Application Note 905 Transmission Line RAPIDESIGNER Operation and

Applications Guide

TEXAS INSTRUMENTS

Transmission Line RAPIDESIGNER© Operation and Applications Guide

INTRODUCTION

The National Semiconductor Transmission Line RAPIDE-SIGNER 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 RAPIDE-SIGNER. 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.

AN011899-1
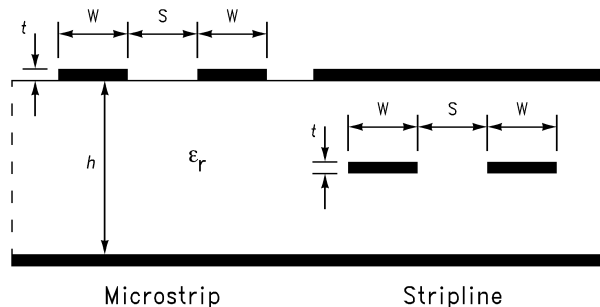
In common practice, *h* represents dielectric thickness for microstrip structures and *b* that for stripline. For simplicity, the

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

1. Find the capacitance value that will give 0.2Ω reactance at 50 MHz.
   A. Set 50 MHz on the Frequency scale opposite the arrow.
   B. Opposite 0.2Ω on the Capacitive Reactance scale, read 17 nF on the Capacitance scale.

2. Find the frequency at which 25 nH will have 10Ω reactance.
   A. Set 0.025 µH (25 nH) on the Inductance scale opposite 10Ω on the Inductive Reactance scale.
   B. Read 63 MHz on the Frequency scale at the arrow.

3. Find the capacitance value that will be resonant with 20 mH at 100 kHz.
   A. Set 100 kHz on the Frequency scale at the arrow.
   B. Opposite 20 mH on the Inductance scale, read 13 kΩ on the Inductive Reactance scale.
   C. Opposite 13 kΩ 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[1−6] 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.

AN011899

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. Kolias, 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. Digiacomo, "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 75Ω 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 75Ω on the Z_0 scale opposite 0.86 on the Factor scale (lower window).

   D. Read 128Ω 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^2 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 ϵ_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 93Ω microstrip on a 0.0813 cm substrate with 1.78×10^{-3} cm (½ oz) copper cladding and dielectric constant of 3.8.

   A. Move slide to set 93Ω on the Microstrip Z_0 scale opposite 3.8 on the ϵ_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 (½ 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 64Ω on the Microstrip Z_0 scale opposite 4.3 on the ϵ_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 ϵ_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 ϵ_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 75Ω microstrip on a substrate having $\epsilon_r = 3.8$.

   A. Move slide to set 75Ω 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 ϵ_r scale of the middle window.

   C. Read 3.95 nH/cm on the Microstrip L_0 scale at 3.8 on the upper ϵ_r scale of the lower window.

2. Find C_0 and L_0 for a 35Ω stripline on a substrate having $\epsilon_r = 2.4$.

   A. Move slide to set 35Ω 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 ϵ_r scale of the middle window.

   C. Read 1.8 nH/cm on the Stripline L_0 scale at 2.4 on the lower ϵ_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

1. Find the maximum length of a 50Ω microstrip stub on a substrate with ϵ_r = 4.3 which is terminated by 10 pF.
   A. Move slide to set 10 pF on the C_t scale opposite 50Ω on the Z_0 scale.
   B. Read 3040 on the Factor scale in the same window at the arrow.
   C. Move slide to set 3040 on the Factor scale (middle window) at the arrow.
   D. Read 27.7 cm on the Microstrip L_{max} scale (bottom window) opposite 4.3 on the upper ϵ_r scale.

