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CHARACTERIZATION OF THIN FILM
MICROSTRIP ATTENUATORS AT
MICROWAVE FREQUENCIES

By F. R. Smith

Published November 1978

Topical Report

Prepared for the United States Department of Energy
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Topical Report
J. L. Taylor, Project Leader

Project Team:
G. D. O'Dell
J. D. Schupbach
F. R. Smith
T. H. Wedaman

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The Bendix Corporation
Kansas City Division
P. O. Box 1159
Kansas City, Missouri 64141

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CONTENTS

Section	Page
SUMMARY.	5
DISCUSSION	6
SCOPE AND PURPOSE.	6
PRIOR WORK	6
ACTIVITY	6
<u>Attenuator Selection</u>	6
<u>Attenuator Fabrication</u>	9
<u>RF Characterization Method</u>	11
<u>Microwave Characteristics.</u>	12
ACCOMPLISHMENTS.	16
FUTURE WORK.	17
REFERENCE	18
DISTRIBUTION	19

ILLUSTRATIONS

Figure		Page
1	Basic Electrical Circuits in an Attenuator . .	7
2	Typical Attenuator Pad Geometries.	8
3	Composite II Thin Film Layout	10
4	$ S_{11} , S_{22} $ Versus Frequency for Basic Attenuator Types	15

TABLES

Number		Page
1	Average Attenuation $[(20)\log(S_{21})]$ Compared to Calculated Attenuation.	13
2	Average Reflection Coefficients ($ S_{11} $ and $ S_{22} $) for Each Attenuator Group	14

SUMMARY

When hybrid microcircuit components are accurately characterized, their electric circuit operations can be predicted. Prior investigation had established a need for characterizing components by developing accurate component models and this project was designed to characterize selected microstrip attenuator geometries and to develop thin film attenuator construction techniques by defining an accurate resistive model. The objective of the study was to develop a readily manufacturable attenuator that would display low reflection coefficients and predictable microwave attenuation.

A simple attenuator can be realized in a thin film resistor network which is easily fabricated on an aluminum oxide ceramic substrate. This study developed the processes required to fabricate a microstrip attenuator, which may be described by either a Π or a T resistive network. The attenuation of a Π or T network can be defined by a mathematical relationship. These relationships determine the value of the resistances required for the individual resistors of the Π or T networks. The predictability of an attenuator's circuit operation is improved by considering the effects of the resistor and conductor geometry on the microwave characteristics. Eleven attenuators with different attenuation values and geometries were built to serve as the basis for this study of microwave characteristics.

The radio frequency (RF) characterization of the attenuators was done on an automatic network analyzer. The microwave scattering parameters for an attenuator type were measured over a 0.1 to 3.3 GHz band. The microwave frequency data was statistically analyzed to generate general characteristics for each attenuator type.

Although this study was not exhaustive, it did reveal some definite circuit parameters and it did develop characteristics which can be related to the fabrication and circuit function of resistive attenuators. The characterization showed that simple resistive models can be used to predict the microwave attenuation value. Variation of the microstrip resistor and conductor path configuration produced definite variations in the microwave reflection characteristics of the different attenuator types. The study showed that a composite Π attenuator type displayed superior circuit characteristics than the others evaluated.

This process development effort resulted in a better understanding of the circuit operation of microstrip attenuators at microwave frequencies, developed models for the various thin film attenuator geometries, and established the fabrication requirements for different attenuators.

DISCUSSION

SCOPE AND PURPOSE

During development work on packaging techniques for microwave hybrid microcircuits, the fabrication process used to produce these circuits was found to require tedious and time-consuming adjustments and rework--largely because of an incomplete understanding of the RF characteristics of components, component attachments, and test fixtures. The microwave characteristics of each hybrid circuit element are the result of the combined effects of both the individual component characteristics and the geometric relationship to the microwave circuit. It is this geometric orientation which results in the reactive field effects often referred to as parasitics.

This report is the first in a series on the characterization of individual radio frequency (RF) hybrid microcircuit elements at microwave frequencies. It relates the fabrication processes and physical geometries of thin film attenuators to their RF circuit functions.

PRIOR WORK

Previous process development effort to evaluate microcircuit components for RF frequencies has been limited to a statement for the need of characterization. The requirement for characterization and development of component models¹ also established the rationale for this study.

ACTIVITY

The effort on this project consisted of developing attenuator pad resistive requirements and laser trim processes, making the microwave characterization, and comparing the microwave attenuator characteristics to their thin film geometries.

