

MICROSTRIP DESIGN MANUAL
WITH FABRICATION GUIDELINES

by

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DEFINITIONS OF SYMBOLS

α	Attenuation
α_c	Attenuation due to conductor loss
α_d	Attenuation due to dielectric loss
C	Capacitance
ϵ	Permittivity
ϵ'	Real part of permittivity
ϵ''	Imaginary part of permittivity
ϵ_o	Permittivity of free space
ϵ_r	Relative permittivity
$\epsilon_{r,eff}$	Effective dielectric constant of microstrip compound dielectric
f	Frequency, Hz
h	Height of dielectric of microstrip
λ_o	Free space wavelength
λ_g	Waveguide wavelength
μ	Magnetic permeability
μ_o	Magnetic permeability of free space
Q	Quality factor of resonant circuit
R_s	Skin resistance of a conductor
ρ	Resistivity
σ	Conductivity
t	Thickness of microstrip conductor
$\tan \delta$	Loss tangent
w	Width of microstrip

Δw	Correction for finite thickness of microstrip conductor
ω	Radian frequency
Z_o	Characteristic impedance of microstrip transmission line

INTRODUCTION

Microstrip is one of the family of strip transmission lines that gained prominence in the late 1940's. The first applications of strip-type transmission media are believed to have occurred during World War II (Barrett, 1955). After the war, these types of waveguide were thought to be a breakthrough in transmission of microwave energy when compared to conventional rectangular or circular waveguide. The advantages noted were smaller size, easier manufacture, and lower cost. Inspired by these advantages, researchers actively sought to characterize these transmission systems. Investigation was quite intense from 1945 to about 1955. However, in the later 1950's and early 1960's interest waned, only to be revived by the major advances in solid state active devices in the early 1960's. The availability of small active devices that could be used with strip transmission lines provided the impetus to then consider production designs using strip lines.

Microstrip is composed of a conducting strip supported above a ground plane by a dielectric sheet (Fig. 1). Its significant operating parameters are impedance, attenuation, guide wavelength, and unloaded Q. Expressions for these, in terms of width w , height h , and relative dielectric constant ϵ_r , have been derived by analyzing the mode of transmission, which resembles, to a certain extent, that of a wire above a ground plane.

Of the many configurations of strip transmission systems, microstrip is one of the most appealing because it enables construction of hybrid UHF and microwave circuits in which the active devices are attached to the passive microstrip circuit pattern. Two other alternatives in fabricating a microwave circuit are use of stripline (Fig. 2) or total integration of

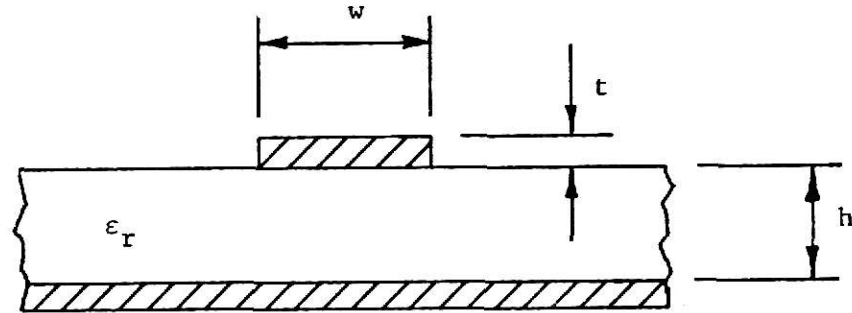


Fig. 1 Microstrip transmission line cross section.

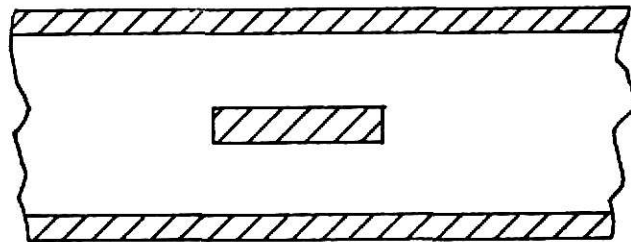


Fig. 2 Stripline transmission line cross section.

active and passive components on a single semiconductor substrate. Stripline is not as attractive as microstrip because of the physical difficulties encountered when trying to include active devices in the sandwich-like structure. Total integration is feasible, but not favored because of questionable economic advantage and performance compromises (Sobol, 1972).

In order to implement a circuit design using microstrip, it is necessary for a designer to acquire familiarity with the equations that characterize it and to know the limitations of these equations. Since there has been much information published in many journals over the years, the process of familiarization is quite lengthy. It would be helpful, then,

to have a digest of this material that cuts straight to the best equations. The objective of this paper is to present design information distilled from the publications listed under REFERENCES in a form suited to direct application. It applies this information to the frequently encountered case of designing a standard 50-ohm transmission line by providing detailed design curves for microstrip on dielectrics of teflon, G-10 glass-epoxy, and alumina. For those cases other than the ones covered by the curves, the Appendix lists computer programs for a completely general design. In addition to this information, fabrication considerations to assist in the transition from a paper design to physical realization are also set forth.

CHAPTER 1

CHARACTERISTIC EQUATIONS OF MICROSTRIP

1.0 Methods of Modeling Microstrip

In the years since microstrip was first modeled mathematically, there has been an improvement in the accuracy of the model with each attempt. It may seem that an accurate solution could be easily obtained, considering its simple shape. However, even though the structure of microstrip appears simple, it is one of the most difficult to represent in a precise, yet practical, mathematical manner. The difficulty stems from the fact that the dielectric interface highly complicates the analysis of a field that would be TEM, like a coaxial transmission line, if the dielectric were infinitely uniform. There exist, then, the two typical approaches to the analysis. One simplifies the problem by assuming that the field can be closely approximated as TEM. The other is completely rigorous mathematically and ignores any simplifying assumptions so that an exact solution to the field problem is obtained. Disregarding all of the intermediate intricacies, the major difference between the two techniques lies in the form of the answer. The equations from the solution by TEM approximation are often in terms of common slide-rule functions; whereas, the equations resulting from the rigorous solution are typically in a form which requires numerical analysis to supply usable values. All investigators who have undertaken solution of this problem have recognized the complications and consequently the ones interested in a useful set of design equations have usually employed the TEM approximation.

Some of the most widely-known work in modeling microstrip was done by Assadourian and Rimai in 1952 and by Wheeler in 1964 and 1965. Between these years, other researchers also made contributions to the theoretical analysis

of microstrip or the experimental measurement of its characteristics (Black and Higgins, 1955; Dukes, 1956; Kostriza, 1955; Arditì, 1953; Arditì and Elefant, 1955; Zublin, 1955; Bowness, 1956; Wu, 1957). The importance of the analysis by Assadourian and Rimai is that it was an attempt to describe microstrip by conventional well known functions. They assumed a structure with an infinitely uniform dielectric, thus allowing them to apply the properties and equations of TEM propagation. They used the equation for characteristic impedance

$$Z_o = \frac{(\mu\epsilon)^{\frac{1}{2}}}{c} \quad (1)$$

and then solved for the capacitance by using conformal mapping for the cases of $w/h \gg 1$ with $t = 0$, $w/h \gg 1$ with a correction for $t > 0$, and $w/h \ll 1$ with $t = 0$. The resulting equations for the first and last cases are shown below.

$w/h \gg 1, t = 0$:

$$Z_o = \frac{\frac{h}{w} \left(\frac{\mu}{\epsilon} \right)^{\frac{1}{2}}}{\left\{ 1 + \frac{2h}{\pi w} \left[\ln \left(1 + \frac{\pi w}{2h} \right) + 1 \right] \right\}} \quad (2)$$

$w/h \ll 1, t = 0$:

$$Z_0 = \frac{1}{2\pi} \left(\frac{\mu}{\epsilon} \right)^{\frac{1}{2}} \ln \frac{8h}{w} \quad (3)$$

These expressions are bounds for the full range of ratios of w to h . It is claimed by Black and Higgins (1955) that the impedance equation for the wide strip approximation is in error by as much as 25%. It can also be shown by a few calculations that the impedance equation for narrow strips is also inaccurate since it is in disagreement with Wheeler's (1965) proven results. This comparison may be unfair in that Wheeler's equation is intended for $w/h < 1$ and not necessarily $w/h \ll 1$ and that the strips of $w/h \ll 1$ are high impedance lines where the concern is not so much for absolute accuracy but for exceeding a minimum value. It should also be noted that these lines may even be impractical to fabricate because of unrealizably narrow line widths. Since these equations are for the extremes of w/h , which are not extensively used in practice, and since they are also not as accurate as others, they will be dismissed. Nevertheless, they are still important as examples of the initial attempts to bring the descriptive expressions for microstrip to the realm of common functions.

Wheeler's analyses in 1964 and 1965 were express attempts to derive a "very close approximation in terms of ordinary functions (exponential and hyperbolic) rather than the exact solution in terms of difficult functions (elliptic)" (Wheeler, 1964:280) for

parallel wide strips of zero thickness. He assumed TEM propagation and, using careful approximations, he applied conformal mapping to solving the problem for both wide ($a/b > 1$) and narrow ($a/b < 1$) parallel strips with an infinite uniform dielectric (Fig. 3a) and with a dielectric interface (Fig. 3b). In his 1964 work he transformed one quadrant of the parallel

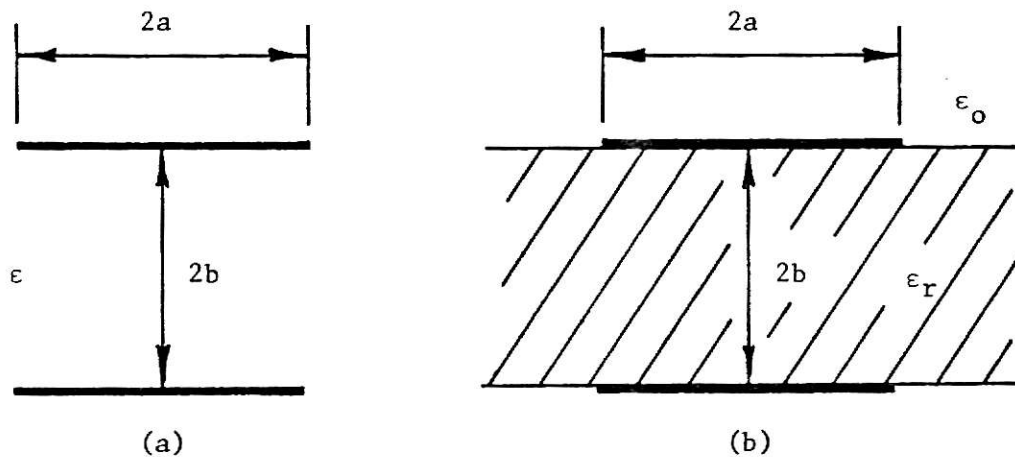


Fig. 3 (a) Parallel-strip transmission line with uniform dielectric (Wheeler, 1964). (b) Parallel-strip transmission line with mixed dielectric (Wheeler, 1965).

strip structure into the shape of a parallel-plate capacitor (Fig. 4) which included both the flux lines terminating on the inner face and those terminating on the outer face of the conductor strip. In his 1965 paper he expanded on this analysis by mapping parallel strips separated by a dielectric sheet into a capacitor with a compound dielectric composed of air and the dielectric material (Fig. 5). The capacitance of this system is between that of one with an air dielectric and one with a solid dielectric and it is expressed as a function of an "effective" relative dielectric constant. The effective dielectric is a weighted mean of the two dielectric constants and depends on the

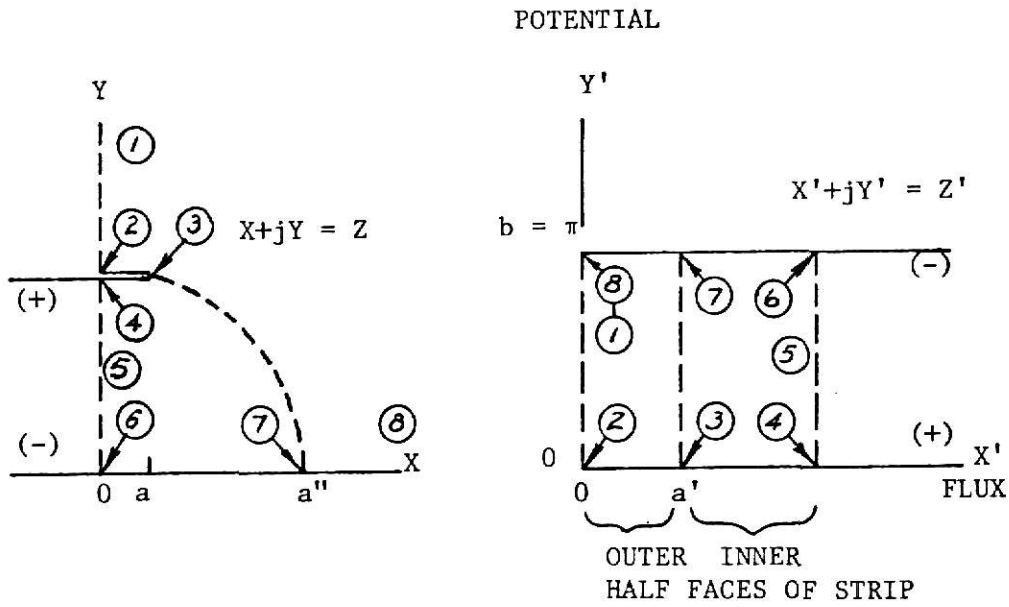


Fig. 4 Wheeler's conformal mapping of parallel-strip transmission line with uniform dielectric.

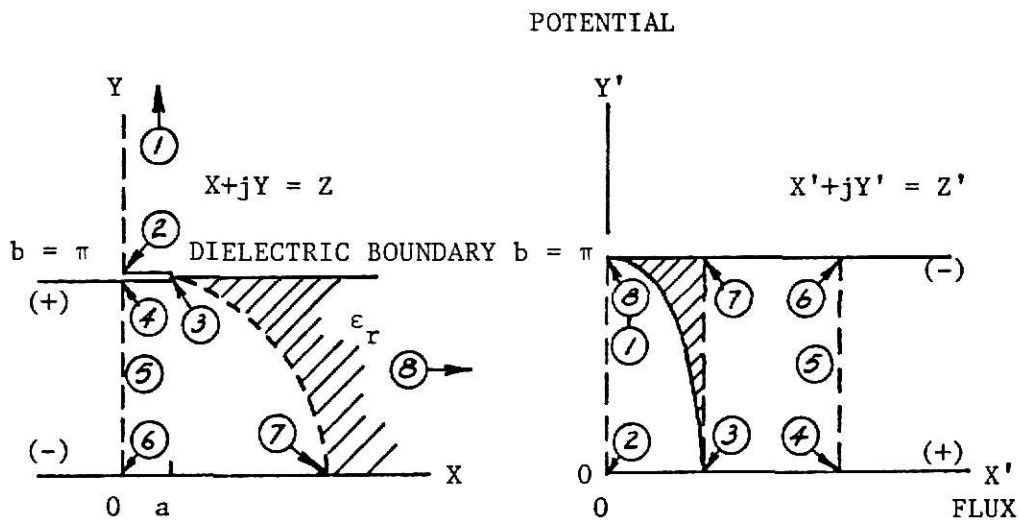


Fig. 5 Wheeler's conformal mapping of parallel-strip transmission line with mixed dielectric.

amount of fringe field enclosed in the dielectric sheet, which in turn depends on w , h , and ϵ_r . In addition to solving the problem for strips of zero thickness, he also derived a correction for finite thickness. The effect of finite thickness is to increase the capacitance of the line; therefore, the correction reduces the capacitance by shrinking the width of the conductor an amount Δw . While this derivation was not precisely for microstrip, it can readily be applied to microstrip by a simple substitution of variables, as will be shown later. Wheeler estimated that his equations are accurate to 1% of the desired impedance value and others (Caulton, et al, 1966; Rosenkranz, 1972) experimentally verified his results. Thus he had found a simple accurate description of the strip transmission structure.

After Wheeler's work, Yamashita and Mittra, Stinehelfer, Kaupp, and Schneider produced analyses of microstrip as a TEM waveguide. Yamashita and Mittra (1968) corroborated Wheeler's theory and Stinehelfer (1968) showed the effect of enclosing microstrip in a box, but their treatments required numerical analysis and therefore were not as convenient as Wheeler's. Kaupp and Schneider, though, dealt with the problem of trying to provide useful expressions for engineering applications.

Kaupp (1967) was apparently not aware of Wheeler's derivations nor some of the other previous papers on microstrip because he employed both empirical and theoretical information in a manner that appears to be independent and original. He formulated an expression for effective dielectric constant by using the ratio of measured propagation delay of microstrip to that of transmission in free space. This expression depends only on ϵ_r and not on the geometrical parameters w and h . However,

he did acknowledge that w and h influenced the effective dielectric constant. He then used the equation for a wire above a ground plane and modified it with a conversion to change the shape of the wire to a rectangular cross section in order to find an expression for impedance of a microstrip line with uniform dielectric. Into this formula he substituted the relation for effective dielectric constant to obtain an equation for microstrip impedance in terms of w , h , t , and ϵ_r for very narrow strip widths. Even though his equation was derived for lines with $w/h \ll 1$, it predicted within 5% the impedance of his experimental lines with w/h up to 2.

Schneider (1969) pursued a path somewhat like Wheeler's to derive his equations for microstrip. He used a conformal mapping of the microstrip structure--as opposed to the parallel-strip structure--with a uniform dielectric and $t = 0$ (Fig. 6). Although he outlined a completely rigorous solution for impedance, he closely approximated the results by using truncated semi-infinite series in order to obtain

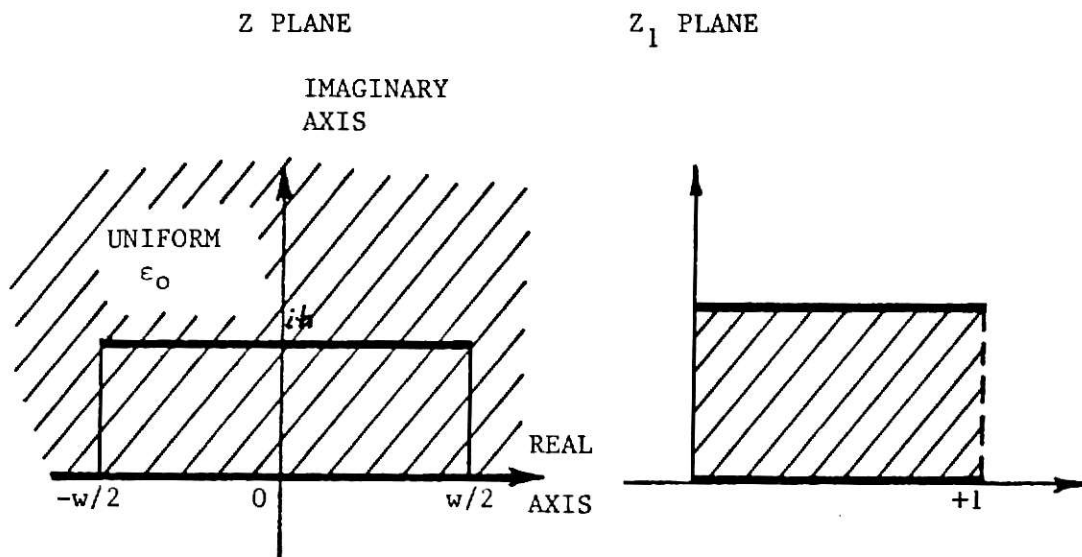


Fig. 6 Schneider's conformal mapping of microstrip structure.

expressions useful for engineering applications. His equations modeled impedance for the regions $w/h \leq 1$ and $w/h \geq 1$. From his mapping he also obtained a practical equation for effective dielectric constant to be used in determining impedance when ϵ_r is not equal to 1. The accuracy of his expressions for impedance was stated as 0.25% and it was well supported by his experimental measurements. Thus Schneider's work yielded another method for accurately modeling microstrip.

Wheeler, Kaupp, and Schneider independently approached the problem of modeling microstrip and showed that it is possible to obtain an accurate model by approximating the propagation as TEM. Therefore it is not necessary to resort to a rigorous analysis to characterize microstrip. Their simplifying assumption of TEM propagation also enabled them to express their results in terms of common functions that lend themselves well to the process of design.

1.1 Presentation, Comparison, and Verification of Equations

Section 1.0 briefly described four analyses of microstrip aimed at producing practical expressions for its characteristics in terms of common functions. The three analyses of Wheeler, Kaupp, and Schneider appear to be accurate and therefore merit comparison. Their analyses did not derive expressions for all characteristics of microstrip, though. Therefore in order to obtain equations for those areas not covered by them, the works of other investigators will be introduced. Thus at least two equations will be presented for each characteristic. With a choice of equations for each electrical parameter of microstrip, it is necessary to know how well they compare with each other and to

determine which is most accurate on an absolute basis if there is a large discrepancy. The comparisons will be based on experimental, as well as theoretical evidence, so that the most realistic analysis is made.

The equations for microstrip impedance as given by Wheeler, Kaupp, and Schneider are presented below. Wheeler's equations are adapted to a form for microstrip by the following substitutions:

- 1) $a = w/2$
- 2) $b = h$
- 3) Z_o (parallel strip) = $2Z_o$ (microstrip)

All variables used in the equations are defined in DEFINITIONS OF SYMBOLS at the beginning of the report.

WHEELER (1965):

$$w/h \leq 2, \quad t = 0$$

$$Z_o = \frac{120(x_1 - x_2)}{\sqrt{2(\epsilon_r + 1)}} \quad (4)$$

$$\text{where } x_1 = \ln \frac{8h}{w} + \frac{1}{32} \left(\frac{w}{h} \right)^2$$

$$\text{and } x_2 = \frac{(\epsilon_r - 1)(0.226 + 0.12/\epsilon_r)}{\epsilon_r + 1}.$$

$$w/h \geq 2, \quad t = 0$$

$$Z_o = \frac{60\pi}{(x_3 + x_4)\sqrt{\epsilon_r}} \quad (5)$$

$$\text{where } x_3 = \frac{w}{2h} + 0.441 + \frac{0.082(\epsilon_r - 1)}{\epsilon_r^2}$$

$$\text{and } x_4 = \frac{\epsilon_r + 1}{2\pi\epsilon_r} \left[\ln \left(\frac{w}{2h} + 0.94 \right) + 1.451 \right].$$

KAUPP (1967):

$$Z_o = \frac{87}{\sqrt{\epsilon_r + 1.41}} \ln \left(\frac{5.98h}{0.8w + t} \right) \quad (6)$$

SCHNEIDER (1969):

$$w/h \leq 1, \quad t = 0$$

$$Z_o = \frac{1}{\sqrt{\epsilon_{r,\text{eff}}}} \left[60 \ln \left(\frac{8h}{w} + \frac{w}{4h} \right) \right] \quad (7)$$

$$w/h \geq 1, t = 0$$

$$Z_0 = \frac{1}{\sqrt{\epsilon_{r,\text{eff}}}} \left[\frac{120\pi}{\frac{w}{h} + 2.42 - \frac{.44h}{w} + \left(1 - \frac{h}{w}\right)^6} \right] \quad (8)$$

where $\epsilon_{r,\text{eff}}$ is given by (12).

