large number of switchable circulators. It is possible to modify the copper disk shape[5] so as to construct a multibit digital nonreciprocal phase shifter for phased array systems.

The first one-piece latched microstrip junction circulator was identical in appearance with the photograph of the composite two-piece latched circulators shown on the far right side of Fig. 4. The platinum-sugar mixture was not used because an embossed die of the desired shape was not available. A 0.010 inch loop of platinum wire was placed on the sheets in the die and the remaining sheets were placed on top and pressed. After the final firing, evidence of shrinkage effects were observed as cracks in the vicinity of the platinum wire emerging from the specimen. Nevertheless, the experimental results established feasibility and, while far from outstanding, did substantiate the fact that the approach warrants further effort. The maximum isolation was 12 dB with a 10 dB isolation bandwidth of 350 MHz. The insertion loss was high, ranging from 2.0 to 5.0 dB over the band. However, a number of factors can account for this loss. The specimen was thicker than a quarter of a guide wavelength and the associated radiation loss was evident. The cracks in the material also contribute to the insertion loss. Furthermore, a thin specimen of the laminated ferrimagnetic material was prepared with size and shape identical with that shown in Fig. 1. This circulator was tested in an electromagnet where it showed a high insertion loss. The ferrimagnetic material was yttrium-iron-garnet, and it was a poor microwave material when compared to the commercially available materials. In all fairness it should be noted that this was the first attempt at RCA to prepare YIG material in laminated sheets since all previous experience has been with ferrite materials for laminated memory sheets. It is a reasonable assumption that a materials study would lead to materials comparable to commercially available material. However, before this is done, the insertion loss versus thickness problem previously discussed must be resolved. Following this, a laminated garnet materials study can be launched, or ferrite laminates could be used. The laminated technique is of significant importance because it provides an inexpensive means for batch fabrication of latched circulators. These circulators would find wide use as individual elements, or as inexpensive digital nonreciprocal phase shifters for phased array systems.[5]

This author's present work, and that of others at Syracuse University[6] where ferrimagnetic substrates have been used to build latched nonreciprocal devices, has established the role of these devices in microwave integrated circuits. Recent work at RCA Laboratories on new magnetic materials, chalcogenides,[7] has expanded this prospective role. Ferromagnetic insulators which can be locally doped to yield semiconductor materials with high mobilities and high carrier densities have been developed. It may be possible to prepare substrates of these materials, dope them locally to provide active devices such as amplifiers and oscillators, and then use the undoped portion of the substrate for passive nonreciprocal (and reciprocal) devices. Operation latched or with a permanent magnet should be feasible. These advances with both materials and devices make the prospect of microwave systems on magnetic substrates a distinct possibility.

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## High-Dielectric Substrates for Microwave Hybrid Integrated Circuitry

***Abstract*—Microstrip transmission-line parameters of temperature-compensated titanium dioxide have been measured. This material has a dielectric constant ranging from 25 to 100. The variations of microstrip wavelength, characteristic impedance, and attenuation with geometry and dielectric constant are in good agreement with the theory. This material is particularly attractive for microwave circuits because of the short guide wavelength and low attenuation.**

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### Introduction

Microstrip transmission-line components are finding wide application in microwave integrated circuits. Properties of the microstrip structure have previously been investigated for semiconductor dielectrics,[1] low-dielectric $k<10$ ceramics,[2] sapphire,[3] and Polyguide.[3] This correspondence will present the properties of high-dielectric $k>10$ substrates in the microstrip configuration.

All of the data were taken from the AlSiMag temperature-compensating series No. T96 manufactured by American Lava Corporation. The dielectric constant of this material is in the range of 25 to 100, and the material itself consists of titanium dioxide with additions of magnesium and titanium to provide a minimum change of capacitance as a function of temperature.

The primary virtue of high-dielectric substrates for microwave circuits is reduced size. By increasing the substrate dielectric constant from 10 to 100 the guide wavelength of a 50 ohm microstrip line can be reduced by a factor of 0.35. Since the high-dielectric microstrip lines also have low loss and a useful range of impedances, this class of circuits will undoubtedly find wide application in microwave integrated circuitry.