Attenuator Selection

RF microstrip attenuators should have geometries which can be readily fabricated and will result in repeatable circuit operation. Attenuators can be manufactured on aluminum oxide (Al_2O_3) ceramic substrates that give predictable and unique microwave characteristics when the geometry and dc resistances are known. The Π and T resistive networks of Figure 1 represent the basic electrical circuits needed to describe an attenuator.

Π RESISTIVE NETWORK

T RESISTIVE NETWORK

Figure 1. Basic Electrical Circuits in an Attenuator

The discrete resistors R_1 , R_2 , and R_3 are well defined and can be used to determine the attenuation by a resistive model. Then the resistive model can be used to predict an attenuator's microwave performance. Determination of high frequency attenuation by resistive models will be enhanced by considering the microstrip geometry. The microstrip resistive and conductive paths should be used to reduce parasitic reactance and loss between the input and output ports. If the microstrip geometry of the resistive network is symmetric, the input and output symmetry of the Π or T network will result in equivalent input and output reflection coefficients. Therefore, the ability to construct an accurate and predictable attenuator at microwave frequencies will be enhanced when the parasitics are reduced and the microstrip attenuator geometry is symmetric.

The Π and T microstrip attenuator pads used in this study are shown in Figure 2. The Π Type 1 Pad represents the basic Π resistive network. Pad Types 2, 3, and 4 were altered to study the effects of pad geometry on microwave performance. The ground straps on the resistive leg of the Π Types 1 and 2 could cause unsymmetric reflection coefficients. The composite Π pad configuration should result in Ports 1 and 2 having equivalent reflection coefficients as a result of identical microstrip resistor and conductor geometries at each port. The discrete resistors R_1 , R_2 , and R_3 of the composite Π configuration are not easily identified by dc measurements, so a more complex approach is needed to identify the discrete resistors for computation of the attenuation. The composite Π microwave attenuation characteristics should be comparable to the typical Π pads, but the composite Π reflection coefficients should be more symmetric.

II TYPE 1

II TYPE 2

COMPOSITE II TYPE 3

COMPOSITE II TYPE 4

T TYPE 1

T TYPE 2

T TYPE 3

T TYPE 4

Figure 2. Typical Attenuator Pad Geometries

The T Type 1 Pad represents the basic T electrical network. The T Pad Types 2, 3, and 4 microstrip attenuator geometries are variations which were made to study T network microwave performance. The T Pad Types 2 and 3 resistive elements (R_2 and R_3) are geometrically constructed to reduce the parasitics between Ports 1 and 2. The geometry of T Pads Type 2 and 3 should lower the reflection coefficients and make the microwave attenuation more predictable than T Pad Type 1.

Attenuator Fabrication

The microwave attenuation of the Π and T networks is predicted by calculating the resistive attenuation of the individual resistive circuit elements. The attenuation value is calculated by terminating Ports 1 or 2 with a 50 Ω characteristic impedance (Z_0). The Π and T attenuation relations are then as shown in Equations 1 and 2.

$$\Pi \text{ Atten(dB)} = 20 \log\{(R_3 Z_0)/[Z_0 R_3 + R_1(Z_0 + R_3)]\} \quad (1)$$

$$T \text{ Atten(dB)} = 20 \log[(R_1 Z_0)/(R_2(Z_0 + R_3 + R_1) + (Z_0 + R_3)R_1)] \quad (2)$$

An attenuator of the Π or T type may be fabricated to a specific attenuation by determining the discrete resistors (R_1 , R_2 , R_3) and application of these equations. The ability to construct an attenuator to a specific attenuation value with a good degree of accuracy will depend on the fabrication of the discrete resistors. HMC thin film resistors can be laser trimmed with good tolerances.

The composite Π geometry requires an alteration of the formulas to determine the resistive attenuation. The difficulty in determining the attenuation of the composite Π geometry is that the discrete resistors R_1 , R_2 , R_3 are not distinct. The discrete resistive elements to be used in the Π attenuation equation may be found by determining the mathematical relation between the Port (I) to Port (J) resistances (Figure 3) and the discrete resistors of the Π network. R_{IJ} is the measured resistance from the Ith terminal to the Jth terminal ($I \neq J$). The relationship between the discrete Π resistors and the port to port resistance values are found by using Equations 3, 4, and 5.

$$R_1 = R_{12}(4-\rho)/2(2-\rho) \quad (3)$$

$$R_2 = R_3 = R_{12}(4-\rho)/2\rho \quad (4)$$

$$\rho = R_{12}/R_{13}; \text{ Assume Port 3 is common and } R_2 = R_3 \quad (5)$$