Figures 7 and 8 show plots of Wheeler's, Schneider's, and Kaupp's equations for $\epsilon_r = 1$. There is an amazingly close agreement between Wheeler's and Schneider's equations; whereas, Kaupp's equation is low by a nearly constant value up to $w/h = 1.5$. To examine more closely the agreement between Wheeler's and Schneider's equations, the per cent difference between them is plotted in Fig. 9. The maximum difference is 0.5%, less than the 1% tolerance on Wheeler's equations alone. However, for values of dielectric constant greater than 1, the per cent difference is larger at all values of w/h . The narrow strip equations of Wheeler and Schneider differ by 0.4% at $w/h = .1$ to 3.0% at $w/h = 1.85$ for dielectric constant values of 2.1, 4.8, and 9.8 and the wide strip equations differ by no more than 0.4% at $w/h = 10$ and less than 1.1% at $w/h = 1.85$ for the same range of dielectric constants. While the characteristic impedance by Kaupp's equation with $\epsilon_r = 1$ is lower than that of Wheeler's narrow strip equation, it approaches and then exceeds the values predicted by Wheeler's equation as ϵ_r varies from 1 through 9.8. In contrast, if the per cent difference between Wheeler's and Schneider's curves is examined at a given value of w/h as a function of ϵ_r , it is virtually constant. The results of

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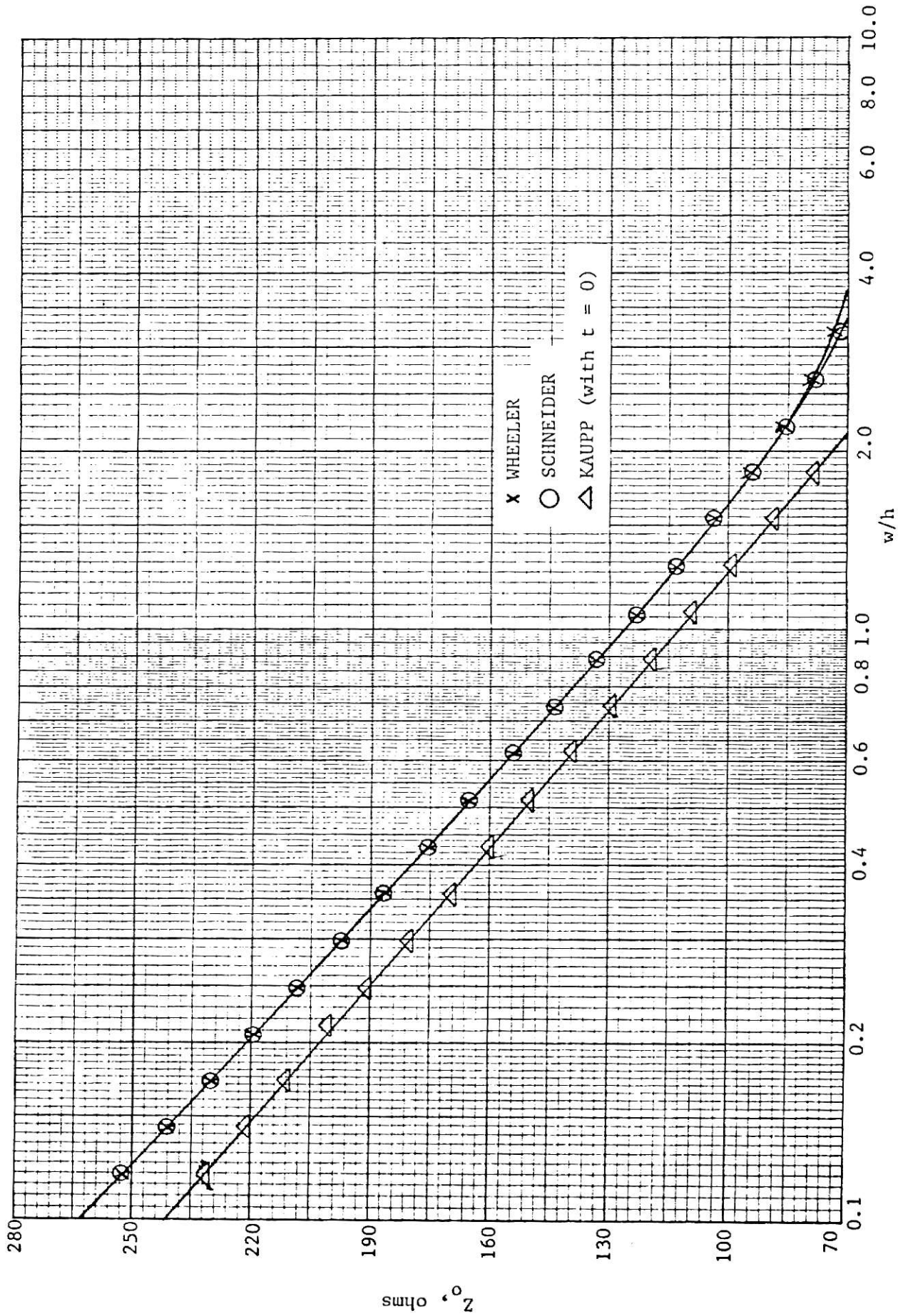


Fig. 7 Comparison of Wheeler's, Schneider's, and Kaupp's equations for microstrip characteristic impedance for narrow strips with $\epsilon_r = 1.0$.

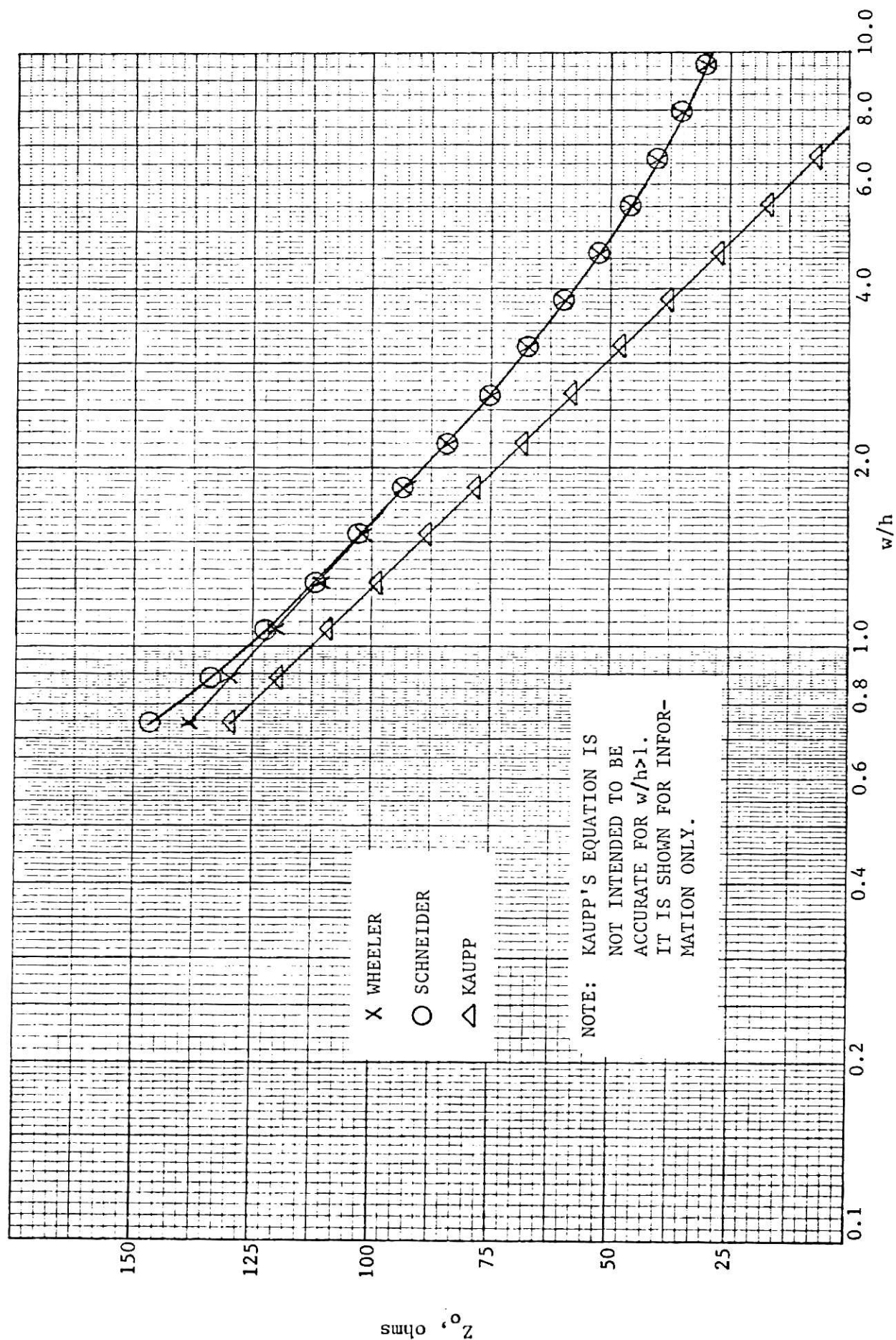


Fig. 8 Comparison of Wheeler's and Schneider's microstrip characteristic impedance equations for wide strips and $\epsilon_r = 1.0$.

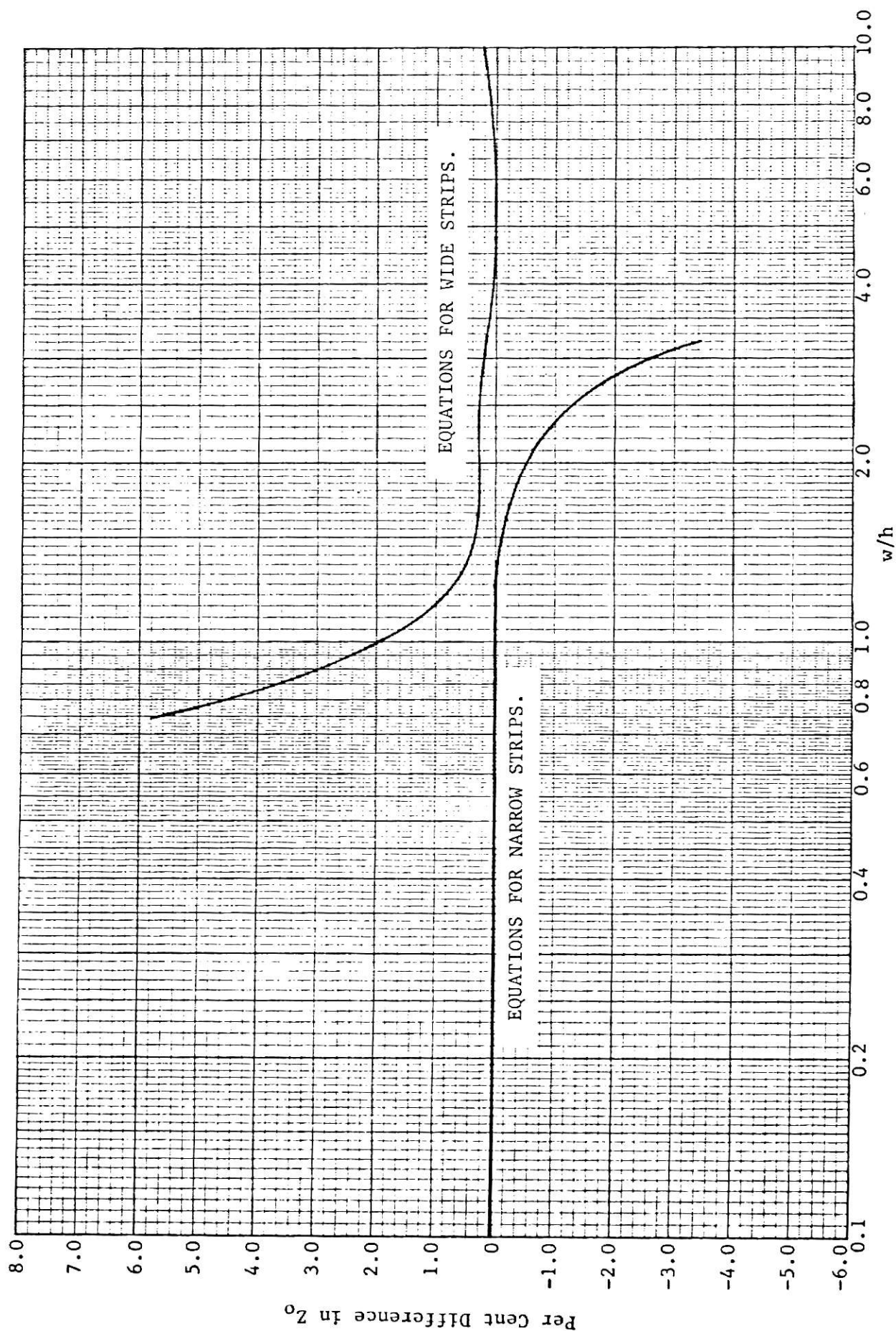


Fig. 9 Per cent difference between Wheeler's and Schneider's microstrip characteristic impedance equations using Wheeler's equation as the reference.

Wheeler's and Schneider's equations differ, but still track as ϵ_r varies. Even though Wheeler's and Schneider's equations do not agree as closely for values of $\epsilon_r > 1$ as they do for $\epsilon_r = 1$, their agreement with respect to ϵ_r is more consistent than the agreement of Kaupp's and Wheeler's equations is with respect to ϵ_r .

The accuracy of equations (4) through (8) has been stated by the authors or implied by measurement, in the case of Kaupp. Wheeler estimated that his equations yielded values of Z_0 with an error less than 1% of the desired Z_0 and Schneider stated that his equations were accurate to 0.25% for $w/h < 10$. Of course, these accuracies are valid only in the proper regions on applicability for the equations. It is reasonable to believe these accuracies because of the virtual identity of the expressions over the range illustrated in Figures 7 and 8. Kaupp, in contrast, did not venture to estimate the accuracy of his equation; however, he did implicitly state by measurement that the error was less than 5% for $w/h \leq 1.5$ and $\epsilon_r = 4.8$. When compared to Wheeler's or Schneider's equations for $\epsilon_r = 1$ and w/h between 0.1 and 1, Kaupp's equation differs by 8% to 11%, but for $\epsilon_r = 4.8$, it differs by a maximum of 1.5%. Kaupp's curve crosses Wheeler's narrow strip curve near the value of $\epsilon_r = 4.8$. Thus, assuming that Wheeler's equation is absolutely accurate, the experimentally determined 5% accuracy of Kaupp's expression correlates with the 1.5% deviation from Wheeler's equation when contributions of experimental uncertainties are considered. This is not necessarily a true indication of the accuracy of Kaupp's equation, though, because the experimental verification was conducted on the dielectric that happens to give the

closest agreement of calculated values with Wheeler's equation. If Wheeler's equation is accurate, then the experimental values could disagree from Kaupp's equation by 11%.

It is necessary now to support Wheeler's and Schneider's theories by experimental evidence to determine that they are indeed as accurate as claimed. In 1966 Caulton, Hughes, and Sobol constructed transmission lines of various values according to Wheeler's equations and attempted to measure the impedances in S band. The results were relatively close to theory (+4% to -10%), but were somewhat inconclusive because of the ± 2.5 ohm ($\pm 5\%$) uncertainty of the measurement technique. In 1972 Rosenkranz performed similar measurements on a 50-ohm transmission line designed by Wheeler's equations. His measurements in S band showed that the fabricated lines were within 4% of 50 ohms. The accuracy of both the measurement techniques and the fabrication processes for these experiments is not high enough to unquestionably prove Wheeler's equations. A technique with an uncertainty much less than 2% is needed.

Schneider verified his equations in a very careful manner by constructing oversized microstrip lines to eliminate concern with dimensional tolerances and also by completely enclosing the conductor strip with polyfoam ($\epsilon_r = 1.032$) to obtain a uniform dielectric. His measurements were made by time domain reflectometry on lines of several different thicknesses and the results for the various thicknesses were used to extrapolate the impedance of a line with zero thickness. The difference between the extrapolated value and the

impedance predicted by his equations was less than 0.4%. Since his equations and Wheeler's agree so closely theoretically, the experimental verification of his equations will be assumed to be verification of Wheeler's also. Therefore the theoretical accuracies stated by Wheeler and Schneider are valid.

Because of the approximations required to obtain accurate expressions for impedance, the equations for impedance must be defined separately as a function of the microstrip cross sectional dimensions. Microstrips with a ratio of w/h less than 1 or 2 are classified as narrow strips. Those with a ratio of w/h greater than 1 or 2 are considered wide strips. The division between narrow and wide strips is not the same for all of the derivations, as can be seen from the restrictions on Wheeler's and Schneider's equations. This is understandable. However, there seems to be a confusion about the designation of wide and narrow strips for Wheeler's equations since some papers (Sobol, 1972; Rosenkranz, 1972) use 1 as the division instead of 2 (Pucel, Masse, and Hartwig, 1968a). By adhering to the substitutions for Wheeler's variables a and b when evaluating the limits, the break between narrow and wide strips is $w/h = 2$. In his 1964 paper Wheeler stated that the wide strip equation is valid for $a/b > 0.9$ ($w/h > 1.8$). It appears that the value of $w/h = 1.8$ may be a more precise division between narrow and wide strips even though straight substitution into the bound $a/b = 1$ leads to $w/h = 2$. The division at $w/h = 1.8$ is supported by the graphical comparison in Fig. 9 which shows a transition region between $w/h = 1.5$ and 2. It is known that $w/h = 1$ is the division between narrow strips and wide strips for Schneider's

equations. Thus it should be possible to use his wide strip equation as a reference to determine that the division between narrow and wide strips is indeed near $w/h = 2$ instead of 1 for Wheeler's equations. Schneider's narrow strip and wide strip equations are exactly equal at a point between $w/h = 0.95$ and $w/h = 1.0$ and it is assumed that the wide strip equation is accurate to 0.25% above $w/h = 1$. When his wide strip equation and Wheeler's narrow strip equation are compared at 1, the percentage difference is 0.33%. Therefore the upswing of the per cent difference between the wide strip equations below $w/h = 1.5$ is caused by the inaccuracy of Wheeler's equation in the range below which it was defined, namely $w/h \geq 2$. A similar comparison of the curves above $w/h \geq 2$ shows that the narrow strip equation of Wheeler differs by more than 2% from either of the wide strip equations. It is evident from direct substitution for the bound $a/b = 1$ that the restrictions on Wheeler's equations should be $w/h \leq 2$ and $w/h \geq 2$ and it is apparent from the graphs that a more precise division may be $w/h \leq 1.8$ and $w/h \geq 1.8$. Nevertheless, the division between Wheeler's narrow strip equation and wide strip equation should not be $w/h = 1$.

Equations (4) through (8) are analysis equations which can be used for design, but are not as direct as synthesis equations. Wheeler derived two equations specifically for determining w/h in terms of Z_0 and ϵ_r .

Narrow strips:

$$\frac{w}{h} = \frac{8}{\exp(h') - 2\exp(-h')} \quad (9)$$

$$\text{where } h' = \frac{Z_0 \sqrt{(\epsilon_r + 1)/2}}{60} + x_1$$

and Z_0 must satisfy the restriction

$$Z_0 > 60 \sqrt{\frac{2}{\epsilon_r + 1}} \left[1.485 - x_1 \right]$$

Wide strips:

$$\frac{w}{h} = \frac{2}{\pi} x_5 - \frac{2}{\pi} \ln(x_6) + \frac{\epsilon_r - 1}{\pi \epsilon_r} x_7 \quad (10)$$

$$\text{where } x_5 = \frac{60\pi^2}{Z_0 \epsilon_r} - 1$$

$$x_6 = \frac{120\pi^2}{Z_0 \epsilon_r} - 1$$

$$x_7 = \ln(x_5) + 0.293 - 0.517/\epsilon_r$$

and where Z_0 satisfies the restriction

$$Z_0 < \frac{30\pi}{\sqrt{\epsilon_r}}$$

When these equations are used within their ranges of definition they are estimated to yield Z_0 within 1% of the specified Z_0 .

Since microstrip is composed of a compound dielectric, it is necessary to obtain a value for the effective dielectric constant, $\epsilon_{r,eff}$, to be used in computations that normally require a value of ϵ_r . Wheeler, Kaupp, and Schneider each derived an expression for $\epsilon_{r,eff}$.

WHEELER (1965):

$$\epsilon_{r,eff} = 1 + q(\epsilon_r - 1) \quad (11)$$

where q is the filling fraction.

SCHNEIDER (1969):

$$\epsilon_{r,eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + \frac{10h}{w} \right]^{-\frac{1}{2}} \quad (12)$$

KAUPP (1967):

$$\epsilon_{r,\text{eff}} = 0.475\epsilon_r + 0.67 \quad (13)$$

Wheeler's equation incorporates the variable, q , the effective filling fraction. It is the fraction of the area in his parallel plate capacitor that is filled with the material of dielectric constant ϵ_r . The filling fraction must be evaluated separately for $w/h \leq 2$ and $w/h \geq 2$. For $w/h \leq 2$ the calculation of q is lengthy but straightforward; however, for $w/h \geq 2$, evaluation is tedious without numerical techniques on a computer. When computer accuracy is not required, a graph of q published by Presser (1968) can be used for slide rule calculations of $\epsilon_{r,\text{eff}}$.

Schneiders equation is valid for all values of w/h and is very convenient when an isolated manual calculation is needed. He states its maximum error is 2%, implying a 1% error for $\sqrt{\epsilon_{r,\text{eff}}}$. This equation (12) was evaluated and compared to values from Wheeler's equation (11) using values of q from Presser's curve. The agreement was within 2% for w/h between .1 and 10 with $\epsilon_r = 2.1$ and 9.8.

Kaupp's expression is empirical and does not consider the influence of w and h . For $\epsilon_r = 2.1$ his equation agrees with Schneider's equation only at $w/h = 0.5$, but for higher values of ϵ_r such as 4.8 or 9.8, it is lower than Schneider's by 4.5% to 37% depending on the value of w/h and ϵ_r .

Caulton, Hughes, and Sobol (1966) indirectly measured $\epsilon_{r,\text{eff}}$ by performing measurements of λ_g on polyguide ($\epsilon_r = 2.32$) and sapphire ($\epsilon_r = 9.35$ and 9.9) and comparing them to the values predicted by using

Wheeler's $\epsilon_{r,eff}$. Their results bracketed Wheeler's theoretical values and their conclusion was that "theory predicts measured wavelength reasonably well" (Caulton, Hughes, and Sobol, 1967). Since their measurements uphold Wheeler's theory and since Schneider's equation agrees well with Wheeler's, it is reasonable to assume that either Wheeler's or Schneider's equation could be used to find $\epsilon_{r,eff}$. From the standpoint of convenience, Schneider's equation is preferred over Wheeler's.

