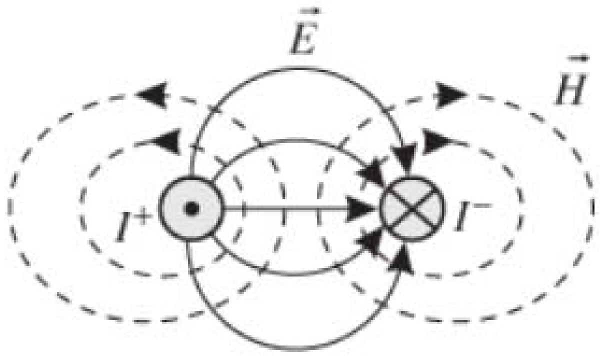
Lecture 3 Transmission Lines (3)

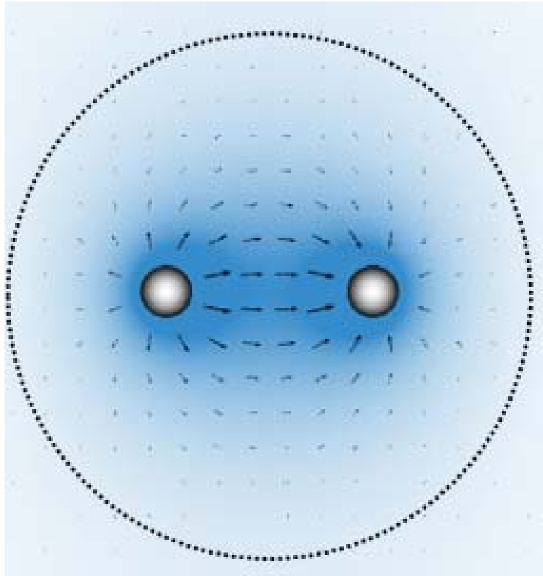
1. Caculation of *RLGC* Parameters of TEM Transmission Lines
2. *RLGC* Formulas of Simple Transmission Lines
3. Microstrip Line
4. Transmission Line Calculators
5. Coding Example

1. Caculation of *RLGC* Parameters of TEM Transmission Lines

- TEM (transverse electromagnetic)

- Transverse field only: $E_z = H_z = 0$





- Number of conductors ≥ 2

- Zero cutoff frequency: $f_c = 0$. For $f < f_c$, the wave cannot propagate.

- No dispersion (ideal case): Dispersion = frequency-dependent *RLGC*

- Simple formula for phase constant and guided wavelength:

$$\beta = \frac{2\pi}{\lambda_g}, \ \lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r}}$$

1. Caculation of *RLGC* Parameters of TEM Transmission Lines

- Examples of TEM transmission lines

- AC power cable

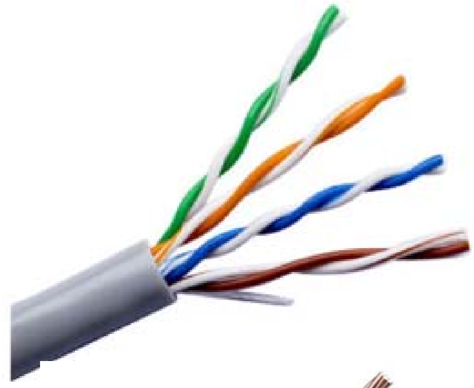
- UTP CAT.5E cable

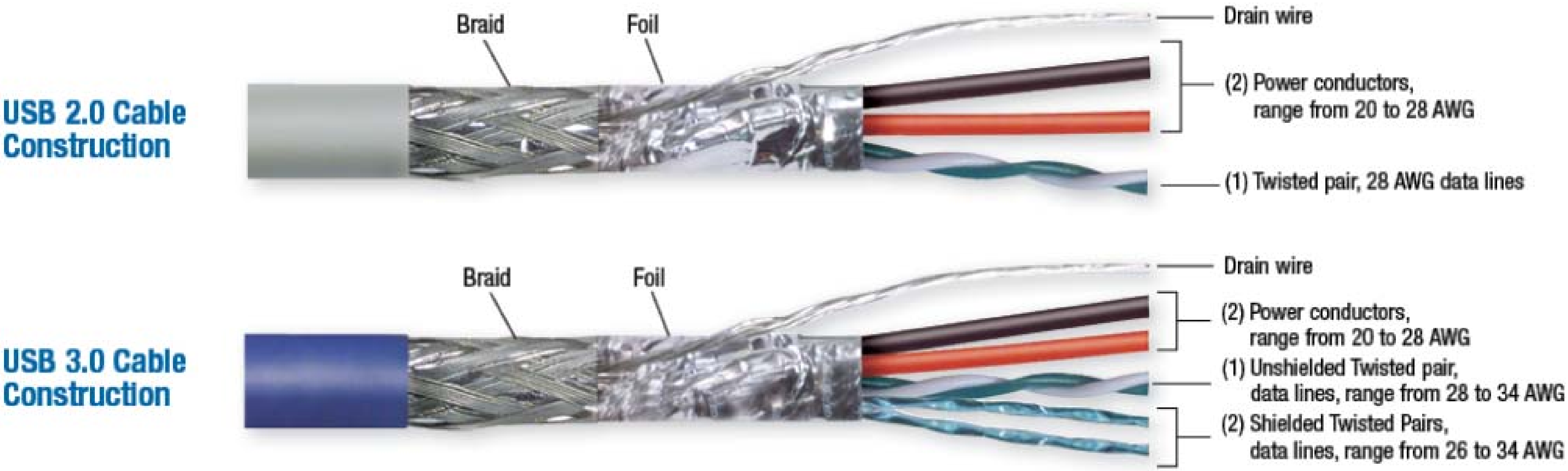
- USB 2.0, 3.0 cables

- Coaxial cable

UTP (Unshielded Twisted Pair)

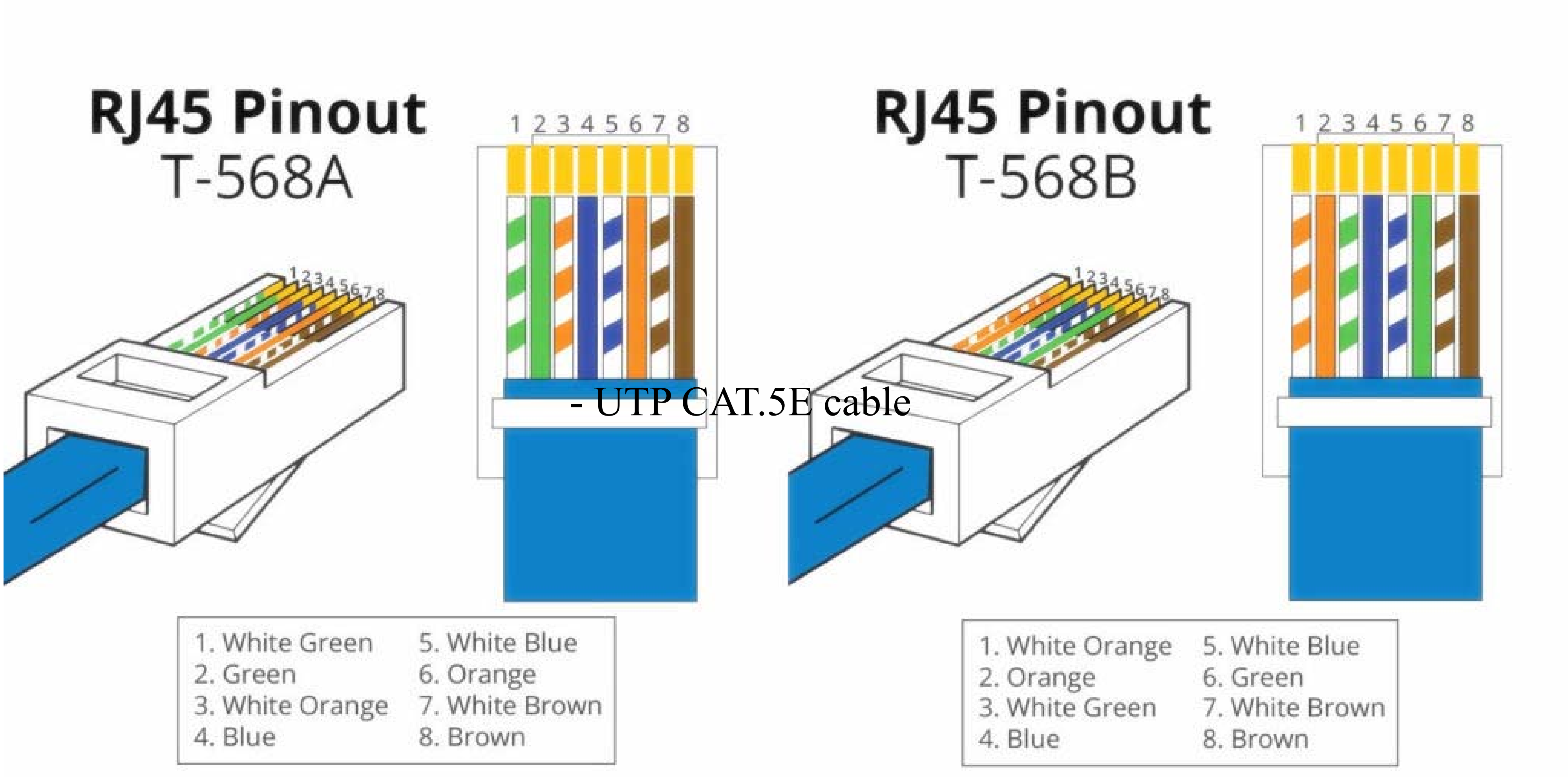
USB (Universal Serial Bus)





USB 3.0 adds two shielded data pairs to the USB 2.0 cable specifications. This addition allows for the faster performance in downloading data or video. Similar concept to changing a 2 lane highway to a 6 lane highway - much more traffic can pass through!

