M1 EECS (Electrical Engineering and Control Systems)

High frequency electronics : Propagation & reflection

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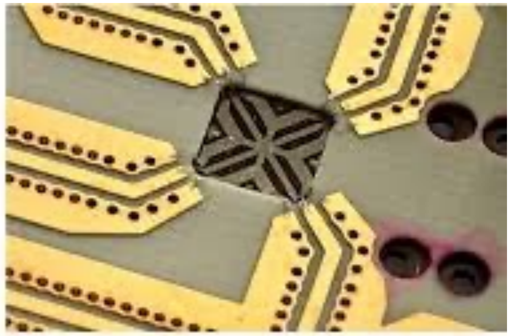
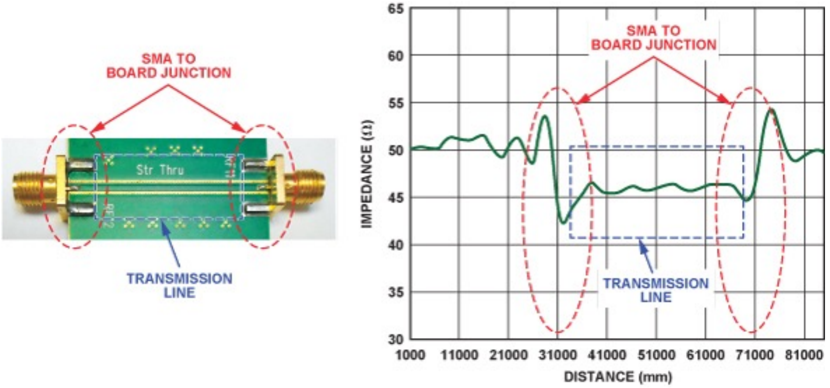
Outline (Part 1) Microwave : Propagation & reflection

- Introduction
- Model and propagation
  - Transmission line parameters
  - Exercice
- Matching and reflection
  - Reflection coefficient
  - Smith chart
- Conclusion





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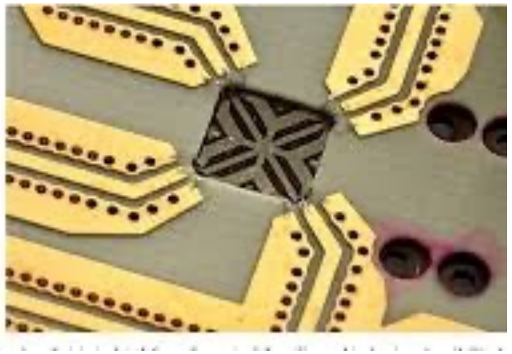
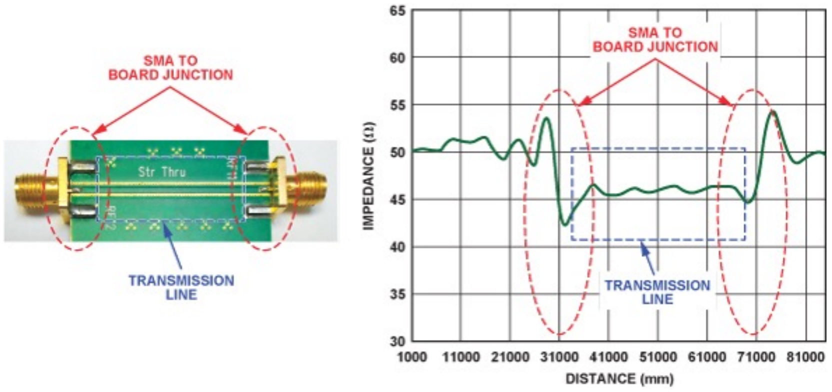
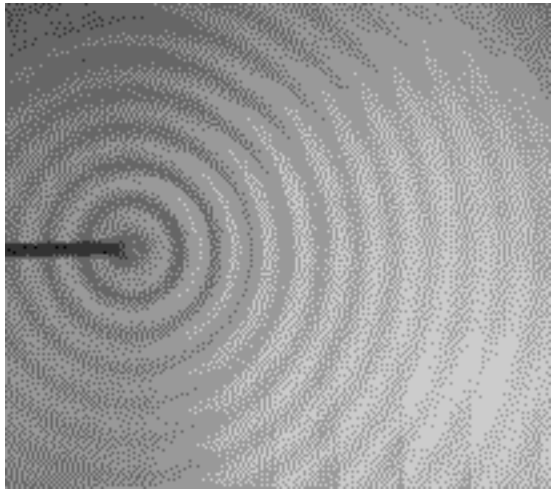
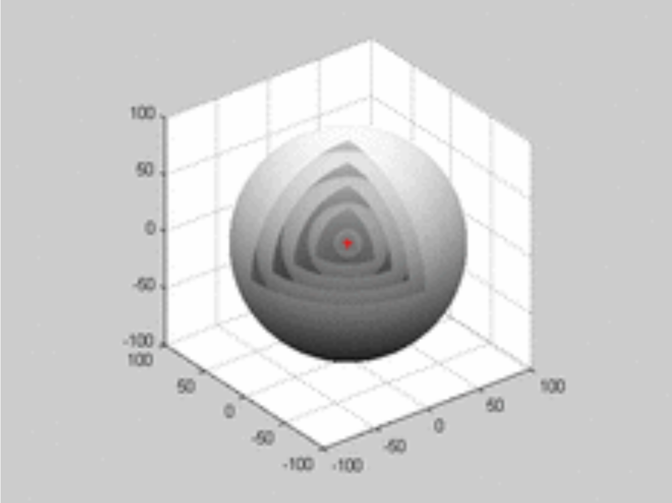




