Reference Pages

Permeability:

$\mu = \mu_r \mu_0$

where μ_r is the relative permeability of the material (this is typically 1 for non-ferromagnetic materials) and μ_0 is the permeability of free space ($\mu_0 = 4\pi \cdot 10^{-7}\mathrm{H/m}$).

Permittivity:

$\varepsilon = \varepsilon_r \varepsilon_0$

where ε_r is the relative permittivity of the dielectric and ε_0 is the permittivity of free space ($\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m).

Electrical resistance:

$R = \frac{\rho l}{A_c}$

where ρ is the resistivity of the conductor, l is the length of the conductor, A_c is the cross-sectional area of the conductor.

Temperature dependence:

$R_1 = R_0 \cdot [1 + \alpha(T_1 - T_0)]$

where R_0 is the resistance at temperature T_0, R_1 is resistance at temperature T_1, and α is the temperature coefficient in 1/K or 1/°C.

Skin depth:

$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$

where ρ is the resistivity of the conductor, f is the frequency of the current through the conductor, μ is the permeability.

Effective area for circular cross-section:

$A_{eff} = \pi(d\delta - \delta^2)$, when $r \gg \delta$

where d is the diameter and r is the radius of the conductor cross-section.

Effective area for rectangular cross-section:

$A_{eff} = 2\delta(w + t - 2\delta)$, when w and $t \gg 2\delta$

where w is the width and t is the thickness of the conductor cross-section.

Inductance and capacitance effects:

$$\Delta V = L\frac{di}{dt} \qquad , \qquad \Delta I = C\frac{dv}{dt}$$

Self-inductance of a conductor with a circular cross-section:

Full equation:

$$L_{self} = \frac{\mu}{2\pi} l \left[ln\left(\frac{l}{r} + \sqrt{1 + \frac{l^2}{r^2}}\right) - \sqrt{1 + \frac{r^2}{l^2}} + \frac{r}{l} + \frac{1}{4} \right]$$

where μ is the permeability in H/m, l is the length in meters, and r is the radius of the conductor in meters.

Simplified equation when $l \gg r$:

$$L_{self} = 0.002l\left[ln\left(\frac{2l}{r}\right) - \frac{3}{4}\right] \quad [\mu\text{H}]$$

where l is the length in centimeters, r is the radius of the conductor in centimeters, and the L_{self} is in units of μH.

Rule of thumb for self-inductance of a wire per unit length:

$$L_{self}/l \approx 25 \text{ nH/in} \approx 1 \text{ nH/mm}$$

Self-inductance of a conductor with a rectangular cross-section:

$$L_{self} = 0.002l\left(ln\left(\frac{2l}{w+t}\right) + 0.50049 + \frac{w+t}{3l}\right) \quad [\mu\text{H}]$$

where l is the length in centimeters, w is the width of the conductor in centimeters, t is the thickness of the conductor in centimeters and the L_{self} is in units of μH.

Mutual-inductance of parallel conductors:

Full equation:

$$M = 0.002l\left[ln\left(\frac{l}{s} + \sqrt{1 + \left(\frac{l}{s}\right)^2}\right) - \sqrt{1 + \left(\frac{s}{l}\right)^2} + \frac{s}{l}\right] \quad [\mu\text{H}]$$

where l is the length in centimeters, s is the spacing between the two conductors in centimeters, and the M is in units of μH.

Simplified equation when $l \gg s$:

$$M = 0.002l\left[ln\left(\frac{2l}{s}\right) - 1\right] \quad [\mu\text{H}]$$

where l is the length in centimeters, s is the spacing between the two conductors in centimeters, and the M is in units of μH.

Total inductance of a loop with two wires carrying current in opposite directions:

$$L_{total} = L_{1,self} + L_{2,self} - 2M_{12}$$

where L_{self} are the self inductances of the wires and M_{12} is the mutual inductance between the two wires.

Effective inductance of two wires in parallel carrying current in the same direction:

Full equation:

$$L_{total} = \frac{L_{1,self}L_{2,self} - M_{12}^2}{L_{1,self} + L_{2,self} - 2M_{12}}$$

where L_{self} are the self inductances of the wires and M_{12} is the mutual inductance between the two wires.

Simplified equation for $L_{1,self} = L_{2,self}$:

$$L_{total} = \frac{L_{self} + M_{12}}{2}$$

where L_{self} are the self inductances of the wires and M_{12} is the mutual inductance between the two wires.

