# Experimental Determination of High-Speed GaAs Digital Circuit Interconnect Parameters

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## Abstract

Coplanar strips that are representative of on-chip high-speed digital circuit interconnects have been fabricated on GaAs and characterized up to 18 GHz. Strip widths of 4, 6, and 8 μm with strip spacings of 4 and 8 μm and conductor thicknesses of 2500Å and 5000Å were used in the experiments. Line parameters such as resistance, capacitance, inductance per unit length, propagation constant, etc. were extracted from these measurements. Measurement results confirm the quasi-TEM properties of such interconnects.

## Introduction

Current high-speed GaAs digital circuits have integration levels of several thousand gates [1]. One of the problems that is encountered with this high level of complexity arises from the conductors that interconnect various gates together. Because of the short rise and fall times of the waveforms in the digital circuits, some of the frequency components of these waveforms extend into the microwave range, and for some of the longer interconnects, wave analysis must be used. So far, some experimental work has been done on loss and impedance characterization for microstrip or coplanar waveguide structures [2, 3], but the only extensive experiments carried out so far with various conductor thicknesses and aspect ratios are those by Haefner in 1937 [4]. In this paper, we report experimental characterization of coplanar strips on GaAs substrates which are representative of on-chip high-speed digital GaAs interconnects. Although the emphasis is on digital-circuits, the observations should have applications to analog circuits as well.

## Fabrication and Measurements

Coplanar strip transmission lines with conductor widths of 4, 6, and 8 μm, and spacings between conductors of 4 and 8 μm were fabricated along with two different conductor thickness values of 2500Å and 5000Å. Patterns were transferred to a 2-inch semi-insulating GaAs wafer using a lift-off technique. The metallization consisted of 500Å of Ti with the rest of it Au, the former to improve the adhesion of Au to the substrate.

The measurements were carried out on-wafer on a Cascade Microtech Probe Station up to 18 GHz using an HP 8510B Automatic Network Analyzer. An odd-mode excitation was sustained by microwave baluns (3 dB, 180° power dividers), since this excitation is typical of interconnects driven by a device connected between them.

## Analysis and Discussions on the Measurements

The measurement results were analyzed by converting the measured S-parameters to ABCD parameters of the transmission line system, from which the characteristic impedance, $Z_{0l}$ and the propagation constant, $\gamma$ of the lines can be extracted. Based on previous theoretical estimations [5], we postulate that the quasi-TEM model can be used to describe these interconnects. In the quasi-TEM model, the characteristic impedance and the propagation constant are given by

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \qquad (1a)$$

$$Z_{0l} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad (1b)$$

where R is the resistance per unit length, C is the capacitance per unit length, L is the inductance per unit length, and G is the shunt conductance per unit length. The measured line parameters can be determined from $Z_{0l}$ and $\gamma$. $\gamma$ can be further decomposed into its real and imaginary parts as $\gamma = \alpha + j\beta$, where $\alpha$ is the attenuation constant in Np/m, and $\beta$ is the phase constant in rad/m.

A group of lines have been measured, and the quasi-TEM parameters have been extracted. The parameters for lines with same widths and spacings have been grouped together and their mean and standard deviation have been calculated. Small standard deviations obtained confirm the accuracy and repeatability of the measurements. Figs. 1-5 show these extracted parameters for the various coplanar strip interconnects of different widths, spacings, and thicknesses. Fig. 1 shows the attenuation constant for interconnects with various cross-sectional dimensions and two thickness values of 2500Å and 5000Å. The increase in $\alpha$ with respect to frequency is due to an increase in the resistance per unit length with frequency, which we observed in the resistance measurements at higher





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frequencies. We also note that $\alpha$ varies as $\sqrt{f}$ at low frequencies, and then assumes a much smaller slope, which are expected [6]. We do not see the skin effect behavior yet, as that occurs at much higher frequencies. Shown in Fig.1 is also a theoretical calculation for the group of lines with w = 4 μm and s = 8 μm, that uses static capacitance and inductance values, and the dc resistance for the lines. We note the good agreement especially at lower frequencies. Theoretical calculations for the other samples also indicate a very close agreement with the measurements.

The phase constants of a group of lines are depicted in Fig. 2. We note that $\beta$ is relatively independent of line dimensions. Since the phase velocity $v_p = \omega / \beta$, it is also independent of the line dimensions, which is an indication of the quasi-TEM behavior. Phase constant calculations using static parameter values agree well with the experimental predictions.

Fig. 3 shows the characteristic impedances of interconnects of various dimensions. We observe the trend that the characteristic impedance approaches a real value at high frequencies, and that its real and imaginary parts have equal magnitudes but opposite signs at low frequencies. These behaviors are expected for quasi-TEM propagation.

Fig. 4 shows the inductance and capacitance per unit length of the interconnects. These measured values agree well with calculations made based on a quasi-TEM approximation [7].