After an expression for $\epsilon_{r,eff}$ is known, calculation of guide wavelength, λ_g , is a simple matter when employing the TEM approximation. It is

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{r,eff}}} \quad (14)$$

where λ_0 is the free space wavelength.

Of all the characteristics that were modeled mathematically, attenuation is the most elusive. Not only is it difficult to describe by equation, it is also hard to measure accurately and repeatably under experimental conditions. It is no wonder then that theorists would develop equations that differ more than those for other characteristics.

In general the total attenuation is the sum of the contributions from conductor losses and dielectric losses and is approximately equal

to α_c since α_c is usually much greater than α_d .

$$\alpha = \alpha_c + \alpha_d \approx \alpha_c \quad (15)$$

The various equations for attenuation are listed below.

CAULTON, HUGHES, AND SOBOL (1966):

$$\alpha_d = \frac{\omega}{2} \left(\frac{\mu}{\epsilon'} \right)^{\frac{1}{2}} \frac{\epsilon''}{\epsilon'} \epsilon' \quad \text{dB/m} \quad (16)$$

$$\alpha_c = \frac{\sqrt{\pi f \mu}}{2Z_o w} \left[\frac{1}{\sqrt{\sigma_{c1}}} + \frac{1}{\sqrt{\sigma_{c2}}} \right] \quad \text{dB/m} \quad (17)$$

where σ_{c1} and σ_{c2} are the conductivities of the conductor strip and ground plane respectively.

PUCEL, MASSE, AND HARTWIG (1968):

$$\alpha_d = 27.3 \frac{q\epsilon_r}{\epsilon_{r,eff}} \cdot \frac{\tan \delta}{\lambda_g} \quad \text{dB/cm} \quad (18)$$

where q is Wheeler's filling fraction.

$$w/h \leq 1/2\pi$$

$$\alpha_c = \frac{8.68 R_s y_1 y_2}{2\pi Z_o h} \text{ dB/cm} \quad (19)$$

$$\text{where } R_s = \sqrt{\pi\mu (\text{henry/cm}) f (\text{Hz}) \rho (\text{ohm-cm})}$$

$$\text{and } y_1 = 1 - \frac{w_{\text{eff}}^2}{4h}$$

$$\text{and } y_2 = 1 + \frac{h}{w_{\text{eff}}} + \frac{h}{\pi w_{\text{eff}}} \left[\ln \left(\frac{4\pi w}{t} \right) + \frac{t}{w} \right]$$

$$1/2\pi < w/h \leq 2$$

$$\alpha_c = \frac{8.68 R_s y_1 y_3}{2\pi Z_o h} \text{ dB/cm} \quad (20)$$

$$\text{where } y_3 = 1 + \frac{h}{w_{\text{eff}}} + \frac{h}{\pi w_{\text{eff}}} \left[\ln \left(\frac{2h}{t} \right) - \frac{t}{h} \right]$$

$$w/h \geq 2$$

$$\alpha_c = \frac{8.68 R_s y_3 y_4}{Z_o h y_5^2} \text{ dB/cm} \quad (21)$$

$$\text{where } y_4 = \frac{w_{\text{eff}}}{h} + \frac{w_{\text{eff}}/\pi h}{\frac{w_{\text{eff}}}{2h} + 0.94}$$

$$\text{and } y_5 = \frac{w_{\text{eff}}}{h} + \frac{2}{\pi} \ln \left\{ 2\pi e \left[\frac{w_{\text{eff}}}{2h} + 0.94 \right] \right\}$$

SCHNEIDER (1969):

$$w/h \leq 1/2\pi$$

$$\alpha_c = \frac{10 R_s y_6 y_7}{\pi h \ln(10) Z_o \exp\left(\frac{Z_o}{60}\right)} \text{ dB/unit length} \quad (22)$$

$$\text{where } y_6 = \frac{8h}{w} - \frac{w}{4h}$$

$$\text{and } y_7 = 1 + \frac{h}{w} + \frac{h}{\pi w} \ln \frac{4\pi w}{t}$$

$$1/2\pi \leq w/h \leq 1$$

$$\alpha_c = \frac{10 R_s y_6 y_8}{\pi h \ln(10) Z_o \exp\left(\frac{Z_o}{60}\right)} \text{ dB/unit length} \quad (23)$$

$$\text{where } y_8 = 1 + \frac{h}{w} + \frac{h}{\pi w} \ln \frac{2h}{t}$$

$$w/h \geq 1$$

$$\alpha_c = \frac{Z_o R_s y_9 y_{10}}{720 \pi^2 h \ln(10)} \text{ dB/unit length} \quad (24)$$

$$\text{where } y_9 = 1 + \frac{0.44h^2}{w^2} + \frac{6h^2}{w^2} \left[1 - \frac{h}{w}\right]^5$$

$$\text{and } y_{10} = 1 + \frac{w}{h} + \frac{1}{\pi} \ln \frac{2h}{t}$$

There are some general variations of attenuation with respect to h , ϵ_r , and t that may not be readily evident from the more complex equations. For a given impedance, α_c is inversely proportional to h and t and is directly proportional to ϵ_r . The relation for t seems normal, but it may not be apparent why the thickness of the dielectric should affect conductor losses. According to the equation for Z_o , a particular w/h

is required for a given Z_0 . Thus, if h is increased, w also increases, reducing losses. The dielectric constant also affects the width of the conductor for a given impedance and h . As ϵ_r increases, it decreases the width needed to maintain a constant Z_0 for a fixed h . Consequently, as ϵ_r increases, loss increases also.

The values of attenuation from the equations of the three authors for three w/h values are listed in Table I.

TABLE I
ATTENUATION AS CALCULATED BY VARIOUS EQUATIONS

$$\begin{aligned}\epsilon_r &= 1.0 & h &= 6.35 \times 10^{-2} \text{ cm} \\ f &= 10. \text{GHz} & t &= 6.35 \times 10^{-4} \text{ cm} \\ \rho &= 2.44 \times 10^{-6} \text{ ohm-cm}\end{aligned}$$

	Attenuation, dB/cm		
	$w/h = .1$ $Z_0 = 263 \text{ ohms}$	$w/h = 1.0$ $Z_0 = 126.5 \text{ ohms}$	$w/h = 10$ $Z_0 = 29.2 \text{ ohms}$
Caulton, et al	1.61×10^{-1}	3.36×10^{-2}	1.45×10^{-2}
Pucel, et al	5.38×10^{-2}	1.82×10^{-2}	1.16×10^{-2}
Schneider	6.79×10^{-2}	2.01×10^{-2}	1.15×10^{-2}

It can be seen that there is an appreciable spread in these theoretical predictions. Equation (17) is not claimed to be precise, but those of Pucel, Masse, and Hartwig and Schneider are rigorous derivations intended to be close predictions of actual attenuation. Even so, they differ by 26% at $w/h = .1$. The reason for the variation is that they applied the thickness correction differently in their derivations.

Experimental attenuation measurements were made by Pucel, et al. The measurements were not consistently in close agreement with theory, but in general they were close enough that they can be said to support theory. Unusually the experimental values were higher than theory. In their experiments they applied a frequency-dependent correction factor to compensate for the surface roughness of the alumina and rutile substrates which they used. Its effect is to increase the calculated attenuation by as much as 100%. This factor does not show up in equations (19), (20), and (21). If it is needed, it is derived in Morgan's 1949 paper and is plotted in Sobol's 1972 publication.

There is a subtle understatement in equations (19) through (24). They are all valid only for $\epsilon_r = 1$ as they are presented. If precise values of attenuation are required for applications with ϵ_r unequal to 1, the derivation presented by Pucel, Masse, and Hartwig must be repeated while including ϵ_r . Schneider provides a more attractive alternative. His equation for α_c can be applied to cases with ϵ_r greater than 1 simply by multiplying (22), (23), or (24) by $\epsilon_{r,eff}$ to obtain the value of attenuation for the circuit using a dielectric of ϵ_r .

After comparing the results of the three models for attenuation, it can be said that either Pucel's or Schneider's equations with a roughness correction will estimate a value within experimental accuracy of the true attenuation. However, for quick calculations equation (17) without any further corrections may be about as close with much less bother. Regardless of how accurate the theoretical equations are, inaccuracy in the real world of measurements will be the limitation on predicting attenuation.

Attenuation is sometimes not as convenient a parameter as unloaded Q when designing a microstrip circuit. If unloaded Q is desired, it can be calculated from the following equations.

SCHNEIDER (1969):

$$Q = \frac{20\pi}{\ln 10} \cdot \frac{1}{\alpha \lambda_g} \quad (25)$$

where α is approximated by equation (22), (23), or (24) and $\alpha \lambda_g$ is in dB.

CAULTON, HUGHES, AND SOBOL (1966):

$$Q = \frac{wZ_o}{6} \sqrt{\epsilon_{r,eff} f_{GHz} \sigma_c} \quad (26)$$

Since Q is a different form of attenuation, it suffers from the same problems as attenuation when trying to correlate theory and experiment. Thus only experience can decide which equation models Q better.

1.2 Limitations of Approximations

It was mentioned previously that the analyses intended to determine practical design equations assumed the approximation of TEM propagation

in addition to other approximations within the derivations. Experimental evidence to this point has shown that the approximations are acceptable, but what are the limitations of the assumptions?

The assumption of $t = 0$ is the only significant approximation in addition to TEM propagation. Thickness of the conductor strip has the effect of increasing the capacitance of the line, thus decreasing the impedance. In order to compensate for the effect of thickness, Wheeler derived two equations that relate nonzero t to a reduction in width Δw .

$$w/h \leq 1/2\pi$$

$$\Delta w = \frac{t}{\pi} \left(1 + \ln \frac{4\pi w}{t} \right) \quad (27)$$

$$w/h \geq 1/2\pi$$

$$\Delta w = \frac{t}{\pi} \left(1 + \ln \frac{2h}{t} \right) \quad (28)$$

He applied the correction in the following equation.

$$w_{\text{eff}} = w + \Delta w \quad (29)$$

where w is the physical dimension of the microstrip and w_{eff} is the dimension used in calculations. For analysis, the value of w_{eff} is substituted for w in (4) and (5). In the case of synthesis, the " w " of (9) and (10) is actually w_{eff} and must be reduced by Δw to obtain the physical width. The Δw correction was derived for the case of $\epsilon_r = 1$ and its direct application to cases with ϵ_r greater than 1 is not recommended by Wheeler. He does not reveal an accurate compensation for the effect of the higher dielectric constant, but suggests that multiplication of Δw by $1/\epsilon_r$ might be reasonable.

The shortcomings of the TEM approximation become evident when dispersion becomes significant. According to Troughton (1969) and Getsinger (1973), dispersion takes effect between roughly 2 and 6 GHz, depending on the value of w/h . Dispersion only slightly decreases impedance (Denlinger, 1971), but causes up to 13% change in $\epsilon_{r,\text{eff}}$, or alternately λ_g , for frequencies up to 12 GHz (Troughton, 1969:Fig. 2). If it is felt that the precision of a given design above 2 GHz requires compensation for dispersion, the references by Denlinger (1971), Troughton (1969), Essayag and Sauve (1972), Zysman and Varon (1969), and Getsinger (1973) should be consulted. Getsinger's paper is particularly clear and presents a technique that enables slide rule calculation of microstrip dispersion.

In the analyses of microstrip that have been covered, the line under consideration has been automatically assumed to be straight, but this is unrealistic when considering the physical constraints of a design. When shapes such as bends, steps in width, or T-junctions are incorporated, they cause discontinuities. The questions then arise: How large is the

discontinuity? Is it substantial enough to cause the design to miss specification? For many designs the effect of a discontinuity in the pattern will be masked by other imperfections of the physical circuit. Therefore compensation for bends, steps, and T's will be neglected. If there is a necessity to determine the magnitude of a discontinuity, there are three papers available by Silvester and Benedek (1972a, 1972b, 1973) and one by James and Tse (1972) that will provide insight into the computations.

1.3 Summary of Selected Design Equations

In Section 1.1 the various equations for the electrical parameters of microstrip were compared in order to choose the most accurate, practical model for each parameter. The following list is a summary of the conclusions reached in Section 1.1. Each equation is identified by the number which was assigned to it previously.

IMPEDANCE ANALYSIS (WHEELER, 1965):

Narrow strips: $w/h \leq 2$, $t = 0$

Accuracy: $< 1\%$

$$Z_o = \frac{120(x_1 - x_2)}{\sqrt{2(\epsilon_r + 1)}} \quad (4)$$

$$\text{where } x_1 = \ln \frac{8h}{w} + \frac{1}{32} \left(\frac{w}{h} \right)^2$$

$$\text{and } x_2 = \frac{(\epsilon_r - 1) (0.226 + 0.12/\epsilon_r)}{\epsilon_r + 1}$$

Wide strips: $w/h \geq 2$, $t = 0$
 Accuracy: $< 1\%$

$$Z_o = \frac{60\pi}{(x_3 + x_4)\sqrt{\epsilon_r}} \quad (5)$$

$$\text{where } x_3 = \frac{w}{2h} + 0.441 + \frac{0.082(\epsilon_r - 1)}{\epsilon_r^2}$$

$$\text{and } x_4 = \frac{\epsilon_r + 1}{2\pi\epsilon_r} \left[\ln \left(\frac{w}{2h} + 0.94 \right) + 1.451 \right]$$

MICROSTRIP SYNTHESIS (WHEELER, 1965):

Narrow Strips: $w/h \leq 2$, $t = 0$
 Accuracy: $< 1\%$

$$\frac{w}{h} = \frac{8}{\exp(h') - 2\exp(-h')} \quad (9)$$

$$\text{where } h' = \frac{Z_o \sqrt{(\epsilon_r + 1)/2}}{60} + x_1$$

Z_o must satisfy the restriction

$$Z_o > 60 \sqrt{\frac{2}{\epsilon_r + 1}} \left[1.485 - x_1 \right]$$

MICROSTRIP SYNTHESIS (WHEELER, 1965):

Wide strips: $w/h \geq 2$, $t = 0$ Accuracy: $< 1\%$

$$\frac{w}{h} = \frac{2}{\pi} x_5 - \frac{2}{\pi} \ln(x_6) + \frac{\epsilon_r - 1}{\pi \epsilon_r} x_7 \quad (10)$$

$$\text{where } x_5 = \frac{60\pi^2}{Z_0 \epsilon_r} - 1$$

$$x_6 = \frac{120\pi^2}{Z_0 \epsilon_r} - 1$$

$$x_7 = \ln(x_5) + 0.293 - 0.517/\epsilon_r$$

 Z_0 must satisfy the restriction

$$Z_0 < \frac{30\pi}{\sqrt{\epsilon_r}}$$

EFFECTIVE DIELECTRIC CONSTANT (SCHNEIDER, 1969):

For all w/h valuesAccuracy: $\leq 2\%$

$$\epsilon_{r,\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + \frac{10h}{w} \right]^{-1/2} \quad (12)$$

WAVEGUIDE WAVELENGTH:

Accuracy: $\leq 1\%$

$$\lambda_g = \frac{\lambda_o}{\sqrt{\epsilon_{r,eff}}} \quad (14)$$

ATTENUATION:

Approximate equation (Caulton, Hughes, and Sobol, 1966):

$$\alpha \approx \alpha_c = \frac{\sqrt{\pi f \mu}}{2Z_o w} \left[\frac{1}{\sqrt{\sigma_{c1}}} + \frac{1}{\sqrt{\sigma_{c2}}} \right] \text{ dB/m} \quad (17)$$

ATTENUATION:

Rigorous calculation (Schneider, 1969):

$w/h \leq 1/2\pi$

$$\alpha \approx \alpha_c = \frac{10 R_s y_6 y_7}{\pi h \ln(10) Z_o \exp\left(\frac{Z_o}{60}\right)} \text{ dB/unit length} \quad (22)$$

$$\text{where } y_6 = \frac{8h}{w} - \frac{w}{4h}$$

$$\text{and } y_7 = 1 + \frac{h}{w} + \frac{h}{\pi w} \ln \frac{4\pi w}{t}$$

$$1/2\pi \leq w/h \leq 1$$

$$\alpha \approx \alpha_c = \frac{10 R_s y_6 y_8}{\pi h \ln(10) Z_o \exp\left(\frac{Z_o}{60}\right)} \text{ dB/unit length} \quad (23)$$

$$\text{where } y_8 = 1 + \frac{h}{w} + \frac{h}{\pi w} \ln \frac{2h}{t}$$

$$w/h \geq 1$$

$$\alpha \approx \alpha_c = \frac{Z_o R_s y_9 y_{10}}{720 \pi^2 h \ln(10)} \text{ dB/unit length} \quad (24)$$

$$\text{where } y_9 = 1 + \frac{0.44h^2}{w^2} + \frac{6h^2}{w^2} \left[1 - \frac{h}{w}\right]^5$$

$$\text{and } y_{10} = 1 + \frac{w}{h} + \frac{1}{\pi} \ln \frac{2h}{t}$$

UNLOADED Q:

Approximate equation (Caulton, Hughes, and Sobol, 1966):

$$Q = \frac{w Z_o}{6} \sqrt{\epsilon_{r,eff} f \text{ GHz } \sigma_c} \quad (26)$$

where w and σ_c are in MKS units.

Rigorous equation using α_c from (22), (23), or (24) (Schneider, 1969):

$$Q = \frac{20\pi}{\ln(10)} \cdot \frac{1}{\alpha\lambda_g} \quad (25)$$

where $\alpha\lambda_g$ is in dB.

CHAPTER 2

DESIGN OF 50-OHM MICROSTRIP

2.0 Introduction

At UHF and microwave frequencies, the most common transmission line impedance is 50 ohms. Consequently, this chapter will focus on design information for a 50-ohm line on the common dielectric materials of teflon, G-10 epoxy glass, and alumina. The intent is to apply the equations of Chapter 1 and present the results in an accurate, easily used manner. Use of a slide rule and the graphs will yield values within 1% of the values obtained by computer.

2.1 Design Procedure

In Wheeler's synthesis equations w/h depends on Z_o and ϵ_r . Since Z_o has been specified as 50 ohms, choosing ϵ_r will determine w/h . A value for w/h is then read directly from Fig. 10 for any value of ϵ_r from 1 to 12. In the region from $w/h = 1.8$ to 2.0, both the narrow strip equations and wide strip equations are estimated to be accurate to 1% of the desired impedance (Wheeler, 1965). From the restrictions on Wheeler's equations, it can be said that below $w/h = 1.8$ the narrow strip equation should be used and above $w/h = 2.0$ the wide strip equation should be used. Between these values, it appears that an average of the two is reasonable. The width w determined from the value of w/h read from Fig. 10 is actually w_{eff} and may require correction by Δw to compensate for finite conductor thickness.

If it is felt that the thickness correction is necessary to meet the accuracy of the design, the value of Δw in mils is read from Fig. 11 for the appropriate value of t . These curves can be made general by normalizing t and w with respect to h . Caution should be observed when applying Δw in that use of the full value will overcorrect if $\epsilon_r > 1$. It would be advisable to compensate by multiplying Δw by $1/\epsilon_r$ as suggested by Wheeler (1965).

The value of w obtained from Figures 10 and 11 will enable fabrication of a 50-ohm microstrip transmission line, subject to material and manufacturing tolerances. Since every design is subject to tolerances, Figures 12, 13, 14, and 15 show the variations of Z_0 , VSWR, and return loss as a function of w . The parameter for the family of curves is a nominal $\epsilon_r \pm 10\%$. These graphs are tailored specifically to the cases of microstrip on 1/16-inch teflon, 1/16-inch G-10 glass-epoxy and .025-inch alumina. Although they are presented as special cases, they can be generalized to other dielectric thicknesses by normalizing w with respect to h , as is shown for some values of w .

When a design requires the value of λ_g , the value of $\sqrt{\epsilon_{r,eff}}$ must be found. If ϵ_r is 2.1, 4.8, or 9.8, it may be read from Fig. 16 for any value of w/h from .1 to 10. For those cases not on Fig. 16, equation (12) or the computer program in the Appendix can be used.

2.2 Design Examples

Two examples will be shown to point out the capabilities of the design graphs. One will use .025-inch alumina as the dielectric and the other will use 1/16-inch G-10 glass-epoxy. It happens that w/h

for glass-epoxy falls at the transition region between narrow and wide strips, and consequently about 3% error in addition to the accuracy of the synthesis equation can be incurred if the wrong curve is used.

The design values are summarized in Table II.

TABLE II
DESIGN DATA FOR 50-OHM TRANSMISSION
LINE ON G-10 GLASS-EPOXY AND ALUMINA.

	Alumina	G-10 Glass-Epoxy	G-10 Glass Epoxy
Equation Used	$w/h \leq 2$	$w/h \leq 2$	$w/h \leq 2$
w/h	.978	1.79	1.77
w , mils	24.4	112	110.5

The data of Table II are compared in Table III to the values calculated by computer using the synthesis equations and to the values read from Figs 13(b) and 14(b), which are a product of Wheeler's analysis equations. The values of w obtained for the line on alumina are in excellent agreement, less than 0.5% difference. Thus the accuracy for design on alumina can be assumed to be essentially the 1% accuracy of the synthesis equations. It can be seen, however, that the design on G-10 glass-epoxy does not share such low uncertainty. For the narrow and wide strip formulae, the analysis graphs differ by 4.6% and the synthesis graphs differ by about 2%. The values obtained by the synthesis equations are bracketed by those from the analysis equations. If there is no strong reason for preferring the wide strip equation over the narrow strip equation,

TABLE III

COMPARISON OF DESIGN DATA BY SYNTHESIS
AND ANALYSIS EQUATIONS

	By Graphs		By Computer
	Synthesis Equation	Analysis Equation	Equations (9) or (10)
Alumina, Equation For $w/h \leq 2$	24.4 From Fig. 10(d)	24.5 From Fig. 15(b)	24.4424
G-10 Glass-Epoxy Equation For $w/h \leq 2$	112 From Fig. 10(b)	114 From Fig. 13(b)	112.062
G-10 Glass-Epoxy, Equation For $w/h \leq 2$	110.5 From Fig. 10(b)	109 From Fig. 14(b)	110.78

or conversely, it seems reasonable to average the values. In this particular example, though, the value of the narrow equation would be used since w/h is less than 1.8. The final number obtained for w will include the 1% inaccuracy of the equations plus an interpolation error that can range up to about 3%.

What are the consequences of a possible 4% error in the design of a 50-ohm transmission line on G-10 glass-epoxy? Neglecting all other tolerances and the thickness correction, some approximations will be made in using Figures 13(b) and 13(c) to roughly estimate the effect of this isolated variation. Assuming that 4% error will result in 4 mils error in w , it is seen that the best VSWR that can be expected is 1.022 or the best expected return loss is 39 dB. These deviations are equivalent to about ± 1 ohm for $Z_0 = 50$ ohms.