### Characterization of Microstrip Transmission Lines

Three properties are required in characterizing microstrip lines: wavelength, characteristic impedance, and attenuation. The wavelength in the microstrip line has been measured by two methods. Using the first method, the line is operated as a half-wavelength filter which is loosely coupled and open circuited at both ends. By measuring the resonant frequencies of the filter the wavelength in the microstrip line may be simply calculated.

An alternative method consists of short circuiting the transmission line and searching for the frequencies where the VSWR minimum positions are identical with those of a short-circuited air line. At these resonant frequencies the line is once again a half-wavelength filter. Better measurement accuracy seems to be obtained from the second method, although both methods give the same value of guide wavelength.

Characteristic impedance may be simply determined from time-domain reflectometer measurements. With the line terminated in 50 ohms, the reflection coefficient is measured for a transmission line which is sufficiently long for transitions at the end of the line to have a negligible effect.

The attenuation of the line may be determined by measuring the loss tangent of the short-circuited resonant line. This loss may be expressed in dB/cm or dB/$\lambda_g$. Using the latter units, the advantages of high-dielectric substrates will become more apparent.

### Measured Performance

The measured and calculated ratio of free-space wavelength to microstrip wavelength is plotted in Fig. 1 as a function of dielectric constant and geometry. This ratio has been

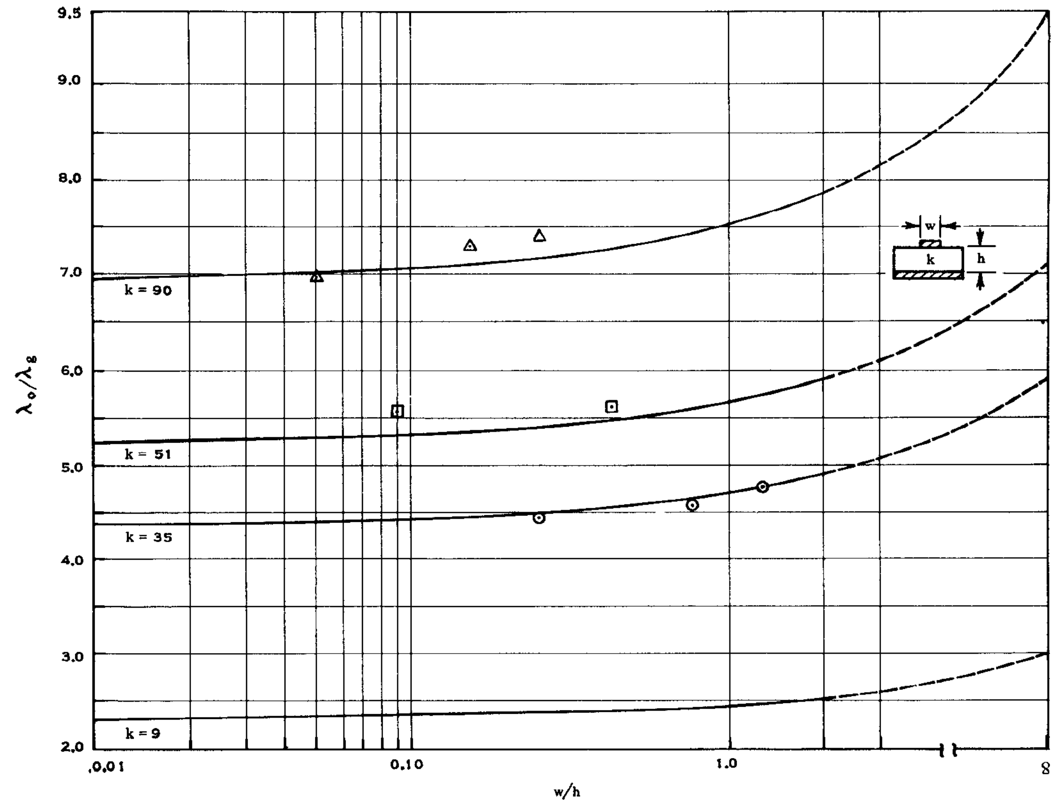


Fig. 1. $\lambda_0/\lambda_g$ versus dielectric constant and geometry for microstrip transmission lines.