(Part1) Introduction - Wave and Microwave ?

- What is a wave?
  - It is a physical phenomenon of propagation or a variation of a parameter with space.
- Acoustic wave : Guitar or violin string (1D)
- Impact of drop on a liquid (2D)
- Electromagnetic wave (3D)





(Part1) Introduction - Electromagnetic Microwave ?

- The radio waves and microwaves are the kinds of **electromagnetic waves.** Microwaves have a higher frequency than radio wave (or a shorter wavelength). Microwaves propagate electromagnetic energy

- The wavelength:

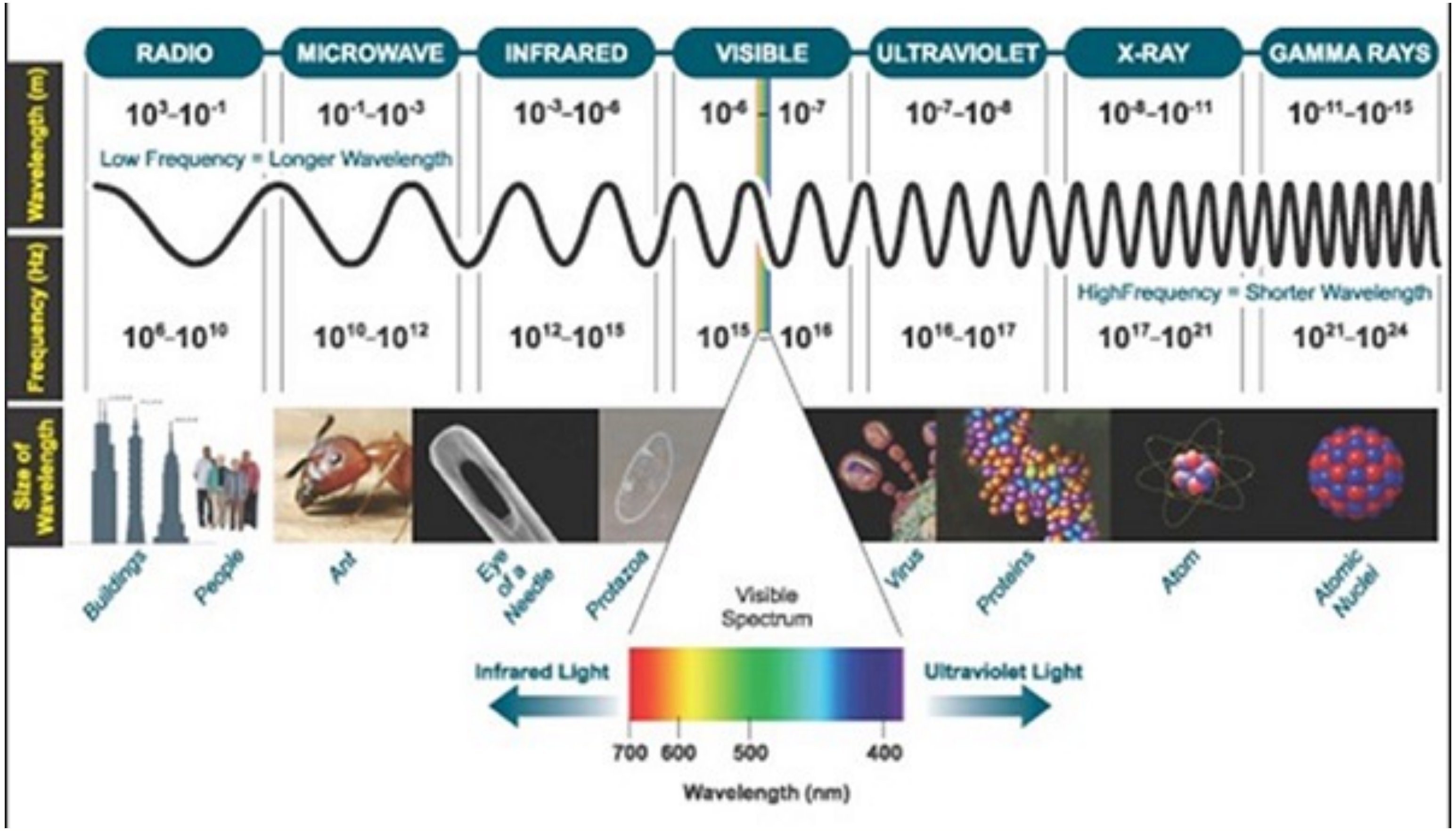
  the wavelength (m),

$$\lambda = \frac{v_\varphi}{f} = \frac{C}{f \cdot \sqrt{\varepsilon_r}}$$

(in the air ε_r = 1)

ie :

The wavelength for a 2,45 GHz (WiFi frequency) is 12,5 cm



(Part1) Introduction - Microwaves Applications

- Wireless Communications : For long distance telephone calls, Bluetooth, WIFi WIMAX operations, RFiD, Satellite television, GPS, …
- Food Industry : Microwave ovens used for reheating and cooking, Roasting food grains/beans, Moisture levelling, Absorbing water molecules, , …
- Medical Applications : Microwave tomography, Monitoring heartbeat, Tumor detection, Therapeutic applications, , …
- Military and Radar : Air traffic control, Weather forecasting, Speed limit enforcement, aiport body scanner
- Radio Astronomy : Mark cosmic microwave background radiation, Detection of powerful waves in the universe, Detection of many radiations in the universe
- Industrial Uses: Drying and reaction processes Sterilizing pharmaceuticals, Chemical synthesis, Waste remediation, Diamond synthesis, …

(Part1) Introduction : Main advantages of Microwaves

- Supports larger bandwidth and hence more information is transmitted. For this reason, microwaves are used for point-to-point communications.Satellite and terrestrial communications with high capacities are possible.
- Higher data rates are transmitted as the bandwidth is more.
- Antenna size gets reduced, as the frequencies are higher.
- Low-cost miniature microwave components can be developed.
- Provides effective reflection area in the radar systems.
- Effect of fading gets reduced by using line of sight propagation.

