

# Transmission Line RAPIDESIGNER<sup>®</sup> Operation and Applications Guide

National Semiconductor  
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## INTRODUCTION

The National Semiconductor Transmission Line RAPIDESIGNER makes quick work of calculations frequently used in the design of data transmission line systems on printed circuit boards. Based on principles contained in our *Interface Databook*, the Transmission Line RAPIDESIGNER benefits from our many years experience in designing and manufacturing data transmission and interface products and from helping our valued customers obtain the most from National's Interface products.

Two versions of the Transmission Line RAPIDESIGNER are available while supplies last. RAPIDESIGNER (Lit. #633200) features ISO metric units. RAPIDESIGNER (Lit. #633201) features English units.

If information about other National Semiconductor products is desired, please contact one of our Customer Response Centers: 1-800-272-9959 (USA), 49-0-180-532-78-32 (Europe, English language), or 81-043-299-2308 (Japan). Our *Worldwide Web* site is: <http://www.national.com>. For applications assistance on Interface products, call our Interface Applications Hotline, 1-408-721-8500 in Santa Clara, CA, USA.

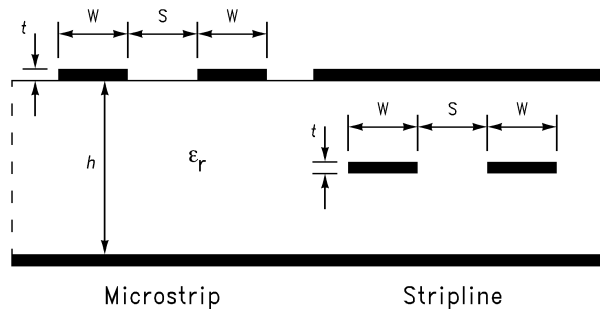
## CAUTIONARY STATEMENT

National Semiconductor assumes no responsibility and accepts no liability for results obtained or application of these results from the use of the Transmission Line RAPIDESIGNER. In order to obtain meaningful and useable results from this calculator, the user must be familiar with general transmission line theory and the application and analysis of transmission lines with pulse excitation.

The resolution of results obtainable from the Transmission Line RAPIDESIGNER is similar to that of most common Napierian sliderules, that being two to three significant digits. The accuracy of results from the sliderule depends on the relationships of the numerical factors as inputs and the approximations used for the calculations. Accuracy limits and restrictions for approximations and calculations is given in Appendix A, if known.

## TRANSMISSION LINE GEOMETRY

Microstrip and Stripline geometries as used in the Transmission line RAPIDESIGNER are defined as shown below.



In common practice,  $h$  represents dielectric thickness for microstrip structures and  $b$  that for stripline. For simplicity, the

Transmission Line RAPIDESIGNER uses only  $h$  to represent dielectric (substrate) thickness. Differential lines are edge-coupled only. Striplines are centered between adjacent image ground planes.

## REACTANCE FREQUENCY (SIDE ONE)

The reactance frequency scales are used to find capacitive reactance  $X_C$ , capacitance  $C$ , or frequency  $f$ , given any two of these parameters. Similarly, inductive reactance  $X_L$ , inductance  $L$ , or frequency  $f$ , may be found on the appropriate scales. In addition, the value of capacitance and inductance that are resonant at a given frequency may be found.

## EXAMPLES

- Find the capacitance value that will give  $0.2\Omega$  reactance at 50 MHz.
  - Set 50 MHz on the Frequency scale opposite the arrow.
  - Opposite  $0.2\Omega$  on the Capacitive Reactance scale, read 17 nF on the Capacitance scale.
- Find the frequency at which 25 nH will have  $10\Omega$  reactance.
  - Set  $0.025\ \mu\text{H}$  (25 nH) on the Inductance scale opposite  $10\Omega$  on the Inductive Reactance scale.
  - Read 63 MHz on the Frequency scale at the arrow.
- Find the capacitance value that will be resonant with 20 mH at 100 kHz.
  - Set 100 kHz on the Frequency scale at the arrow.
  - Opposite 20 mH on the Inductance scale, read 13 k $\Omega$  on the Inductive Reactance scale.
  - Opposite 13 k $\Omega$  on the Capacitive Reactance scale, read 130 pF on the Capacitance scale. (The hand-calculated value is 127 pF.)

## DIFFERENTIAL $Z_0$ (SIDE ONE)

The differential  $Z_0$  scales find the approximate characteristic impedance of edge-coupled, differential-pair microstrips or striplines. Before using these scales, the characteristic impedance  $Z_0$ , of the individual conductor must first be found using the **Microstrip and Stripline  $Z_0$**  scales on Side Two. Next, the differential impedance,  $Z_{diff}$ , is found based on the line spacing,  $s$ , and dielectric thickness,  $h$ . Both conductors of the pair must have the same physical cross sectional dimensions. Spacing between pairs of differential conductors should be greater than  $2s$  to avoid excessive crosstalk between and avoid affecting the impedance of adjacent line structures.