2. A 35 cm stripline stub is terminated by 5 pF. If the substrate has an ϵ_r = 2.4 and the line impedance is 75Ω, is the stub length too long?
   A. Move slide to set 5 pF on the C_t scale opposite 75Ω on the Z_0 scale.
   B. Read 3150 on the Factor scale in the same window at the arrow.
   C. Move slide to set 3150 on the Factor scale (middle window) at the arrow.
   D. Read 30.5 cm on the Stripline L_{max} scale (bottom window) opposite 2.4 on the lower ϵ_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

1. 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 ϵ_r of 4.3.
   A. Move the slide to set 4 pF/cm on the C_D scale opposite 50Ω on the Unloaded Z_0 scale.
   B. Read 3100 on the Microstrip δ' Factor scale at 4.3 on the upper ϵ_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 ϵ_r scale of the left-hand, bottom window.
   C. Then move slide to set 3100 on the Factor scale (upper right-hand window) at the arrow.
   D. Read 120 ps/cm on the Loaded δ' scale opposite ϵ_r = 4.3 in the right-hand, middle window.
   E. Reset slide to set 2.13 on the Factor scale (upper right-hand window) at the arrow.
   F. Read 24Ω on the Microstrip Loaded Z_0' scale opposite 50Ω on the upper Z_0 scale of the lower right-hand window.

2. 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 ϵ_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.
   A. Move slide to set 50Ω on the Microstrip Loaded Z_0' scale (lower, right-hand window) opposite 75Ω on the upper Z_0 scale.
   B. Read 1.55 on the Factor scale in the upper, right-hand window.
   C. Then move slide to set 1.55 on the Microstrip Z_0' Factor scale (lower, left-hand window) opposite 3.8 on the upper ϵ_r scale.
   D. Read 1.0 pF/cm on the C_D scale (upper, left-hand window) opposite 75Ω on the Unloaded Z_0 scale.
   E. 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

1. Find the reflection coefficient when a 50Ω line is terminated in 75Ω.
   A. Move slide to set 50Ω at arrow.
   B. Read ρ_L = +0.2 at 75Ω.

2. Find the line impedance if a 5V transmitted pulse measures 3.3V across a 20Ω termination resistor.
   A. Since only 67% of the 5V pulse was measured at the load, the ρ_L = −0.33. Move slide to set 20Ω at −0.33.
   B. Read Z_0 = 40Ω at arrow.

EXAMPLE CALCULATIONS — ENGLISH UNITS

DIFFERENTIAL Z_o (SIDE ONE)

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

MICROSTRIP AND STRIPLINE Z_0 (SIDE TWO)

1. Find the conductor width to yield a 93Ω microstrip on a 30 mil substrate with 0.7 mil (½ oz) copper cladding and dielectric constant of 3.8.
   A. Move slide to set 93Ω on the Microstrip Z_0 scale opposite 3.8 on the ϵ_r scale directly below.
   B. Read 25 on Microstrip Factor scale at the arrow.
   C. Move slide to set 30 mils on the h scale at the arrow, top window.
   D. In the window for t = 0.7 mils (½ oz), read 18 mils on the w scale opposite 25 on the Factor scale directly above.

2. Find the impedance of a 25 mils wide microstrip line on a substrate with ϵ_r = 4.3, t = 1.4 mils (1 oz cu.) and h = 20 mils.
   A. Move slide to set 20 mils on the h scale at the upper arrow, top window.
   B. 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.
   C. Move slide to set −17 on the Microstrip Factor scale at the arrow.
   D. Read 63Ω on the Microstrip Z_0 scale opposite 4.3 on the ϵ_r scale directly below.

INTRINSIC DELAY (SIDE TWO)

1. Find the per unit length delay of a stripline with ϵ_r = 2.8.
   A. Move slide to set 2.8 on the Stripline ϵ_r scale at the arrow.
   B. Read 142 ps/in on the T_d scale at the lower arrow.

MICROSTRIP AND STRIPLINE, C_o AND L_o (SIDE THREE)

1. Find C_o and L_o for a 75Ω microstrip on a substrate having ϵ_r = 3.8.
   A. Move slide to set 75Ω on the Unloaded Z_0 scale at the arrow.
   B. Read 1.78 pF/in on the Microstrip C_o scale opposite 3.8 on the upper ϵ_r scale.
   C. Next read 10 nH/in on the Microstrip L_o scale opposite 3.8 on the upper ϵ_r scale.

