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Microstrip Design in a Silicon Technology using Closed Form Analytical Expressions

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In this article, the author develops design equations for microstrip lines on a silicon substrate, using the metal and oxide layers as conductor, ground and dielectric

This article deals with the design of microstrip lines on a silicon substrate. Silicon is not a preferred microstrip substrate because in the usual case of integrated circuits, it has a low resistivity causing losses at high frequencies. Figure 1 shows a microstrip line that lies on top of a SiO_2 layer that in turn lies on a silicon substrate.

Since the resistivity of the silicon substrate is usually quite low in standard silicon processes, the electric field gets virtually shorted near the top of the substrate. However, for usual operating frequencies the magnetic field penetrates the substrate completely [1]. This imbalance causes multiple deleterious effects to take place in this configuration, including increased losses, wave velocity a function of substrate, slow velocity of signal propagation, and others.

As silicon technology advances toward high frequency performance with continually shrinking line widths, it becomes important to understand the behavior of the interconnect (and other distributed passive components). This understanding can only benefit the design of high performance ICs, both analog and digital.

In this article microstrip design on silicon is studied from the viewpoint of practical closed form expressions.

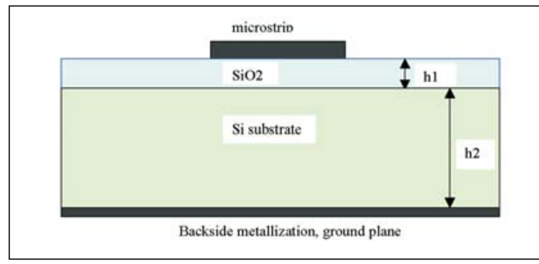

Figure 1 · Microstrip line on a silicon substrate with backside metallization and a layer of silicon dioxide.

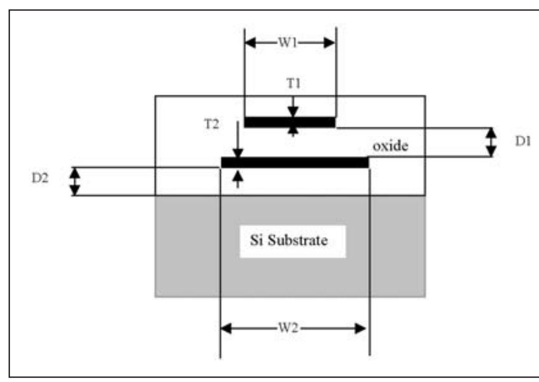

Figure 2 · Microstrip—substrate structure under study. T1 = thickness of microstrip line and T2 = thickness of ground return (bottom plate). D1 is oxide spacing (height of microstrip substrate). D2 is oxide spacing to the silicon substrate. W1 is the width of the microstrip line and W2 is width of ground return or bottom plate.

Structure

There are two methods of using microstrip on a silicon IC substrate. One is to treat the entire device (including the bulk silicon) as the substrate (as above) and the other is to use the interconnect layers of metal and the IMD (intermetal dielectric) as the de-facto substrate [2]. This is the method employed in this discussion and in all results presented. We

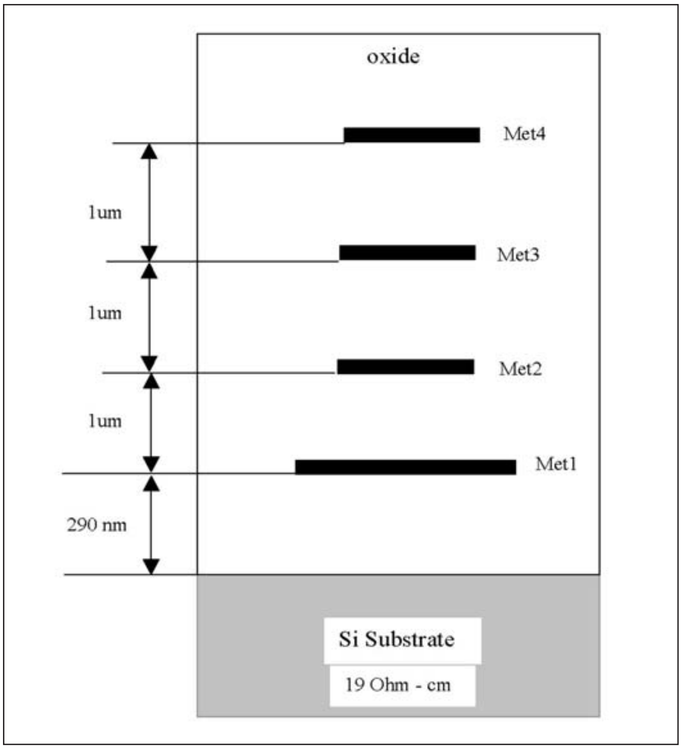

Figure 3 · The metallization structure for the process used in the study.