Figure 3. Composite Π Thin Film Layout

Then the attenuation for the composite Π geometry may be found by using the Π attenuation equation and the port R_{IJ} resistive measurements. The main assumption in development of the composite Π attenuation model is that the discrete resistors R_2 and R_3 are equivalent. If R_2 equals R_3 then the port resistance (R_{13} and R_{23}) measurements will be equivalent and the composite Π model will accurately predict the attenuation value. For the R_{13} and R_{23} measurements to be equivalent, the microstrip resistive geometry must be symmetric and the thin film resistive material must be uniform. If the R_{13} and R_{23} resistor measurements are not equal, then the composite Π attenuation model will be erroneous. The symmetric trim procedure (Figure 3) should minimize any error and maintain the accuracy of the composite Π model.

The typical Π model requires a ribbon grounding strap on the resistive leg. The composite Π configuration eliminates the need for the ribbon ground. Therefore, fabricating a composite Π attenuator requires no ribbon bonding, which makes the composite geometry more desirable to manufacture. To fabricate the composite Π attenuator by the previously outlined model, a process was incorporated to trim the nondistinct resistive configuration.

The process to laser trim the composite Π attenuator to a design attenuation value is as follows.

1. Measure the R_{IJ} resistances (R_{12} , R_{23} , R_{13}).
2. If the measured values are below nominal values and R_{13} and R_{23} are approximately equal (± 10 percent) calculate the target trim values as:

$$R_{12} \text{ target} = \frac{\left(\frac{R_{12}^N [4 - (R_{12}^N / R_{13}^N)]}{2 [2 - (R_{12}^N / R_{13}^N)]} \right) (4R_{13}^M - R_{12}^M)}{\frac{R_{12}^N [4 - (R_{12}^N / R_{13}^N)]}{2 [2 - (R_{12}^N / R_{13}^N)]} + (4R_{13}^M - R_{12}^M)}, \text{ and} \quad (6)$$

$$R_{13} \text{ target} = \frac{\left(\frac{4R_{13}^N - R_{12}^N}{2} \right) \left(\frac{4R_{13}^M - R_{12}^M}{2} + \frac{(4R_{13}^M - R_{12}^M)(R_{12} \text{ target})}{(4R_{13}^M - R_{12}^M - R_{12} \text{ target})} \right)}{\frac{(4R_{13}^N - R_{12}^N)}{2} + \frac{4R_{13}^M - R_{12}^M}{2} + \frac{(4R_{13}^M - R_{12}^M)(R_{12} \text{ target})}{(4R_{13}^M - R_{12}^M - R_{12} \text{ target})}}. \quad (7)$$

$$R_{23} \text{ target} = R_{23} \text{ nominal}, \quad (8)$$

where:

R_{IJ}^N = nominal resistor values, and

R_{IJ}^M = pretrim measured values.

3. Trim to the calculated target values starting with R_{12} on the lower portion of the resistive branch between R_{13} and R_{23} , as shown in Figure 3. Follow with R_{13} and trim to the calculated target value starting at the lower edge of the previous laser trim. Finally, trim R_{23} to its nominal value starting at the lower portion of the R_{12} trim. All of the laser scribing is illustrated in Figure 3.

The trimming procedure for the composite Π requires only one trim per R_{IJ} with the precision directly proportional to the capability of the trimming operation. The outlined equations may be programmed into an automatic laser trimming process.

RF Characterization Method

Five different attenuation values were constructed using the 8 geometry types of Figure 2--resulting in 11 attenuator groups. The attenuators were laser trimmed to achieve the design attenuation

value. Eighteen individual attenuators of each group were fabricated to statistically evaluate the repeatability and determine the degree of correlation between the resistive trim value and the general microwave characteristics. The microwave attenuation and reflection coefficients were measured on an automatic network analyzer. The network analyzer measured the two-port scattering parameters from 100 MHz to 3.3 GHz for each of the attenuator groups (18 attenuators per group). Tables 1 and 2 give the average scattering parameters of the attenuator groups measured on the network analyzer.

Microwave Characteristics

Each attenuator used in this study displayed characteristics which described the circuit performance of that particular geometric type. The microwave test data (Tables 1 and 2) may be used to evaluate and predict the general characteristics of a geometric type. To evaluate the microwave performance data of an attenuator, one must consider the microwave attenuator parameters and reflection coefficients and compare each characteristic to circuit requirements.