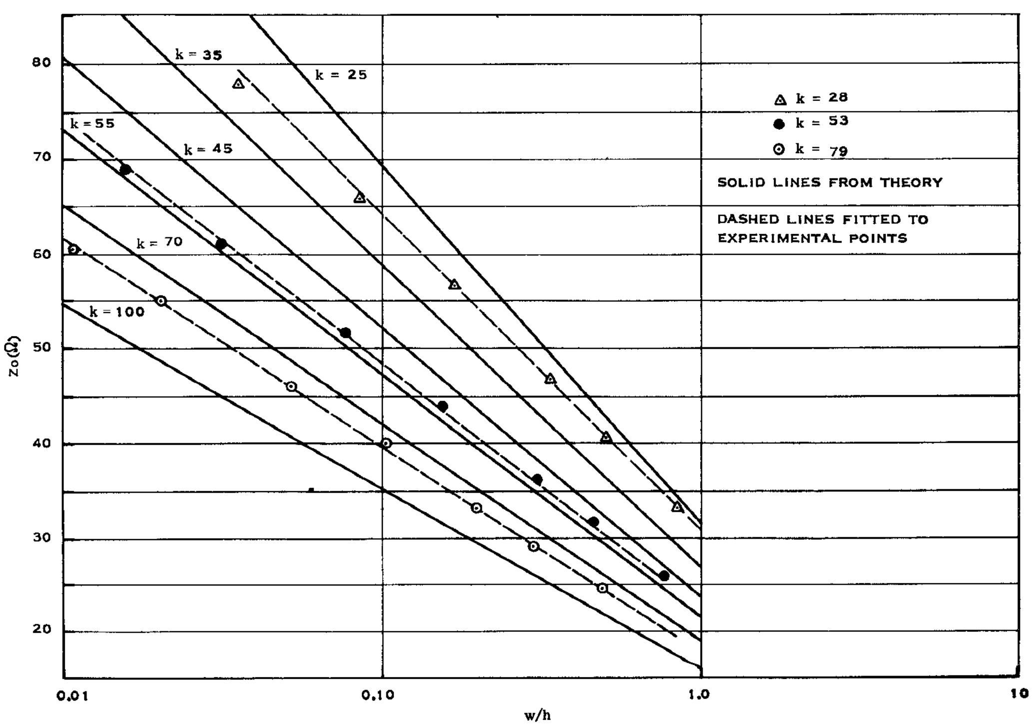


Fig. 2. Characteristic impedance of microstrip transmission lines versus dielectric constant and geometry.