The formulations and computational method used are unique to the Transmission Line RAPIDESIGNER. The computation is based on an approximation of the reverse-crosstalk parameter of a coupled line pair. It has been shown<sup>(1-6)</sup> that this parameter can be used to express the mutual inductance and capacitance of the line pair. Therefore, the approximate characteristic impedance of the differential pair may be computed.

**Note:** For the RAPIDESIGNER the range of  $s/h$  for microstrip is limited to  $0.20 \leq s/h \leq 3.0$ . The range of  $s/h$  for stripline is  $0.20 \leq s/h \leq 1.5$ .

1. H.R. Kaupp, "Pulse Crosstalk Between Microstrip Transmission Lines", *7th International Electronic Circuit Symposium Record*, Aug. 1966, Wescon.
2. John A. DeFalco, "Predicting Crosstalk in Digital Systems", *Computer Design*, June 1973, p.p. 69–75.
3. H.R. Kaupp, "Effects of Embedding Microstrip Interconnections", *Proceedings International Electronic Packaging and Production Conference (Inter/Nepcon 69)*, Oct. 1969, p.p. 189–201.
4. N.C. Arvanitakis, J.T. Koliass, and W. Radzelovage, "Coupled Noise Prediction in Printed Circuit Boards for a High-Speed Computer System", *7th International Electronic Circuit Symposium Record*, Aug. 1966, Wescon.
5. A. Feller, H.R. Kaupp and J.J. Digiacomio, "Crosstalk and Reflections in High-Speed Digital Systems", *Proceedings—Fall Joint Computer Conference*, 1965, p.p. 511–525.
6. Ivor Catt, "Crosstalk (Noise) in Digital Systems", *IEEE Transactions on Electronic Computers*, Vol. EC-16, No. 6, Dec. 1967, p.p. 743–763.

#### EXAMPLE

1. Find the differential impedance for an edge-coupled pair of  $75\Omega$  microstrips spaced 0.10 cm apart on a 0.076 cm thick substrate.
  - A. Move slide to set 0.10 cm on the s-scale at 0.076 cm on the h-scale (upper window).
  - B. Read 0.86 on the Microstrip Factor scale at the arrow (middle window).
  - C. Move slide to set  $75\Omega$  on the  $Z_0$  scale opposite 0.86 on the Factor scale (lower window).
  - D. Read  $128\Omega$  on the  $Z_{DIFF}$  scale at arrow.

#### MICROSTRIP AND STRIPLINE $Z_0$ (SIDE TWO)

The Microstrip and Stripline  $Z_0$  scales calculate the characteristic impedance of microstrip or stripline transmission lines. The formulations used are based on material published in the National Semiconductor *Interface Databook*, Section 12. Additional material may be found in our *F100K ECL Data Book and Design Guide*, Application Notes Section.

In solving microstrip and stripline problems, the Transmission Line RAPIDESIGNER uses separate scale sets based on the conductor thickness  $t$ . The values for  $t$  are the standard thicknesses for copper cladding used in printed circuit board material manufacture. As a convenience to those who are not familiar with metric representations, thickness is also given in the common oz/ft<sup>2</sup> values.

The two most common uses of these scales are to find:

1. impedance  $Z_0$ , given line width  $w$ , dielectric thickness  $h$ , conductor thickness  $t$ , and dielectric constant  $\epsilon_r$ ; or
2. line width  $w$  given the other factors.

The procedures given in the following examples are the same for either microstrip or stripline. Of course, the Factor and  $Z_0$  scales appropriate to the particular line type must be used.

#### EXAMPLES

1. Find the conductor line width to yield a  $93\Omega$  microstrip on a 0.0813 cm substrate with  $1.78 \times 10^{-3}$  cm ( $\frac{1}{2}$  oz) copper cladding and dielectric constant of 3.8.

- A. Move slide to set  $93\Omega$  on the Microstrip  $Z_0$  scale opposite 3.8 on the  $\epsilon_r$  scale.
  - B. Read +25 on the Microstrip Factor scale at the arrow.
  - C. Move slide to set 0.0813 cm on the h-scale at the upper arrow.
  - D. In the section for  $t = 1.78 \times 10^{-3}$  cm ( $\frac{1}{2}$  oz), read 0.051 cm on the w-scale opposite +25 on the Factor scale.
2. Find the impedance of a 0.127 cm wide microstrip conductor on a substrate with  $\epsilon_r = 4.3$ ,  $t = 3.556 \times 10^{-3}$  cm (1 oz cu.) and  $h = 0.102$  cm.
    - A. Move slide to set 0.102 cm on the h-scale at the upper arrow.
    - B. In the section for  $t = 3.556 \times 10^{-3}$  cm (1 oz), read -15 on the Factor scale opposite 0.127 cm on the w-scale.
    - C. Then move slide to set -15 on the Microstrip Factor scale at the arrow in middle window.
    - D. Read  $64\Omega$  on the Microstrip  $Z_0$  scale opposite 4.3 on the  $\epsilon_r$  scale.