Metal level	Mean thickness (nm)	Sheet resistance (mohm/sq) (Mean)
Met1	665	70
Met2	640	70
Met3	640	70
Met4	2800	10

Table 1 · Summary of metal layer thickness and resistance values.

assume that the field is confined to the top signal line and the bottom ground return. Ref [2] presents results where the losses become relatively independent of strip width if the ratio of the top line and the ground return is greater than 5.0. Figure 2 shows the structure. The technology that was used in these calculations and presented results, is an industry standard, freely available 0.35 µm SiGe based process. Figure 3 shows the various dimensions of the interconnect layers in this process that were used to analyze the performance of the microstrip.

Disclaimer

This article is a presentation of procedure, formulae and simulated results that enable a design engineer to quickly do an initial design of microstrip for silicon substrates such as those found in CMOS, Bipolar, BiCMOS and SiGe-BiCMOS processes. It does not address MICs on alumina substrates or other materials, such as ferrite, etc. The data presented here and the procedures described should always be checked with EM simulations for the final implementation on the product device. A follow-on paper on these techniques and (public domain) software is anticipated from the author.

Met1, Met2, Met3 and Met4 are the 4 levels of metal. Met4 is thicker metal. See Table 1 for metal thickness and sheet resistance.

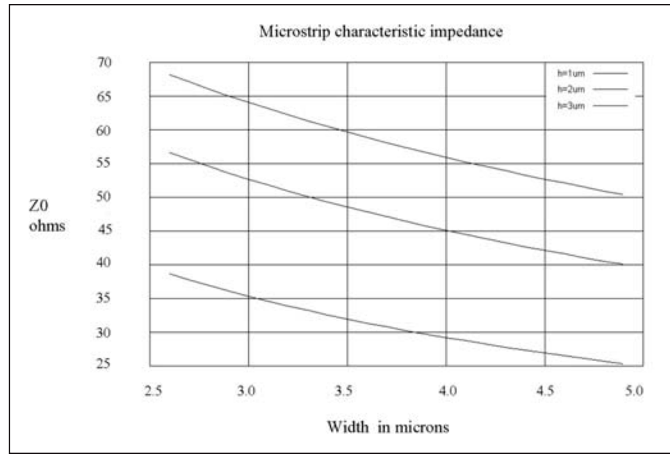

Figure 4 · Characteristic Impedance for varying width at 1 µm, 2 µm and 3 µm oxide thickness. Top curve is for *h* = 3 µm, middle curve is for *h* = 2 µm, bottom curve is for *h* = 1 µm.

Characteristic Impedance and Effective Permittivity

The starting point for the study is the models developed by Hammerstad and Jensen, widely accepted as very accurate (impedance accurate to within 0.01% for w/h ratios of less than or equal to 1.0 and 0.03% accurate for w/h ratios of less than or equal to 1000).

In order to calculate the characteristic impedance from the Hammerstad and Jensen equation the quantity η, or the wave impedance of SiO_2 must be found. In this article the following value is calculated and justified. (Note that this value is not available in the literature or the Web easily. The author has failed to find it even after assiduous effort. Comments are welcome.)

The wave impedance for any medium is defined as $\sqrt{(\mu/\varepsilon)}$, i.e., the square root of the ratio of the permeability of the medium to its permittivity.

The assumption for the calculation of the wave impedance is that the magnetic permeability of silicon dioxide is approximately the same as that of free space, i.e., $4\pi \times 10^{-7}$ H/m and that the permittivity is 34.5×10^{-12} F/m $(8.854 \times 10^{-12}) \times 3.9$). This yields the static wave impedance of 190.85 ohms. The wave impedance of