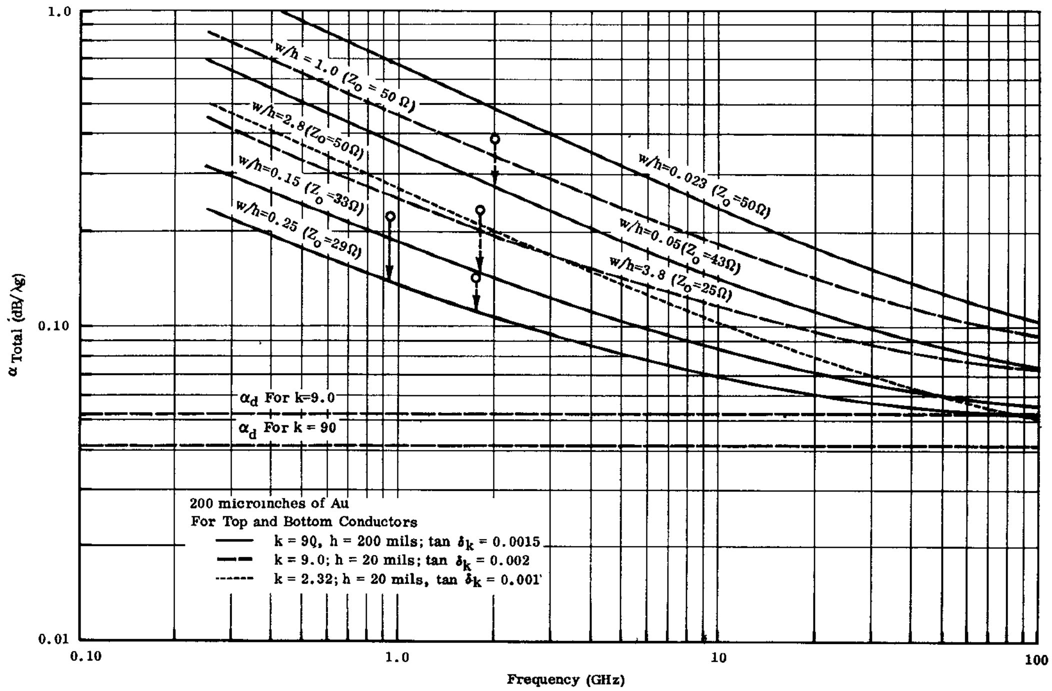


Fig. 3. Attenuation constant versus frequency and geometry.

computed from a conformal mapping solution given by Wheeler.[4]

$$\lambda_0/\lambda_g = \sqrt{k'} \quad (1)$$

$$k' = 1 + q(k - 1) \quad (2)$$

where

$k'$ is the effective dielectric constant;
$k$ is the substrate dielectric constant;
$q$ is the effective filling fraction.

The measured and calculated characteristic impedance is plotted in Fig. 2 as a function of geometry and dielectric constant. The calculated impedance is based on the conformal mapping solution given by Wheeler.[4] Notice that the high-dielectric substrates require smaller values of $w/h$ for high-impedance levels because of the higher transmission-line capacitance. Since line width is restricted by thin-film technology limitations, thicker substrates will be required for high-dielectric microstrip circuits.

From measuring the total loss tangent, the attenuation constant is given by

$$\alpha = 27.3 \tan \delta \quad (\text{dB}/\lambda_g) \quad (3)$$

where $\tan \delta$ includes both dielectric and conductor loss. The theoretical attenuation may be computed for a TEM wave. The attenuation constant is the sum of the dielectric losses and the conductor losses.

$$\alpha = \alpha_d + \alpha_c. \quad (4)$$

Dielectric losses must include the effective dielectric constant.[5] At low frequencies, where ohmic losses dominate, the dielectric attenuation constant becomes

$$\alpha_d \cong \frac{\omega}{2} (\mu k)^{1/2} \tan \delta_k (k/k')^{1/2} q \ (\text{Np/m}). \quad (5)$$

Conductor losses may be approximately calculated by assuming a uniform current across the width of the conductor and also assuming that the ground plane current is distributed uniformly under the conductor. When the conductor thickness is greater than the skin depth, the conductor attenuation becomes

$$\alpha_c \cong \frac{\sqrt{\pi f \mu \rho}}{Z_0 w} \quad (\text{Np/m}) \quad (6)$$

where

$\rho$ is the conductor resistivity;
$f$ is the frequency;
$\mu$ is the magnetic permeability.

Using the relations above, the theoretical attenuation constant and measured values have been plotted in Fig. 3 as a function of frequency and geometry.

## Conclusions

High-dielectric substrates consisting of a temperature-compensated titanium dioxide homogeneous mixture have been shown to have the properties required for reduced-size microwave integrated circuits. The variations of microstrip wavelength, characteristic impedance, and attenuation with geometry and dielectric constant are in good agreement with the theory. The low values of attenuation and guide wavelength make this material particularly attractive for low-loss microwave circuitry.

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# A Thin-Film *X*-Band Varactor Quadrupler

***Abstract*—A thin-film single idler varactor quadrupler which uses microstrip transmission-line circuitry on ceramic substrate and an unpackaged beam lead varactor are described. Circuit design and the resulting microstrip pattern are discussed; experimental data are presented. Multiplier construction, including information concerning the beam lead varactor and the techniques for bonding it in the circuit pattern, is discussed.**

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