This example has shown that the synthesis graphs provided will produce results within 1% of computer-calculated values using the synthesis equation. For values of w/h outside the transition region from 1.8 to 2.0, the accuracy of the results is essentially the 1% accuracy of the synthesis equation. However, within the transition, region, the uncertainty is the 1% equation accuracy plus up to 3% interpolation error. The effects of tolerances in the design parameters can be estimated from Figures 12, 13, 14, and 15.

2.3 Designs For Arbitrary Z_o and ϵ_r

When a design requires values of Z_o other than 50 ohms or relative dielectric constants other than those graphed, the graphs of this chapter are inapplicable. To provide a flexible design capability, the Appendix lists in BASIC language the general computer programs used to plot the special cases of Figures 10 to 16. If BASIC is not on an available computer, the programs can be translated to the appropriate language. They will at least serve as a guideline for program flow.

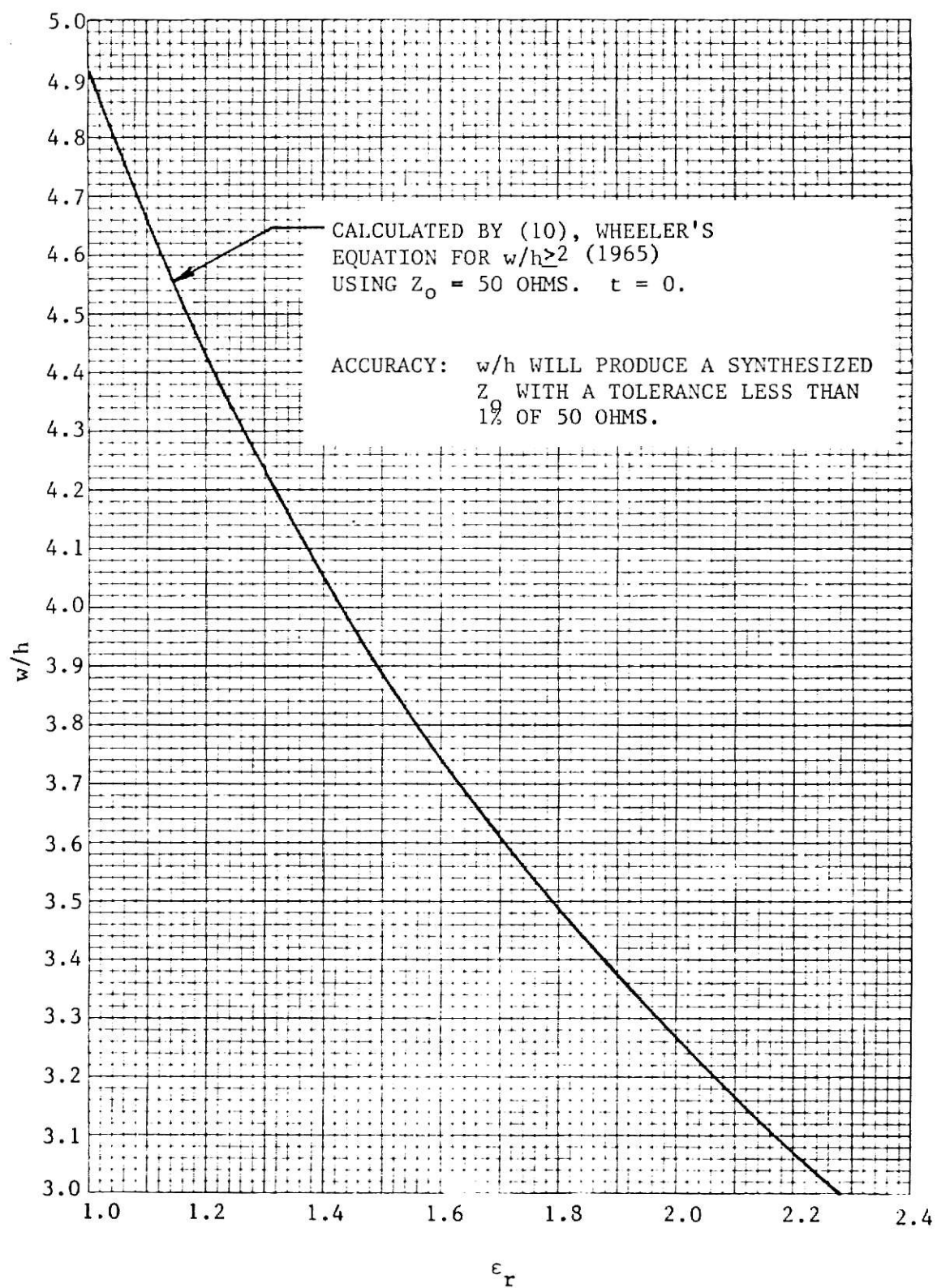


Fig. 10(a) Microstrip synthesis graph for $Z_0 = 50$ ohms, with conductor thickness $t = 0$ and ϵ_r from 1.0 to 2.4.

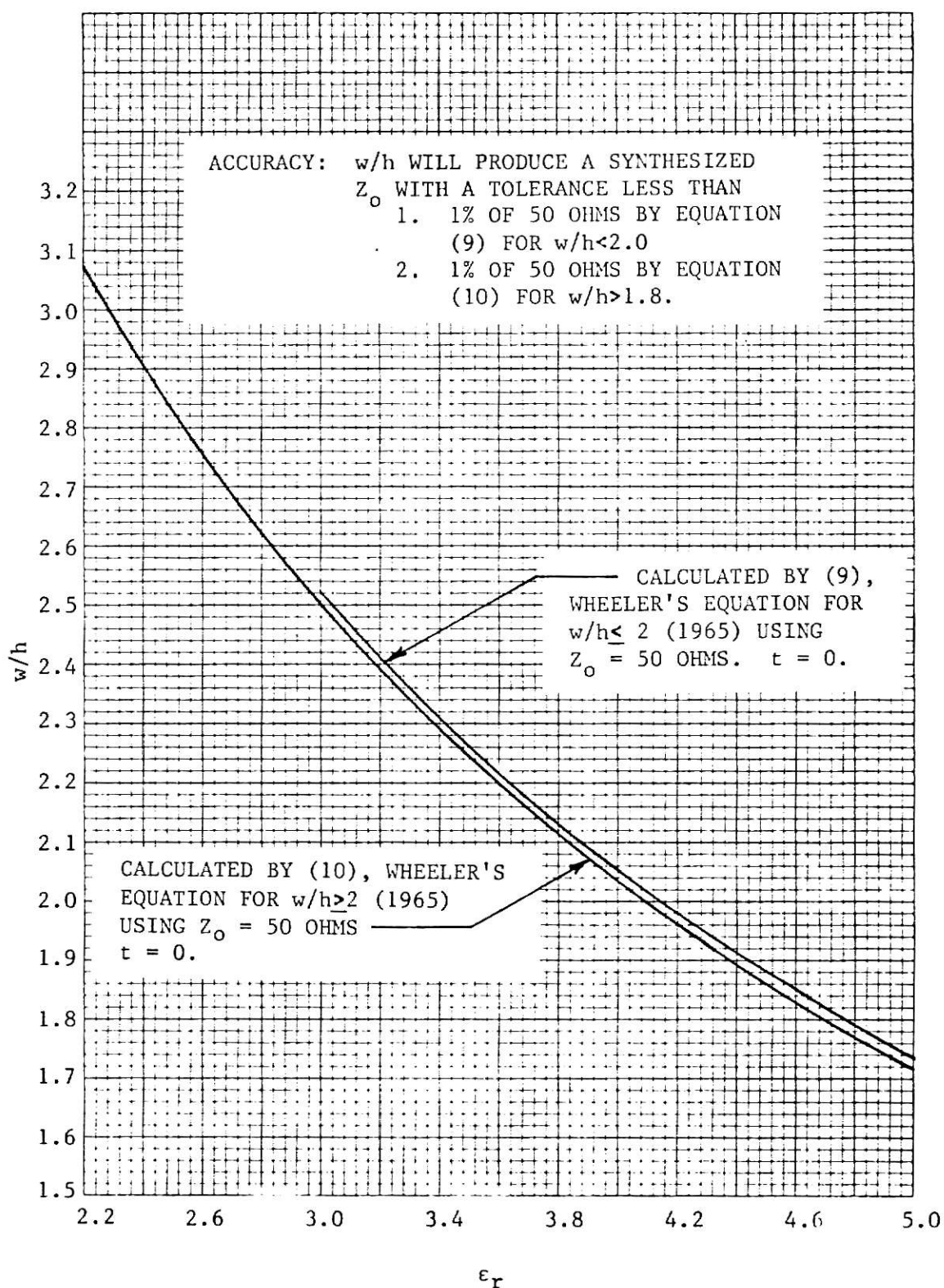


Fig. 10(b) Microstrip synthesis graph for $Z_0 = 50$ ohms, with conductor thickness $t = 0$ and ϵ_r from 2.2 to 5.0.

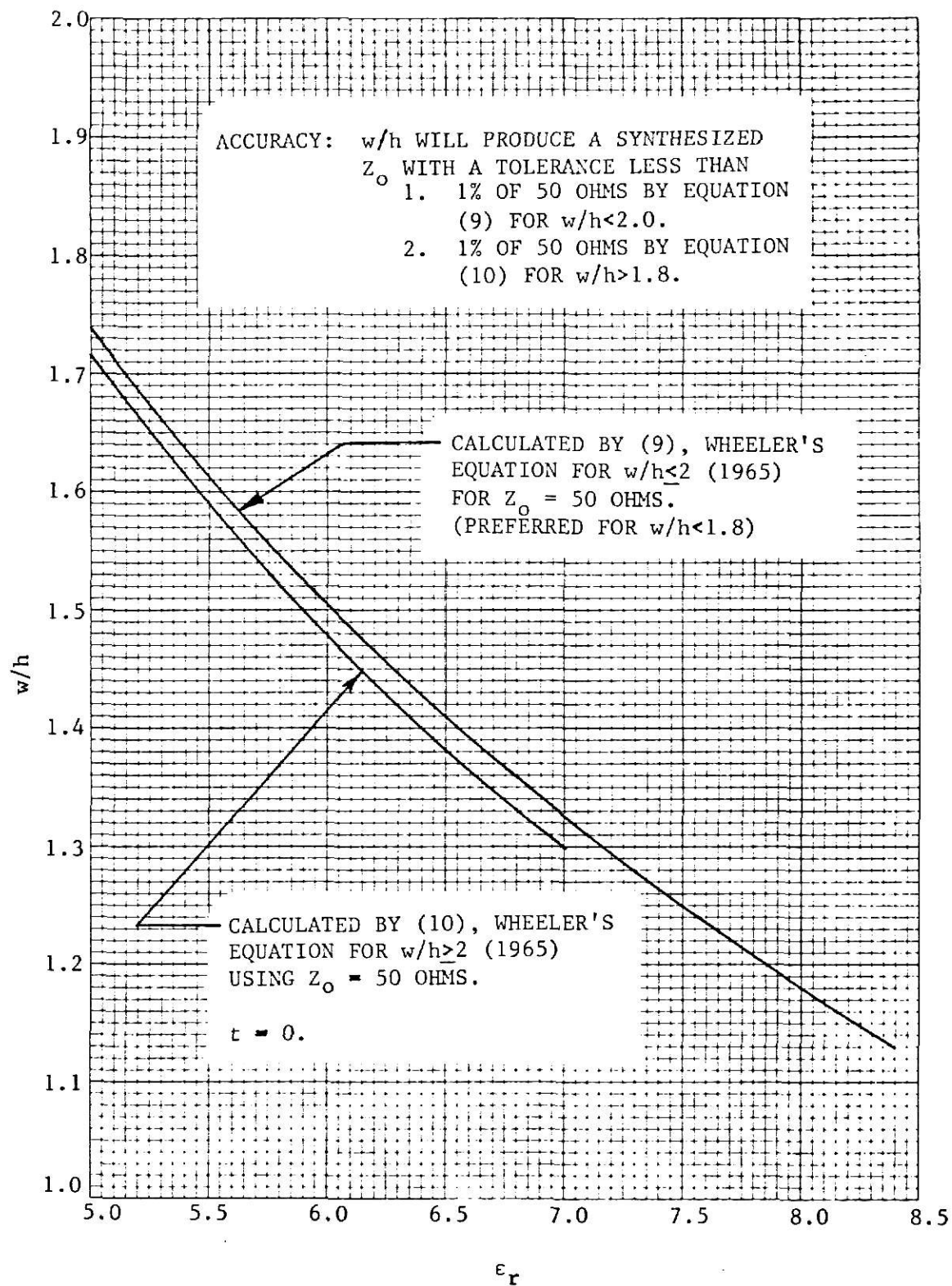


Fig. 10(c) Microstrip synthesis graph for $Z_0 = 50$ ohms, with conductor thickness $t = 0$ and ϵ_r from 5.0 to 8.5.

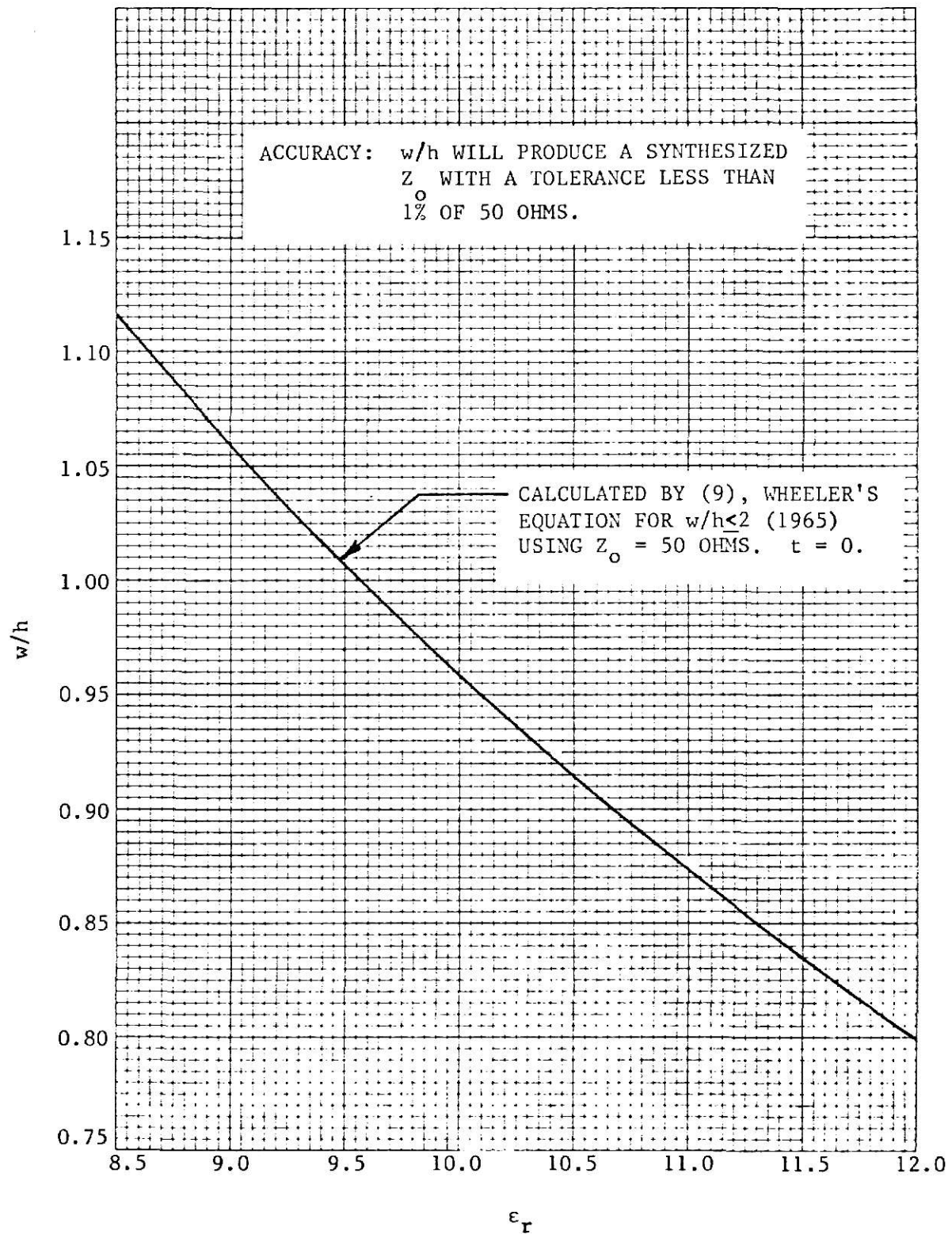


Fig. 10(d) Microstrip synthesis graph for $Z_o = 50$ ohms, with conductor thickness $t = 0$ and ϵ_r from 8.5 to 12.0

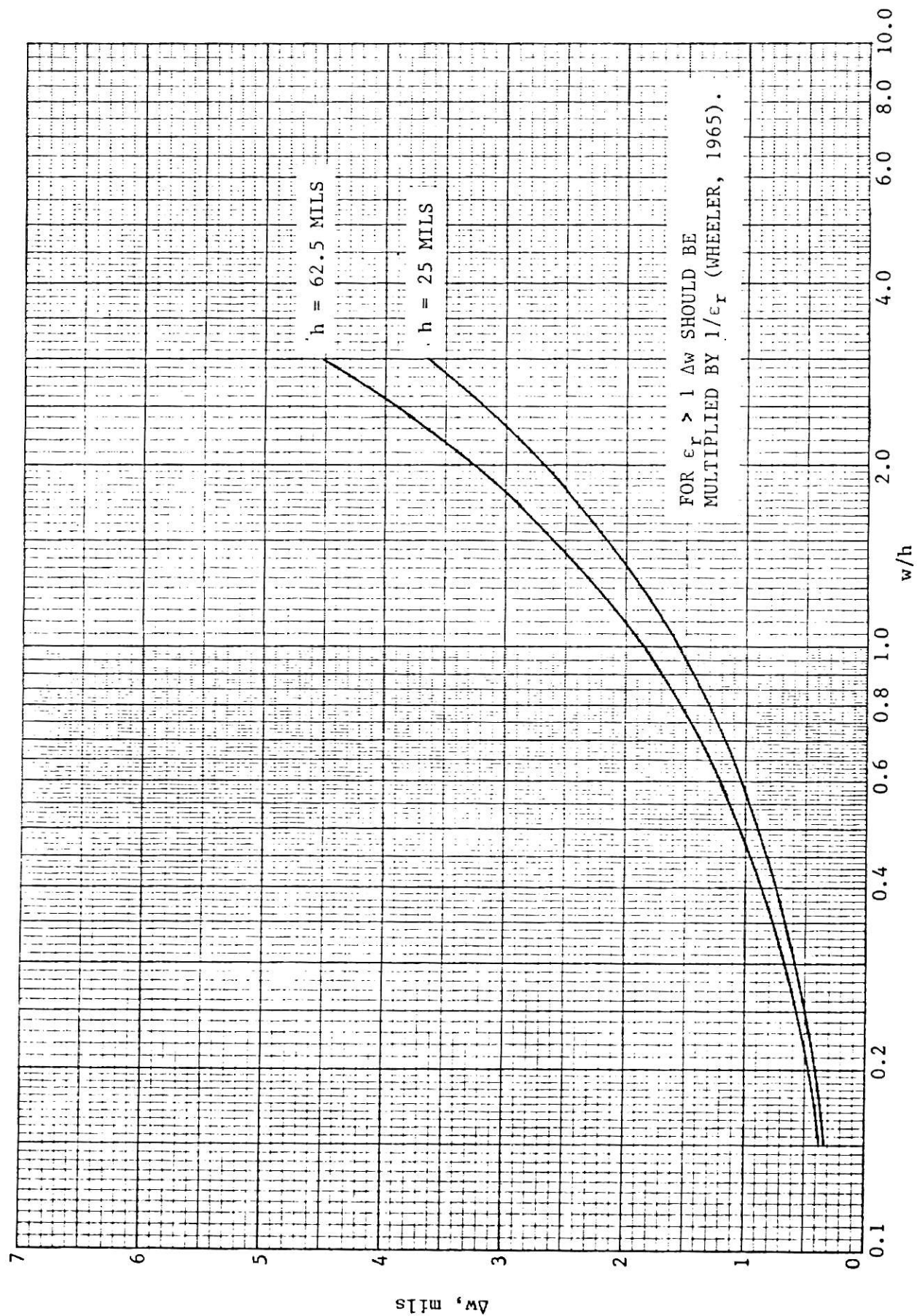


Fig. 11 Microstrip width correction, Δw , to compensate for finite thickness, t .

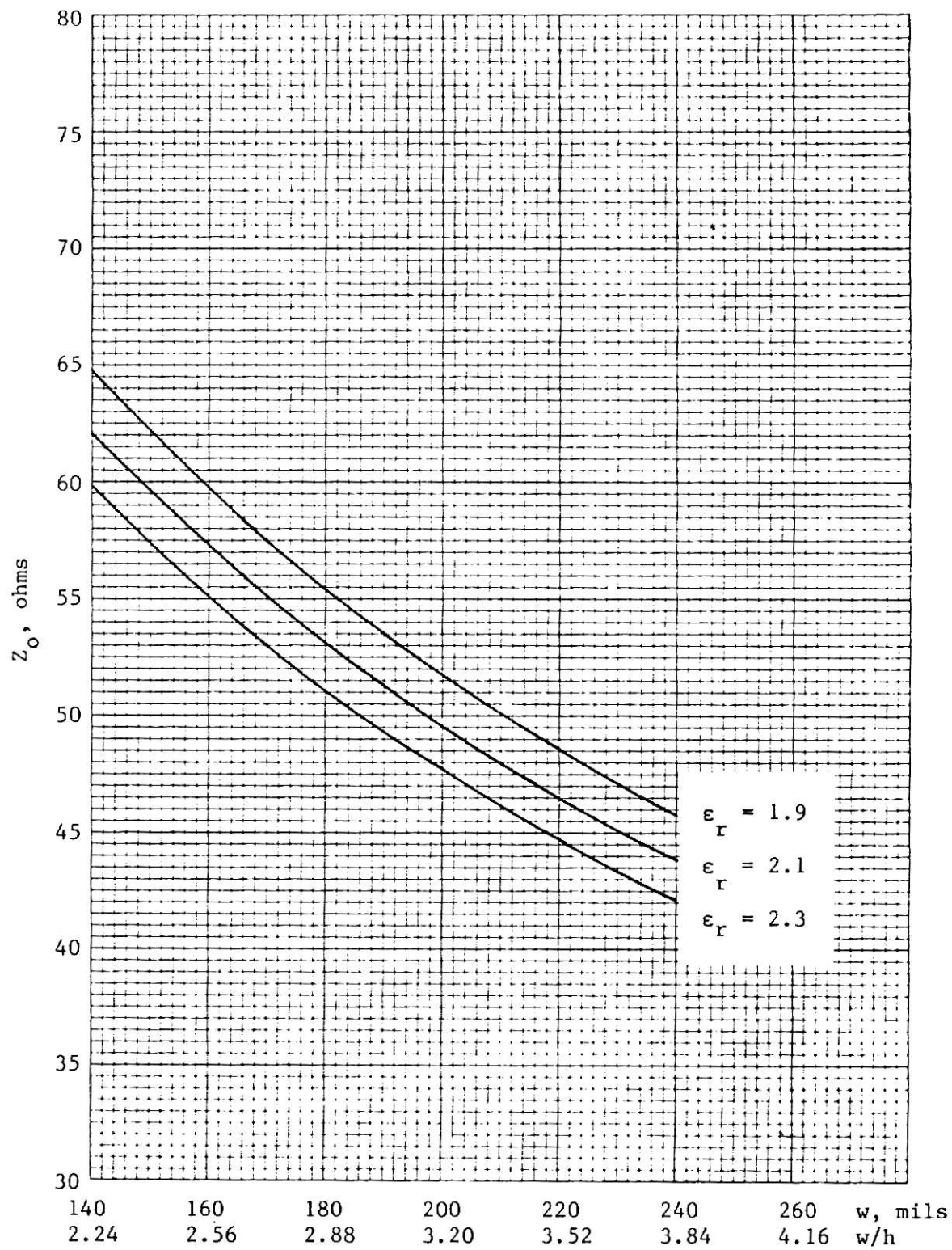


Fig. 12(a) Microstrip characteristic impedance versus conductor width on teflon dielectric, calculated by Wheeler's wide strip analysis equation.

