R-2

MEASUREMENT OF THE CHARACTERISTIC IMPEDANCE OF MICROSTRIP OVER A WIDE FREQUENCY RANGE*

W. J. Getsinger

COMSAT Laboratories, 22300 COMSAT Drive, Clarksburg, Maryland 20871

Summary

Measurement of the characteristic impedance of a 0.25-in.-wide microstrip on 0.25-in. alumina by two new, accurate techniques showed the expected small decrease as frequency changed from 400 to 1000 MHz, and an unexpected increase as frequency went from 1000 to 2400 MHz.

Introduction

Microstrip characteristic impedance (ZO) has not yet been defined in the literature in a manner rigorously consistent with both electromagnetic and circuit theory, except at zero frequency.

Bianco et al.[1] showed that various proposed definitions predict completely different variations with frequency. The LSE approximation[2] to microstrip predicted the widely used decrease in ZO with the square root of the effective dielectric constant.

Napoli and Hughes[3] reported measurements of ZO with frequency, but their handling of the microstrip-to-coax transitions and the relation between the measurement data presented and ZO were not conclusive.

With the present emphasis on computer-aided design of microwave circuits, exemplified by the wide use of programs such as SUPERCOMPACT, it is essential that reliable information on the frequency variation of microstrip characteristic impedance be available to microwave designers.

This paper presents new measurement techniques for determining characteristic impedance and gives the results for a nominally 50-Ω line on an alumina substrate.

The Problem

The situation can be described as follows: it is desired to measure the characteristic impedance of a microstrip line over a wide frequency range; the measuring instrument is in coaxial line, which has a known reference characteristic impedance; and between the measuring instrument and the microstrip is an unknown circuit representing the effects of the coaxial connector and the microstrip-to-coax transition. The problem is to make coaxial line measurements which, when processed, separate the microstrip characteristic impedance from the effects of the transition circuit.

Because the frequency variation of ZO is expected to be only a few percent over the usable range of the microstrip, it is necessary that the measurements be accurate and repeatable.

Bianco's Argument

Bianco[4] has questioned if a meaningful measurement of this type is even possible by arguing that a frequency variation of the microstrip impedance cannot, by measurements made external to the microstrip, be distinguished from a frequency variation in the transition circuit. In circuit terms, this implies a possible ideal transformer, which may be a function of frequency, as part of the transition circuit.

In this work, it is accepted that Bianco's Argument is mathematically sound, but there is no engineering reason to believe that such a transformer exists. Thus, by the principle of parsimony, it is not necessary to include a transformer in the equivalent circuit until it can be shown to be essential.

Measurements

The proposed two methods of measuring characteristic impedance have not been described before, to the author's knowledge. They attempt to achieve good accuracy by observing the following constraints:

a. The same mounted microstrip is measured to evaluate dispersion, the transition element values, and the characteristic impedance.

b. Although more or less microwave energy is observed, only frequency and distance need to be measured because the circuit is essentially reactive and is measured with a slotted line.

c. The measurements are scaled by a factor of ten to ease mechanical tolerances and allow the use of GR-900 coaxial connectors in the frequency range where their reflection is negligible. Also, the coax-to-microstrip transition is physically abrupt (of small extent in wavelengths) to ensure that it can be represented by a tee or pi network over a wide frequency range.

Both measurement methods require evaluation of the dispersion characteristic of the microstrip in its mount, shorted with flat plates at both ends. In the first technique, the measured dispersion characteristic is fitted to a mathematical function to allow prediction of those frequencies for which a short at one end places impedances (lossless assumption) of 0, ∞, and $\pm j$ZO at the other end. Then, with one flat plate replaced by a transition to coax, impedance measurements at those frequencies yield the transition element values and reactances of ±ZO, transformed by the transition. Simple de-embedding gives values for ZO.

*This paper is based upon work performed at COMSAT Laboratories under the sponsorship of the Communications Satellite Corporation and the COMPACT Engineering Division of COMSAT General Integrated Systems.

In the second technique, measurements of slotted-line minimum positions are made at a small frequency increment on either side of each of the resonance frequencies of the shorted microstrip. This yields the resonator slope parameters which, along with the rate of dispersion with frequency, is proportional to the characteristic impedance of the resonant microstrip. Over the small frequency range measured for each resonance, the reactances of the transition elements do not change appreciably and can be neglected.