Fig. 5 shows the resistance per unit length for the coplanar strip interconnects. We note that the resistance increases as a function of frequency. The increase in the resistance from the low to the high frequency end of the measurements is, however, much more pronounced as a function of thickness than width. That is to say, the resistance of lines with thicker conductors vary more with frequency than the resistance of lines with wider conductors.

The conductance per unit length is not shown because its value is small compared to the capacitive reactance in the frequency range of measurements, and is overwhelmed by experimental error. Thus it is not easy to extract G from the measurements.

## Conclusions

The analysis of the experimental results yield a few noteworthy points. Firstly the extracted capacitance and inductance values come out to be nearly frequency independent in the frequency range of measurements and agree well with static calculations based on quasi-TEM assumptions, thereby justifying this approach in interconnect parameter calculation. Another justification of quasi-TEM approximation appears in the measured phase constant, which comes out to be almost independent of interconnect dimensions. We further note that both the attenuation and the phase constant agree closely with the static calculations.

The resistance per unit length of the interconnects is found to vary as much as 38% in the widest and thickest lines from the low to the high frequency end of the measurement range. Calculations made on the attenuation constant $\alpha$, however, showed that assuming the dc value for the transmission line resistance per unit length is a very good approximation at low frequencies. The maximum error associated with this approximation at high frequencies, for example at 10 GHz, is no more than 8% in the attenuation constant.

These findings suggest the use of simulation programs like Spice by modelling the interconnects with lumped static inductance and capacitance values with a periodic loading with the dc resistance to account for the loss. This way, fast time-domain analyses could also be carried out.

## References


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## Figures

In all the figures, the following legend is used (dark markers depict 2500Å lines, light ones 5000Å lines):

circles : w = 8 μm, s = 8 μm
rectangles : w = 8 μm, s = 4 μm
diamonds : w = 6 μm, s = 8 μm
triangles : w = 4 μm, s = 8 μm

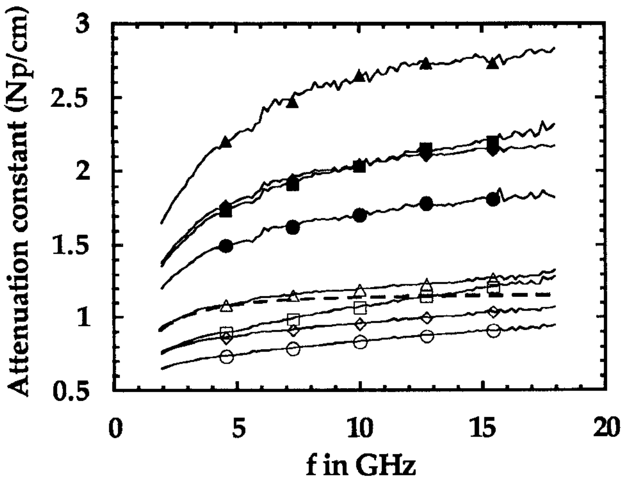



**Figure 1.** Attenuation constants for the coplanar strips. The dashed line shows the calculated attenuation for the group of lines with w = 4 μm, s = 8 μm, which assumed that the resistance stayed constant at its dc value.