Shannon-Hartley equation

$$D_{max} = \Delta f \; log_2(1 + SNR)$$

$$\lambda = \frac{\boldsymbol{v_\varphi}}{f}$$

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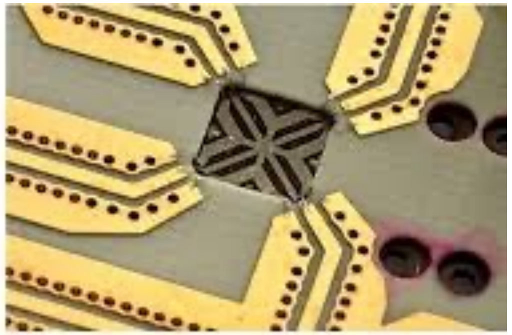
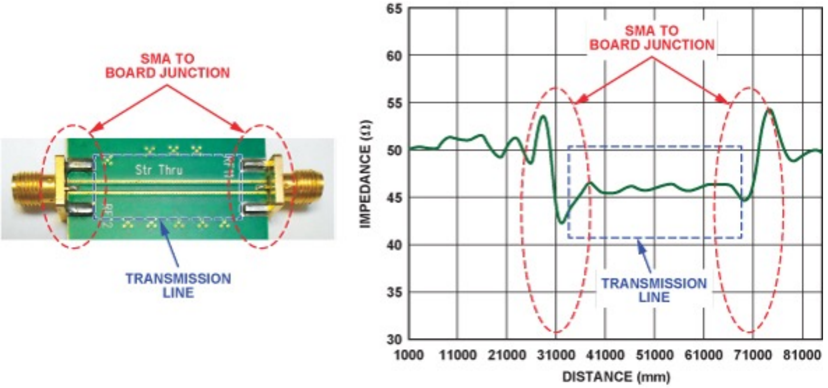
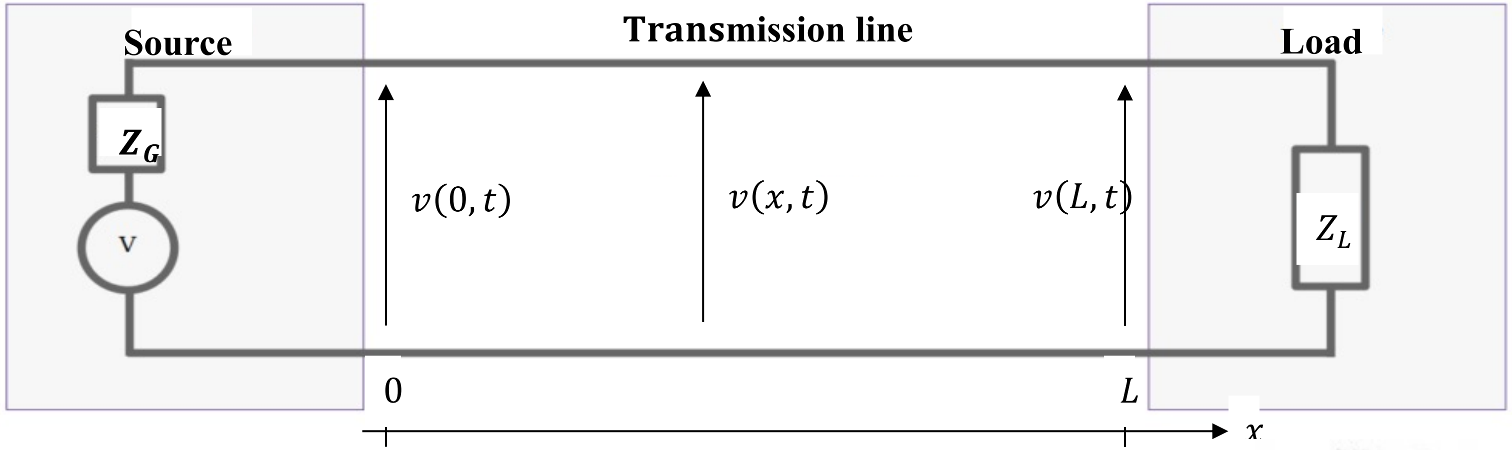


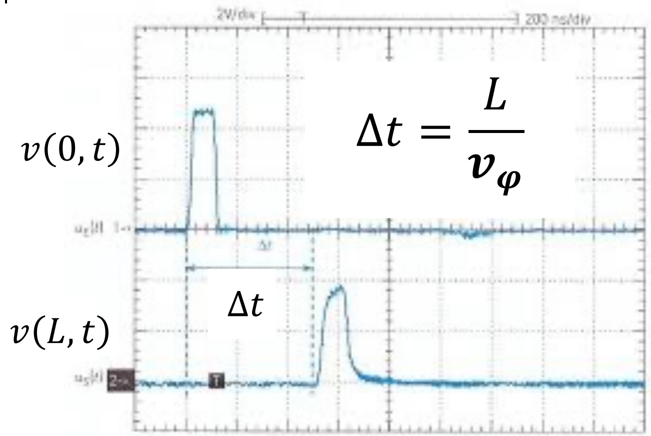


(Part 1) : Model and propagation- Pulse propagation

- Speed propagation is finite and smaller than light speed $v_\varphi = \frac{C}{\sqrt{\varepsilon_r}}$