#### INTRINSIC DELAY (SIDE TWO)

This scale calculates the per unit-length propagation delay of a wave traveling on an unloaded microstrip or stripline transmission line.

#### EXAMPLE

1. Find the delay of a stripline with  $\epsilon_r = 2.8$ .
  - A. Move slide to set 2.8 on the Stripline  $\epsilon_r$  scale at the upper arrow.
  - B. Read 56 ps/cm on the  $T_d$  scale at the lower arrow.

#### MICROSTRIP AND STRIPLINE, $C_0$ AND $L_0$ (SIDE THREE)

This scale computes the intrinsic per-unit-length values of capacitance,  $C_0$ , and inductance,  $L_0$ , for an unloaded microstrip or stripline. Normally, the known parameters are unloaded  $Z_0$  and  $\epsilon_r$ . The scales have been paired so that a simultaneous comparison of the same intrinsic property for both line types may be made with only one setting of the slide.

#### EXAMPLES

1. Find  $C_0$  and  $L_0$  for a  $75\Omega$  microstrip on a substrate having  $\epsilon_r = 3.8$ .
  - A. Move slide to set  $75\Omega$  on the Unloaded  $Z_0$  scale at the arrow.
  - B. Read 0.70 pF/cm on the Microstrip  $C_0$  scale at 3.8 on the upper  $\epsilon_r$  scale of the middle window.
  - C. Read 3.95 nH/cm on the Microstrip  $L_0$  scale at 3.8 on the upper  $\epsilon_r$  scale of the lower window.
2. Find  $C_0$  and  $L_0$  for a  $35\Omega$  stripline on a substrate having  $\epsilon_r = 2.4$ .
  - A. Move slide to set  $35\Omega$  on the Unloaded  $Z_0$  scale at the arrow.
  - B. Read 1.47 pF/cm on the Stripline  $C_0$  scale at 2.4 on the lower  $\epsilon_r$  scale of the middle window.
  - C. Read 1.8 nH/cm on the Stripline  $L_0$  scale at 2.4 on the lower  $\epsilon_r$  scale of the lower window.

### UNTERMINATED STUB LENGTH (SIDE THREE)

These scales find the allowable maximum length of a transmission line or line stub which is terminated by a single capacitance load. This capacitance is normally the input capacitance of an active device. The known parameters are unloaded line impedance  $Z_0$  and termination capacitance  $C_t$ . The scales were formulated using a nominal risetime of 3.5 ns.  $L_{MAX}$  will change in proportion as  $t_r$  changes. If  $t_r$  is halved,  $L_{MAX}$  is halved.

#### EXAMPLES

- Find the maximum length of a 50Ω microstrip stub on a substrate with  $\epsilon_r = 4.3$  which is terminated by 10 pF.
  - Move slide to set 10 pF on the  $C_t$  scale opposite 50Ω on the  $Z_0$  scale.
  - Read 3040 on the Factor scale in the same window at the arrow.
  - Move slide to set 3040 on the Factor scale (middle window) at the arrow.
  - Read 27.7 cm on the Microstrip  $L_{max}$  scale (bottom window) opposite 4.3 on the upper  $\epsilon_r$  scale.
- A 35 cm stripline stub is terminated by 5 pF. If the substrate has an  $\epsilon_r = 2.4$  and the line impedance is 75Ω, is the stub length too long?
  - Move slide to set 5 pF on the  $C_t$  scale opposite 75Ω on the  $Z_0$  scale.
  - Read 3150 on the Factor scale in the same window at the arrow.
  - Move slide to set 3150 on the Factor scale (middle window) at the arrow.
  - Read 30.5 cm on the Stripline  $L_{max}$  scale (bottom window) opposite 2.4 on the lower  $\epsilon_r$  scale.

The 35 cm stub is more than 10% longer than calculated. Therefore, reflections may result unless the stub is terminated in a value near its characteristic impedance.