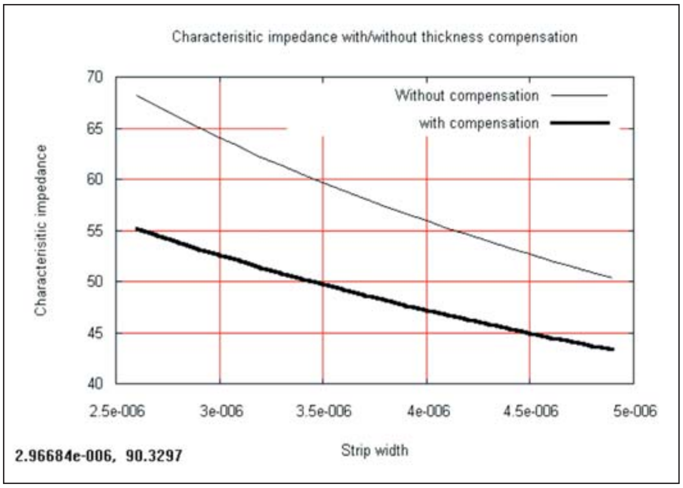

Figure 5 · Characteristic impedance, with and without thickness compensation for a substrate height of 3.0 µm and strip thickness of 2.8 µm (lower curve).

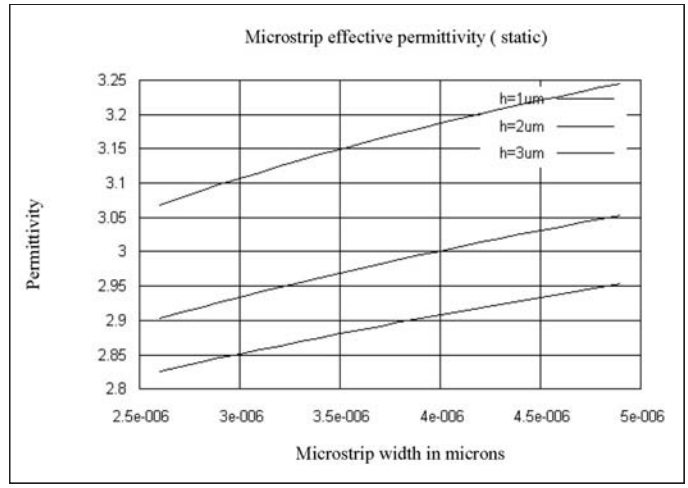

Figure 6 · Effective permittivity (static) variation with strip width (ε_r = 3.9). Top curve is for *h* = 1 µm, middle curve is for *h* = 2 µm and bottom curve is for *h* = 3 µm (*h* is the substrate thickness.

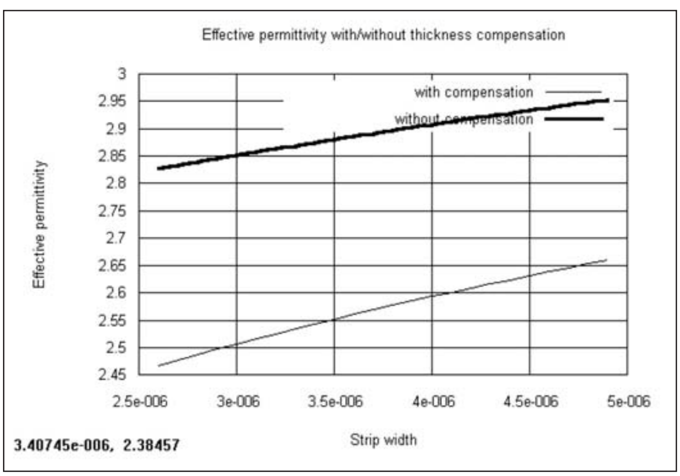

Figure 7 · Effective permittivity as a function of microstrip width with and without strip thickness as a parameter. h = 3.0 µm, thickness t = 2.8 µm.

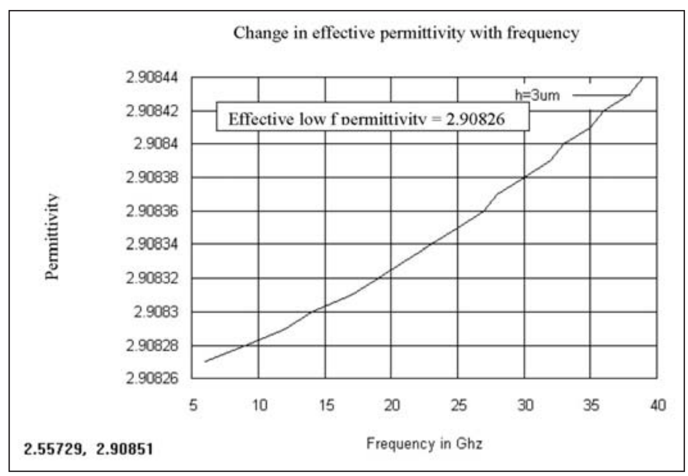

Figure 8 · Change in effective permittivity with frequency (width = 4.0 µm, substrate height = 3.0 µm).

a vacuum is 376.73 ohms.

