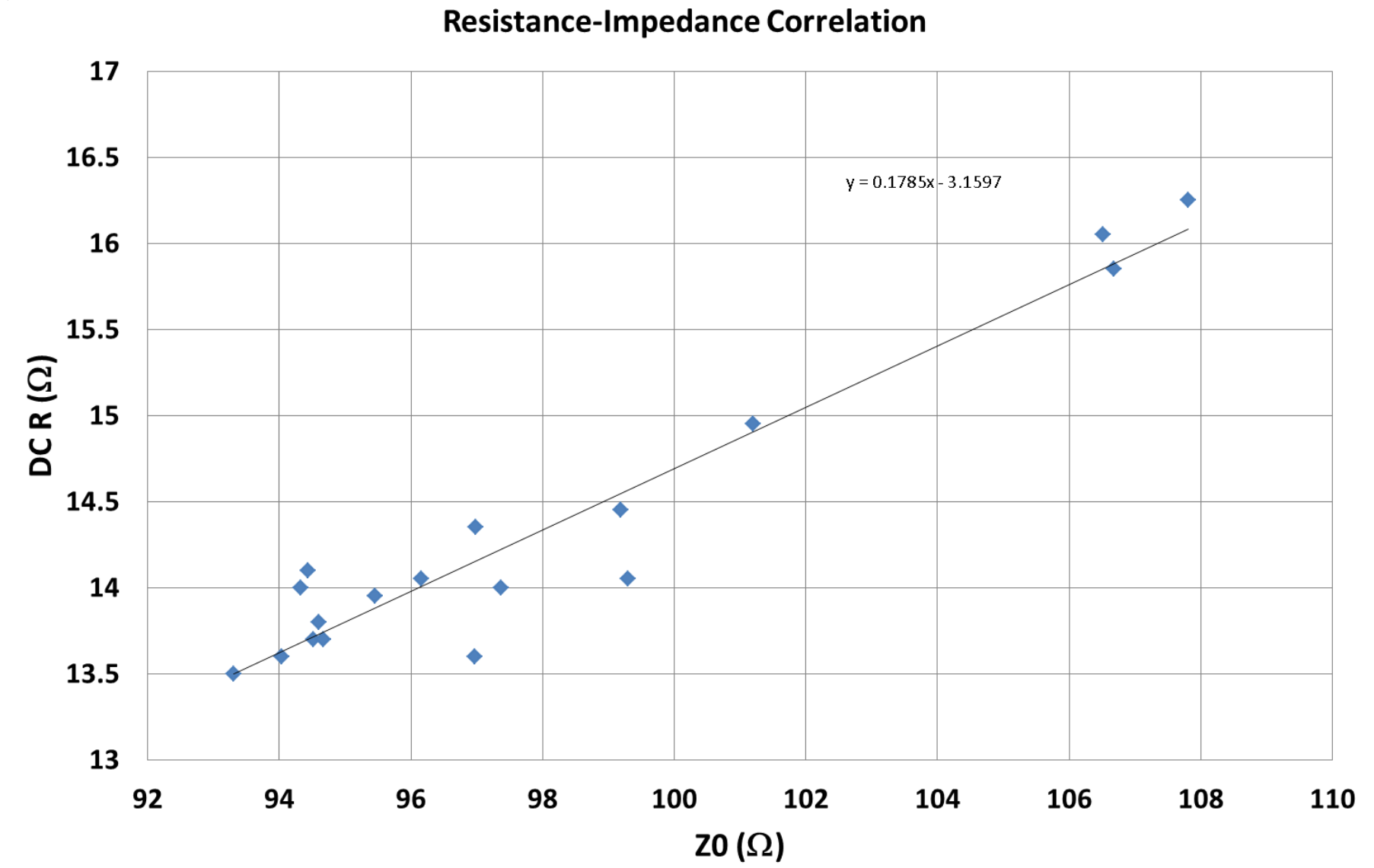
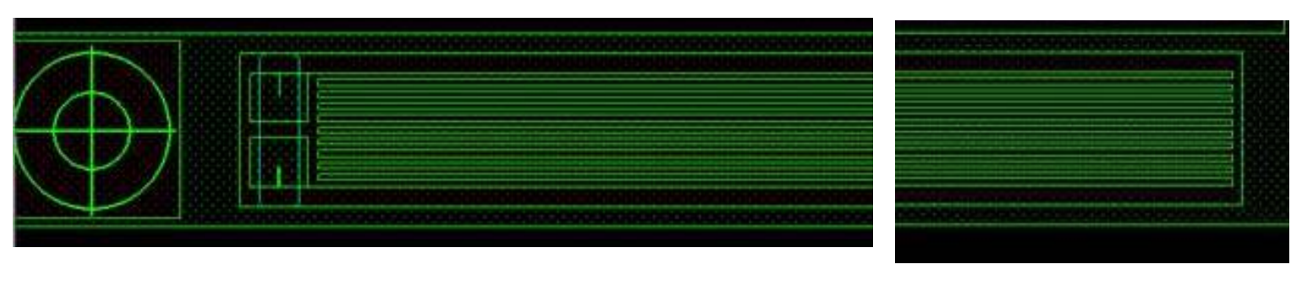
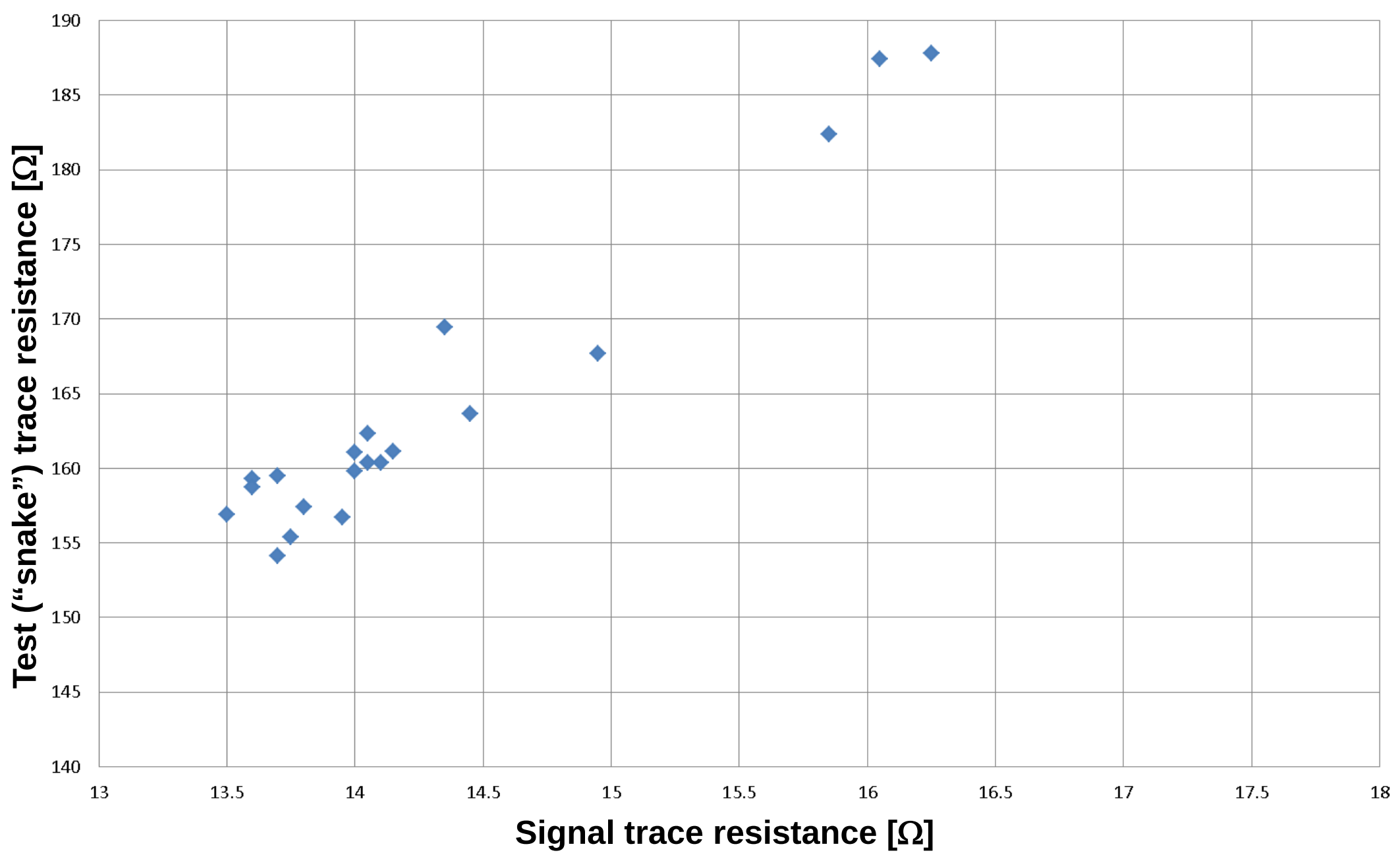