### PROPAGATION DELAY AND LOADED $Z_0$ (SIDE FOUR)

These scales find the loaded line impedance and per-unit-length value of propagation delay which result from adding distributed capacitance to a line. The capacitance may be associated with any type of line discontinuity including vias, line junctions or semiconductor device inputs or outputs. Normally, this capacitance occurs in discrete lumps. To simplify calculating its effect on the line, the total capacitance can be treated as though it is uniformly distributed along the line. This is permissible in most cases because the distance between loads is small compared to the distance traversed by the propagating wavefront during its risetime. Therefore, in preparation for this calculation, sum the value of all capacitances connected along the line and divide this total by the line's length to obtain  $C_D$ .

Loaded line impedance is the apparent instantaneous value of impedance seen by the propagating wavefront as it encounters a discontinuity. Since the wavefront has a large and finite risetime, the line's impedance may be considered as appearing altered over a distance approximately equal to that traversed by the propagating wavefront during its risetime. In actual fact, the presence of discontinuities along a line causes the apparent impedance of the line to be tapered to a lower value. If the line were to be severed an infinitesimal distance down-stream from a discontinuity, the impedance seen looking up-stream into the line at that point would

be the loaded (reduced) value. This loaded impedance is useful for determining either termination network resistances or additional propagation delay.

Bear in mind that this so-called loaded line impedance is only a useful mathematical fiction. The effect of the finite risetime of the signal versus the distance (meaning delay) between the loads only makes the impedance **appear** to have been uniformly reduced. The actual impedance of the line segments is still their unloaded characteristic impedance. This effect can be seen clearly when the  $Z_0$  of a transmission line with added lumped loads is measured using a device with an extremely fast risetime like a time-domain reflectometer. The  $Z_0$  is seen to be reduced only at the point of the attached load.

#### EXAMPLES

- Find the loaded line impedance and per-unit-length propagation delay resulting from adding 4 pF/cm to a micro-strip line having an unloaded  $Z_0$  of 50Ω and  $\epsilon_r$  of 4.3.
  - Move the slide to set 4 pF/cm on the  $C_D$  scale opposite 50Ω on the Unloaded  $Z_0$  scale.
  - Read 3100 on the Microstrip  $\delta'$  Factor scale at 4.3 on the upper  $\epsilon_r$  scale of the left-hand, middle window. Also, read 2.13 on the Microstrip  $Z_0'$  Factor scale at 4.3 on the upper  $\epsilon_r$  scale of the left-hand, bottom window.
  - Then move slide to set 3100 on the Factor scale (upper right-hand window) at the arrow.
  - Read 120 ps/cm on the Loaded  $\delta'$  scale opposite  $\epsilon_r = 4.3$  in the right-hand, middle window.
  - Reset slide to set 2.13 on the Factor scale (upper right-hand window) at the arrow.
  - Read 24Ω on the Microstrip Loaded  $Z_0'$  scale opposite 50Ω on the upper  $Z_0$  scale of the lower right-hand window.
- Find the individual capacitance value for 10 loads uniformly spaced along a 30 cm length of 75Ω microstrip transmission line if a 50Ω termination resistance results in no reflections. The substrate is known to have an  $\epsilon_r$  of 3.8. This type of measurement and computation is particularly useful for determining the actual value of loads distributed along a transmission line.
  - Move slide to set 50Ω on the Microstrip Loaded  $Z_0'$  scale (lower, right-hand window) opposite 75Ω on the upper  $Z_0$  scale.
  - Read 1.55 on the Factor scale in the upper, right-hand window.
  - Then move slide to set 1.55 on the Microstrip  $Z_0'$  Factor scale (lower, left-hand window) opposite 3.8 on the upper  $\epsilon_r$  scale.
  - Read 1.0 pF/cm on the  $C_D$  scale (upper, left-hand window) opposite 75Ω on the Unloaded  $Z_0$  scale.
  - A total of 30 pF is distributed among 10 loads; therefore, the capacitance of each load is 3 pF.

### REFLECTION COEFFICIENT (SIDE FOUR)

These scales calculate the reflection coefficient when line impedance  $Z_0$ , and the source or load impedance are known. The reflection coefficient, a dimensionless quantity, is the fraction of voltage reflected back toward the driving

source (or load) by a discontinuity in a transmission line. A discontinuity results from any physical change to the line that alters its characteristic impedance. The discontinuity may be an attached load, transmission line intersection, via in the line, termination device or even a change in the line's geometry.

#### EXAMPLES

- Find the reflection coefficient when a  $50\Omega$  line is terminated in  $75\Omega$ .
  - Move slide to set  $50\Omega$  at arrow.
  - Read  $\rho_L = +0.2$  at  $75\Omega$ .
- Find the line impedance if a 5V transmitted pulse measures 3.3V across a  $20\Omega$  termination resistor.
  - Since only 67% of the 5V pulse was measured at the load, the  $\rho_L = -0.33$ . Move slide to set  $20\Omega$  at  $-0.33$ .
  - Read  $Z_0 = 40\Omega$  at arrow.