UNTERMINATED STUB LENGTH (SIDE THREE)

1. Find the maximum length of an unterminated 50Ω microstrip on a substrate with ϵ_r = 4.3 and loaded by 10 pF.
   A. Move slide to set 10 pF on the C_t scale opposite 50Ω on the Z_0 scale.
   B. Read 3040 on the Factor scale in the same window at the arrow.
   C. Move slide to set 3040 on the Factor scale, middle window at the arrow.
   D. Read 10.9 in. on the Microstrip L_{max} scale opposite 4.3 on the upper ϵ_r scale.

PROPAGATION DELAY AND LOADED Z_0 (SIDE FOUR)

1. 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 = 50Ω and ϵ_r of 2.4.
   A. Move slide to set 4 pF/in on the Distributed C_D scale opposite 50Ω on the Unloaded Z_0 scale.
   B. Read 2000 on the Microstrip δ' Factor scale opposite 2.4 on the ϵ_r scale directly above. Read 1.53 on the Microstrip Z_0' Factor scale opposite 2.4 on the ϵ_r scale directly above.
   C. Next, move slide to set 2000 at the arrow for the Factor scale, upper right-hand window.
   D. Read 190 ps/in on the Microstrip Loaded δ' scale opposite 2.4 on the ϵ_r scale directly above.
   E. Next, move slide to set 1.53 at the arrow for the Factor scale at the upper right-hand window.
   F. Read 33Ω on the Microstrip Loaded Z_0' scale opposite 50Ω 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:

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

Where: w = trace width in cm., t = trace thickness in cm., *h* = dielectric thickness in cm., ϵ_r = relative dielectric constant (dimension less). **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:

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

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:

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

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

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

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

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, ϵ_r = relative dielectric constant (dimensionless) and ϵ_{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:

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

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 $\epsilon_r > 1$, $\epsilon_{\text{reff}} < \epsilon_r$

1. For Microstrip, the complete forms are:

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

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

1. For Stripline, the complete forms are:

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

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

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), ϵ_r = the relative dielectric constant. These equations were formulated assuming t_r = 3.5 ns = 3.5 x 10^3 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: ρ_L = load reflection coefficient, ρ_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

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

$$X_L = 2\pi f L \text{ Ohms}$$

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, ϵ_r = relative dielectric constant (dimensionless) and ϵ_{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 $\epsilon_r > 1$, $\epsilon_{reff} < \epsilon_r$

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), ϵ_r = the relative dielectric constant. These equations were formulated assuming t_r = 3.5 ns = 3.5 x 10^3 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 ϵ_r FOR COMMON MATERIALS

Description	Dielectric	ϵ_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

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal, regulatory and safety-related requirements concerning their products and any use of TI products in such safety-critical applications, notwithstanding any applications-related information or support that may be provided by TI. Further, Buyers must fully indemnify TI and its representatives against any damages arising out of the use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or "enhanced plastic." Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer's risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		Applications	
Audio	www.ti.com/audio	Communications and Telecom	www.ti.com/communications
Amplifiers	amplifier.ti.com	Computers and Peripherals	www.ti.com/computers
Data Converters	dataconverter.ti.com	Consumer Electronics	www.ti.com/consumer-apps
DLP® Products	www.dlp.com	Energy and Lighting	www.ti.com/energy
DSP	dsp.ti.com	Industrial	www.ti.com/industrial
Clocks and Timers	www.ti.com/clocks	Medical	www.ti.com/medical
Interface	interface.ti.com	Security	www.ti.com/security
Logic	logic.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Power Mgmt	power.ti.com	Transportation and Automotive	www.ti.com/automotive
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Mobile Processors	www.ti.com/omap		
Wireless Connectivity	www.ti.com/wirelessconnectivity		

TI E2E Community Home Page   e2e.ti.com

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2011, Texas Instruments Incorporated