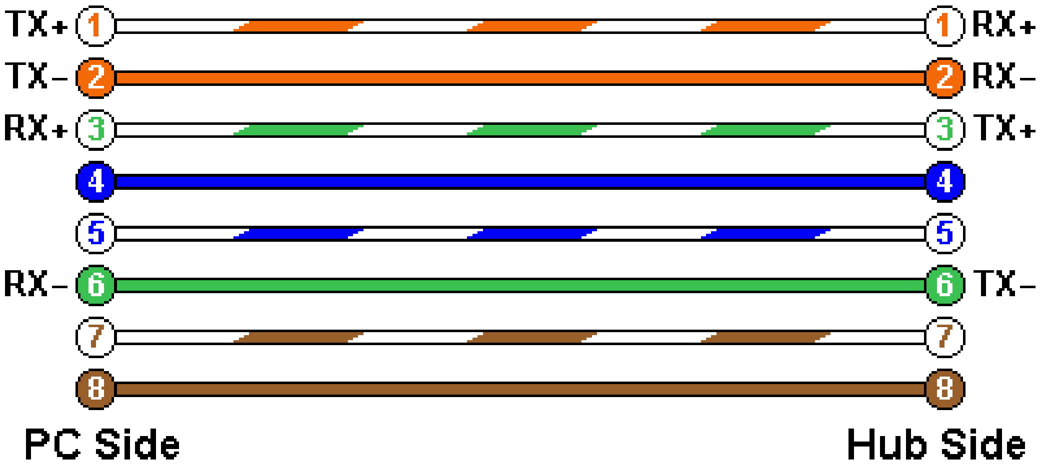
- Cat 5e - RJ45 connection



- UTP CAT.5E cable

1. Caculation of *RLGC* Parameters of TEM Transmission Lines

- Cat 5e wire designation



RJ45 Pin #	Wire Color (T568A)	Wire Diagram (T568A)	10Base-T Signal 100Base-TX Signal	1000Base-T Signal
1	White/Green		Transmit+	BI_DA+
2	Green		Transmit-	BI_DA-
3	White/Orange		Receive+	BI_DB+
4	Blue		Unused	BI_DC+
5	White/Blue		Unused	BI_DC-
6	Orange		Receive-	BI_DB-
7	White/Brown		Unused	BI_DD+
8	Brown		Unused	BI_DD-

- Use of *RLGC* parameters

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \text{ (characteristic impedance)}$$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta \text{ (propagation constant)}$$

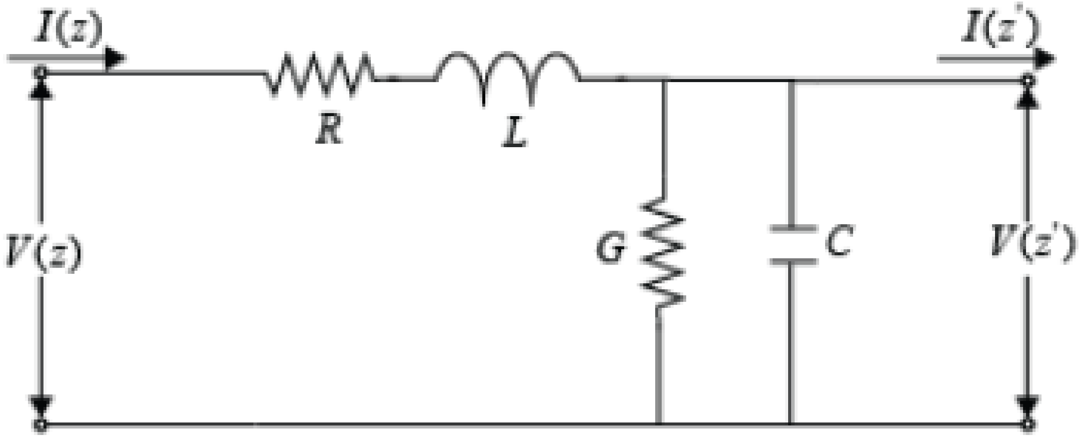
α : attenuation constant

β : phase constant

$$V(z) = V_0^+ e^{-\gamma z} + \Gamma(0) V_0^+ e^{\gamma z}$$

$$I(z) = \frac{V_0^+ e^{-\gamma z}}{Z_0} - \frac{\Gamma(0) V_0^+ e^{\gamma z}}{Z_0}$$

$$Z_{\text{in}}(z) = \frac{V(z)}{I(z)}$$



Low-loss line

$R << \omega L$ and $G << \omega C$

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{1}{Y_0} \text{ (characteristic impedance)}$$

$$\gamma = \alpha + j\beta \text{ (propagation constant)}$$

$$\alpha = \alpha_c + \alpha_d \text{ (attenuation constant)}$$

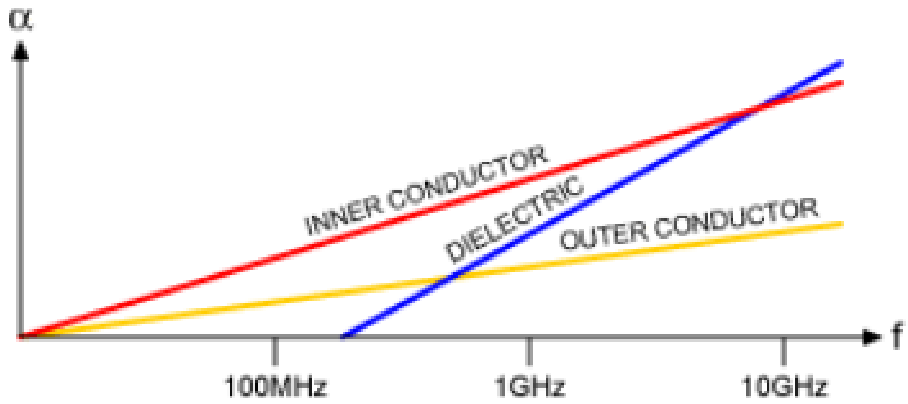
$$\alpha_c = \frac{R}{2Z_0} \text{ (attenuation constant due to conductor loss)}$$

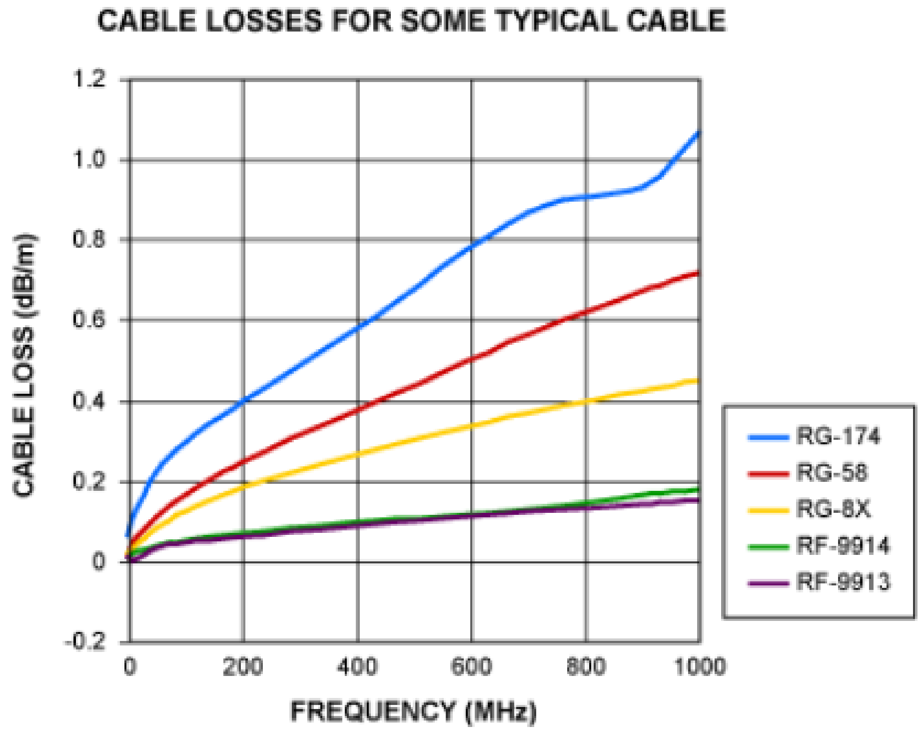
$$\alpha_d = \frac{G}{2Y_0} \text{ (attenuation constant due to dielectric loss)}$$