#### EXAMPLE CALCULATIONS—ENGLISH UNITS

##### DIFFERENTIAL $Z_0$ (SIDE ONE)

- Find the differential impedance for a coupled pair of  $75\Omega$  microstrips spaced 10 mils apart on a 20 mils thick substrate.
  - Move slide to set 10 mils on the s scale at 20 mils on the h scale.
  - Read 0.702 on the Microstrip Factor scale at the arrow.
  - Move slide to set  $75\Omega$  on the  $Z_0$  scale opposite 0.702 on the Factor scale in lower window.
  - Read  $105\Omega$  on the  $Z_{diff}$  scale at the arrow.

##### MICROSTRIP AND STRIPLINE $Z_0$ (SIDE TWO)

- Find the conductor width to yield a  $93\Omega$  microstrip on a 30 mil substrate with 0.7 mil ( $\frac{1}{2}$  oz) copper cladding and dielectric constant of 3.8.
  - Move slide to set  $93\Omega$  on the Microstrip  $Z_0$  scale opposite 3.8 on the  $\epsilon_r$  scale directly below.
  - Read 25 on Microstrip Factor scale at the arrow.
  - Move slide to set 30 mils on the h scale at the arrow, top window.
  - In the window for  $t = 0.7$  mils ( $\frac{1}{2}$  oz), read 18 mils on the w scale opposite 25 on the Factor scale directly above.
- Find the impedance of a 25 mils wide microstrip line on a substrate with  $\epsilon_r = 4.3$ ,  $t = 1.4$  mils (1 oz cu.) and  $h = 20$  mils.
  - Move slide to set 20 mils on the h scale at the upper arrow, top window.
  - In the section for  $t = 1.4$  mils (1 oz) opposite 25 mils on the t scale, read  $-17$  on the Factor scale directly below.
  - Move slide to set  $-17$  on the Microstrip Factor scale at the arrow.
  - Read  $63\Omega$  on the Microstrip  $Z_0$  scale opposite 4.3 on the  $\epsilon_r$  scale directly below.

##### INTRINSIC DELAY (SIDE TWO)

- Find the per unit length delay of a stripline with  $\epsilon_r = 2.8$ .
  - Move slide to set 2.8 on the Stripline  $\epsilon_r$  scale at the arrow.
  - Read 142 ps/in on the  $T_d$  scale at the lower arrow.

##### MICROSTRIP AND STRIPLINE, $C_0$ AND $L_0$ (SIDE THREE)

- Find  $C_0$  and  $L_0$  for a  $75\Omega$  microstrip on a substrate having  $\epsilon_r = 3.8$ .
  - Move slide to set  $75\Omega$  on the Unloaded  $Z_0$  scale at the arrow.
  - Read 1.78 pF/in on the Microstrip  $C_0$  scale opposite 3.8 on the upper  $\epsilon_r$  scale.
  - Next read 10 nH/in on the Microstrip  $L_0$  scale opposite 3.8 on the upper  $\epsilon_r$  scale.

##### UNTERMINATED STUB LENGTH (SIDE THREE)

- Find the maximum length of an unterminated  $50\Omega$  microstrip on a substrate with  $\epsilon_r = 4.3$  and loaded by 10 pF.
  - Move slide to set 10 pF on the  $C_L$  scale opposite  $50\Omega$  on the  $Z_0$  scale.
  - Read 3040 on the Factor scale in the same window at the arrow.
  - Move slide to set 3040 on the Factor scale, middle window at the arrow.
  - Read 10.9 in. on the Microstrip  $L_{max}$  scale opposite 4.3 on the upper  $\epsilon_r$  scale.

##### PROPAGATION DELAY AND LOADED $Z_0$ (SIDE FOUR)

- Find the propagation delay and loaded line impedance when 4 pF/in of load capacitance is added to a microstrip line with unloaded  $Z_0 = 50\Omega$  and  $\epsilon_r$  of 2.4.
  - Move slide to set 4 pF/in on the Distributed  $C_D$  scale opposite  $50\Omega$  on the Unloaded  $Z_0$  scale.
  - Read 2000 on the Microstrip  $\delta'$  Factor scale opposite 2.4 on the  $\epsilon_r$  scale directly above. Read 1.53 on the Microstrip  $Z_0'$  Factor scale opposite 2.4 on the  $\epsilon_r$  scale directly above.
  - Next, move slide to set 2000 at the arrow for the Factor scale, upper right-hand window.
  - Read 190 ps/in on the Microstrip Loaded  $\delta'$  scale opposite 2.4 on the  $\epsilon_r$  scale directly above.
  - Next, move slide to set 1.53 at the arrow for the Factor scale at the upper right-hand window.
  - Read  $33\Omega$  on the Microstrip Loaded  $Z_0'$  scale opposite  $50\Omega$  on the  $Z_0$  scale directly above.