Figure 10 DC resistance of the signal lines vs. impedance.

Figure 11 Test trace geometry (below) and correlation between resistances of the test trace and signal trace (right).





CONCLUSIONS

We have fabricated a batch of data transmission tapes with a new design featuring copper ground layer underneath the data lines to avoid the detrimental influence of carbon fiber. We investigated the tape geometry. The metal layer thickness is very close to the nominal 17.4 μm when checked by weighting tape sections and resistance measurements. The direct assessment of cross-sectional examination did not work as well. The metal traces have width smaller than the designed 100 μm.

The tapes have built-in test lines in the periphery, where the dielectric thickness has also been reduced, from the nominal 75 μm to 50 μm. For these lines the impedance measurements are close to the nominal 100 Ω, indicating that the two effects cancel each other. This was further corroborated by HFSS impedance simulations. The impedance distribution for the tape batch is very uniform and it is within the specifications. The attenuation measurements are well within the specifications.

We observed a strong correlation between the resistances of the test trace and signal traces, indicating that the etching influence is rather uniform across the tape. The resistance also correlates with impedance measurements, which can be useful for QC monitoring during production.

FUTURE WORK

We are investigating tape designs which utilizes polyimide layer with double metal (Figure 12). Such design may lead to more straightforward fabrication and utilization in stave assembly.

Figure 12 Tape stackup using polyimide layer with double metal .

ACKNOWLEDGMENTS

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