$$\beta = \frac{2\pi}{\lambda_g} = \omega\sqrt{LC} \text{ (phase propagation constant)}$$

$$\lambda_g = \frac{v_p}{f} \text{ (guided wavelength)}$$

$$v_p = \frac{1}{\sqrt{LC}} \text{ (phase velocity)}$$



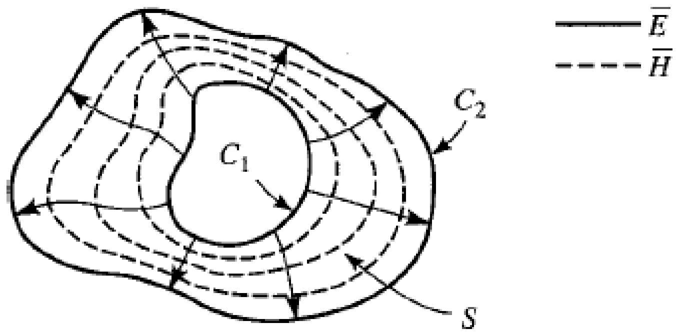


▪ High-frequency formulas for *RLGC* parameter calculation

- $R >> R_{DC}$ for $f >> 1$

$$R = \frac{R_s}{|I_o|^2} \int_{C_1+C_2} \bar{H} \cdot \bar{H}^* dl \ \Omega/\text{m}. \qquad L = \frac{\mu}{|I_o|^2} \int_S \bar{H} \cdot \bar{H}^* ds \ \text{H/m}.$$

$$G = \frac{\omega\epsilon''}{|V_o|^2} \int_S \bar{E} \cdot \bar{E}^* ds \ \text{S/m}. \qquad C = \frac{\epsilon}{|V_o|^2} \int_S \bar{E} \cdot \bar{E}^* ds \ \text{F/m}.$$



$$G = \frac{\omega\varepsilon''}{\varepsilon} C$$

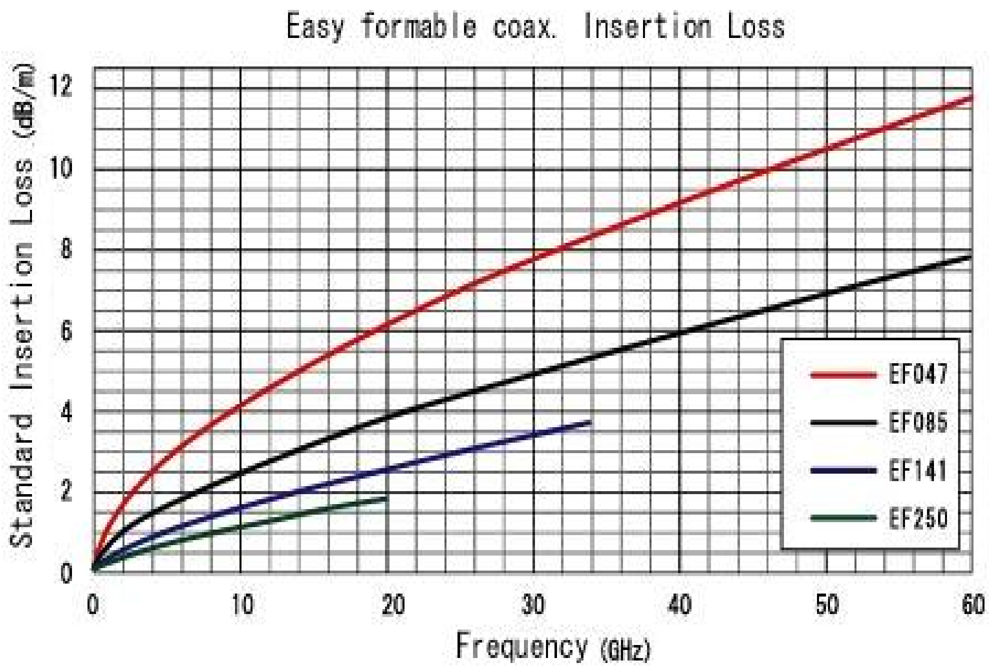
$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\pi f \mu}{\sigma}} \text{ (surface resistance)}$$

$$\delta = \sqrt{\frac{1}{\pi f \mu\sigma}}, \quad \sigma = \frac{1}{\rho} \text{ (conductivity of metal)}$$

$\mu = \mu_0 \mu_r$ (permeability)

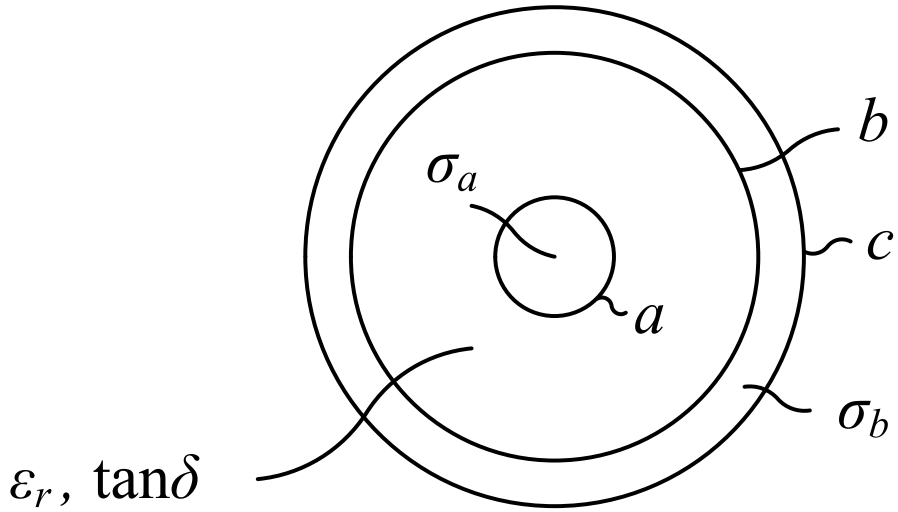
$\varepsilon'' = \varepsilon_0 \varepsilon_r''$ (imaginary part of permittivity)

$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 \varepsilon_r'$ (real part of permittivity)



- **All-frequency formulas for *RLGC* parameter calculation**

[F. Tesche, T-EMC, 49(1), 2007**]**



$$Z = Z_a + Z_b + j\omega L,\ Y = G + j\omega C$$

$$Z_0 = \sqrt{\frac{Z}{Y}},\ \gamma = \sqrt{ZY}$$

$$C = \frac{2\pi\varepsilon}{\ln(b/a)},\ L = \frac{\mu\varepsilon}{C},\ G = (\omega\tan\delta)C$$

$$R_{a1} = \frac{1}{\sigma_a(\pi a^2)},R_{b1} = \frac{1}{\sigma_b(\pi c^2 - \pi b^2)}$$

$$L_{ai} = \frac{\mu_0}{4\pi},L_{bi} = \frac{\mu_0}{2\pi}\left[\frac{c^4\ln(c/b)}{(c^2-b^2)^2} + \frac{b^2-3c^2}{4(c^2-b^2)}\right]$$

$$R_{a2} = \frac{R_s}{2\pi a},R_{b2} = \frac{R_s}{2\pi b},L_{a2} = \frac{R_{a2}}{\omega},L_{b2} = \frac{R_{b2}}{\omega}$$

$$Z_a = R_{a1} + \frac{j\omega L_{ai}(R_{a2} + j\omega L_{a2})}{R_{a2} + j\omega(L_{a1} + L_{a2})},\ Z_b = R_{b1} + \frac{j\omega L_{bi}(R_{b2} + j\omega L_{b2})}{R_{b2} + j\omega(L_{b1} + L_{b2})}$$