## APPENDIX A—SCALE FORMULATIONS—ISO METRIC UNITS

### MICROSTRIP AND STRIPLINE $Z_0$

Microstrip characteristic impedance is:

$$Z_0 = \frac{60}{\sqrt{0.475\epsilon_r + 0.67}} \ln \left[ \frac{4h}{0.67(0.8w + t)} \right] \text{ Ohms.}$$

If  $w \leq 2h$  (maximum error  $\cong 3\%$ ).

Microstrip line width is:

$$w = \frac{7.463h}{\exp \left( \frac{Z_0 \sqrt{0.475\epsilon_r + 0.67}}{60} \right)} - 1.25t \text{ cm}$$

Where:  $w$  = trace width in cm.,  $t$  = trace thickness in cm.,  $h$  = dielectric thickness in cm.,  $\epsilon_r$  = relative dielectric constant (dimensionless). **Note:** All geometric variables must be in the same dimensional units.

Stripline characteristic impedance is:

$$Z_0 = \frac{60}{\sqrt{\epsilon_r}} \ln \left[ \frac{4b}{0.67\pi(0.8w + t)} \right] \text{ Ohms.}$$

Best accuracy results if parameters are kept within these guiding ratios:  $b - t > 2w$  and  $b > 4t$ .

Stripline line width is:

$$w = \frac{2.375b}{\exp \left( \frac{Z_0 \sqrt{\epsilon_r}}{60} \right)} - 1.25t \text{ cm.}$$

Where:  $b$  = dielectric thickness (between ground planes) in cm. All other variables are as previously defined. **Note:** As for  $Z_0$ , guiding ratios apply.

### DIFFERENTIAL $Z_0$

For microstrip line the differential impedance,  $Z_{diff}$ , is:

$$Z_{diff} \cong 2Z_0 \left( 1 - 0.48e^{-0.96 \frac{s}{h}} \right) \text{ Ohms.}$$

For stripline the differential impedance,  $Z_{diff}$ , is:

$$Z_{diff} \cong 2Z_0 \left( 1 - 0.374e^{-2.9 \frac{s}{h}} \right) \text{ Ohms.}$$

**Note:** These functions were derived from empirical data. The actual accuracy has not been determined experimentally. Various sources cite possible errors of up to  $\pm 10\%$ . The practical ranges for  $Z_0$  and  $Z_{diff}$  are from  $20\Omega$  to about  $150\Omega$ .

### MICROSTRIP AND STRIPLINE, $C_0$ AND $L_0$

For microstrip, the intrinsic capacitance is:

$$C_0 = \frac{T_d}{Z_0} = \frac{33.36 \sqrt{0.475\epsilon_r + 0.67}}{Z_0} \text{ pF/cm.};$$

and the intrinsic inductance is:

$$L_0 = Z_0 T_d = 33.36 Z_0 \sqrt{0.475\epsilon_r + 0.67} \times 10^{-3} \text{ nH/cm.}$$

For stripline, the intrinsic capacitance is:

$$C_0 = \frac{T_d}{Z_0} = \frac{33.36 \sqrt{\epsilon_r}}{Z_0} \text{ pF/cm.};$$

and the intrinsic inductance is:

$$L_0 = Z_0 T_d = 33.36 Z_0 \sqrt{\epsilon_r} \times 10^{-3} \text{ nH/cm.}$$

### PROPAGATION VELOCITY AND INTRINSIC DELAY

The velocity of propagation for microstrip is:

$$v = \frac{1}{\sqrt{0.475\epsilon_r + 0.67}}$$

The intrinsic propagation delay for microstrip is:

$$T_d = 33.36 \sqrt{0.475\epsilon_r + 0.67} \text{ ps/cm.}$$

The velocity of propagation for stripline is:

$$v = \frac{1}{\sqrt{\epsilon_r}}$$

The intrinsic propagation delay for stripline is:

$$T_d = 33.36 \sqrt{\epsilon_r} \text{ ps/cm.}$$

Where,  $\epsilon_r$  = relative dielectric constant (dimensionless) and  $\epsilon_{reff}$  = effective relative dielectric constant.

### PROPAGATION DELAY AND LOADED $Z_0$

The general formula for loaded propagation delay is:

$$\delta' = \sqrt{T_d^2 + T_d Z_0 C_D} \text{ ps/cm.}$$

Loaded line impedance is:

$$Z_0' = \frac{Z_0}{\sqrt{\frac{C_D Z_0}{T_d} + 1}} \text{ Ohms } (\Omega),$$

Where: for microstrip

$$T_d = 33.36 \sqrt{0.475\epsilon_r + 0.67} \text{ ps/cm}$$

and for stripline.

$$T_d = 33.36 \sqrt{\epsilon_r} \text{ ps/cm}$$

$C_D$  is in pF and  $Z_0$  is in Ohms.