A 10-in.-long microstrip on 0.25-in.-thick alumina (measured dielectric constant, 9.74) was mounted in a 2-in.-wide metal box with flat-plate ends in which transitions to GR-900 coaxial line and connectors were set. Figure 1 shows the structure and its circuit. The metallization (1.3 mils) was applied to the substrate by conventional MIC techniques. The center strip was 0.250 inches wide and predominantly copper. Metal sides extended above the substrate by about 1.50 inches. In the exact center of one side at substrate level, an OSM connector was mounted. From this connector, a nominally 50-Ω stub of adhesive-coated copper foil could be extended toward the microstrip, leaving a gap. Low frequency capacitance at different gap widths was measured.

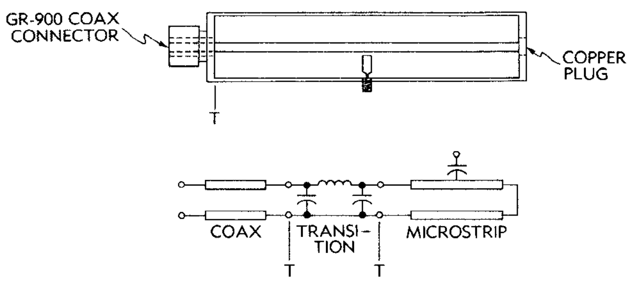

Figure 1. Microstrip Test Piece and Equivalent Circuit

The microwave measurement began with evaluation of return loss and insertion loss to determine the quality of the line and its transitions. Return loss is shown in Figure 2.

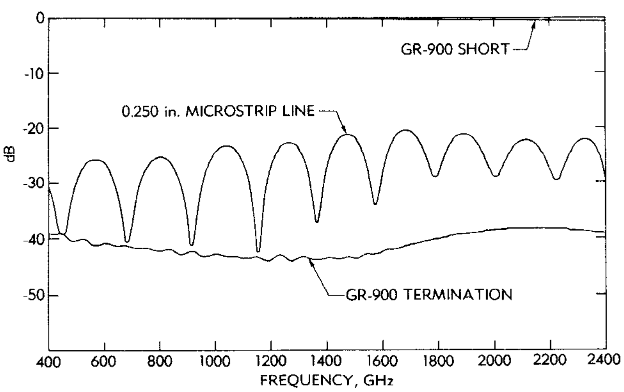

Figure 2. Return Loss of Test Piece

The GR-900 coax was replaced by copper plugs in the end walls to short circuit the microstrip. The short circuits were enhanced by small amounts of silver epoxy. The resulting flat-plate shorts introduced no discontinuity effect.

The shorted microstrip was resonated at its natural frequencies between 200 and 2400 MHz. This was repeated for the different gap widths. The data were extrapolated to find the frequencies of resonance for zero coupling capacitance. The effective dielectric constant was calculated from the line length and these frequencies, and the results were fitted to a mathematical function to allow accurate prediction of effective dielectric constant at other frequencies. One shorting plug was replaced by a GR-900 line and connector.

The previous description applies to both measurement techniques. The following remarks apply only to the first technique. Frequencies were calculated at which the microstrip would present zero and infinite (lossless assumption) reactance at the end-wall, which was defined as the terminal plane of interest. A GR-900 slotted line was used to measure positions of voltage minima relative to those of a reference short having the same terminal plane distance from the slotted line.

Assuming a pi or tee network for the transition, the short-circuit measurement gave its series inductive reactance, while the open-circuit measurement gave its shunt capacitive susceptance. These measurements are plotted in Figure 3. Because the factor $\omega^2 LC$ was found to be much smaller than 1.0 at the highest frequency of interest, the transition could be represented as accurately by an L-network of either orientation as by a pi or tee.

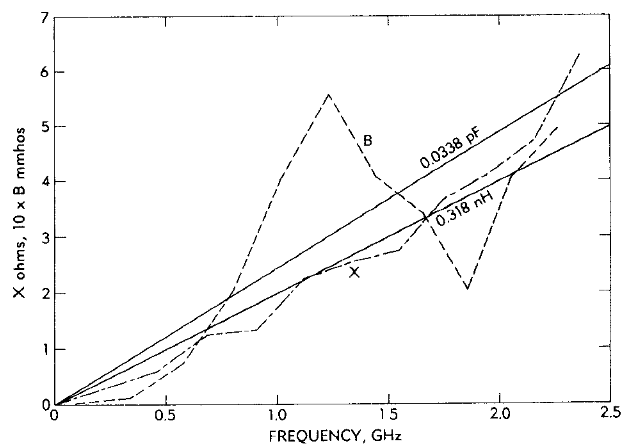

Figure 3. Reactance and Susceptance of Transition

Finally, frequencies were calculated at which the microstrip presented $\pm jZO$ at the terminal plane, that is, an electrical angle of $\pi/4$ from the short- or open-circuit frequencies. Measurements at these frequencies, transformed through the transition circuit, gave the microstrip characteristic impedance plotted in Figure 4, labeled "de-embedding technique."