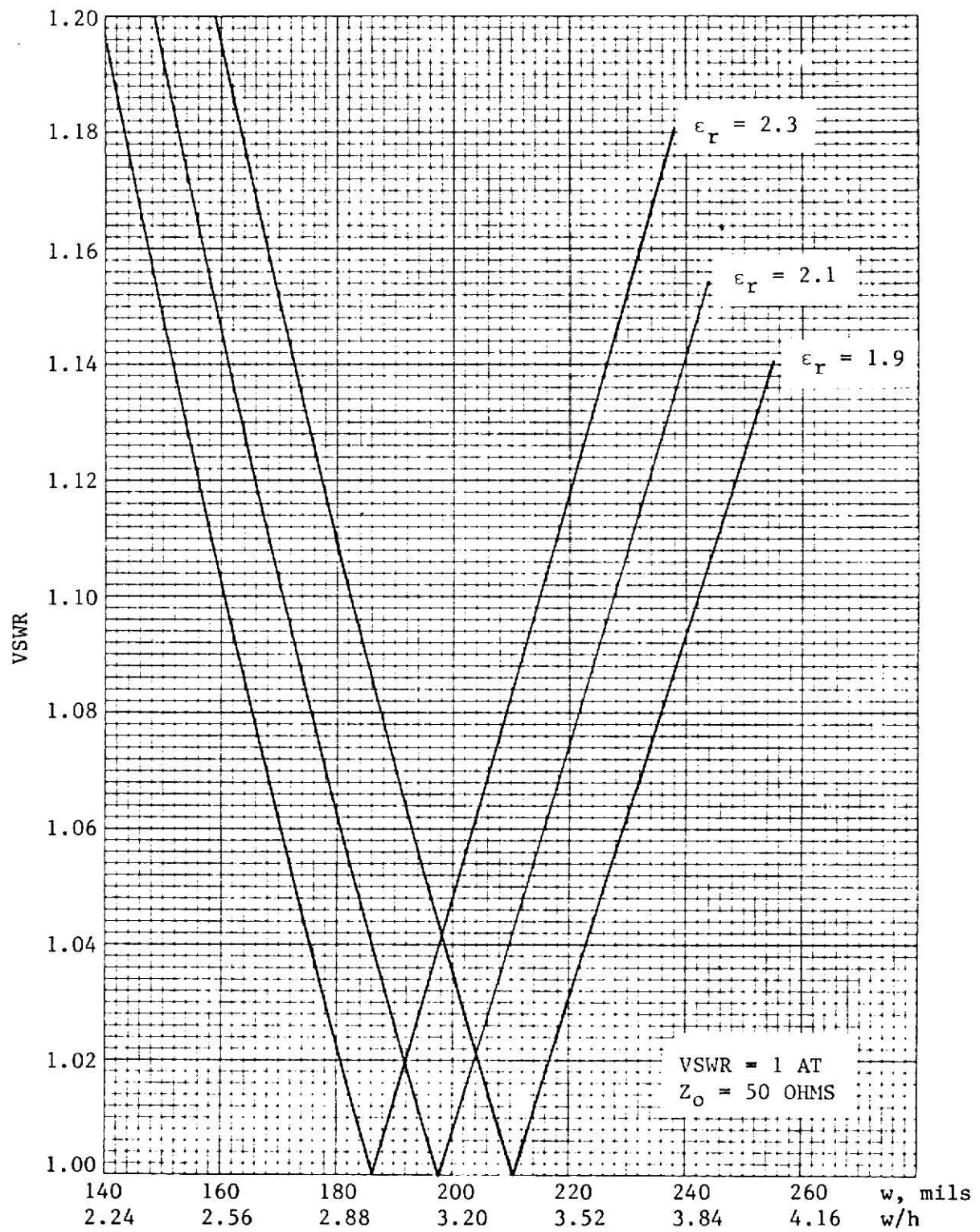


Fig. 12(b) Microstrip VSWR versus conductor width for teflon dielectric.

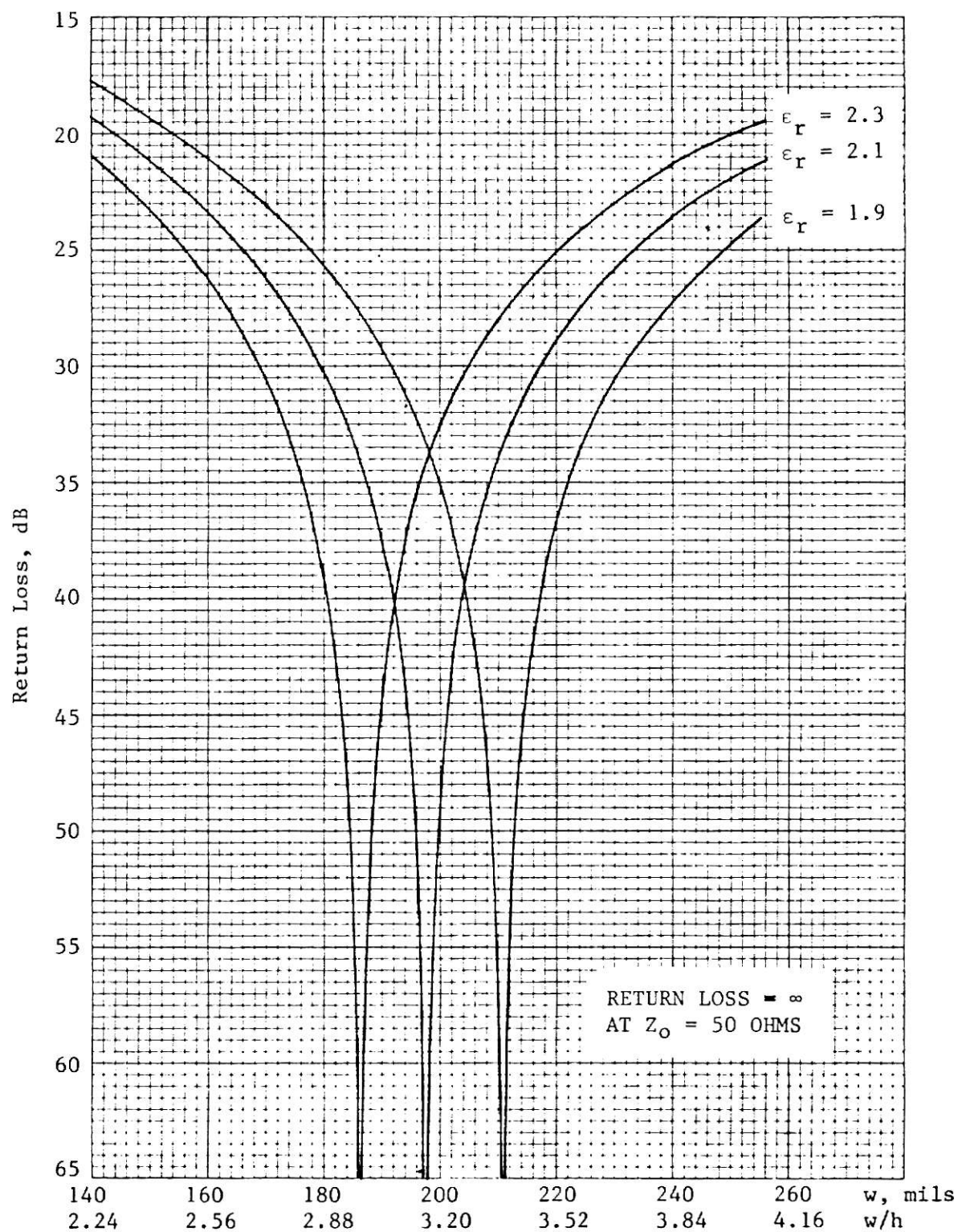


Fig. 12(c) Microstrip return loss versus conductor width for teflon dielectric.

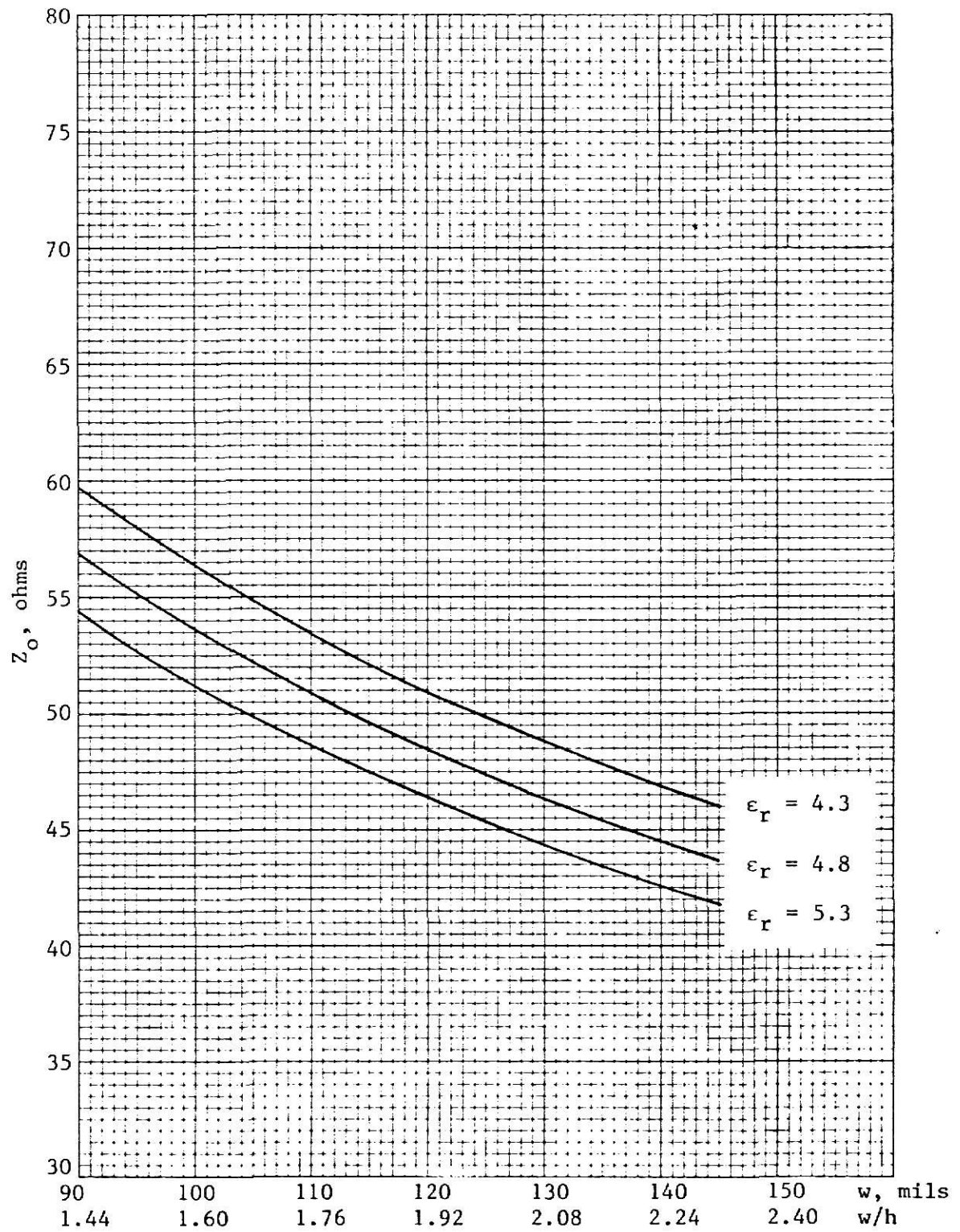


Fig. 13(a) Microstrip characteristic impedance versus conductor width for G-10 glass-epoxy dielectric, calculated by Wheeler's narrow strip analysis equation.

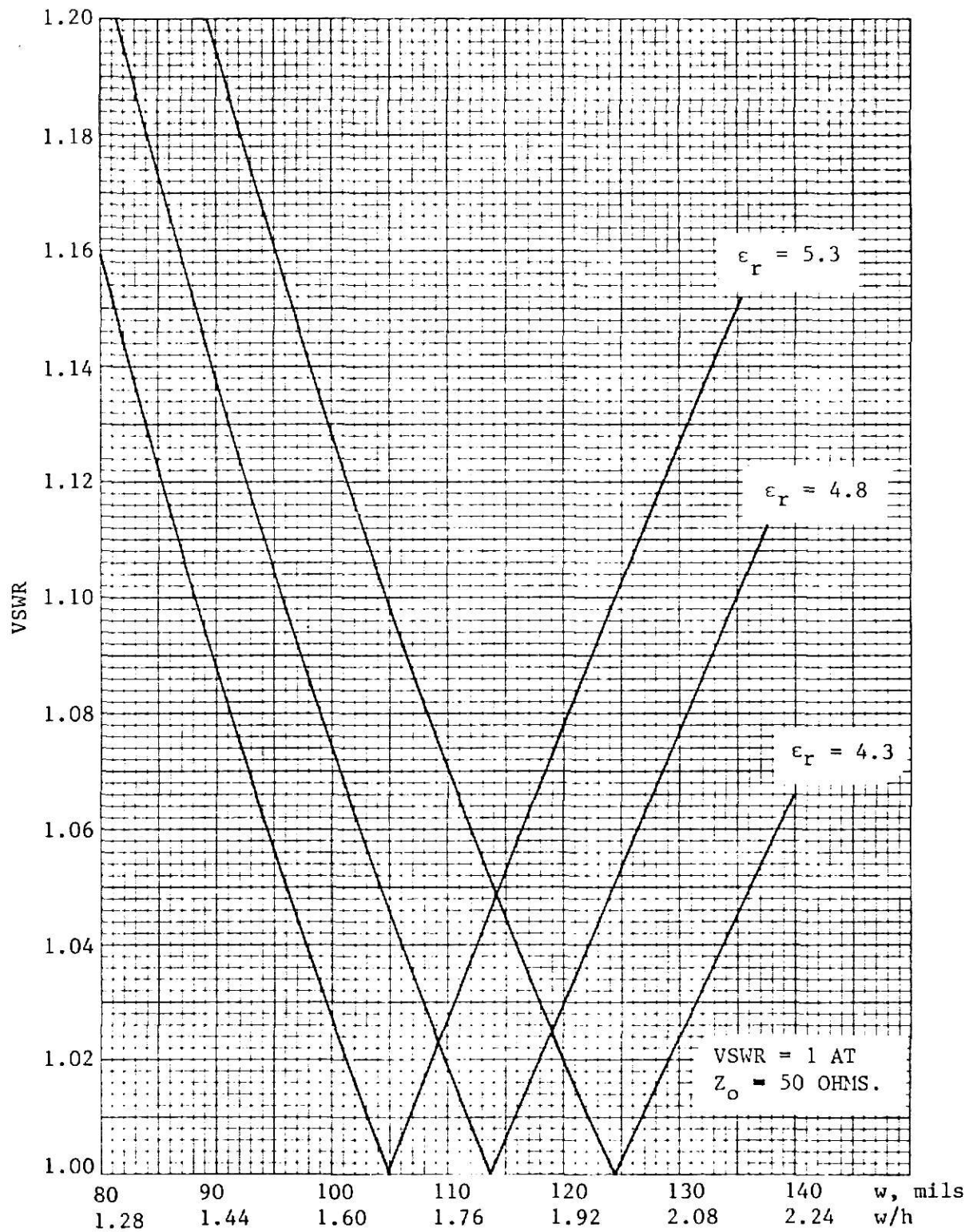


Fig. 13(b) Microstrip VSWR versus conductor width for G-10 glass-epoxy dielectric.

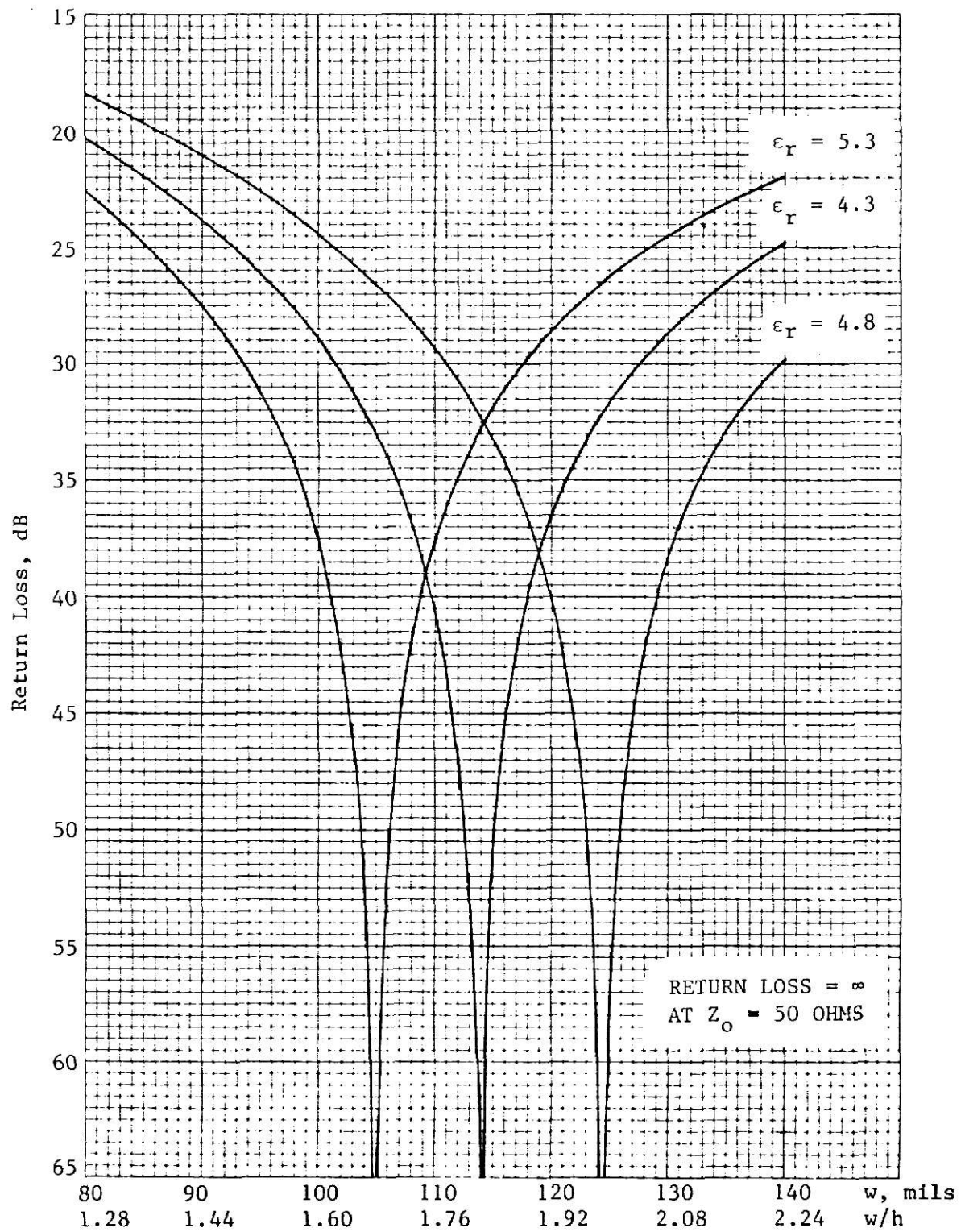


Fig. 13(c) Microstrip return loss versus conductor width for G-10 glass-epoxy dielectric.

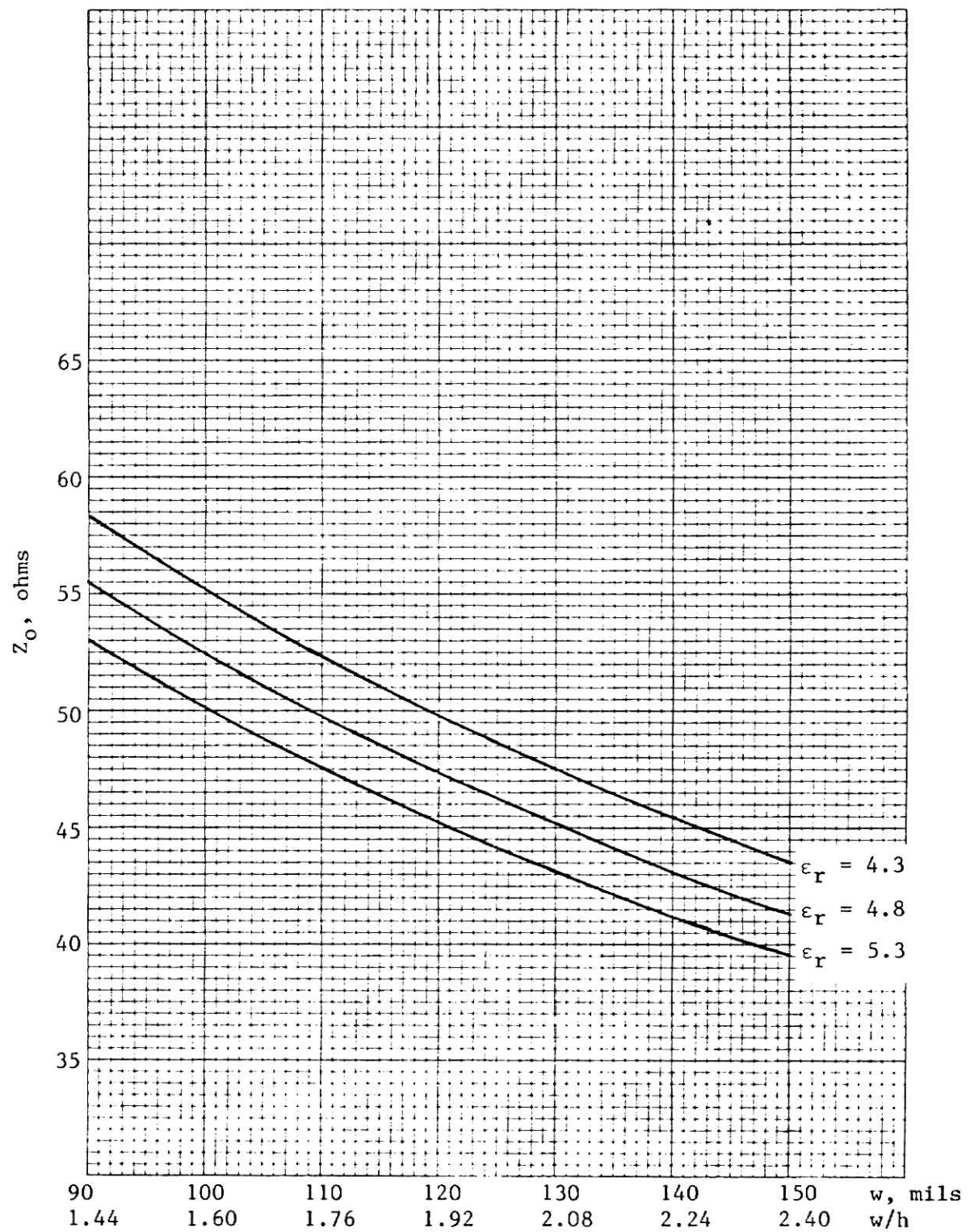


Fig. 14(a) Microstrip characteristic impedance versus conductor width for G-10 glass-epoxy dielectric, calculated by Wheeler's wide strip analysis equation.