The plot in Figure 4 shows the values of characteristic impedance on a typical silicon substrate with IMD thicknesses of 1 µm, 2 µm, 3 µm and varying width.

Figure 6 shows the variation of effective permittivity with line width for three different IMD thicknesses (1 µm, 2 µm and 3 µm) which in our case correspond to Metal1 to Metal2, Metal1 to Metal3 and Metal1 to Metal4, IMDs.

These two quantities (Z_0 and permittivity) are the key to analyzing microstrip on a silicon (or silicon oxide) substrate. Once the characteristic impedance and the effective permittivity is known other characteristics of the system can be analyzed.

Microstrip Thickness Corrections

The results obtained for microstrip characteristic impedance and effective permittivity above were based on a microstrip thickness of t = 0. When microstrip thickness is finite, the thickness can be compensated by a reduction of width. Figure 5 shows the characteristic impedance with and without thickness correction. In this calculation the height of the substrate is 3.0 µm, the thickness of the strip is 2.8 µm (in the thickness corrected curve). The closed expressions that were used in this case are due to Hammerstad and Jensen. These give better accuracy for narrower strips and substrates with lower dielectric constants.

w = 2.5 μm

H (μm)	TM Mode frequency (Hz)	Transverse Resonance frequency (Hz)
1	2.9E17	2.58E15
2	1.48E17	2.2E15
3	9.9E16	2.02E15

w = 5 μm

H (μm)	TM Mode frequency (Hz)	Transverse Resonance frequency (Hz)
1	2.97E17	1.38E15
2	1.48E17	1.29E15
3	9.9E16	1.2E15

w = 10 μm

H (μm)	TM Mode frequency (Hz)	Transverse Resonance frequency (Hz)
1	2.9E17	7.2E14
2	1.48E17	6.94E14
3	9.9E16	6.69E14

Table 2 · TM mode and transverse resonance frequencies for three line widths at three heights (ε_r = 4.0).

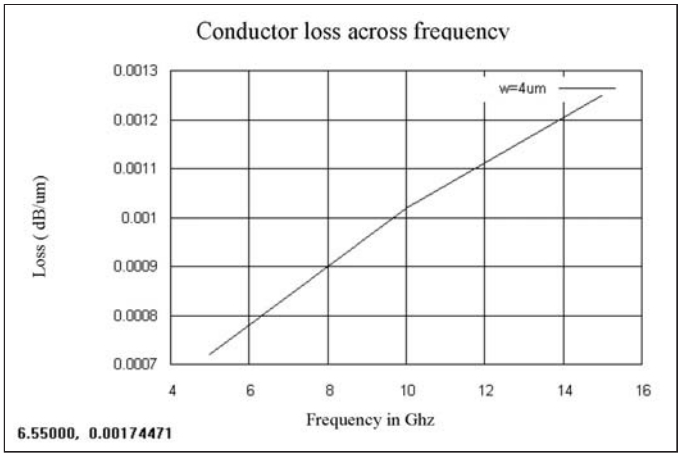

Figure 9 · Conductor loss in a 4 μm wide microstrip over a 3 μm thick oxide substrate at various frequencies. The characteristic impedance was 55.9196 ohms.

Thickness Correction for Permittivity

The calculated permittivity also changes when the thickness of the microstrip is taken into account. The curves in Figure 7 show the calculated permittivity with and without thickness correction for a 3 μm high substrate and varying width.

Change of Permittivity with Frequency

The effective permittivity also changes with frequency. So to find the actual guide wavelength at a frequency it is necessary to know the effective permittivity at that frequency (specially at high frequencies). The plot in Figure 8 shows the changes of effective permittivity with frequency.

The expressions used for the analysis of effective permittivity change with frequency are those developed by Kirschning and Jansen. Once the permittivity is known the wavelength can be calculated as $\lambda g = \lambda_0/\sqrt{eff(f)}$, where λg = guide wavelength, λ_0 = free space wavelength.

Operating Frequency Limitations for Microstrip on Silicon

There are two operating frequency limitations for microstrip. These are: TM mode limitation and the transverse microstrip resonance. Operation at these frequencies or above should be avoided. Table 2 presents the TM mode and transverse microstrip resonance frequencies for a particular height and width of microstrip.