- **All-frequency formulas for *RLGC* parameter calculation**

  [J. Yoho, dissertation, UTP cable 24 AWG**]**

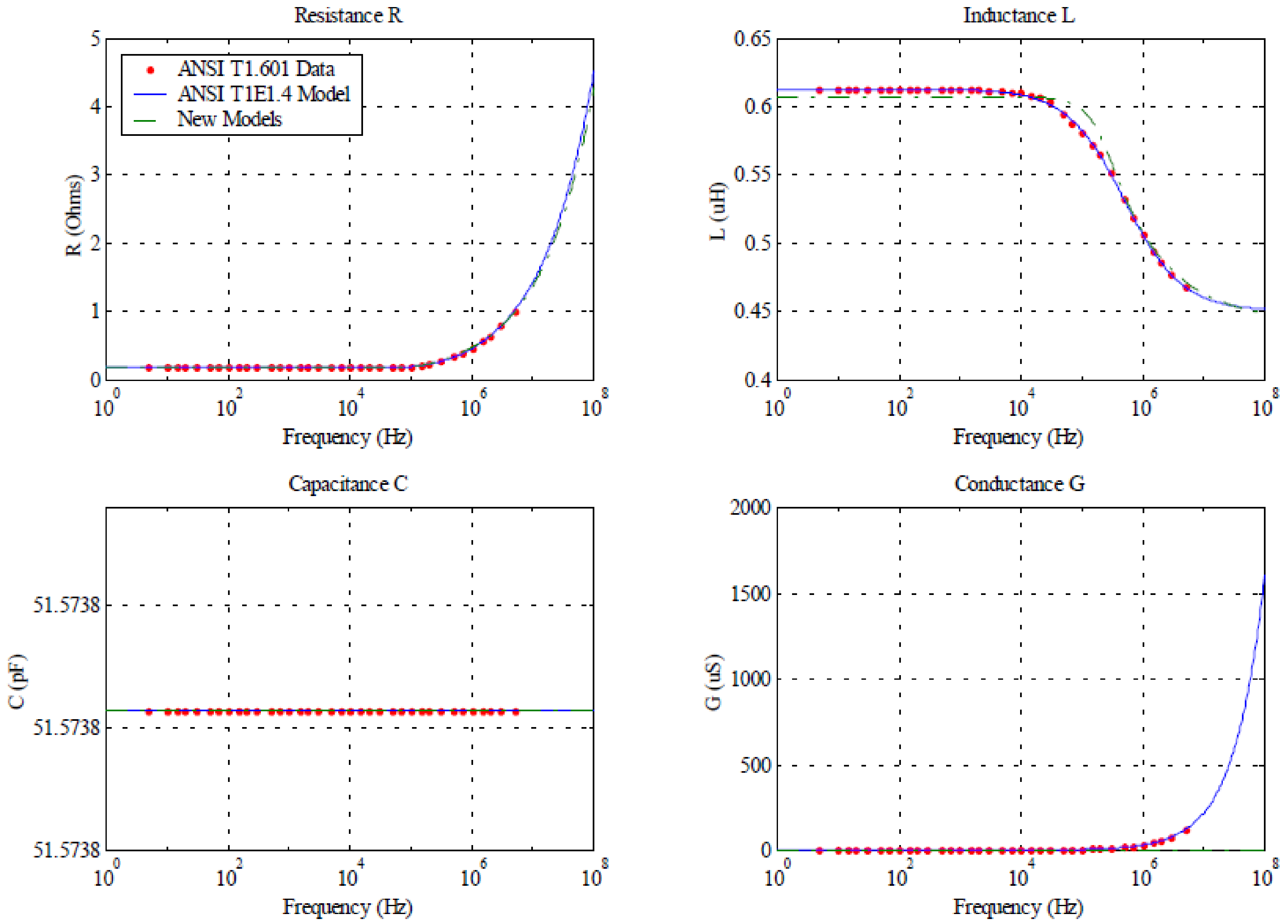
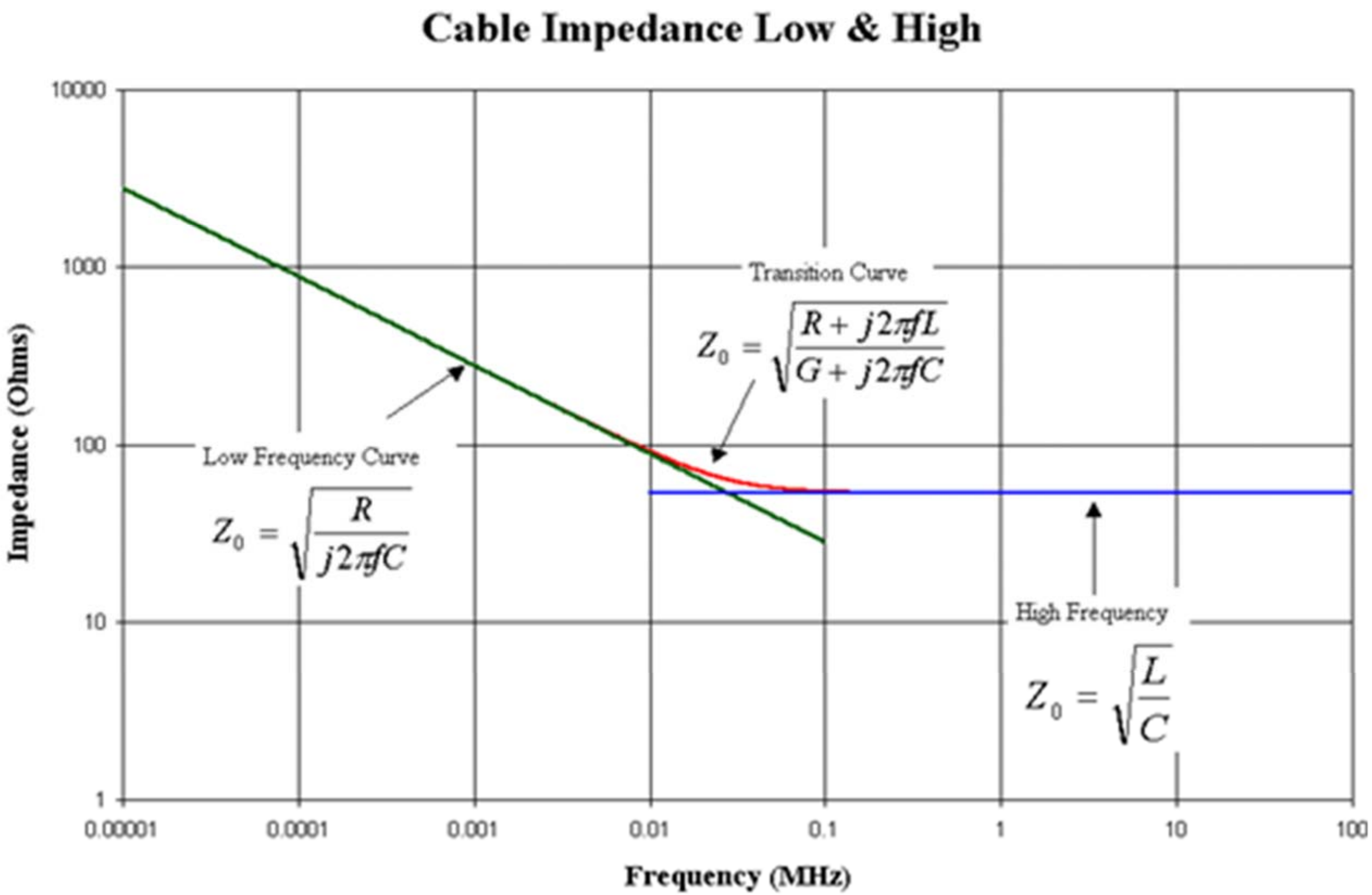


Figure 5-8: Model comparison to ANSI T1.601-1999 data of a 24 AWG SEALPIC cable.