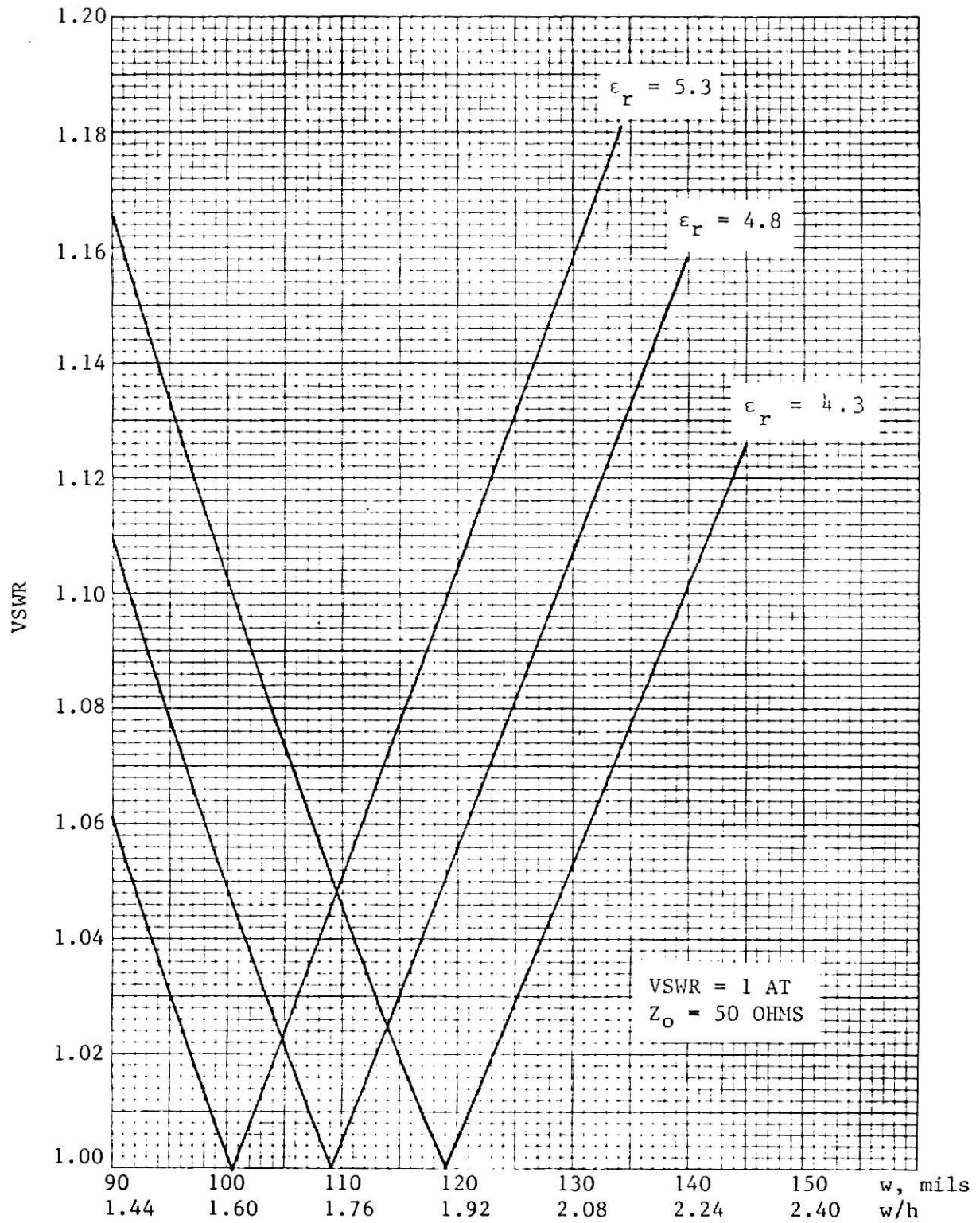


Fig. 14(b) Microstrip VSWR versus conductor width for G-10 glass-epoxy dielectric.

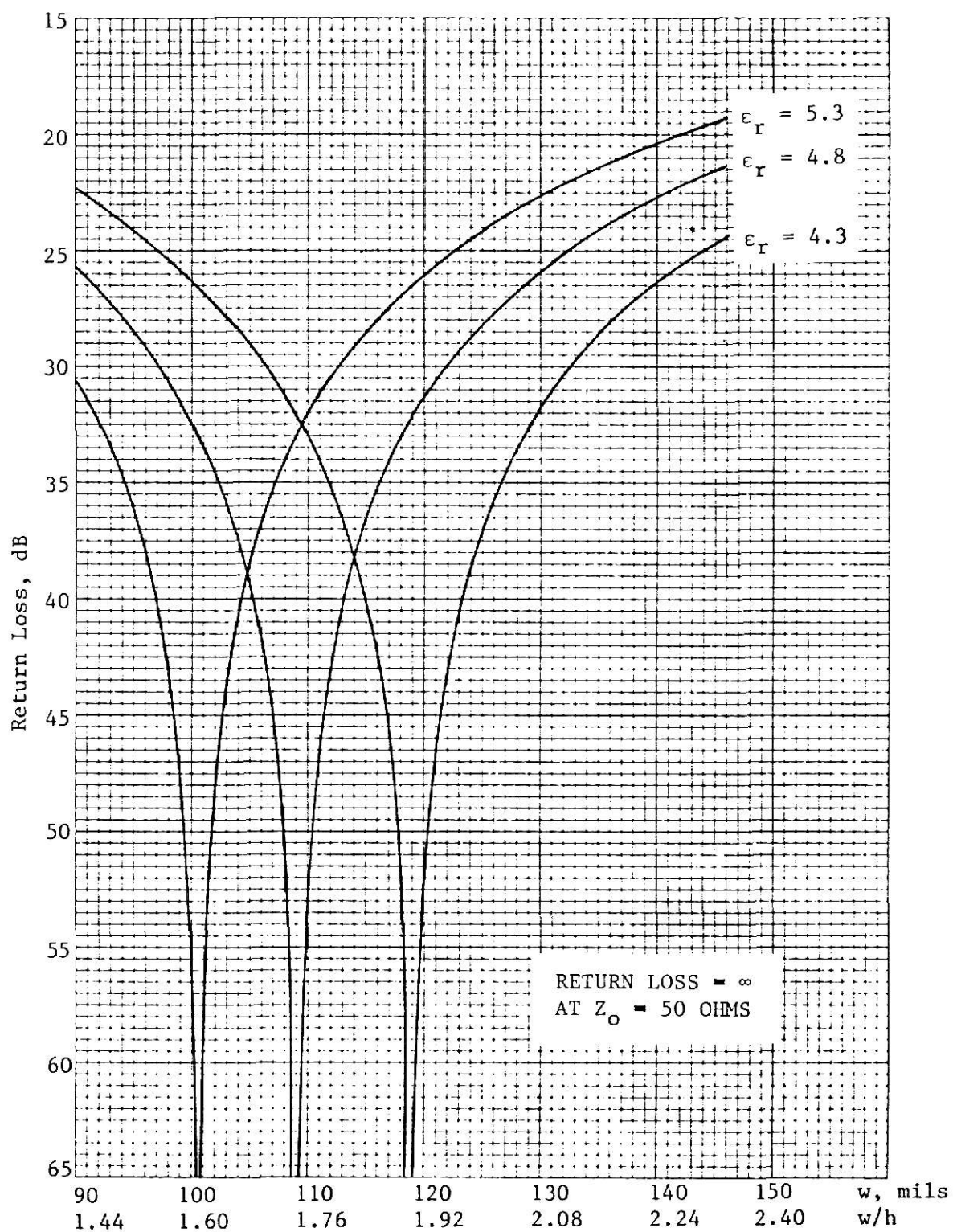


Fig. 14(c) Microstrip return loss versus conductor width for G-10 glass-epoxy dielectric.

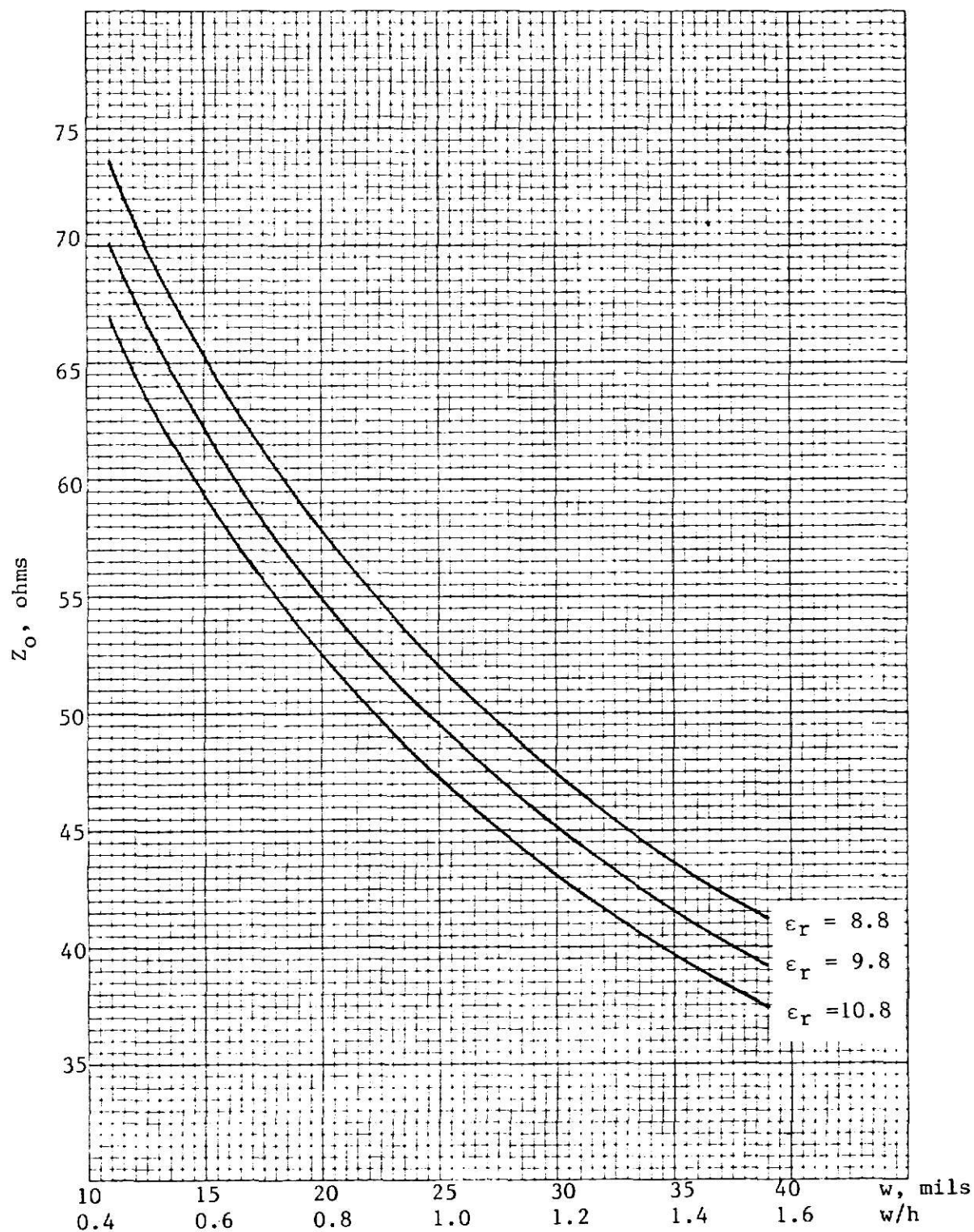


Fig. 15(a) Microstrip characteristic impedance versus conductor width for alumina dielectric, calculated by Wheeler's narrow strip analysis equation.

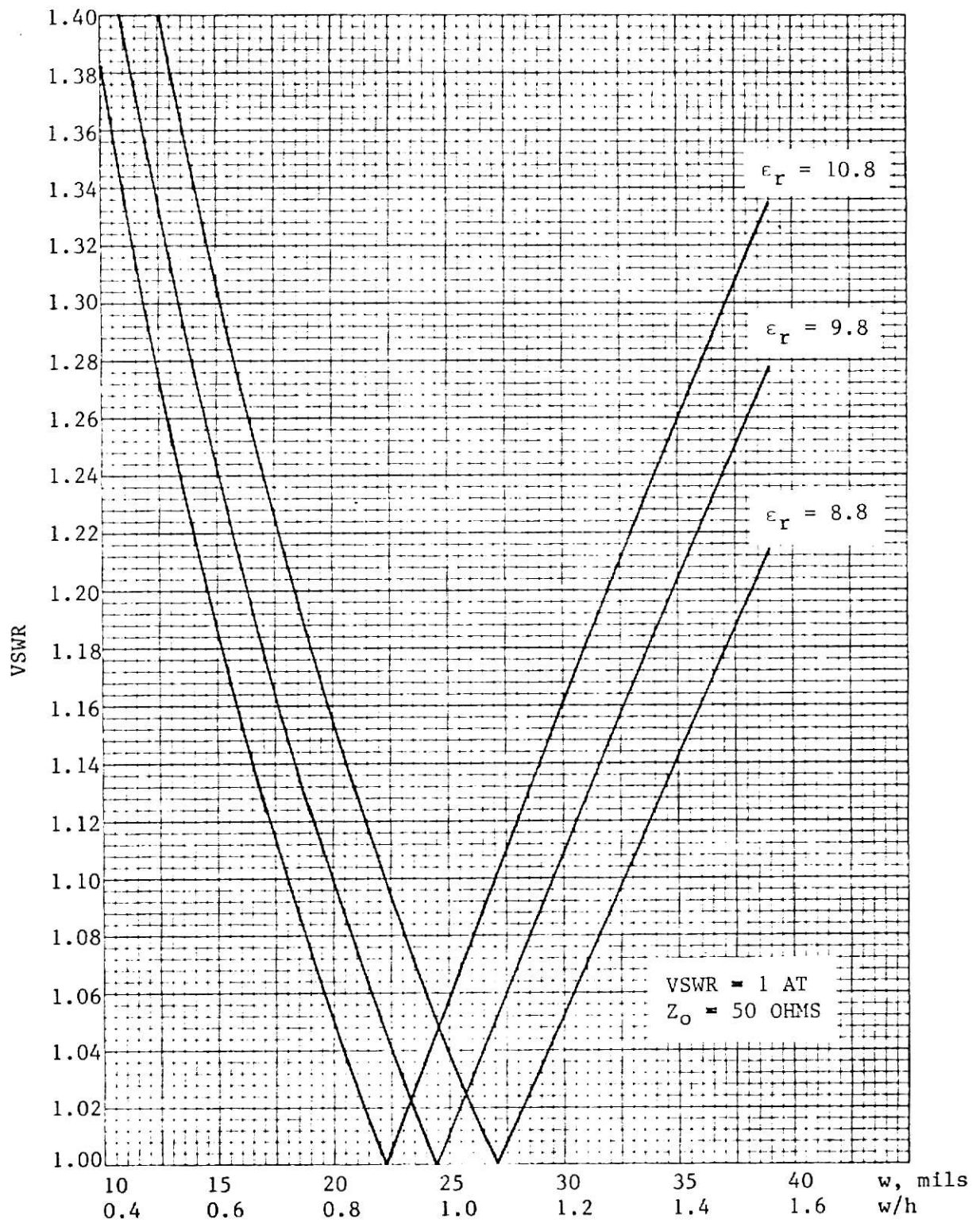


Fig. 15(b) Microstrip VSWR versus conductor width for alumina dielectric.

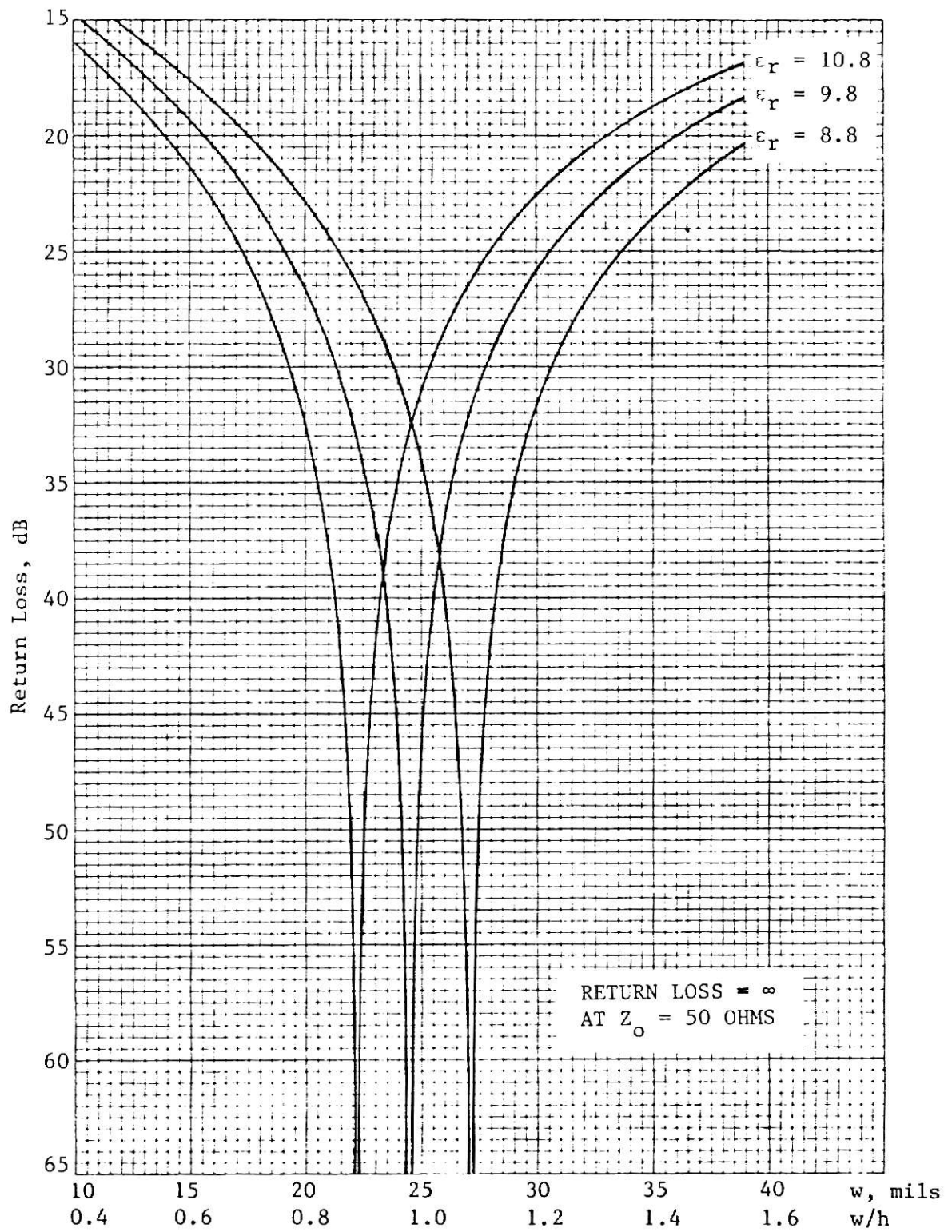


Fig. 15(c) Microstrip return loss versus conductor width for alumina dielectric.

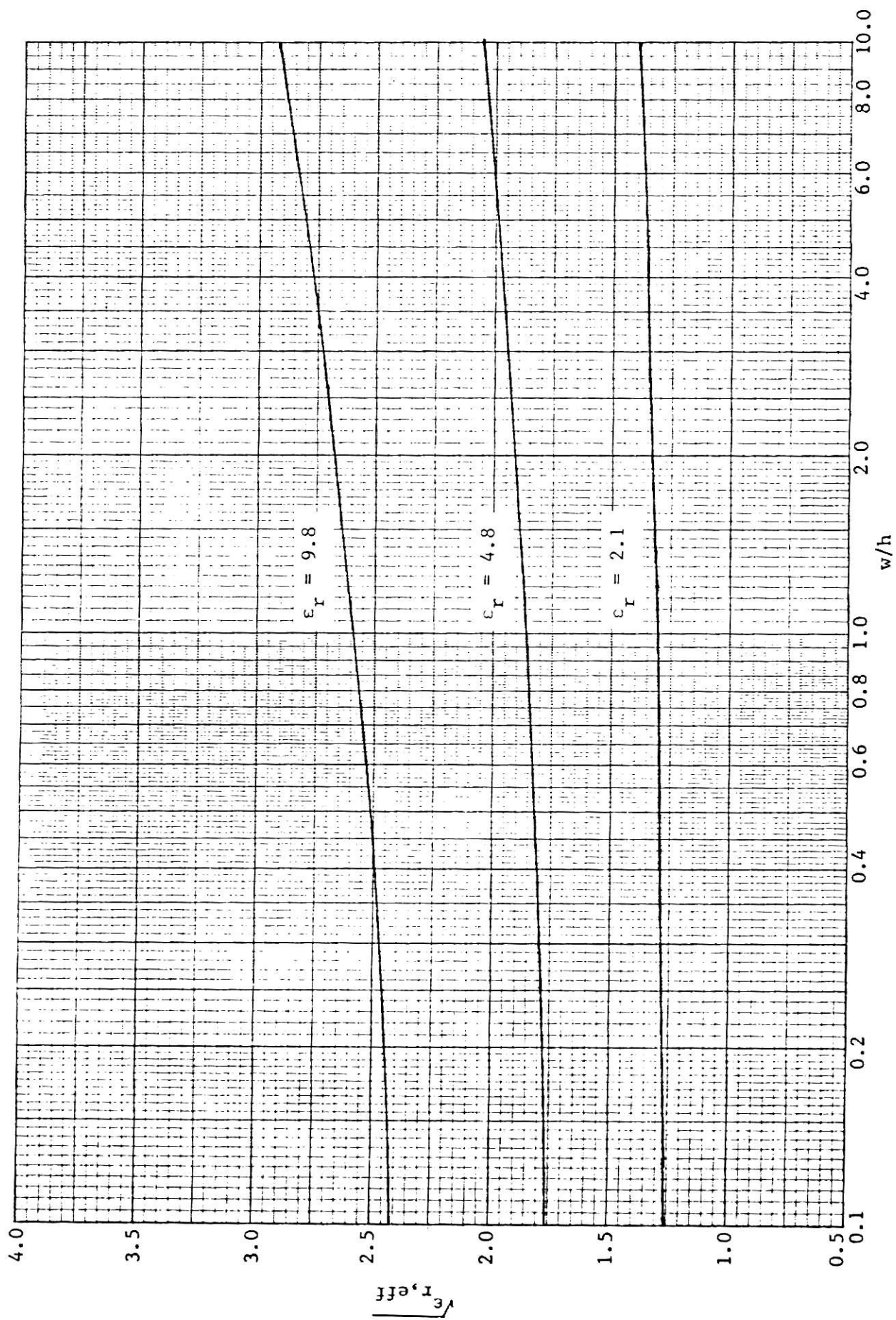


Fig. 16 Square root of effective relative dielectric constant plotted as a function of w/h , with ϵ_r as a parameter.