From these tables it appears that for typical silicon-based design of devices these limitations are well above the frequencies of operation encountered in today's designs and may not be a factor.

Losses in microstrip

There are two major losses in microstrip. These are the conductor loss and the dielectric loss. The computed data for a particular width and height of substrate are shown in Figure 9. The sheet resistance was extracted from the manufacturers design rules.

Figure 10 presents the dielectric loss for a SiO_2 (de-facto) substrate. Note that both losses are very small.

Q Factor

Another important parameter is the quality factor or *Q* factor of the microstrip. Figure 11 shows the *Q* factor for various guide wavelengths for a 4 µm wide microstrip line on a 3 µm high substrate. The sheet resistance of the metal is 70 milliohm per square. Obviously the important quantity here is the attenuation per micron of line length derived retroactively from the quality factor values of a 1 meter line.

The parameters of the calculation in Figure 11 are the width of the line, the height of the substrate, the length of line, the characteristic impedance of the line and its effective permittivity at the frequency of operation. These latter parameters are extracted using algorithms and expressions reported above. The characteristic impedance was 55.9196 ohms.

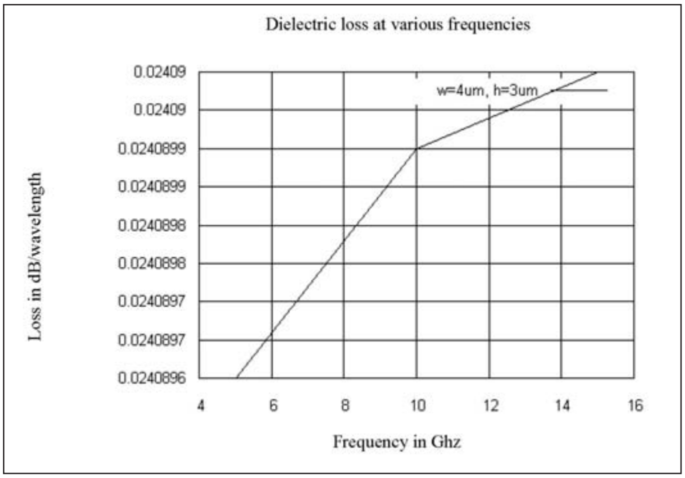

Figure 10 · Dielectric loss with varying frequencies for a 4 µm wide microstrip on a 3 µm thick oxide substrate.

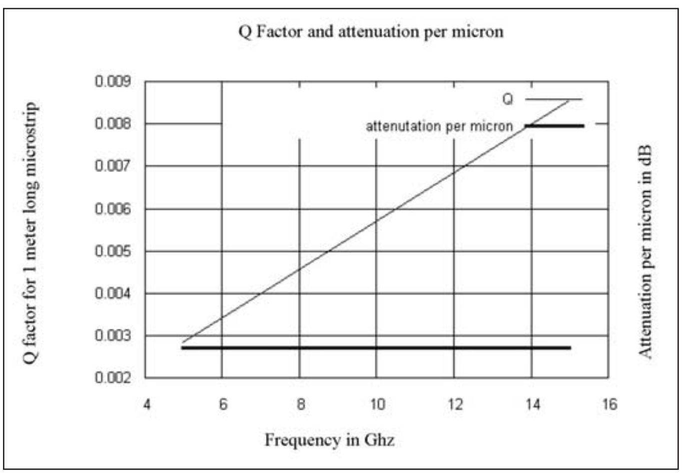

Figure 11 · The Q factor for a 1 meter long, 4 um wide microstrip line is shown. Also shown is the attenuation per micron of the microstrip in dB.

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Appendiix 1—Some Relevant Properties of Silicon Dioxide (SiO_2)

Property	Quantity
Dielectric constant	3.9
Refractive index	1.48
DC resistivity at 25 deg C	10^{14} to 10^{16} ohm-cm
Permeability	Free space (Note 1)
Wave impedance	190.85 ohms (Note 1)
Energy gap at 300K	9.0 eV
Thermal conductivity at 300K	0.014 W/cm-degK

Note 1—These quantities were estimated from the characteristics of SiO_2 and used in the calculations shown above.