- 50-ohm coaxial cable Z_0 vs frequency



- Air-filled transmission line

$$Z_{0,\text{air}} = \sqrt{\frac{L_0}{C_0}},\ L_0 C_0 = \mu_0 \varepsilon_0,\ \mu_0 \varepsilon_0 = 1/c^2,\ c = 3 \times 10^8 \text{ m/s (speed of light in vacuum)}$$

$$Z_{0,\text{air}} = \frac{\sqrt{\mu_0 \varepsilon_0}}{C_0} = \frac{1}{c C_0}$$

$$Z_{0,\text{air}} = \frac{L_0}{\sqrt{\mu_0 \varepsilon_0}} = c L_0$$

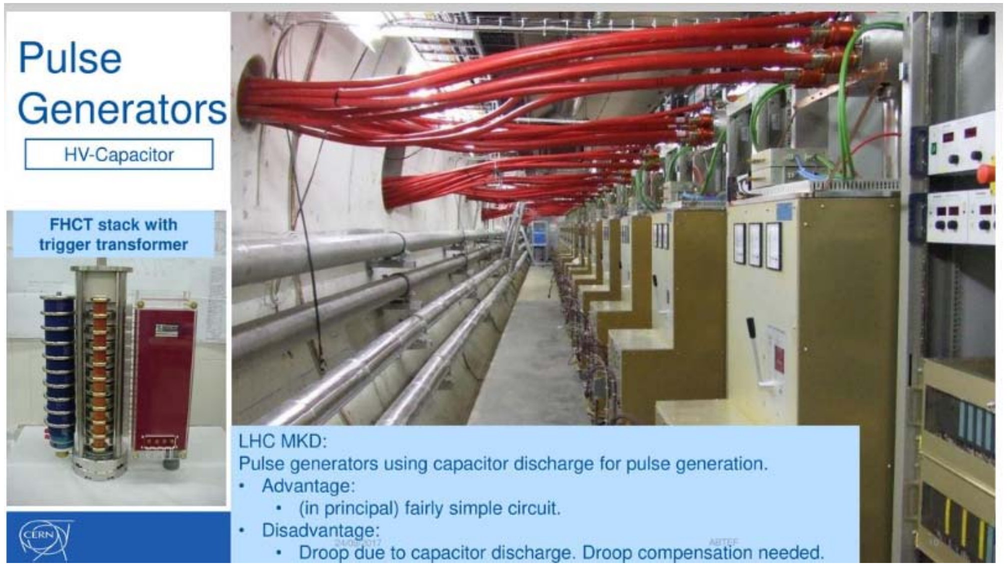
$$\boxed{C_0 = \frac{1}{c Z_{0,\text{air}}}}$$

$$\boxed{L_0 = \frac{Z_{0,\text{air}}}{c}}$$

H7-50

H7-50, HELIAX® Standard Air Dielectric Coaxial Cable, corrugated copper, 1-5/8 in, unjacketed

- SF6 gas filled high-voltage coxial cable



SF6 gas filled HV-cable (kickers)

- Dielectric: thin PE foil wrapped around inner conductor, pressurized with SF6 gas - fills all voids
- Superior dielectric strength
- Lower velocity factor due to low density PE core
- No issues with surface discharge of spacers used in large diameter coax cables.
- Low attenuation/losses (large ID, no semiconducting layers)

- ~14 km in operation at CERN since the seventies (no issues seen so far)
- Nominal voltages up to 80 kV

Disadvantage:
- Vacuum and SF6 gas systems needed
- Special gas tight connectors (in house production)
- No quick disconnect
- Cable relatively stiff and heavy (FAK: 1PFL =2.6 t)
- Not produced anymore!

- TEM transmission lines uniformly filled with dielectric material

$$Z_0 = \sqrt{\frac{L}{C}},\ LC = \mu\varepsilon = (\mu_r \mu_0)(\varepsilon_r \varepsilon_0)$$

$\mu_0 \varepsilon_0 = 1/c^2$, $c = 3 \times 10^8$ m/s (speed of light in vacuum)

$$L = \frac{\mu\varepsilon}{C} \rightarrow Z_0 = \frac{\sqrt{\mu\varepsilon}}{C} = \frac{\sqrt{\mu_r \varepsilon_r}\sqrt{\mu_0 \varepsilon_0}}{C} = \frac{\sqrt{\mu_r \varepsilon_r}}{cC} \rightarrow \boxed{C = \frac{\sqrt{\mu_r \varepsilon_r}}{cZ_0}}$$

$$C = \frac{\mu\varepsilon}{L} \rightarrow Z_0 = \frac{L}{\sqrt{\mu\varepsilon}} = \frac{L}{\sqrt{\mu_r \varepsilon_r}\sqrt{\mu_0 \varepsilon_0}} = \frac{cL}{\sqrt{\mu_r \varepsilon_r}} \rightarrow \boxed{L = \frac{Z_0 \sqrt{\mu_r \varepsilon_r}}{c}}$$

- Example

For an air-filled line with $Z_0 = 50\ \Omega$, $\alpha_c = 1$ dB/m, $\alpha_d = 0.8$ dB/m, find the transmission line parameters R, L, G and C.

(Solution)

$$\alpha_c(\text{Np/m}) = \alpha_c(\text{dB/m})/8.68 = 0.115 \rightarrow R = \alpha_c(2Z_0) = 11.5\ \Omega/\text{m}$$

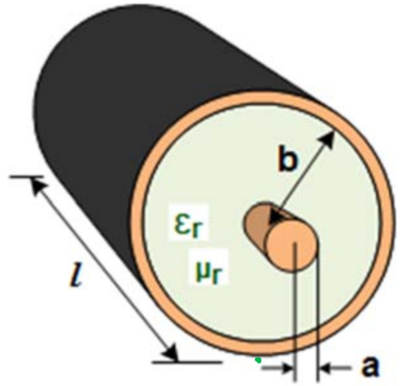
$$L = \frac{Z_{0,\text{air}}}{c} = 166.7\ \text{nH/m}$$

$$\alpha_d(\text{Np/m}) = \alpha_d(\text{dB/m})/8.68 = 0.0921 \rightarrow G = \alpha_d(2Y_0) = 3.69\ \text{mS/m}$$

$$C = \frac{1}{cZ_{0,\text{air}}} = 66.7\ \text{pF/m}$$

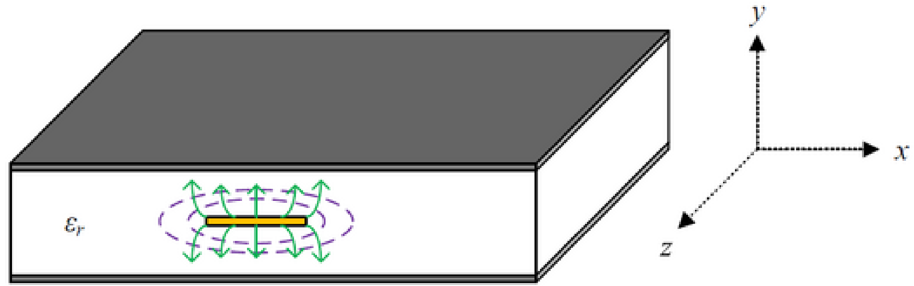
- Uniformly dielectric filled line

- *RLGC* extraction from Z_0, ε_r, α_c, α_d



$$Z_{0,\mathrm{air}} = \sqrt{\frac{L}{C}},\ LC = \mu_0\varepsilon_0\varepsilon_r,\ \mu_0\varepsilon_0 = 1/c^2$$

$$Z_0 = \frac{Z_{0,\mathrm{air}}}{\sqrt{\varepsilon_r}} = \frac{\sqrt{\varepsilon_r}}{cC}$$



$$Z_0 = \frac{Z_{0,\mathrm{air}}}{\sqrt{\varepsilon_r}} = \frac{L_0}{\sqrt{\mu_0\varepsilon_0\varepsilon_r}} = \frac{cL_0}{\sqrt{\varepsilon_r}}$$

$$\boxed{C = \frac{\varepsilon_r}{cZ_{0,\mathrm{air}}}},\ \boxed{L = \frac{Z_{0,\mathrm{air}}}{c} = L_0}$$

$$\alpha = \frac{1}{2}\left(\frac{R}{Z_0} + \frac{G}{Y_0}\right) = \alpha_c + \alpha_d \rightarrow R = 2\alpha_c Z_0,\ G = 2\alpha_d Y_0$$

$$Y_0 = 1/Z_0$$

- Partially dielectric filled line

- *RLGC* extraction from Z_0, ε_{re}, α_c, α_d

$$Z_{0,\mathrm{air}} = \sqrt{\frac{L}{C}},\ LC = \mu_0\varepsilon_0\varepsilon_{re},\ \mu_0\varepsilon_0 = 1/c^2$$

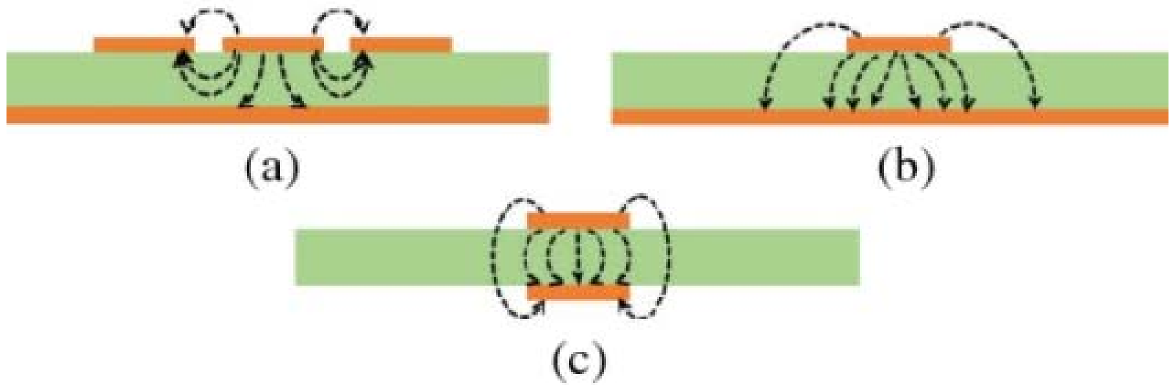
$$Z_0 = \frac{Z_{0,\mathrm{air}}}{\sqrt{\varepsilon_{re}}} = \frac{\sqrt{\varepsilon_{re}}}{cC}$$

$$Z_0 = \frac{Z_{0,\mathrm{air}}}{\sqrt{\varepsilon_{re}}} = \frac{L_0}{\sqrt{\mu_0\varepsilon_0\varepsilon_{re}}} = \frac{cL_0}{\sqrt{\varepsilon_{re}}}$$

$$\boxed{C = \frac{\varepsilon_{re}}{cZ_{0,\mathrm{air}}}},\ \boxed{L = \frac{Z_{0,\mathrm{air}}}{c} = L_0}$$