CHAPTER 3

MICROSTRIP FABRICATION CONSIDERATIONS

3.0 Introduction

The design theory discussed in the previous chapters has been an idealization of the physical world. Since real circuits are non-ideal, their performance departs from that of the theoretical models. In some cases, the difference between theory and the real world may be small, but in others there may be a surprisingly large discrepancy. Although theory usually includes compensation for some physical effects, it is unable to predict all effects that will be encountered in fabrication. A designer must be aware of the phenomena not forecast by theory and adjust it so that he creates a realizable design and a physical product that agrees well with his calculations. The guidelines discussed in the following sections reveal some imperfections in manufacturing processes and materials that are peculiar to their applications at UHF and microwave frequencies.

Manufacturing tolerances and imperfect material combine to degrade the performance of physical circuits below theoretical operation. In general the manufacturing process and materials are not independent. Choice of one will determine or influence choice of the other. The properties of each category are listed below.

Manufacturing process variables:

1. Adequate conductor thickness
2. Dimensional tolerances of circuit pattern
3. Conductivity

Material imperfections:

1. Finite conductivity
2. Tolerance of ϵ_r value
3. Dielectric losses
4. Non-uniform thickness of dielectric
5. Surface roughness of dielectric

It is assumed for this discussion that tolerances such as thickness of the dielectric are material variations even though at some point they were manufacturing tolerances.

3.1 Available Fabrication Processes

When selecting a fabrication process, a designer has three from which to choose.

1. Printed circuit techniques with copper-clad dielectrics
2. Thin film
3. Thick film

Printed circuit techniques for microstrip will not be developed in this paper since thin film and thick film processes are more attractive for fabrication of microstrip for the high UHF range through microwave frequencies.

The thin film process is a method by which a metal film a few hundred angstroms thick is vapor deposited or sputtered onto a dielectric substrate. To increase the thickness of the metalization, the initial deposition is usually plated up to the desired thickness. Then the metalized substrate is coated with photoresist, exposed with the con-

ductor pattern, and developed. Chemical milling is used to remove the unwanted conductor areas.

The thick film technique uses a conductor paste, or "ink," composed of a finely powdered metal and a glass frit. The process itself consists of applying the paste to a substrate through a silk screen pattern, drying the paste for a few minutes, and firing the printed substrate at 750-950°C to form a bond between the glass frit and the substrate.

There are some generally accepted criteria about the suitability of each of the processes for various operating frequencies or types of circuits. The upper frequency at which thick film should be used is 4 GHz (Digionomenico and Foster, 1973), whereas thin film can be used from DC through 30 GHz. One reason for the applicability of thin film to higher frequencies is that it is capable of better line definition than thick film. Line resolution also determines the bandwidth and the type of the circuits that can be produced by thick film. For circuits with bandwidths less than 20%, thick or thin film can be applied. However, for bandwidths between 20% and one octave (67%), only thin film is able to produce workable circuits. Certain types of circuits, such as filters, for instance, require much closer control of conductor spacing than is realizable with thick film. Even though the mentioned areas are closed to the thick film technique, there are many circuits, such as a radar receiver in S-band, a power divider/combiner, and a high-performance amplifier (Digiondomenico and Foster, 1973), that are suitable for thick film production. Historically thin film was better for making microwave circuits than thick film (Keister, 1968), but the thick film process has been improving (Waugh, et al, 1973). Some circuits perform equally well when made by either process.

Nearly all of the shortcomings of physical circuits, when compared to theory, can be assigned to the physical tolerances or non-ideal electrical properties of either the conductor or the dielectric substrate. Some of the differences may stem from manufacturing processes, while others may be caused by material deficiencies.

3.2 Effects of Characteristics of Conductors

Conductors primarily affect attenuation because of their finite conductivity although their physical tolerances can affect impedance. The first consideration for conductors when designing microstrip is that the metal is at least 4 skin depths thick at the lowest operating frequency (Keister, 1968). For example, the skin depth of gold is 98 μ inch (2.48×10^{-4} cm) at 1 GHz and 31 μ inch (7.86×10^{-5} cm) at 10 GHz. Four skin depths then is about 0.4 mil ($\approx 10^{-3}$ cm) at 1 GHz and about 0.12 mil (3.1×10^{-4} cm) at 10 GHz. Thick film conductors are normally 0.3 to 0.6 mil thick as processed. This thickness is adequate to carry at least 3 skin depths, 95% of the current, at 1 GHz and more than 10 skin depths at 10 GHz. Thin film conductors, however, must be plated after the initial metal deposition to achieve the necessary 4 skin-depth thickness even at high frequencies.

Finite conductivity naturally affects the attenuation or Q of microstrip and conductivity is, of course, determined by the metal selected. The preferred metals are gold, copper, and silver - the choice depending partly on the fabrication process. The performance of a given metal is not the same when it is fabricated by thick film and thin film techniques.

Nor is it necessarily consistent when fabricated by thick film under different process conditions. With all of these variations possible, it is necessary to set forth some data to show their relative importance.

Regardless of which metal is used for thin film fabrication, a thin layer of chromium must be deposited on the substrate since none of the metals will bond well directly to alumina, the typical substrate material. The chromium acts as a glue between alumina and the conductor since it does form a chemical bond with alumina. Its contribution to attenuation is negligible because the layer is less than 1000 Å thick. Opinions vary about which metal is the best. Schilling in 1968 stated that chrome-copper caused less attenuation than chrome-gold. His figures were 0.110 dB/inch for chrome-copper and 0.120 dB/inch for chrome-gold. Keister, also in 1968, showed that a chrome-gold film with gold plating produced a circuit with a Q of 251, as compared to a Q of 195 for a chrome-gold film with copper plating. From this data it seems that either chrome-copper or chrome-gold should work well for thin film circuits.

When the thick film process is used, the best conductors are either gold or silver. Keister (1968) measured the Q of a silver thick film circuit as 151 and the Q of a gold thick film circuit as 138, while Waugh, et al, (1973) measured Q's of 175 for silver and 179 for gold. It is possible that Waugh's readings are better than Keister's because of improvements of the thick film materials in the intervening years. Gold is preferred over silver by most designers for the same reasons as outlined by Waugh. It is compatible with wire bonding, has excellent environmental characteristics, and exhibits about the same loss as silver.

When the thin film and thick film processes are used to fabricate microstrip with the same metal, the relative performances can be compared in terms of attenuation or Q. Waugh, et al (1973) measured the attenuation of transmission lines produced by both processes. Their data are listed in Table IV and show that thin film transmission lines consistently have lower loss than thick film lines.

TABLE IV

PERFORMANCE OF THICK FILM AND
THIN FILM CONDUCTORS
(WAUGH, et al, 1973)

		Thin Film	Thick Film
Loss, dB/inch	S-Band	.25	.40
	C-Band	.37	.52
	X-Band	.46	.60

These microwave measurements correlate rather well with the DC resistivities of the metals. For thin film gold the resistivity is typically near 3×10^{-6} ohm-cm (Schneider, 1969) and for thick film gold it is about 5×10^{-6} ohm-cm as calculated from manufacturer's data. Although these values are not necessarily the same resistivities as those used by Waugh, et al, the square root of their ratio is in the range of the ratio of the attenuations in Table IV. Thus there is a correlation between the DC resistivity and microwave attenuation.

It may be wondered why the thick film conductors are not as conductive as thin film conductors. The answer appears to be that the

glass frit prevents formation of a conductor with a density equal to that of pure metal. In addition to lowering the concentration of metal, the glass tends to contribute its own loss at microwave frequencies because it has a high dissipation factor.

The conductivity of thick film conductors exhibits another peculiarity in that the end product varies widely with the process variables. This is old information to anyone who is familiar with thick film. Both Patel (1970) and Corkhill and O'Donnell (1972) observed variations with different process conditions. Corkhill and O'Donnell noted that firing profile affected Q and that the best Q was obtained with the highest permissible firing temperature. Variables such as this should not deter use of thick film, however, since they can be controlled once an optimum is determined. Thin film apparently does not have similar effects dependent on the process.

The last conductor effect to be examined is dimensional tolerance. It has already been said that thin film is capable of better dimensional control than thick film and that some circuits are realizable only by thin film because of the better resolution. Assuming that a circuit can be fabricated by either technique, dimensional tolerance will affect characteristic impedance and attenuation. Thick film lines can be produced with less than a ± 0.5 mil width tolerance, which corresponds to 50 ± 0.5 ohm ($VSWR = 1.01$ or return loss = 45 dB) by Figure 15. Since thin film line definition is about an order of magnitude better, it can be assumed to have no effect on characteristic impedance. The effect of thick film dimensional tolerance was demonstrated by Keister (1968) when he compared the Q 's of circuits that were screened and fired only and

circuits that were screened, fired, and etched. For two of three different silver inks, he saw no improvement by etching, but for one ink he did note an improvement from a Q of 93 to 138 by etching. Apparently the Q was increased because the rough conductor edges were removed. It is obvious that etching is not an automatic guarantee of lower loss, but it is possible to reduce the loss of some types of pastes by etching. Since the thin film technique already requires etching, it can not benefit from use of etching as the thick film process can. The loss of a thin film circuit would be altered only insignificantly by changing the conductor width the full amount of the width tolerance, as born out by calculation with Schneider's attenuation equation.

3.3 Effects of Characteristics of Dielectric Materials

Alumina (Al_2O_3) is the most widely used substrate material for the dielectric of microstrip because it is nearest to ideal. Circuits produced with it perform better than those on other substrates (Keister, 1968). It is also a good compromise with respect to other available materials from the standpoint of considerations such as size reduction and thermal conductivity. Its significant properties are:

- Purity
- Dielectric constant
- Dissipation factor
- Surface smoothness
- Thickness

Purity is a dominant characteristic in that the dielectric constant, dis-

sipation factor, and smoothness are linked to it. It also influences the repeatability of manufactured circuits. A brief discussion of the properties and their normal range of values will be given before proceeding with their effects on microstrip.

Alumina purity is the per cent by weight of the material that is actually Al_2O_3 . The other constituents are inherent impurities in its manufacture or are introduced impurities to enable improvement of other specifications such as smoothness. Usually these impurities are categorically called the "glassy phase" since some of them form glasses during the sintering operation. The most popular values of purity are 96% and 99.5%

The dielectric constant, ϵ_r , is related to the density, or grain size, (Bosnell, 1971) and the grain orientation (van Heuven and Vlek, 1972) of the alumina. Generally the dielectric constant is higher for higher purity substrates since the grain size is smaller. Typical values of ϵ_r range from 8.8 (Reference Data For Radio Engineers) to 10.15 (Bosnell, 1971).

The dissipation factor, or loss tangent is defined as

$$\tan \delta = \frac{\epsilon''}{\epsilon'}$$

where $\epsilon = \epsilon' + j \epsilon''$. It describes the loss of the substrate. For alumina the losses are caused by its impurities. Ideally the dissipation factor should be zero, but it is typically .0001 to .0006 in reality.

Surface smoothness is a function of grain size, or purity, of as-fired substrates. Those with higher purity have smoother surfaces. Grinding and polishing can be used to improve surface smoothness, with the

ultimate smoothness being better for higher purity substrates. Substrates can be purchased with surface finishes from 2 microinch to 40 microinch RMS.

The thickness of alumina substrates ranges from 0.020 to 0.050 inch, with common thicknesses being 0.025 inch and 0.040 inch. The tolerance on this dimension is given as $\pm 10\%$ by one manufacturer.

When selecting substrates for thin film and thick film fabrication, 99.5% purity is preferred over 96% because it is the smoother and because it provides the most repeatable results. It does cause some difficulties with thick film circuits, though, by reducing the conductor adhesion. Thick film conductors depend on the glassy phase of the substrate to bond with the glass frit in the conductor, as well as a certain amount of mechanical bonding resulting from the substrate roughness. Since 99.5% pure alumina contains less glass and is smoother than 96% alumina, the conductor adhesion is reduced. In the case of thin film circuits, the smoothness is required for the process and adhesion is not impaired because the bonding mechanism is chemical.

According to Schilling and Lehrfeld (1969) and Bosnell (1971), the repeatability of 99.5% alumina is superior to that of 96% alumina. Schilling and Lehrfeld noted that the dielectric constant, dissipation factor, surface finish, and grain structure of 96% alumina were inconsistent from lot to lot; whereas the properties of 99.5% alumina were constant from one batch to the next. Not only is 99.5% alumina more consistent as a product, it is also more constant after undergoing thick film processing conditions. Bosnell found that the dielectric constant

of 96% alumina decreased by as much as 20% after cycling it through a belt furnace with a peak temperature of 900°C. He also found that the dissipation factor increased by a factor of at least 2. In contrast, he observed that 99.5% alumina remained virtually unchanged when subjected to the same process. The impact of these two investigations is that thick film circuits fabricated on 99.5% alumina will have a narrower distribution than those on 96% alumina for two reasons: 1) better product consistency of the 99.5% alumina and 2) better stability of the 99.5% alumina under process conditions. Since thin film circuits require a smoother surface than that of the 96% alumina, they are immune to the repeatability problems with 96% alumina because it can not be used.

It is evident that thick film circuit fabrication is caught in a conflict between adhesion and repeatability. Consequently a compromise is necessitated if it is to be used for production of a circuit.

Now that the deficiencies and variations of alumina have been presented, it is necessary to examine their effect on the performance of microstrip. Not one of the electrical parameters of microstrip escapes change when the properties of alumina vary. Impedance, λ_g , and attenuation all depend on the choice of purity or the tolerances of a particular purity. Since the dielectric constant and thickness determine the impedance, any changes in them from one substrate to the next will cause fluctuations in it. The trend for impedance variations as a function of some typical material variations can be found by using Fig. 15 of Chapter 2 or by the microstrip analysis computer program. A specific experimental analysis of the effects of known changes in alumina on characteristic impedance has not been performed since

studies on alumina changes, such as Bosnell's, implicitly state the corresponding changes in impedance.

The guide wavelength λ_g of microstrip also depends on dielectric constant and h ; however, it is primarily dependent on dielectric constant. Thus for applications such as filters or resonators where λ_g is an important parameter it is necessary to know the value of the dielectric constant and maintain it.

Thickness, dissipation factor, and surface smoothness, all affect attenuation of the completed microstrip. Schilling (1968) performed an experimental comparison of their effects using thin film fabrication of 50-ohm lines on 99.5% alumina. He held constant all other variables except the one under test. The results of his study are shown in Table V.

TABLE V
LOSS DATA
(Schilling, 1968: Table 3)

Effect Under Test	Substrate Properties	Loss, dB/inch		
		3 GHz	6 GHz	9 GHz
Dissipation Factor	0.0006 (96% Alumina)	0.176	0.217	0.345
	0.0001 (99.5% Alumina)	0.166	0.221	0.332
Substrate Thickness	.025 inch	0.139	0.185	0.244
	.050 inch	0.091	0.106	0.144
Surface Finish	24 μ inch	0.166	0.221	0.332
	10 μ inch	0.139	0.185	0.244
	2 μ inch	0.110	0.140	0.179

The influence of dissipation factor of different purities of alumina is normally assumed to be negligible in designs and this assumption is upheld by Schilling's data. It seems obvious that his findings would show less attenuation for lines on thicker substrates since w increases as h increases for a constant impedance. His data on attenuation as a function of surface finish shows two relationships. For a constant frequency, the smoothest substrate will yield the circuit with the lowest attenuation and for a constant surface finish, the lowest frequency will suffer the least attenuation. Thus it has been shown that attenuation is affected by the properties of thickness, dissipation factor, and surface finish and that it is affected to different degrees by each.

3.4 Summary of Fabrication Considerations

From this discussion of material and process characteristics, it is evident that there can be a wide variation in the performance of the finished circuit depending on which process is used and the quality of the materials used. The operating frequency and dimensional requirements of a circuit are the primary factors that determine the choice of thick film or thin film fabrication. Secondary considerations after a manufacturing process has been selected are the substrate surface smoothness and conductor losses. The dissipation factor is a rather insignificant property when alumina of either 96% or 99.5% purity is used. Even though no microstrip circuit will match theoretical performance, optimum performance can be attained by observing the process and material behaviors mentioned in this chapter or, similarly, a known compromise in performance can be realized by observing them.

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APPENDIX

APPENDIX

COMPUTER PROGRAMS
FOR GENERAL MICROSTRIP DESIGN OR ANALYSIS

This appendix lists four BASIC language programs that were used to generate the data for the graphs of Figures 10 through 16:

- I. Microstrip Synthesis
- II. Microstrip Analysis
- III. Microstrip Effective Dielectric Constant
- IV. Microstrip Attenuation

A summary of the capabilities of each program is presented and a sample run of each program is included after the listing.

I. Microstrip Synthesis

Purpose: To calculate the conductor width w of a microstrip for an arbitrary set of values of Z_0 , h , and ϵ_r to meet a specified return loss.

Input: Z_0 , h , ϵ_r (K), and return loss, R .

Output: Z , Z_0 , h , K , R , w , and w/h .

- Features:
1. Any value of Z_0 may be specified.
 2. Microstrip impedance may be chosen equal to Z_0 or unequal to Z_0 .
 3. If the impedance is unequal to Z_0 , the return loss is used as the input that determines the impedance of the line. VSWR must be converted to return loss for input.

4. It offers the option of using either Wheeler's narrow strip equation or his wide strip equation or both to calculate the strip width w .
5. After an initial set of calculations is completed, the option is given to repeat the calculations for different values of h , R , or Z .

```

180 PRINT "MICROSTRIP SYNTHESIS"
181 PRINT "CALCULATION OF W & W/H AS A FUNCTION OF ";
182 PRINT "K AND RETURN LOSS."
183 PRINT "IT USES WHEELER'S EQUATIONS (1965)."

```



```

270 REM   CALCULATE REFLECTION COEFFICIENT, GAMMA.
275 REM   LET G=GAMMA
280 LET G= EXP (-R/8.68588)
285 LET Z1=Z0*(1-G)/(1+G)
290 LET Z2=Z0*(1+G)/(1-G)
300 LET N1=Z2-Z1
301 RETURN
400 LET Z=Z0
410 LET Z1=Z0
420 LET Z2=Z0
430 LET N1=1
440 LET R=1E+38
500 PRINT "IF YOU WANT CALCULATIONS USING EQUATIONS FOR"
501 PRINT "W/H <= 2, TYPE 1"
502 PRINT "W/H => 2, TYPE 0"
503 PRINT "OR BOTH, TYPE 2. ";
520 INPUT Q1
530 PRINT
1005 PRINT
1010 PRINT
1015 PRINT
1020 FOR Z=Z1 TO Z2 STEP N1
1022   PRINT "Z0 = ";Z0;" OHMS"
1025   PRINT "RETURN LOSS = ";R;" DB"
1026   IF Z1=Z2 GOTO 1047
1030   IF Z=Z2 GOTO 1045
1035   PRINT "Z-LO = ";Z1;" OHMS"
1040   GOTO 1050
1045   PRINT "Z-HI = ";Z2;" OHMS"
1046   GOTO 1050
1047   PRINT "Z = ";Z;" OHMS"
1050   PRINT "H = ";H;" MILS"
1055   PRINT
1060   IF Q1=0 GOTO 1485
1180   PRINT "CALCULATION OF W USING EQUATION FOR";
1181   PRINT "W/H <= 2."
1185   PRINT
1186   PRINT TAB 3;"K"; TAB 19;"W"; TAB 32;"W/H"
1187   PRINT
1190   FOR K=E1 TO E2 STEP E3
1200     LET A1=(K+1)/2
1210     LET A2= SQR (A1)
1220     LET A3=(K-1)/(K+1)
1230     LET A4=(.226+.12/K)
1240     LET C=A2*Z/60+A3*A4
1250     REM B1 = W/H
1260     LET B1=4/((.5* EXP (C)- EXP (-C))
1270     LET W=B1*H
1300     PRINT K,W,B1
1320   NEXT K
1324   PRINT
1325   PRINT

```

```

1330 IF Q1=2 GOTO 1485
1335 GOTO 1663
1485 PRINT "CALCULATION OF W USING EQUATION FOR";
1486 PRINT "W/H => 2"
1490 PRINT
1500 PRINT TAB 3;"K"; TAB 19;"W"; TAB 32;"W/H"
1510 FOR K=E1 TO E2 STEP E3
1520 LET D1=3.14159*377/( SQR (K)*Z)
1530 LET D2=D1/2
1540 LET D3=D2-1
1550 LET D4= LOG (D1-1)
1560 LET D5=(K-1)/2/K
1570 LET D6= LOG (D2-1)
1580 LET D7=.517/K
1590 REM B1 = W/H
1600 LET B1=.637*(D3-D4+D5*(D6+.293-D7))
1610 LET W=B1*H
1650 PRINT K,W,B1
1660 NEXT K
1661 PRINT
1662 PRINT
1663 PRINT
1665 NEXT Z
1666 PRINT
1667 PRINT
1670 PRINT "DO YOU WANT TO REPEAT CALCULATIONS FOR";
1671 PRINT "A DIFFERENT H?"
1680 PRINT "YES - TYPE 1; OR NO - TYPE 0.";
1690 INPUT Q2
1700 PRINT
1710 IF Q2= 0 GOTO 1730
1720 PRINT "ENTER H, IN MILS";
1721 INPUT H
1722 PRINT
1723 GOTO 1010
1730 PRINT "DO YOU WANT TO REPEAT CALCULATIONS FOR A"
1731 PRINT "DIFFERENT RETURN LOSS OR Z? YES(1) OR NO(0)";
1750 INPUT Q3
1760 PRINT
1770 IF Q3= 0 GOTO 9999
1780 PRINT "WHICH ONE? RETURN LOSS(1) OR Z(0)";
1790 INPUT Q4
1800 PRINT
1810 IF Q4=0 GOTO 1900
1820 PRINT "ENTER RETURN LOSS IN DB";
1830 INPUT R
1831 PRINT
1840 GOSUB 280
1850 GOTO 1005
1900 PRINT "ENTER Z IN OHMS";
1910 INPUT Z

```

```
1920 PRINT
1930 LET Z1=Z
1940 LET Z2=Z
1950 LET N1=1
1960 IF Z=Z0 GOTO 2000
1970 LET G= ABS ((Z-Z0)/(Z+Z0)) ,
1980 LET R=-8.68588* LOG (G)
1990 GOTO 500
2000 LET R=1E+38
2010 GOTO 500
9999 END
```

RUN
 MICROSTRIP SYNTHESIS
 CALCULATION OF W & W/H AS A FUNCTION OF K AND RETURN LOSS.
 IT USES WHEELER'S EQUATIONS (1965).