**Note:** For  $\epsilon_r > 1$ ,  $\epsilon_{reff} < \epsilon_r$

1. For Microstrip, the complete forms are:

$$\delta' = 5.776 \sqrt{15.85\epsilon_r + 22.35 + C_D Z_0 \sqrt{0.475\epsilon_r + 0.67}} \text{ ps/cm}$$

$$Z_0' = \frac{Z_0}{\sqrt{\frac{C_D Z_0}{33.36 \sqrt{0.475\epsilon_r + 0.67}} + 1}} \text{ Ohms } (\Omega)$$

1. For Stripline, the complete forms are:

$$\delta' = 5.776 \sqrt{33.36\epsilon_r + C_D Z_0 \sqrt{\epsilon_r}} \text{ ps/cm}$$

$$Z_0' = \frac{Z_0}{\sqrt{\frac{C_D Z_0}{33.36 \sqrt{\epsilon_r}} + 1}} \text{ Ohms } (\Omega)$$

**UNTERMINATED STUB LENGTH**

The general equation for unterminated stub length is:

$$L_{\max} = \frac{\sqrt{(C_t Z_0)^2 + t_r^2} - C_t Z_0}{2T_d} \text{ cm.}$$

Where:  $C_t$  in pF,  $t_r$  in ps and  $T_d$  in ps/cm.

As implemented for microstrip,

$$L_{\max} = \frac{\sqrt{(C_t Z_0)^2 + (12.3 \times 10^6)} - C_t Z_0}{66.7 \sqrt{0.475\epsilon_r + 0.67}} \text{ cm.}$$

and for stripline,

$$L_{\max} = \frac{\sqrt{(C_t Z_0)^2 + (12.3 \times 10^6)} - C_t Z_0}{66.7 \sqrt{\epsilon_r}} \text{ cm.}$$

Where:  $Z_0$  = line characteristics impedance (in Ohms),  $C_t$  = the total lumped value of capacitance terminating the line or stub (in pF),  $\epsilon_r$  = the relative dielectric constant. These equations were formulated assuming  $t_r = 3.5 \text{ ns} = 3.5 \times 10^3 \text{ ps}$ .

**REFLECTION COEFFICIENT**

$$\rho_L = \frac{R_L - Z_0}{R_L + Z_0}$$

$$\rho_S = \frac{R_S - Z_0}{R_S + Z_0}$$

Where:  $\rho_L$  = load reflection coefficient,  $\rho_S$  = source reflection coefficient,  $R_L$  = load resistance in Ohms,

$R_S$  = source driving-point resistance in Ohms,  $Z_0$  = transmission line impedance in Ohms

**REACTANCE FREQUENCY**

$$X_C = \frac{1}{2\pi fC} \text{ Ohms}$$

$$X_L = 2\pi fL \text{ Ohms}$$

**APPENDIX B—SCALE FORMULATIONS—ENGLISH UNITS****MICROSTRIP AND STRIPLINE  $Z_0$** 

Same as shown in Appendix A. All units are mils.

**DIFFERENTIAL  $Z_0$** 

Same as shown in Appendix A. All units are mils.

**MICROSTRIP AND STRIPLINE,  $C_0$  AND  $L_0$** 

For microstrip, the intrinsic capacitance is:

$$C_0 = \frac{T_d}{Z_0} = \frac{84.73 \sqrt{0.475\epsilon_r + 0.67}}{Z_0} \text{ pF/in.}$$

and the intrinsic inductance is:

$$L_0 = Z_0 T_d = 84.73 Z_0 \sqrt{0.475\epsilon_r + 0.67} \times 10^{-3} \text{ nH/in.}$$

For stripline, the intrinsic capacitance is:

$$C_0 = \frac{T_d}{Z_0} = \frac{84.73 \sqrt{\epsilon_r}}{Z_0} \text{ pF/in.}$$

and the intrinsic inductance is:

$$L_0 = Z_0 T_d = 84.73 Z_0 \sqrt{\epsilon_r} \times 10^{-3} \text{ nH/in.}$$

**PROPAGATION VELOCITY AND INTRINSIC DELAY**

The velocity of propagation for microstrip is the same as shown in Appendix A.

The intrinsic propagation delay for microstrip is:

$$T_d = 84.73 \sqrt{0.475\epsilon_r + 0.67} \text{ ps/in.}$$

The velocity of propagation for stripline is the same as shown in Appendix A.