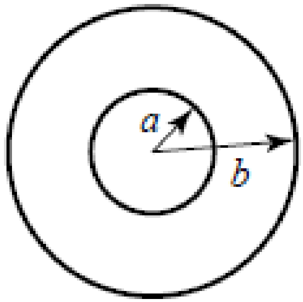
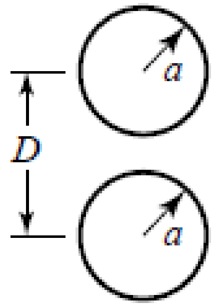
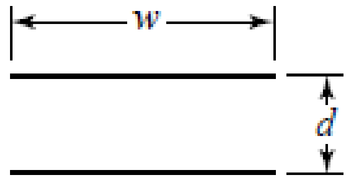
$$\alpha = \frac{1}{2}\left(\frac{R}{Z_0} + \frac{G}{Y_0}\right) = \alpha_c + \alpha_d \rightarrow R = 2\alpha_c Z_0,\ G = 2\alpha_d Y_0$$

$$Y_0 = 1/Z_0$$



2. *RLGC* Formulas of Simple Transmission Lines

- Coaxial, two-wire, parallel-plate lines

	COAX	TWO-WIRE	PARALLEL PLATE
			
L	$\frac{\mu}{2\pi}\ln\frac{b}{a}$	$\frac{\mu}{\pi}\cosh^{-1}\left(\frac{D}{2a}\right)$	$\frac{\mu d}{w}$
C	$\frac{2\pi\epsilon'}{\ln b/a}$	$\frac{\pi\epsilon'}{\cosh^{-1}(D/2a)}$	$\frac{\epsilon' w}{d}$
R	$\frac{R_s}{2\pi}\left(\frac{1}{a}+\frac{1}{b}\right)$	$\frac{R_s}{\pi a}$	$\frac{2R_s}{w}$
G	$\frac{2\pi\omega\epsilon''}{\ln b/a}$	$\frac{\pi\omega\epsilon''}{\cosh^{-1}(D/2a)}$	$\frac{\omega\epsilon'' w}{d}$

- Constants in *RLGC* calculation

$\omega = 2\pi f$

$\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m (non-magnetic dielectric materials)

$\varepsilon' = \varepsilon_0 \varepsilon_r$ (real part of complex permittivity)

$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m (permittivity of vacuum)

ε_r : dielectric constant

$\varepsilon'' = \varepsilon_0 \varepsilon_r \tan\delta$ (imaginary part of complex permittivity)

$\tan\delta$: loss tangent

$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\pi f \mu}{\sigma}}$ (surface resistance)

σ : conductivity (S/m), $\sigma = 5.8 \times 10^{7}$ S/m (copper)

$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$ (m) : skin depth

- Conductivity of metals relative to Cu

Material	σ_r	μ_r	$\sigma_r \mu_r$	σ_r / μ_r
Silver	1.05	1	1.05	1.05
Copper	1	1	1	1
Gold	0.7	1	0.7	0.7
Aluminum	0.61	1	0.61	0.61
Brass	0.26	1	0.26	0.26
Bronze	0.18	1	0.18	0.18
Tin	0.15	1	0.15	0.15
Lead	0.08	1	0.08	0.08
Nickel	0.2	100	20	2×10^{-3}
Stainless steel (430)	0.02	500	10	4×10^{-5}
Mumetal (at 1 kHz)	0.03	20,000	600	1.5×10^{-6}
Superpermalloy (at 1 kHz)	0.03	100,000	3,000	3×10^{-7}

- Dielectric constant and dissipation factor (loss tangent) of coaxial cable dielectrics

Ranking by Dielectric Constant	Ranking by Dissipation Factor	Dielectric Material	Dielectric Constant	Dissipation Factor	Temperature Range (°c)
1	1	Air in Vacuum (for reference)	1.000000	0.00000?	
2	2	Low Density or Expanded PTFE	1.30	<0.00008	-245 / +260
3	3	(PTFE) Polytetrafluoroethylene	2.05	<0.0002	-245 / +260
4	4	(PFA) Perfluoroalkoxy	2.0	<0.0004	-185 / +260
5	5	(FEP) Fluorinated Ethylene Propylene	2.1	<0.0007	-73 / +204
6	3	(PE) Polyethylene	2.25	<0.0002	-34 / +82
7	6	(PVC) Polyvinyl Chloride	3.18	<.016	-40 / +104

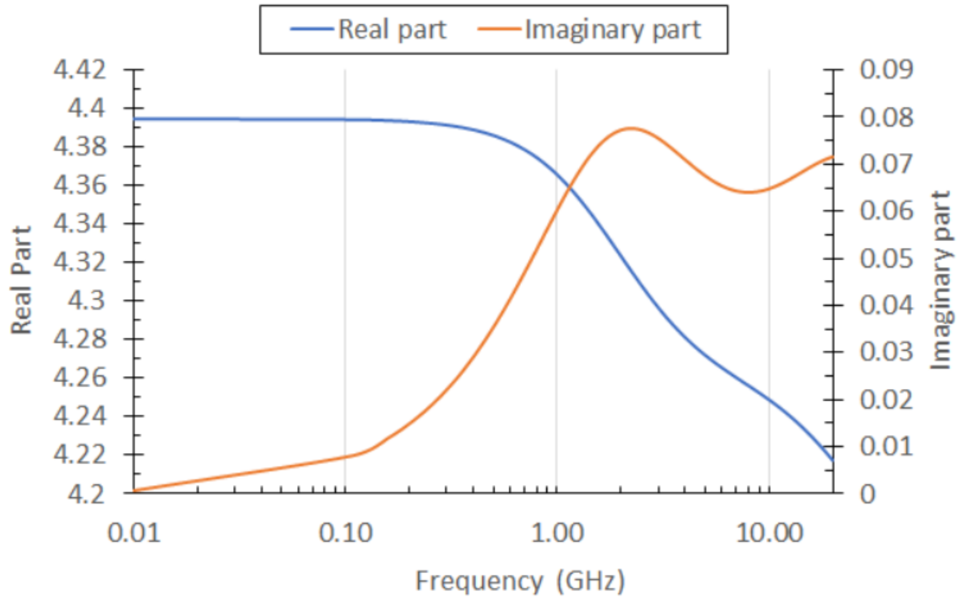
Table 1: Comparison of Common Coaxial Cable Dielectrics