An important aspect of hybrid microstrip circuitry is that simple resistive elements can be manufactured to exhibit repeatable electrical characteristics. The ability to fabricate and model an attenuator geometry by the previously developed resistive attenuation equations may be evaluated by considering the averaged attenuation results. The averaged attenuation calculated for each geometric type has a small standard deviation which implies a good repeatability for fabricating a specific attenuator. The tabulated value of the averaged calculated attenuation compared to the design attenuation requirement indicates that Π and T models are fairly accurate in predicting circuit attenuation.

The circuit operation of an attenuator type can be determined by comparing the averaged attenuation calculated from the dc resistance measurements to the microwave attenuation characteristics. The tabulated data shows that the measured microwave attenuation (S_{21}) correlates well with all of the resistive models. The S_{21} parameter changes less than 0.4 dB over the frequency of 0.1 to 3.3 GHz and is within 0.6 dB of the averaged calculated attenuation values for all of the geometric types. A review of the attenuation results presented in Table 1 leads to the following conclusions:

- An attenuator can be fabricated with good repeatability.
- The dc resistance measurements accurately predict microwave attenuation.
- Neither of the microstrip geometries is superior in achieving desired attenuation nor displays better S_{21} microwave performance over the frequency band.

Table 1. Average Attenuation $[(20)\log(|S_{21}|)]$ Compared to Calculated Attenuation

Design Attenuator	Average Attenuation $ S_{21} $ (dB)			
	Calculated	100 MHz	1.5 GHz	3.3 GHz
II Type 1, 12.5 dB	12.5	12.44	12.65	12.46
σ^*	0.031	0.358	0.151	0.135
II Type 2, 3 dB	3.12	2.78	3.12	3.40
σ^*	0.509	0.384	0.361	0.393
II Type 2, 4 dB	4.03	3.77	3.98	4.09
σ^*	0.132	0.105	0.136	0.20
II Type 3, 5 dB	4.88	4.79	5.10	5.06
σ^*	0.086	0.079	0.066	0.066
II Type 3, 10 dB	9.67	9.65	9.99	9.96
σ^*	0.467	0.396	0.418	0.463
II Type 3, 15 dB	14.42	13.91	14.28	14.0
σ^*	0.785	0.777	0.747	0.689
II Type 4, 3 dB	2.95	2.89	3.08	3.13
σ^*	0.313	0.264	0.261	0.28
T Type 1, 10 dB	9.95	9.73	9.90	9.95
σ^*	0.174	0.254	0.25	0.274
T Type 2, 3 dB	3.16	2.92	3.08	3.17
σ^*	0.275	0.16	0.168	0.229
T Type 3, 5 dB	5.6	5.22	5.39	5.48
σ^*	0.277	0.231	0.243	0.281
T Type 4, 15 dB	14.70	14.39	14.58	14.65
σ^*	0.313	0.318	0.365	0.344

* σ is the standard deviation

Evaluation of the reflection coefficients S_{11} and S_{22} is required to completely develop the characteristics for the attenuator geometries.

The reflection parameters S_{11} and S_{22} for an ideal attenuator should be 0 for all frequencies, but because of the parasitic reactances and losses of the resistive and conductive paths, some wave reflections will be detected. Table 2 and Figure 4 show the averaged reflection parameters measured on the automatic network analyzer for the 11 attenuator types.

Table 2. Average Reflection Coefficients ($|S_{11}|$ and $|S_{22}|$) for Each Attenuator Group

Design Attenuator	Average $ S_{11} $			Average $ S_{22} $		
	100 MHz	1.5 GHz	3.36 GHz	100 MHz	1.5 GHz	3.3 GHz
Π Type 1 12.5 dB	0.003	0.028	0.050	0.004	0.037	0.047
Π Type 2 3 dB	0.005	0.084	0.100	0.009	0.080	0.106
Π Type 2 4 dB	0.004	0.039	0.021	0.007	0.044	0.023
Π Type 3 5 dB	0.013	0.013	0.013	0.008	0.008	0.008
Π Type 3 10 dB	0.018	0.018	0.018	0.016	0.016	0.016
Π Type 3 15 dB	0.038	0.064	0.080	0.028	0.064	0.068
Π Type 4 3 dB	0.005	0.019	0.026	0.002	0.015	0.021
T Type 1 10 dB	0.009	0.023	0.075	0.012	0.023	0.079
T Type 2 3 dB	0.013	0.027	0.034	0.012	0.025	0.038
T Type 3 5 dB	0.032	0.045	0.060	0.027	0.046	0.062
T Type 4 15 dB	0.007	0.037	0.100	0.006	0.036	0.098