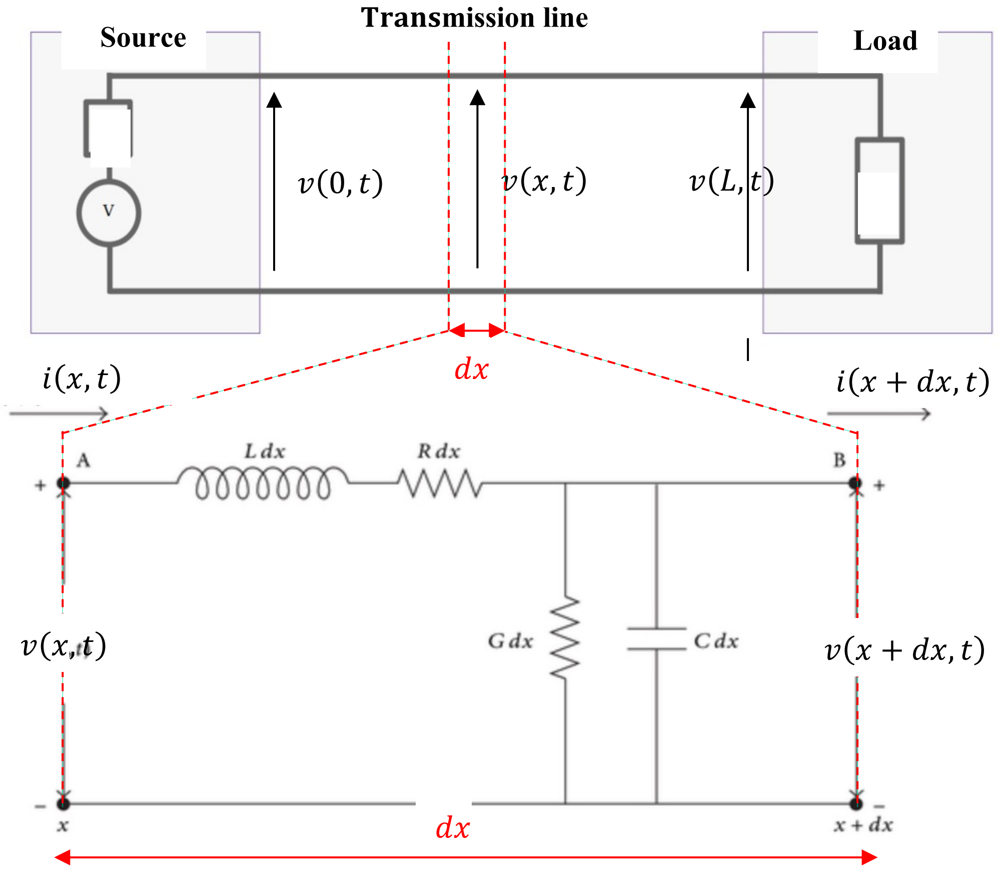
- Pulse transmission is not instantaneous
- Delay between input and output (transient)
- The shape of the pulse is modified
  (Attenuation, filtring,…



How describe this phenomena in electronic ?