Total inductance for a wire above a ground plane where one is the source and the other is the return:

$$L_{total} = \frac{\mu l}{2\pi}\cosh^{-1}\left(\frac{2s}{d}\right)$$

where μ is the permeability, l is the length, d is the diameter of the wire, and s is the spacing/distance between the center of the wire and the ground plane. Assumes $l \gg s$ and $s \gg d$.

Total inductance for parallel planes where one is the source and the other is the return:

$$L_{total} = \frac{\mu l s}{w}$$

where μ is the permeability, l is the length of the planes, w is the width of the planes, and s is the spacing/distance between the two parallel planes. Assumes $l \gg s$.

Capacitance for overlapping conductors:

$$C = \frac{\varepsilon A}{d}$$

where ε is the permittivity, A is the overlapping area, and d is the spacing/distance between the two overlapping conductors.

Transmission lines:

Propagation velocity:

$$v_p = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \quad \text{[m/s]}$$

where $c = 2.998 \times 10^8 \text{ m/s}$ is the speed of light in a vacuum.

Propagation delay:

$$t_{pd} = \frac{1}{v_p} = \frac{\sqrt{\mu_r \varepsilon_r}}{c} = \sqrt{L_0 C_0} \quad \text{[s/m]}$$

where $c = 2.998 \times 10^8 \text{ m/s}$ is the speed of light in a vacuum, L_0 is the characteristic inductance in H/m, and C_0 is the characteristic capacitance in F/m.

Wavelength:

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r \mu_r}} \quad \text{[m]}$$

where $c = 2.998 \times 10^8 \text{ m/s}$ is the speed of light in a vacuum.

Check for transmission-line effects:

$$t_r \leq (33.3 \text{ ps/cm}) \sqrt{\varepsilon_r} \times 2l \qquad \text{or} \qquad l > \frac{0.5\, t_r}{(33.3 \text{ ps/cm}) \sqrt{\varepsilon_r}}$$

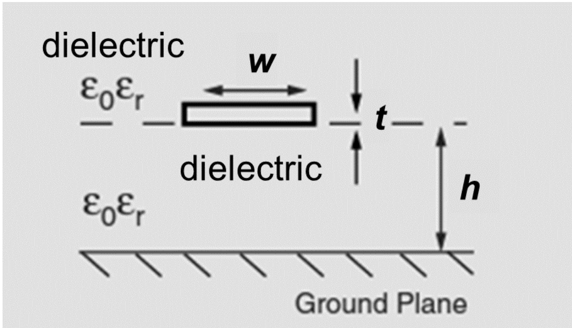
where t_r is the rise time of the signal in picoseconds, ε_r is the relative permittivity of the dielectric, l is the length of the interconnect in centimeters.

Characteristic impedance:

$$Z_0 = \sqrt{\frac{L_0}{C_0}} \quad [\Omega]$$

where L_0 is the characteristic inductance in H/m, and C_0 is the characteristic capacitance in F/m.

Microstrip embedded in a dielectric:



Propagation velocity for an embedded microstrip:

$$v_p = \frac{1}{\sqrt{\mu\varepsilon}}$$

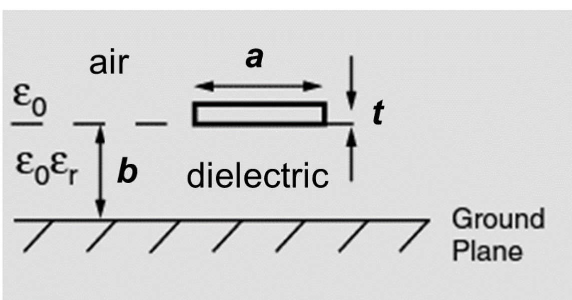
where μ is the permeability and ε is the permittivity.

Characteristic impedance for an embedded microstrip:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r + 1.41}} \ln\left(\frac{5.98h}{0.8w + t}\right)$$

where w is the width of the strip, h is the distance between the strip and the ground plane, t is the thickness of the strip, and ε_r is the relative permittivity of the dielectric.

Microstrip on the surface of a dielectric:



Propagation velocity for a microstrip on the surface of a dielectric:

$$v_p = \frac{1}{\sqrt{\mu\varepsilon_{eff}}}$$

$$\varepsilon_{eff} = \varepsilon_0 \left[\frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12\frac{b}{a}}}\right]$$

where a is the width of the strip, b is the distance between the strip and the ground plane, μ is the permeability, ε_r is the relative permittivity of the dielectric, and ε_0 is the relative permittivity of free space.