The Types 1 and 2 Π geometry showed reflection characteristics which may not be suitable for RF attenuator pads. These pads have asymmetric input and output reflection coefficients whose magnitudes are frequency dependent. The composite Π geometry (Type 3 and 4) was selected in an effort to remove the geometric asymmetry of the typical Π configuration. The composite Π geometric alteration resulted in S_{11} and S_{22} parameters that were small in magnitude, of constant magnitude with respect to frequency, and fairly symmetrical. The 15 dB Π Type 3 attenuator displayed reflection characteristics higher and more frequency-sensitive than the other composite Π configurations. This implies that the composite Π attenuator may have undesirable reflection characteristics for attenuation values greater than 10 dB. The composite Π geometry operated with expected reflection characteristics and exhibited superior characteristics over the other Π geometries.

Figure 4. $|S_{11}|$, $|S_{22}|$ Versus Frequency for Basic Attenuator Types

The T attenuators had reflection coefficients whose magnitudes were frequency dependent and possessed port symmetry. The altered geometry of T Types 2 and 3 should have improved the characteristics of the S_{21} attenuation parameter and the port reflection parameters. The test results showed little change in S_{11} and S_{22} reflection coefficients compared to the reflection characteristics of the typical T geometry. The T geometries did present a more symmetric reflection coefficient than the Π geometries. The T attenuator geometries displayed similar characteristics for the four types analyzed, although the geometric alterations

for the T Types 2, 3, and 4 were expected to improve the reflection characteristics of the T geometry. A review of the reflection coefficient data displayed in Figures 1 through 4 and in Table 2 lead to the following conclusions.

- The typical Π geometries had S_{11} and S_{22} parameters which were frequency dependent and asymmetric with respect to the input and output ports.
- The T geometries had S_{11} and S_{22} parameters which were frequency dependent and symmetric with respect to the input and output ports.
- The composite Π geometries had S_{11} and S_{22} parameters which were independent of frequency, symmetric with respect to the input and output ports, and small in magnitude.

ACCOMPLISHMENTS

The investigation of thin film microstrip attenuators resulted in the development of characteristics for attenuator fabrication and defined the criteria for microwave performance. The microwave circuit operation of each attenuator type, when measured in sufficient quantities on the automatic network analyzer, was consistent and repeatable. Although the study was not representative of all possible attenuator configurations, some valuable recommendations can be made.

The microwave attenuation was fairly constant over frequency and was within 0.4 dB of the design attenuation. All of the attenuators evaluated had repeatable attenuation characteristics and the mathematical fabrication model for an attenuator was accurate in predicting the microwave attenuation. The model easily can be programmed in an automatic laser trim process for repeatable and efficient thin film attenuator fabrication.

The measured results for the reflection parameters were the most significant characteristics. The reflection coefficients of the composite Π geometry with attenuation less than 10 dB were small in magnitude, constant with frequency, and symmetric. The other geometric types had good attenuation parameters but reflection coefficients were fairly high in magnitude and varied with frequency. Overall, the study improved the understanding of microstrip resistive attenuator characteristics at microwave frequencies, defined the process of modeling and fabricating the thin film networks, and developed an attenuator configuration (the composite Π) which approaches ideal microwave operation.

FUTURE WORK

Recommendations for future work on thin film attenuators fall into two major categories.

The first category involves the intermediate application of product processes developed by this endeavor for the composite Π attenuator. The development of software for active laser resistor trimming of composite Π attenuators according to the process steps defined in this report is recommended.

The second category is based upon the anticipated requirements of future product design. There are three items of possible future work that will fall in this category. They are listed below in order of relative importance.

- The RF characteristics of thin film attenuators presented in this report used thin film resistors having 100 Ω per square. The RF characteristics of thin film attenuators made with thin film resistors having 50 Ω per square should be determined and compared to the characteristics presented in this report.
- The RF power limitations of the thin film attenuators should be determined.
- A more detailed computer model, which accounts for the reactive nature of the parasitic RF fields, should be developed for attenuator geometries proposed for application in RF HMC production.

REFERENCE

¹G. D. O'Dell, *The Necessity of Characterizing Hybrid Microcircuit Elements at Microwave Frequencies* Topical Report. Bendix Kansas City: BDX-613-1477, September 1976 (Available From NTIS).

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ELECTRICAL: Attenuator Characterization

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