The intrinsic propagation delay for stripline is:

$$T_d = 84.73 \sqrt{\epsilon_r} \text{ ps/in.}$$

Where,  $\epsilon_r$  = relative dielectric constant (dimensionless) and  $\epsilon_{\text{reff}}$  = effective relative dielectric constant.

**PROPAGATION DELAY AND LOADED  $Z_0$** 

The general formula for loaded propagation delay is the same as shown in Appendix A.

Loaded line impedance is the same as shown in Appendix A.

Except:

$$T_d = 84.73 \sqrt{0.475\epsilon_r + 0.67} \text{ ps/in.}$$

for microstrip and

$$T_d = 84.73 \sqrt{\epsilon_r} \text{ ps/in.}$$

for stripline.  $C_D$  is in pF and  $Z_0$  is in Ohms.

**Note:** For  $\epsilon_r > 1$ ,  $\epsilon_{\text{reff}} < \epsilon_r$

1. For Microstrip, the complete forms are:

$$\delta' = 9.205 \sqrt{40.25\epsilon_r + 56.77 + C_D Z_0 \sqrt{0.475\epsilon_r + 0.67}} \text{ ps/in.}$$

$$Z_0' = \frac{Z_0}{\sqrt{\frac{C_D Z_0}{84.73 \sqrt{0.475\epsilon_r + 0.67}} + 1}} \text{ Ohms } (\Omega)$$

2. For Stripline, the complete forms are:

$$\delta' = 9.205 \sqrt{84.73\epsilon_r + C_D Z_0 \sqrt{\epsilon_r}} \text{ ps/in.}$$

$$Z_0' = \frac{Z_0}{\sqrt{\frac{C_D Z_0}{84.73 \sqrt{\epsilon_r}} + 1}} \text{ Ohms } (\Omega)$$

**UNTERMINATED STUB LENGTH**

The general equation for unterminated stub length is:

$$L_{\max} = \frac{\sqrt{(C_t Z_0)^2 + t_r^2} - C_t Z_0}{2T_d} \text{ in.}$$

Where:  $C_t$  in pF,  $t_r$  in ps and  $T_d$  in ps/in.

As implemented for microstrip,

$$L_{\max} = \frac{\sqrt{(C_t Z_0)^2 + (12.3 \times 10^6)} - C_t Z_0}{169.3\sqrt{0.475\epsilon_r + 0.67}} \text{ in.}$$

and for stripline,

$$L_{\max} = \frac{\sqrt{(C_t Z_0)^2 + (12.3 \times 10^6)} - C_t Z_0}{169.3\sqrt{\epsilon_r}} \text{ in.}$$

Where:  $Z_0$  = line characteristic impedance (in Ohms),  $C_t$  = the total lumped value of capacitance terminating the line or stub (in pF),  $\epsilon_r$  = the relative dielectric constant. These equations were formulated assuming  $t_r = 3.5 \text{ ns} = 3.5 \times 10^3 \text{ ps}$ .

**REFLECTION COEFFICIENT**

See Appendix A

**REACTANCE FREQUENCY**

See Appendix A

**APPENDIX C—STANDARD 1% RESISTOR DECADES**

**STANDARD 1% RESISTOR DECADES**

10.0	12.1	14.7	17.8	21.5	26.1	31.6	38.3	46.4	56.2	68.1	82.5
10.2	12.4	15.0	18.2	22.1	26.7	32.4	39.2	47.5	57.6	69.8	84.5
10.5	12.7	15.4	18.7	22.6	27.4	33.2	40.2	48.7	59.0	71.5	86.6
10.7	13.0	15.8	19.1	23.2	28.0	34.0	41.2	49.9	60.4	73.2	88.7
11.0	13.3	16.2	19.6	23.7	28.7	34.8	42.2	51.1	61.9	75.0	90.9
11.3	13.7	16.5	20.0	24.3	29.4	35.7	43.2	52.3	63.4	76.8	93.1
11.5	14.0	16.9	20.5	24.9	30.1	36.5	44.2	53.6	64.9	78.7	95.3
11.8	14.3	17.4	21.0	25.5	30.9	37.4	45.3	54.9	66.5	80.6	97.6

**Note 1:** To obtain Standard Values, multiply values from Decade Table by powers of 10.

**APPENDIX D—VALUES OF  $\epsilon_r$  FOR COMMON MATERIALS**

Description	Dielectric	$\epsilon_r$
Epoxy/Glass	FR-4 Generic	4.3
Epoxy/Glass	G-10 Generic	4.3 ± 0.05
Polyimide G-30	Polyimide	4.2
PTFE/Glass	PTFE	2.4 nom
Polysulfone	Polysulfone	3.5–3.9

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