Based on the second measurement technique, locations of voltage minima on the slotted line were found at frequencies of 8 MHz on either side of the resonant (Z = 0) frequencies. This yielded the slope parameter at each resonant frequency. Rate of change of effective dielectric constant with frequency was found analytically, using the function based on dispersion measurements mentioned previously. This information was reduced analytically to give ZO at each resonant frequency. These results are also shown in Figure 4.

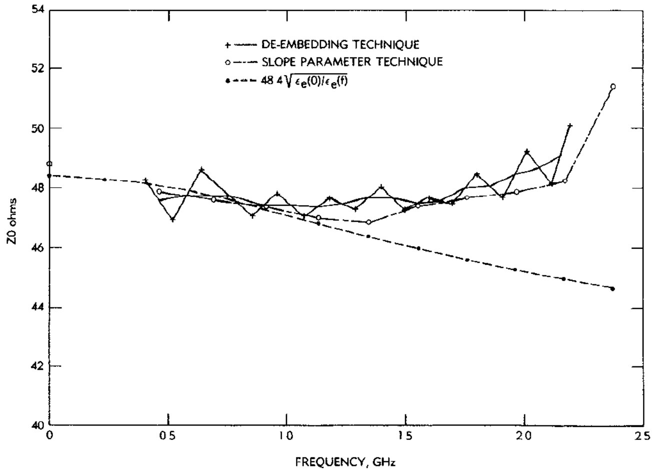

Figure 4. Characteristic Impedance of Microstrip

Discussion

The advantage of the first method is that it gives values directly for total series inductance and total shunt capacitance of the transition. Errors in transition values show up on the final plot of ZO as alternating high and low values about the correct impedance; therefore, the best value of impedance is midway between adjacent alternating points.

The advantage of the second method is that it automatically suppresses the transition circuit, and requires fewer measurements.

The curvature in the reactance (Figure 3) of the transition circuitry would require about 15 pF if it were caused by a parallel capacitor, as might be expected with a pi network. However, neither the return loss nor the open-circuit measurements of the total transition capacitance support this interpretation. It is assumed that the transition inductance changes with frequency. This is not unreasonable because the field configuration of the microstrip to which the transition couples changes with frequency as the microwave energy becomes more concentrated in the dielectric region of the microstrip. This may imply that the coax-to-microstrip transition cannot be represented rigorously over a wide frequency range by a simple tee or pi network.

The variation in transition capacitance shown in Figure 3 appears large only because of the scale; the total capacitance is quite small.

These techniques do not disprove Bianco's Argument. If an ideal transformer exists, it cannot be detected by measurements with open and short circuits on the microstrip side of the transition.

The characteristic impedance measured appears to follow the square root of the effective dielectric constant up to about 1000 MHz. The rise in impedance above 1000 MHz was not expected, and remains unexplained.

Discrepancies in construction and higher-order mode effects are under consideration as possible sources of variation in the measured impedance.

Conclusion

Two techniques have been devised to measure the characteristic impedance of microstrip as a function of frequency. A nominally 50-Ω microstrip line on alumina showed that ZO decreased with frequency at lower frequencies, but increased as frequency continued to rise. This was not expected for the thin strip measured.

References

1. B. Bianco et al., "Some Considerations About the Frequency Dependence of the Characteristic Impedance of Uniform Microstrips," IEEE Transactions on Microwave Theory and Techniques, MTT-26, March 1978, pp. 182-185.

2. W. J. Getsinger, "Microstrip Characteristic Impedance," IEEE Transactions on Microwave Theory and Techniques, MTT-27, April 1979, p. 293.

3. L. Napoli and J. Hughes, "High Frequency Behavior of Microstrip Transmission Lines," RCA Review, June 1969, pp. 268-276.

4. B. Bianco et al., "Launcher and Microstrip Characterization," IEEE Transactions on Instrumentation and Measurement, December 1976, pp. 320-323.