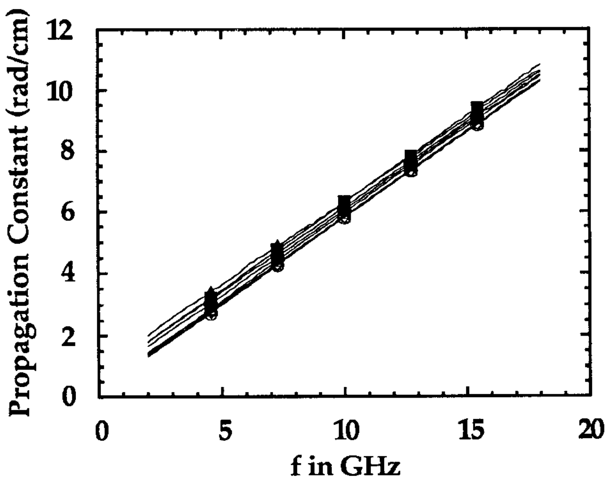



**Figure 2.** Phase constants for various coplanar strips.

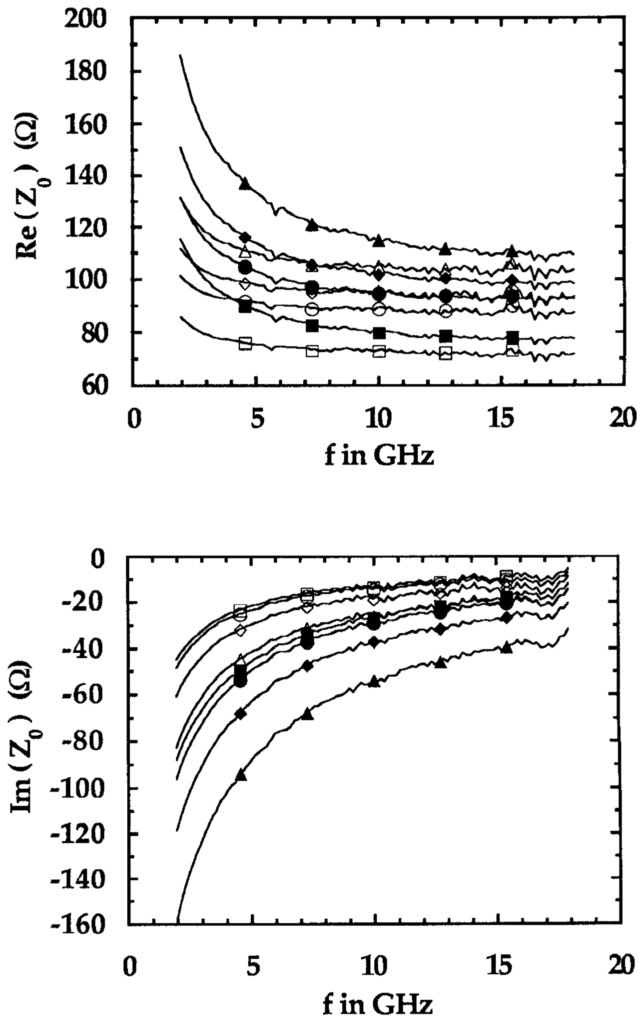
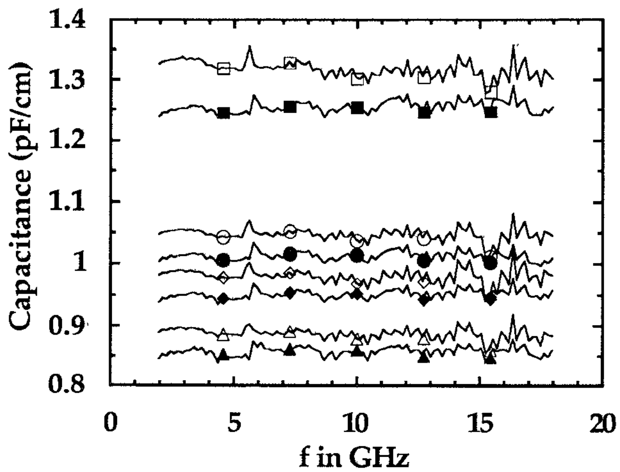



**Figure 3.** The real and imaginary parts of the characteristic impedances for interconnects of various dimensions.



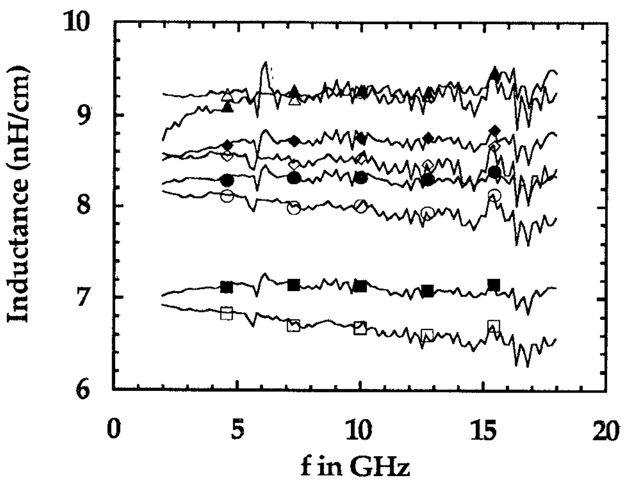




**Figure 4.** Capacitance and inductance per unit length for the various coplanar strips. As an example, the calculated static capacitance and inductance values for the lines with w = 4 μm, s = 8 μm, and t = 5000Å are C = 0.85 pF/cm, and L = 9.4 nH/cm. We note the good agreement with the measurements. Calculated values for the other lines are also in good agreement with the experiments.

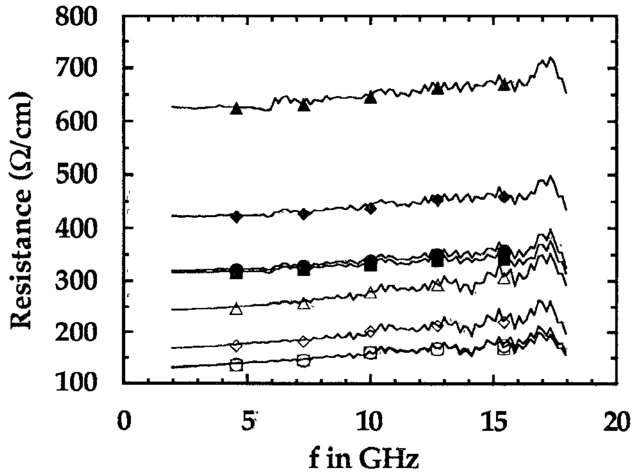



**Figure 5.** Resistance per unit length for the various coplanar strips.