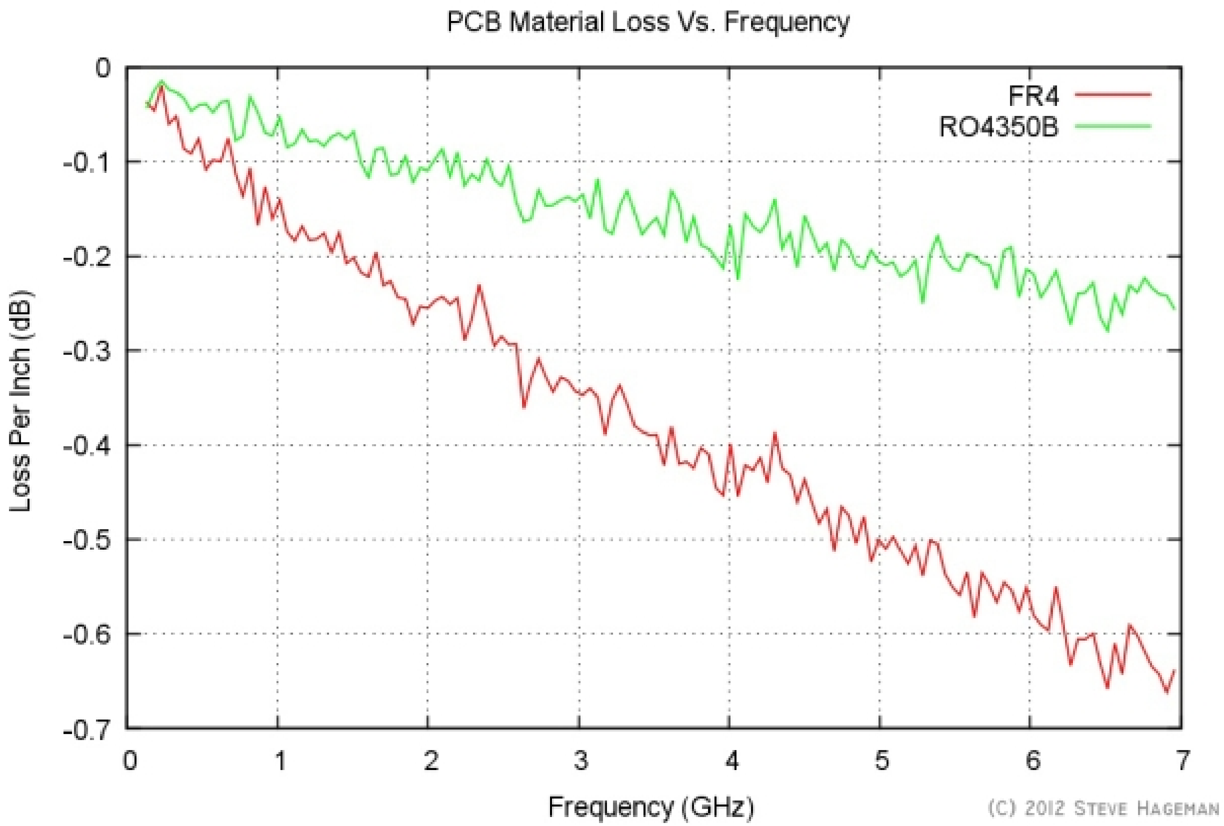
- Dielectric constant of PCB substrate materials

Material	Surface roughness (μm)	$10^4 \tan\delta$ (at 10 GHz)	ε_r	Thermal conductivity K (W/cm^2/°C)	Dielectric strength (kV/cm)
Air (dry)	N/A	≈ 0	1	0.00024	30
Alumina:					
99.5%	0.05–0.25	1-2	10.1	0.37	4×10^3
96%	5–20	6	9.6	0.28	4×10^3
85%	30-50	15	8.5	0.2	4×10^3
Sapphire[1]	0.005–0.025	0.4–0.7	9.4, 11.6	0.4	4×10^3
Glass, typical	0.025	20	5	0.01	–
Polyimide	–	50	3.2	0.002	4.3
Irradiated polyolefin	1		2.3	0.001	≈ 300
Quartz (fused) i.e. SiO_2	0.006–0.025	1	3.8	0.01	10×10^3
Beryllia (BeO)[2]	0.05–1.25	1	6.6	2.5	–
Rutile	0.25–2.5	4	100		–
Ferrite/garnet	0.25	2	13–16	0.03	4×10^3
FR4 circuit board	≈ 6	100	4.3–4.5	0.005	–
RT-duroid® 5880	0.75–1[3] 4.25–8.75[4]	5–15	2.16–2.24	0.0026	–
RT-duroid® 6010	0.75–1[3] 4.25–8.75[4]	10–60	10.2–10.7	0.0041	–
AT-1000®	–	20	10.0–13.0	0.0037	–
Cu-flon	–	4.5	2.1	–	–

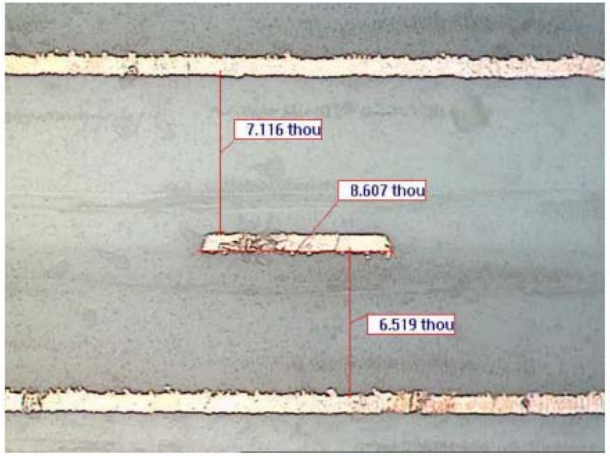
- Properties of FR-4 substrate

Substrate Parameter	Value
Dielectric constant: ε_r	4.5
Substrate thickness: h	1.5 mm
Loss tangent: δ	0.019
Conductor (copper) thickness: t	0.035 mm





- Sripline on FR-4 substrate



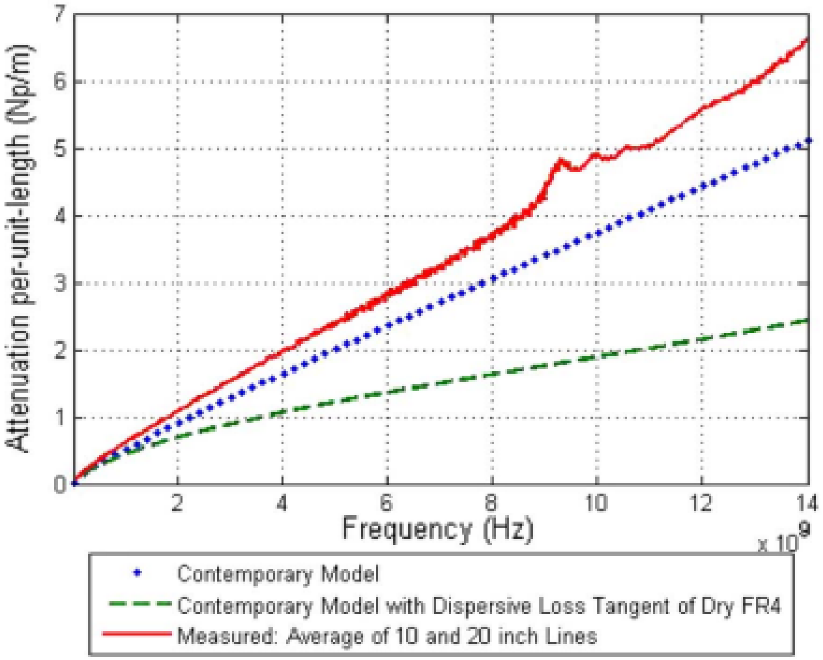


Fig. 5. Contemporary model with the dispersive loss tangent of dry FR-4 plotted with benchmark measured and modeled data.

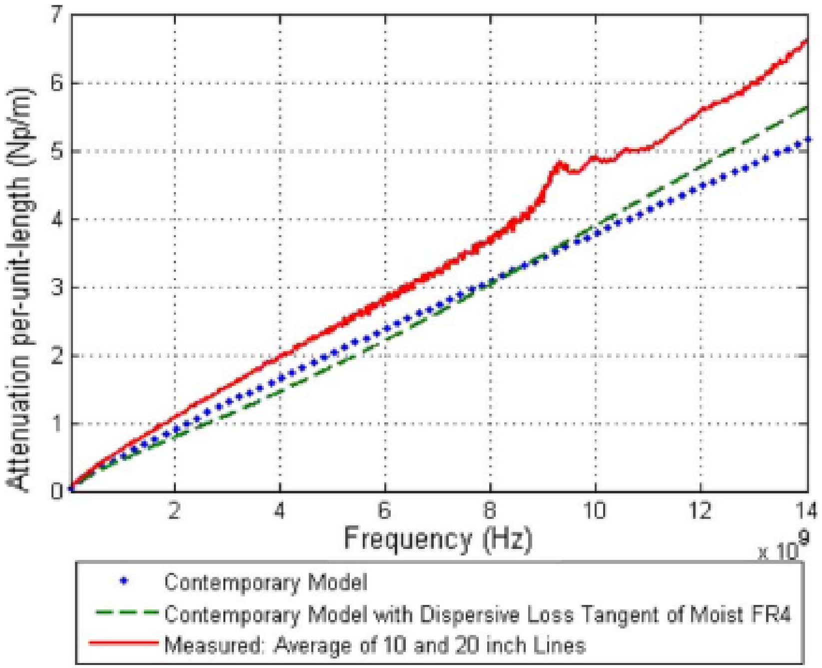


Fig. 6. Contemporary model with the dispersive loss tangent of FR-4 including moisture plotted with benchmark measured and modeled data.