(Part 1) : Model and propagation- Primary parameters

- Electrical model of a propagation line (telegraph's model)
- Equivalent **distributed model** for a transmission line segment of length dx (with $dx << \lambda$)
- Transmission Line Primary Parameters
  - L (H/m): series linear inductance (magnetic behavior of the transmission line).
  - R (Ω/m) : series linear resistance (conductive losses of the transmission line).
  - C (F/m) : parallel linear capacitance (electrostatic behavior of the transmission line)
  - G (S/m) : parallel linear conductance (dielectric losses of the transmission line)



(Part 1) : Model and propagation- Propagation equations

- Kirchhoff's circuit laws on voltage and current (2 coupled differential equations as for the fields)

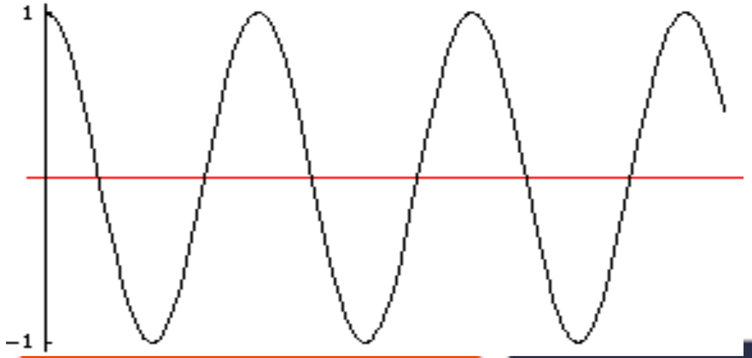
$$dv(x,t) = v(x+dx,t) - v(x,t) = -R.dx.i(x,t) - L.dx.\frac{di(x,t)}{dt}$$

$$di(x,t) = i(x+dx,t) - i(x,t) = -G.dx.v(x,t) - C.dx.\frac{dv(x,t)}{dt}$$

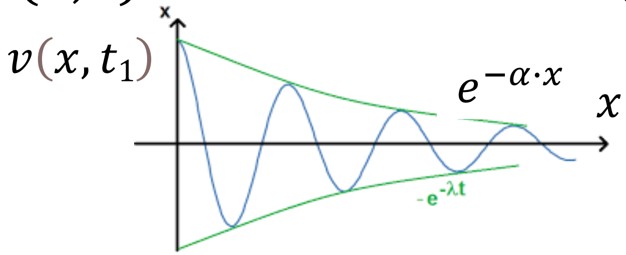
- Deriving the voltage equation and reintroducing the current equation leads to

$$\frac{d^2v(x,t)}{dx^2} = R.G.v(x,t) + (R.C + L.G)\frac{dv(x,t)}{dt} + L.C.\frac{d^2v(x,t)}{dt^2}$$

- The general solution of this second order differential equation is two exponential attenuated propagation waves



$$v(x,t) = V_{0+} \cdot e^{-\alpha \cdot x} \cdot \cos(\omega t - \beta x) + V_{0-} \cdot e^{-\alpha \cdot x} \cdot \cos(\omega t + \beta x)$$



β (rad/m) : **phase constant → $\beta = \frac{\omega}{v_\varphi}$**

α (nepers/m) : **attenuation constant**

(Part 1) : Model and propagation- Propagation equations

- If losses could be neglected ($\propto \approx 0$ or $(R.C + L.G) \approx 0$) the equation is

$$\frac{\partial^2 v(x,t)}{\partial x^2} - \left(\frac{1}{{v_\varphi}^2}\right)\frac{\partial^2 v(x,t)}{\partial t^2} = 0 \rightarrow v(x,t) = V_{0+}cos(\omega t - kx) + V_{0-}cos(\omega t + kx) \qquad \boldsymbol{k = \frac{\omega}{v_\varphi}}$$

- General voltage and current equations with (progressive and regressive)

$$v(x,t) = \; v_+(x,t) + v_-(x,t) = V_{0+} \cdot e^{-\alpha \cdot x} \cdot cos(\omega t - \beta x) + V_{0-} \cdot e^{-\alpha \cdot x} \cdot cos(\omega t + \beta x)$$
$$i(x,t) = \; i_+(x,t) + i_-(x,t) = I_{0+} \cdot e^{-\alpha \cdot x} \cdot cos(\omega t - \beta x) + I_{0-} \cdot e^{-\alpha \cdot x} \cdot cos(\omega t + \beta x)$$