Z IS MICROSTRIP IMPEDANCE
 Z0 IS MICROSTRIP CHARACTERISTIC IMPEDANCE
 H IS THICKNESS OF DIELECTRIC
 W IS WIDTH OF CONDUCTOR
 K IS RELATIVE DIELECTRIC CONSTANT

ENTER Z0, IN OHMS? 50
 DOES Z = Z0? YES(1) OR NO(0)? 0
 ENTER H, IN MILS? 25
 ENTER RANGE OF K - LOWEST VALUE, HIGHEST VALUE, INCREMENT.
 ? 8.8? 10.8? 1
 ENTER RETURN LOSS IN DB? 30
 IF YOU WANT CALCULATIONS USING EQUATIONS FOR
 W/H <= 2, TYPE 1
 W/H >= 2, TYPE 0
 OR BOTH, TYPE 2. ? 1

Z0 = 50 OHMS
 RETURN LOSS = 30 DB
 Z-L0 = 46.9347 OHMS
 H = 25 MILS

CALCULATION OF W USING EQUATION FOR W/H <= 2.

K	W	W/H
8.8	30.5617	1.22247
9.8	27.7392	1.10957
10.8	25.3295	1.01318

Z0 = 50 OHMS
 RETURN LOSS = 30 DB
 Z-HI = 53.2655 OHMS
 H = 25 MILS

CALCULATION OF W USING EQUATION FOR W/H <= 2.

K	W	W/H
8.8	23.7988	.951953
9.8	21.3997	.855988
10.8	19.3613	.77445

DO YOU WANT TO REPEAT CALCULATIONS FOR A DIFFERENT H?

YES - TYPE 1; OR NO - TYPE 0? 0

DO YOU WANT TO REPEAT CALCULATIONS FOR A
DIFFERENT RETURN LOSS OR Z? YES(1) OR NO(0)? 1

WHICH ONE? RETURN LOSS(1) OR Z(0)? 0

ENTER Z IN OHMS? 50

IF YOU WANT CALCULATIONS USING EQUATIONS FOR

W/H $\leq$ 2, TYPE 1

W/H $\geq$ 2, TYPE 0

OR BOTH, TYPE 2. ? 1

Z0 = 50 OHMS

RETURN LOSS = 1E+38 DB

Z = 50 OHMS

H = 25 MILS

CALCULATION OF W USING EQUATION FOR W/H $\leq$ 2.

K	W	W/H
8.8	27.049	1.08196
9.8	24.4423	.977694
10.8	22.2215	.888859

DO YOU WANT TO REPEAT CALCULATIONS FOR A DIFFERENT H?

YES - TYPE 1; OR NO - TYPE 0? 0

DO YOU WANT TO REPEAT CALCULATIONS FOR A
DIFFERENT RETURN LOSS OR Z? YES(1) OR NO(0)? 0

*READY

II. Microstrip Analysis

Purpose: To calculate the microstrip impedance and its associated return loss and VSWR as a function of h , ϵ_r (K), and w .

Input: Z_0 , h , range and increment of K, range and increment of w .

Output: h , K, Z_0 , w , Z, return loss, VSWR, and w/h .

- Features:
1. Selection of any real value of characteristic impedance Z_0 .
 2. Any value of h may be used.
 3. Calculations are performed for incremental series of K and w .
 4. A choice is given to use either Wheeler's narrow strip equation or his wide strip equation or both.
 5. After computation is complete, an option is given to repeat the calculations for a different h .

```

499 PRINT "MICROSTRIP ANALYSIS"
500 PRINT "CALCULATING Z, RETURN LOSS, VSWR, AND W/H"
502 PRINT "AS A FUNCTION OF W, H, AND K."
505 PRINT "IT USES WHEELER'S EQUATIONS (1965)."
```

```

509 PRINT
510 PRINT "Z IS MICROSTRIP IMPEDANCE"
520 PRINT "Z0 IS MICROSTRIP CHARACTERISTIC IMPEDANCE"
530 REM R IS RETURN LOSS
540 PRINT "H IS THICKNESS OF DIELECTRIC"
550 PRINT "W IS WIDTH OF CONDUCTOR"
560 PRINT "K IS RELATIVE DIELECTRIC CONSTANT"
565 PRINT
570 PRINT "ENTER Z0 IN OHMS. ";
580 INPUT Z0
590 PRINT
600 PRINT "ENTER H IN MILS";
620 INPUT H
650 PRINT
670 PRINT "ENTER RANGE OF K - LOWEST VALUE, ";
675 PRINT "HIGHEST VALUE, INCREMENT."
690 INPUT B1, B2, B3
720 PRINT
```

```

740 PRINT "ENTER W IN MILS - LOWEST VALUE, ";
745 PRINT "HIGHEST VALUE, INCREMENT."
760 INPUT C1, C2, C3
790 PRINT
810 REM CALCULATION OF Z.
1000 PRINT "DO YOU WANT TO CALCULATE Z FOR -"
1001 PRINT "W/H <= 2, TYPE 1"
1002 PRINT "W/H => 2, TYPE 0"
1003 PRINT "OR BOTH, TYPE 2. ";
1010 INPUT Q1
1020 PRINT
1030 IF Q1= 0 GOTO 1530
1050 FOR K=81 TO 82 STEP 83
1060 PRINT
1070 PRINT
1080 PRINT "CALCULATION OF Z USING EQUATION FOR ";
1081 PRINT "W/H <= 2.0"
1100 PRINT "H = ";H;" MILS"
1110 PRINT "K = ";K
1115 PRINT "Z0 = ";Z0;" OHMS"
1120 PRINT
1130 PRINT "W, MILS"; TAB 16;"Z, OHMS"; TAB 30;
1131 PRINT "RET. LOSS, DB"; TAB 47;"VSWR"; TAB 62;"W/H"
1140 PRINT
1150 FOR W=C1 TO C2 STEP C3
1160 LET D1= SQRT (2*(K+1))
1170 LET D2= LOG (8*H/W)
1180 LET D3= W*W/H/H/32
1190 LET D4= (K-1)/(K+1)
1200 LET D5= .226+.12/K
1300 LET Z=120*(D2+D3-D4*D5)/D1
1305 LET W1=W/H
1310 REM CALCULATE RETURN LOSS
1320 IF Z=Z0 GOTO 1360
1330 LET G=(Z-Z0)/(Z+Z0)
1335 LET P= ABS (G)
1340 LET R=-8.68588* LOG (P)
1342 REM V=VSWR
1344 LET V=(1+P)/(1-P)
1350 GOTO 1370
1360 LET R=1E+38
1362 LET V=1
1370 PRINT W,Z,R,V,W1
1380 NEXT W
1390 NEXT K
1500 IF Q1=2 GOTO 1530
1510 GOTO 1970
1530 FOR K=81 TO 82 STEP 83
1540 PRINT
1550 PRINT
1560 PRINT "CALCULATION OF Z USING EQUATION FOR ";
1561 PRINT "W/H => 2.0"
1580 PRINT "H = ";H;" MILS"

```

```

1590 PRINT "K = ";K
1595 PRINT "Z0 = ";Z0;" OHMS"
1600 PRINT
1700 PRINT "W, MILS"; TAB 16;"Z, OHMS"; TAB 30;
1701 PRINT "RET. LOSS, DB"; TAB 47;"VSWR"; TAB 62;"W/H"
1710 PRINT
1720 FOR W=C1 TO C2 STEP C3
1730 LET E1=377/2/SQR (K)
1740 LET E2=.5*W/H+.441
1750 LET E3=(K+1)/2/3.14159/K
1760 LET E4= LOG (.5*W/H+.94)+1.45
1770 LET E5=.082*(K-1)/K/K
1780 LET Z=E1/(E2+E3+E4+E5)
1785 LET W1=W/H
1790 REM CALCULATE RETURN LOSS
1800 IF Z=Z0 GOTO 1930
1900 LET G=(Z-Z0)/(Z+Z0)
1905 LET P= ABS (G)
1910 LET R=-8.68588* LOG (P)
1912 REM V=VSWR
1914 LET V=(1+P)/(1-P)
1920 GOTO 1940
1930 LET R=1E+38
1932 LET V=1
1940 PRINT W,Z,R,V,W1
1950 NEXT W
1960 NEXT K
1970 PRINT "DO YOU WANT TO REPEAT CALCULATIONS"
1980 PRINT "FOR A DIFFERENT H?"
1991 PRINT "YES, TYPE 1 OR NO, TYPE 0. ";
1990 INPUT Q2
2100 PRINT
2110 PRINT
2120 IF Q2=1 GOTO 600
9999 END

```


RIJN

MICROSTRIP ANALYSIS

CALCULATING Z, RETURN LOSS, VSWR, AND W/H
AS A FUNCTION OF W, H, AND K.

IT USES WHEELER'S EQUATIONS (1965).

Z IS MICROSTRIP IMPEDANCE

Z0 IS MICROSTRIP CHARACTERISTIC IMPEDANCE

H IS THICKNESS OF DIELECTRIC

W IS WIDTH OF CONDUCTOR

K IS RELATIVE DIELECTRIC CONSTANT

ENTER Z0 IN OHMS? 50

ENTER H IN MILS? 25

ENTER RANGE OF K - LOWEST VALUE, HIGHEST VALUE, INCREMENT.

? 8.8? 9.8? 1

ENTER W IN MILS - LOWEST VALUE, HIGHEST VALUE, INCREMENT.

? 23.5? 25.5? .5

DO YOU WANT TO CALCULATE Z FOR -

W/H <= 2, TYPE 1

W/H > 2, TYPE 0

OR BOTH, TYPE 2. ? 1

CALCULATION OF Z USING EQUATION FOR W/H <= 2.0

H = 25 MILS

K = 8.8

Z0 = 50 OHMS

W, MILS	Z, OHMS	RET. LOSS, DB	VSWR	W/H
23.5	53.6195	29.1359	1.07239	.94
24	53.081	30.4897	1.06162	.96
24.5	52.555	32.0712	1.0511	.98
25	52.041	33.9786	1.04082	1
25.5	51.5384	36.3914	1.03077	1.02

CALCULATION OF Z USING EQUATION FOR W/H <= 2.0

H = 25 MILS

K = 9.8

Z0 = 50 OHMS

W, MILS	Z, OHMS	RET. LOSS, DB	VSWR	W/H
23.5	50.9892	40.1801	1.01978	.94
24	50.4762	46.4849	1.00952	.96
24.5	49.9752	52.0996	1.0005	.98
25	49.4855	55.728	1.0104	1
25.5	49.0067	59.972	1.02027	1.02

DO YOU WANT TO REPEAT CALCULATIONS FOR A DIFFERENT H?

YES, TYPE 1 OR NO, TYPE 0. ? 0

*READY

III. Microstrip Effective Dielectric Constant

Purpose: To calculate $\epsilon_{r,eff}$, $K(EFF)$, and $\sqrt{\epsilon_{r,eff}}$, $SQR(K(EFF))$, for arbitrary values of w/h and ϵ_r , K .

Input: K , range and incremental multiplier of w/h .

Output: K , w/h , $K(EFF)$, $SQR(K(EFF))$.

Features: 1. It allows input of any relative dielectric constant.
2. The independent variable w/h is varied logarithmically by incrementing it by a multiplier for each step.

```

499 PRINT "MICROSTRIP EFFECTIVE DIELECTRIC CONSTANT"
500 PRINT "CALCULATING K(EFF) AND SQR(K(EFF)) AS A"
510 PRINT "FUNCTION OF W/H BASED ON SCHNEIDER'S EQN."
520 PRINT "K IS RELATIVE DIELECTRIC CONSTANT."
524 PRINT "K(EFF) IS EFFECTIVE RELATIVE ";
525 PRINT "DIELECTRIC CONSTANT."
526 PRINT "ENTER K";
527 INPUT K
528 PRINT
530 PRINT "W/H, LOWEST VALUE, HIGHEST VALUE, MULTIPLIER."
540 INPUT A1,A2,M1
541 PRINT
542 PRINT
543 PRINT
544 PRINT "K = ";K
545 PRINT "W/H"; TAB 16;"K(EFF)"; TAB 29;"SQR(K(EFF))"
546 PRINT
550 REM CALCULATE K(EFF)
555 LET A3=A1
560 LET K1=(K+1)/2+(K-1)/2/ SQR (1+10/A3)
570 LET K2= SQR (K1)
580 PRINT A3,K1,K2
590 LET A3=A3*M1
600 IF A3>(A2*M1) GOTO 9999
610 GOTO 560
9999 END

```

RUN

MICROSTRIP EFFECTIVE DIELECTRIC CONSTANT
CALCULATING K(EFF) AND SQR(K(EFF)) AS A
FUNCTION OF W/H BASED ON SCHNEIDER'S EQN.

K IS RELATIVE DIELECTRIC CONSTANT.

K(EFF) IS EFFECTIVE RELATIVE DIELECTRIC CONSTANT

ENTER K? 9.8

W/H, LOWEST VALUE, HIGHEST VALUE, MULTIPLIER.

? .1? 10? 1.77828

K = 9.8

W/H

K(EFF)

SQR(K(EFF))

.1	5.83782	2.41616
.177828	5.9316	2.44573
.316228	6.17036	2.48402
.562342	6.41525	2.53283
1	6.72665	2.59358
1.77828	7.10967	2.6664
3.16228	7.55669	2.74894
5.62342	8.03976	2.83545
10	8.51127	2.91741

*READY

IV. Microstrip Attenuation

Purpose: To calculate normalized attenuation as a function of h, K, t, and w/h by two different equations.

Input: h, K, t, and range and incremental multiplier for w/h.

Output: h, K, t, w/h, Z_0 .

Loss according to Schneider's equation.

Loss according to the equation of Pucel, Masse, and Hartwig.

- Features:
1. Any value of h, t, or K may be used.
 2. Any range or multiplier for w/h may be used.
 3. Caution: The output from Pucel's equation is always the value for $K = 1$ since the equation is not a function of K.
Schneider's output does give the proper value of normalized attenuation by accounting for the actual value of K.
 6. The normalized attenuation is used for flexibility. The actual attenuation can be calculated by multiplying the output by $R_s/Z_0 h$.

$$\alpha = \frac{R_s}{Z_0 h} \cdot (\text{OUTPUT})$$

```

500 PRINT "MICROSTRIP ATTENUATION"
510 PRINT "THIS PROGRAM CALCULATES NORMALIZED MICROSTRIP"
520 PRINT "ATTENUATION AS A FUNCTION OF W/H, H, T, AND K."
525 PRINT "TO FIND ACTUAL ATTENUATION, MULTIPLY";
526 PRINT "OUTPUT BY RS/(Z0*H)."
527 PRINT "PUCEL'S OUTPUT ALWAYS GIVES LOSS FOR K=1."
528 PRINT "SCHNEIDER'S OUTPUT ACCOUNTS FOR THE SELECTED K."
530 PRINT
540 PRINT "K IS RELATIVE DIELECTRIC CONSTANT."
550 PRINT "T IS THICKNESS OF STRIP CONDUCTOR."
551 PRINT "RS IS CONDUCTOR SKIN RESISTANCE IN OHMS."

```

```

552 PRINT "T AND H ARE IN MILS."
560 PRINT
600 PRINT "ENTER H, T, AND K";
610 INPUT H,T1,K
615 LET P1=3.14159
620 PRINT
630 PRINT "ENTER RANGE OF W/H - LOWEST VALUE,"
631 PRINT "HIGHEST VALUE, MULTIPLIER."
640 INPUT A1,A2,M1
650 PRINT
700 DEF FNA(A)=60* LOG (3/A+A/4)
710 DEF FNC(A)=(K+1)/2+(K-1)/2/ SQR (1+10/A)
720 DEF FNL(A)=(1-1/A)**6
730 DEF FNB(A)=376.991/(A+2.42-.44/A+ FNL(A))
740 DEF FNM(A)=1.3824*(8/A-A/4)/ FNA(A)/(8/A+A/4)
760 DEF FNE(A)=1+1/A+ LOG (2*H/T1)/A/P1
770 DEF FNN(A)=1+.44/A/A+6*(1-1/A)**5/A/A
780 DEF FNF(A)=FNB(A)*FNN(A)*(1+A+LOG(2*H/T1)/P1)*6.11157E-5
790 DEF FNG(A)=W1+T1*(1+ LOG (4*P1*A*H/T1))/P1
800 DEF FNH(A)=W1+T1*(1+ LOG (2*W1/A/T1))/P1
810 DEF FNO(H)=1+H/FNH(A)+H*(LOG(2*H/T1)-T1/H)/FNH(A)/P1
820 DEF FNP(H)=FNH(A)/H+2*(LOG(FNH(A)/H/2+.94)+2.83787)/P1
830 DEF FNG(H)=1+H/FNG(A)+H*(LOG(4*P1*W1/T1)+T1/W1)/FNG(A)/P1
840 DEF FNI(H)=1.3824*(1-FNG(A)*FNG(A)/H/H/16)*FNO(H)
850 DEF FNJ(H)=1.3824*(1- FNH(A)* FNH(A)/H/H/16)* FNO(H)
870 DEF FNR(H)= FNH(A)/H+ FNH(A)/P1/H/( FNH(A)/2/H+.94)
880 DEF FNS(A)=1+1/A+ LOG (4*P1*W1/T1)/A/P1
900 PRINT
901 PRINT
902 PRINT
910 PRINT "K = ";K
920 PRINT "H = ";H;" MILS"
930 PRINT "T = ";T1;" MILS"
935 PRINT
940 PRINT "W/H"; TAB 17;"Z0"; TAB 31;"LOSS, DB"; TAB 45;
941 PRINT "LOSS, DB"
945 PRINT TAB 30;"SCHNEIDER"; TAB 46;"PUCEL"
950 PRINT
1000 LET A=A1
1010 LET W1=A*H
1050 IF A>.159155 GOTO 1500
1070 LET X1= FNM(A)
1080 LET X2= FNS(A)
1090 LET X3= FNA(A)/ SQR ( FNC(A))
1095 LET X4= FNC(A)
1100 LET L1=X1*X2*X3*X4
1110 LET L2= FNI(H)
1120 PRINT A,X3,L1,L2
1130 GOTO 3500
1500 IF A>1 GOTO 2000
1510 LET X3= FNA(A)/ SQR ( FNC(A))
1520 LET X2= FNF(A)
1530 LET X1= FNM(A)

```

```
1532 LET X4= FNC(A)
1535 LET L1=X1*X2*X3*X4
1540 LET L2= FNJ(H)
1560 PRINT A,X3,L1,L2
1570 IF A=1 GOTO 2000
1580 GOTO 3500
2000 IF A>2 GOTO 2500
2010 LET X3= FNB(A)/ SQR ( FNC(A))
2015 LET X4= FNC(A)
2020 LET L1=X3* FNF(A)*X4
2040 LET L2= FNJ(H)
2050 PRINT A,X3,L1,L2
2060 IF A=2 GOTO 2500
2070 GOTO 3500
2500 LET X3= FNB(A)/ SQR ( FNC(A))
2505 LET X4= FNC(A)
2510 LET L1=X3*X4*FNF(A)
2515 LET Y1= FNR(H)
2520 LET Y2= FND(H)
2522 LET Y3= FNP(H)
2525 LET L2=8.63588*Y1*Y2/Y3/Y3
2530 PRINT A,X3,L1,L2
3500 LET A=A*M1
3510 IF A<A2*.99*M1 GOTO 1010
9999 END
```

RUN

MICROSTRIP ATTENUATION

THIS PROGRAM CALCULATES NORMALIZED MICROSTRIP
ATTENUATION AS A FUNCTION OF W/H, H, T, AND K.

TO FIND ACTUAL ATTENUATION, MULTIPLY OUTPUT BY $RS/(Z_0 \cdot H)$.

PUCEL'S OUTPUT ALWAYS GIVES LOSS FOR $K=1$.

SCHNEIDER'S OUTPUT ACCOUNTS FOR THE SELECTED K.

K IS RELATIVE DIELECTRIC CONSTANT.

T IS THICKNESS OF STRIP CONDUCTOR.

RS IS CONDUCTOR SKIN RESISTANCE IN OHMS.

T AND H ARE IN MILS.

ENTER H, T, AND K? 25? .6? 1

ENTER RANGE OF W/H. LOWEST, HIGHEST, MULTIPLIER.

? .1? 10? 1.77828

K = 1
H = 25 MILS
T = .6 MILS

W/H	Z_0	LOSS, DB SCHNEIDER	LOSS, DB PUCEL
.1	262.94	32.6031	24.7775
.177828	228.442	20.0607	16.466
.316228	194.031	11.8341	10.5744
.562342	159.895	7.15866	6.72123
1	126.613	4.80381	4.25876
1.77828	95.2508	2.71482	2.54232
3.16228	67.9834	1.78367	1.74385
5.62342	45.5632	1.10578	1.09823
10	29.2073	.672656	.675196

*READY

MICROSTRIP DESIGN MANUAL
WITH FABRICATION GUIDELINES

by

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Microstrip has been recognized as a configuration for implementing microwave circuits since the early 1950's. Over the years much information has been published in journals about it, creating a voluminous amount of material to digest in obtaining the most useful data. Design information has been sifted from the available sources and is presented in this paper in a manner suited to direct application. Background is established for selection of synthesis and analysis equations by presenting several analyses of microstrip, comparing them, and supporting them with experimental data. The most convenient, most accurate equations are chosen and then applied in the form of detailed design graphs for the frequently encountered case of a 50-ohm microstrip transmission line on dielectric materials of teflon, G-10 glass-epoxy, and alumina. For those cases not covered by these special design curves, computer programs are listed to enable design of microstrip with completely general specifications. In addition to this information, thin film and thick film fabrication considerations are discussed to assist in compensating for physical effects when making the transition from theory to physical realization of a circuit.