- Example:

Find R, L, G, C of the following lines with $f = 10$ GHz, $\varepsilon_r = 2$, $\tan\delta = 0.002$,

$\sigma = 5\times10^7$ S/m,

1. Coaxial: $a = 2$ mm, $b = 4$ mm

2. Two-wire: $a = 5$ mm, $D = 12$ mm

3. Parallel-plate: $w = 10$ mm, $d = 2$ mm

- Example:

Find Z_0 and γ of the following lines with $f = 10$ GHz, $\varepsilon_r = 2$, $\tan\delta = 0.002$,

$\sigma = 5\times10^7$ S/m,

1. Coaxial: $a = 2$ mm, $b = 4$ mm

2. Two-wire: $a = 5$ mm, $D = 12$ mm

3. Parallel-plate: $w = 10$ mm, $d = 2$ mm

3. Microstrip Line

$$u = w/h$$

$$Z_{0,\text{air}} = 30\log\left\{1+(4/u)\left[8/u+\sqrt{(8/u)^2+\pi^2}\right]\right\} \text{ [Wheeler(1977)]}$$

$$\varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12/u}} \text{ [Hammerstad(1975)]}$$

$$Z_0 = \frac{Z_{0,\text{air}}}{\sqrt{\varepsilon_{re}}}$$

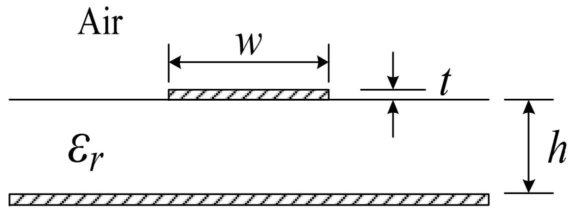
$$R = \frac{2R_s}{w},\ R_s = \sqrt{\frac{\pi f\mu}{\sigma}},\ \alpha_c = \frac{R}{2Z_0} \text{ (parallel-plate approximation)}$$

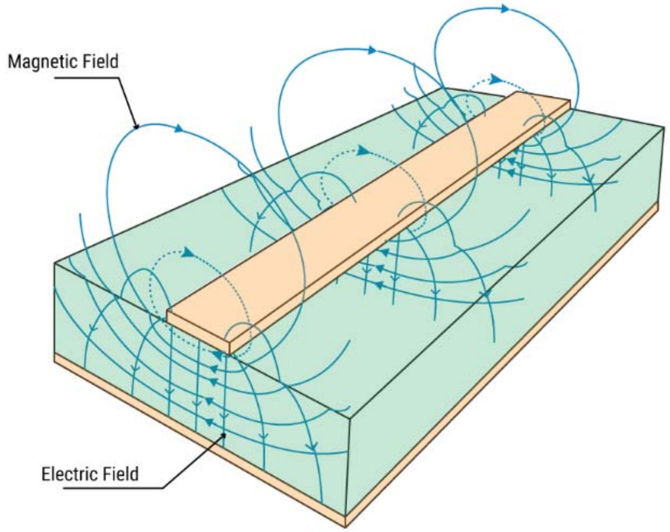
$$G = (\omega\tan\delta)\frac{w}{h},\ \alpha_d = \frac{G}{2Y_0} \text{ (parallel-plate approximation)}$$

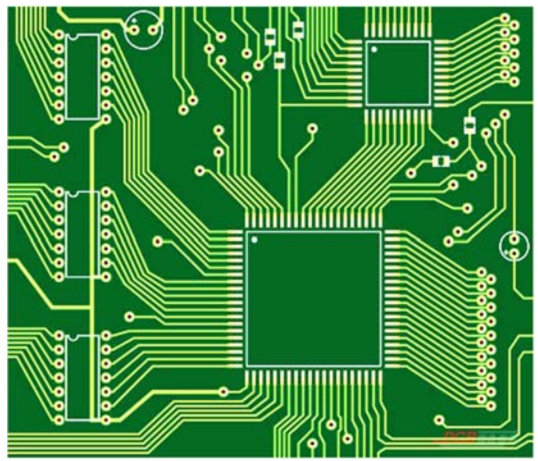
$$\alpha = \alpha_c + \alpha_d$$

$$\beta = \frac{2\pi}{\lambda_g},\ \lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{re}}}$$

$$C = \frac{\varepsilon_{re}}{cZ_{0,\text{air}}},\ L = \frac{Z_{0,\text{air}}}{c} = L_0$$







- Example

Find R, L, G, C, Z_0, γ of microstrip lines with $f = 10$ GHz, $\varepsilon_r = 2$, $\tan\delta = 0.002$,

$\sigma = 5\times10^7$ S/m,

1. $h = 0.580$ mm, $w = 2$ mm

2. $h = 0.787$ mm, $w = 0.2$ mm

3. $h = 1.27$ mm, $w = 4$ mm

4. Transmission Line Calculator

- **CST Studio Suite**

- Calculation module

- Draw transmission line structure, set up two wave ports, and do port analysis only.

2. Microstrip Analysis/Synthesis Calculator: loss included

http://mcalc.sourceforge.net/

3. RFDH

Coaxial line calculator: http://www.rfdh.com/rfdb/coaxline.htm

Microstrip calculator: http://www.rfdh.com/rfdb/msline.htm

Inverted microstrip calculator: http://www.rfdh.com/rfdb/msline_i.htm

Suspended microstrip calculator: http://www.rfdh.com/rfdb/msline_s.htm

Stripline calculator: http://www.rfdh.com/rfdb/sline.htm

Coplanar waveguide (CPW) calculator: http://www.rfdh.com/rfdb/cpw.htm

GCPW (CPW with ground) calculator: http://www.rfdh.com/rfdb/cpwg.htm

Coplnar strip (CPS) calculator: http://www.rfdh.com/rfdb/cps.htm

Slot line calculator: http://www.rfdh.com/rfdb/slotline.htm

5. Coding Example

- **Example**

Microstrip:

Given f, w, h, ε_r, tanδ, σ

Find Z_0, ε_{re} ,R, L, G, C, α_c (dB/m) , α_d (dB/m) , α (dB/m), β, λ_g

(Solution)

```
# Microwave Engingineering, Lecture 3 Python Code
# Microstrip calculation:
# Input: f, w, h, er, tand, sigma
# Output: Z0, ere, R, L, G, C, ac, ad, a, beta, lambda_g
#
from math import *
pi=3.14159265;mu=4*pi*1e-7;v=3e8;e0=8.854e-12
while True:
  f=float(input('Frequency f (Hz, 1e9) ='))
  w=float(input('Strip width w (mm, 2) ='))
  h=float(input('Substrate thickness h (mm, 1) ='))
  er=float(input('Substrate dielectric constant er (4.3) ='))
  tand=float(input('Substrate loss tangent tand (0.02)='))
  sigma=float(input('Strip/groundplane conductivity sigma (S/m, 5.8e7)='))
  u=w/h
  z0air=30*log(1+4/u*(8/u+sqrt(u**2+pi**2)))
  ere=(er+1)/2+(er-1)/2/sqrt(1+12/u)
```

5. Coding Example

```
z0=z0air/sqrt(ere)
lambda_0=3e8/f
lambda_g=lambda_0/sqrt(ere)
beta=2*pi/lambda_g
rs=sqrt(pi*f*mu/sigma)
r=2*rs/(w*1e-3)
L=z0air/v
c=ere/(v*z0air)
g=2*pi*f*e0*er*tand*w/h
ac=r/(2*z0);ad=g/(2/z0);a=ac+ad
print('  Z0 (ohm) =',z0)
print('  ere =',ere)
print('  R (Ohm/m) =',r)
print('  G (Ohm/m) =',g)
print('  L (H/m) =',L)
print('  C (F/m) =',c)
print('  ac (dB/m) =',ac*8.68)
print('  ad (dB/m) =',ad*8.68)
print('  a (dB/m) =',a*8.68)
print('  beta (rad/m) =',beta)
print('  lambda_g (m) =',lambda_g)
```

5. Coding Example

```
'''
Frequency f (Hz, 1e9) =
1e9
Strip width w (mm, 2) =
2
Substrate thickness h (mm, 1) =
1
Substrate dielectric constant er (4.3) =
4.3
Substrate loss tangent tand (0.02)=
0.02
Strip/groundplane conductivity sigma (S/m, 5.8e7)=
5.8e7
  Z0 (ohm) = 46.43003113343705
  ere = 3.2736413804652247
  R (Ohm/m) = 8.250226487396457
  G (Ohm/m) = 0.0095685874951464
  L (H/m) = 2.800227207970832e-07
  C (F/m) = 1.2989586349544232e-10
  ac (dB/m) = 0.7711815409383731
  ad (dB/m) = 1.9281309984135606
  a (dB/m) = 2.6993125393519337
  beta (rad/m) = 37.894323997365646
  lambda_g (m) = 0.16580808514849868
Frequency f (Hz, 1e9) =
'''
```

Fin

(End)