Appendix 2.0—Closed Form Expressions

The following models were used in the calculations presented above:

• *Hammerstad and Jensen models for characteristic impedance and effective permittivity:*

Characteristic Impedance, Z_0, without thickness correction:

$$Z_0(u) = (\eta/2\pi)\ln[f(u)/u + \sqrt{(1.0 + (2/u)2)}]$$

(continued on pg. 28)

Appendix 2.0—Closed Form Expressions *(continued)*

Where η is the wave impedance of SiO_2 (190.85 ohms). The other quantities are defined below.

• *The effective permittivity without thickness correction is modeled by:*

$\varepsilon_e(u,\varepsilon_r) = (\varepsilon_r+1.0)/2 + (\varepsilon_r-1.0)/2\ [(1.0+10.0/u)^{-a(u)b(\varepsilon_r)}]$

Here u = aspect ratio w/h of the microstrip, where w = width and h is the thickness of the substrate,

ε_r = dielectric constant of substrate (In this case, SiO_2) = 3.9

The exponents a and b are defined below.

$a(u) = 1.0+(1/49)\ln[\{u^4 + (u/52)^2\}/\{u^4 + 0.432\}] + (1/18.7)\ln[1.0 + (u/18.1)^3]$

$b(\varepsilon_r) = 0.564[(\varepsilon_r - 0.9)/(\varepsilon_r + 3.0)]^{0.053}$

• *The microstrip thickness corrections are given by:*

$Z_0(u,t,\varepsilon_r) = Z_0(ur)/\sqrt{\varepsilon_e}\,(ur, \varepsilon_r)$

$e_{eff}(u, t, \varepsilon_r) = \varepsilon_e(ur, \varepsilon_r)[Z_0(u1)/ Z_0(ur)]^2$

$u1 = u + \Delta u1$ and $ur = u + \Delta ur$.

$\Delta u1 = (t/\pi)\ln[1.0 + (4.0\exp(1))/(t^*\coth^2 \sqrt{(6.517u)}]$

Thickness t is normalized to h, the thickness of the substrate i.e, t = thickness/h

$\Delta ur = 0.5[1.0 + (1.0/\cosh \sqrt{(\varepsilon_r - 1.0)}]\Delta u1$.

• *Frequency dependence of effective permittivity is based on Kirschning and Jansen's identities [] shown below:*

$e_{eff}(f) = \varepsilon_r - [(\varepsilon_r - e_{eff})/(1.0 + P(f))]$

f = frequency.

$P(f) = P1P2\{(0.1844 + P3P4)10fh\}^{1.5763}$

Here frequency is in GHz and thickness h is in cm.

$P1 = 0.27488+[0.6315+0.525/(1.0+0.157fh)^{20}](w/h) - 0.065683\exp(-8.7513w/h)$

$P2 = 0.33622[1.0 - \exp(-0.03442\varepsilon_r)]$

$P3 = 0.0363\exp(-4.6w/h)\{1.0 - \exp[-(fh/3.87)^{4.97}]\}$

$P4 = 1.0+2.751\{1.0 - \exp[-(\varepsilon_r/15.916)^8]\}$

• *Operating frequency limitations: The following expressions were used for this model:*

TM Mode limitation:

$f_{TEM,1} = c^*\tan^{-1}(\varepsilon_r)/[\sqrt{2}^*(\pi h)\sqrt{(\varepsilon_r - 1.0)}]$

c = speed of light.

Transverse resonance frequency limitation:

$f_{CT} = c/[\sqrt{\varepsilon_r}^*(2w + 0.8h)]$

• *Conductor and dielectric losses:*

Conductor loss is modeled by—

Alpha_dash = alpha_c$\{1.0+(2.0/\pi)\tan^{-1}[1.4(\Delta/\delta s)^2]\}$

Alpha_c = $0.072[\sqrt{(f)}/(wZ_0)]$lg dB/microstrip wavelength.

δs = skin depth at the operating frequency= $\sqrt{(\rho/(\pi f \mu)}$

where,
ρ = resisitivity of the microstrip material
μ = permeability = $4\pi 10^{-7}$
f = frequency.
λg = guide wavelength

Dielectric loss is modeled by—

Alpha_d = $27.3[\varepsilon_r(e_{eff} - 1.0)\tan\delta]/[e_{eff}(\varepsilon_r - 1.0)]$ dB/microstrip wavelength

$\tan\delta$ = loss tangent (typically of the order of 1×10^{-3})

• *Q factor:*

$Q = \pi/\alpha\lambda g$

λg = guide wavelength

α = attenuation in Nepers per meter