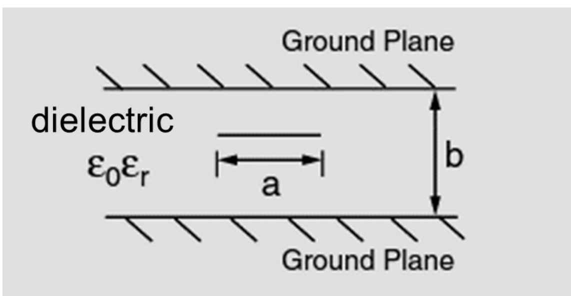
Characteristic impedance for a microstrip on the surface of a dielectric:

For $a < b$: $Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon_{eff}}}\ln\left(\frac{8b}{a} + \frac{a}{4b}\right)$

For $a > b$: $Z_0 = \sqrt{\frac{\mu}{\varepsilon_{eff}}}\left[\frac{1}{\frac{a}{b}+1.393+0.667\ln\left(\frac{a}{b}+1.444\right)}\right]$

where a is the width of the strip, b is the distance between the strip and the ground plane, μ is the permeability, and ε is the permittivity.

Stripline embedded in a dielectric:



Propagation velocity for a stripline embedded in a dielectric:

$$v_p = \frac{1}{\sqrt{\mu\varepsilon}}$$

where μ is the permeability and ε is the permittivity.

Characteristic impedance for a stripline embedded in a dielectric:

$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_r}}\frac{b}{a_{eff}+0.441b}$

For $a > 0.35b$: $a_{eff} = a$

For $a < 0.35b$: $a_{eff} = a - \left(0.35 - \frac{a}{b}\right)^2 b$

where a is the width of the strip, b is the distance between the two ground planes, and ε_r is the relative permittivity of the dielectric.

Reflection:

Reflection coefficient (source):

$\rho_s = \frac{R_s - Z_o}{R_s + Z_o}$

where R_s is the resistance of the source and Z_0 is the characteristic impedance of the line.

Reflection coefficient (output):

$\rho_o = \frac{R_o - Z_o}{R_o + Z_o}$

where R_o is the resistance of the output and Z_0 is the characteristic impedance of the line.

Thermal resistance:

General equation:

$$R_{th} = \frac{\Delta T}{q}$$

where R_{th} is the thermal resistance K/W or °C/W, q is the heat flow in W, and ΔT is the temperature difference.

Junction-to-ambient:

$R_{th,j-a} = \frac{T_j - T_a}{q} = R_{th,j-c} + R_{th,c-a}$

where $R_{th,j-a}$ is the junction-to-ambient thermal resistance, T_j is the junction temperature, T_a is the ambient temperature, $R_{th,j-c}$ is the junction-to-case thermal resistance, and $R_{th,c-a}$ is the case-to-ambient thermal resistance.

Conduction:

$q = \frac{kA_c\Delta T}{L}$, $R_{th,cond} = \frac{L}{kA_c}$

where q is the heat flow through an object, $R_{th,cond}$ is the thermal resistance of the object, k is the thermal conductivity of the object, A_c is the cross-sectional area of the object, ΔT is the temperature difference across the object, and L is the length.

Effective thermal conductivity:

$k_{eff} = k_m a_m + k_i(1 - a_m)$

where k_m is the thermal conductivity of the metal, k_i is the thermal conductivity of the insulator, a_m is the fraction of the area occupied by the metal.

Convection:

$q = hA_s(T_s - T_f) \quad , \quad R_{th,conv} = \frac{1}{hA_s}$

where q is the heat flow from a surface to a fluid in motion, $R_{th,conv}$ is the convective thermal resistance, h is the heat transfer coefficient, A_s is the wetted surface area, and T_s is the surface temperature, T_f is the fluid temperature.

Heat spreading:

Spreading width for a 45-degree spreading angle:

$w_{spread} = 2L + w$

where w_{spread} is the width the heat spreads, L is the length the heat travels (i.e., the thickness of the object), and w is the width of the heat source applied to the heat spreader.

Effective cross-sectional area for a 45-degree spreading angle:

$A_{eff} = \frac{(2L+w)^2+w^2}{2}$

where L is the length the heat travels (i.e., the thickness of the object) and w is the width of the heat applied to the heat spreader.

Unit conversions:

1 inch = 25.4 mm

1 mil = 25.4 µm

1 mil = 0.001 inch