- In frequency domaine, complex magnitudes of current and voltage $\left(\frac{d.}{dt} \rightarrow j\omega\right)$

$$\bar{V}\;(x,\omega) = \bar{V}_+(x,\omega) + \bar{V}_-(x,\omega) = V_{0+}(\omega) \cdot e^{-\bar{\gamma} \cdot x} + V_{0-}(\omega) \cdot e^{-\bar{\gamma} \cdot x}$$
$$\bar{I}\;(x,\omega) = \bar{I}_+(x,\omega) + \bar{I}_-(x,\omega) = I_{0+}(\omega) \cdot e^{-\bar{\gamma} \cdot x} + I_{0-}(\omega) \cdot e^{-\bar{\gamma} \cdot x}$$

with γ $(1/m)$ **complex propagation constant**

$$\boldsymbol{\bar{\gamma} = \alpha + j\beta = \sqrt{(R + jL\omega)(G + jC\omega)} = j\omega\sqrt{LC}.\sqrt{(1 + R/jL\omega)(1 + G/jC\omega)}}$$

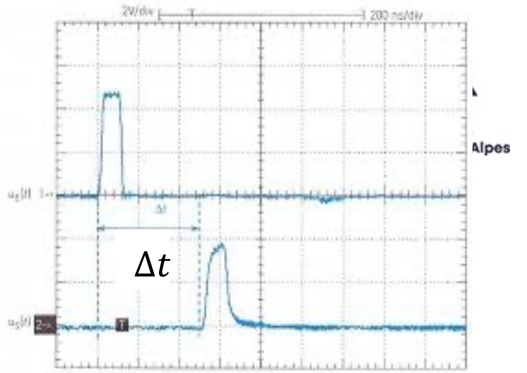
(Part 1) : Model and propagation- Secondary parameter

- Characteristic impedance is the ratio of voltage over current for each wave (progressive and regressive) (linked to ratio $|\vec{E}|\,/\,|\vec{H}|$)

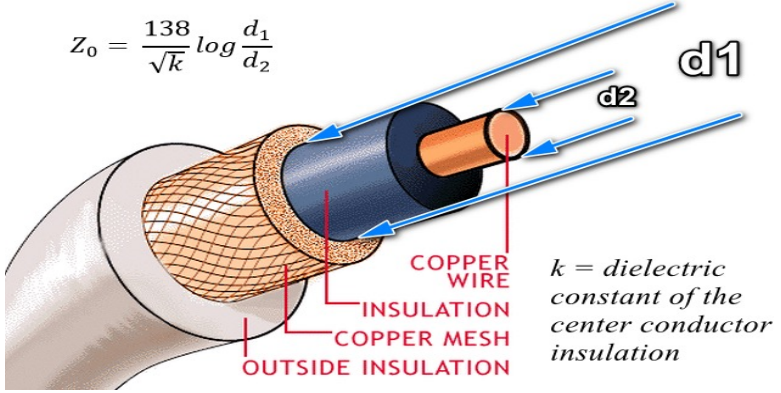
$$\overline{Z_c} = \frac{\overline{V}_+(x,\omega)}{\overline{I}_+(x,\omega)} = -\frac{\overline{V}_-(x,\omega)}{\overline{I}_-(x,\omega)} = \sqrt{\frac{(R+jL\omega)}{(G+jC\omega)}} = \sqrt{\frac{L}{C}}\cdot\sqrt{\frac{(1+R/jL\omega)}{(1+G/jC\omega)}}$$

- Transmission Line secondary Parameters (in low-loss condition)
  - $Z_c(\Omega)$: characteristic impedance → $\overline{Z_c} = \sqrt{\frac{L}{C}}\cdot\sqrt{\frac{(1+R/jL\omega)}{(1+G/jC\omega)}} \approx \sqrt{\frac{L}{C}}$
  - β (rad/m) : phase constant → $\beta = \frac{\omega}{v_\varphi} \approx \omega\sqrt{LC}$ or $v_\varphi \approx \frac{1}{\sqrt{LC}}$
  - α (nepers/m) : attenuation constant → $\alpha \approx \frac{1}{2}\frac{R}{Z_c} + \frac{1}{2} G Z_c$
    - $\alpha_{dB/m} = 20 \cdot Log(e^{\alpha}) = 8,68 \cdot \alpha_{np/m}$

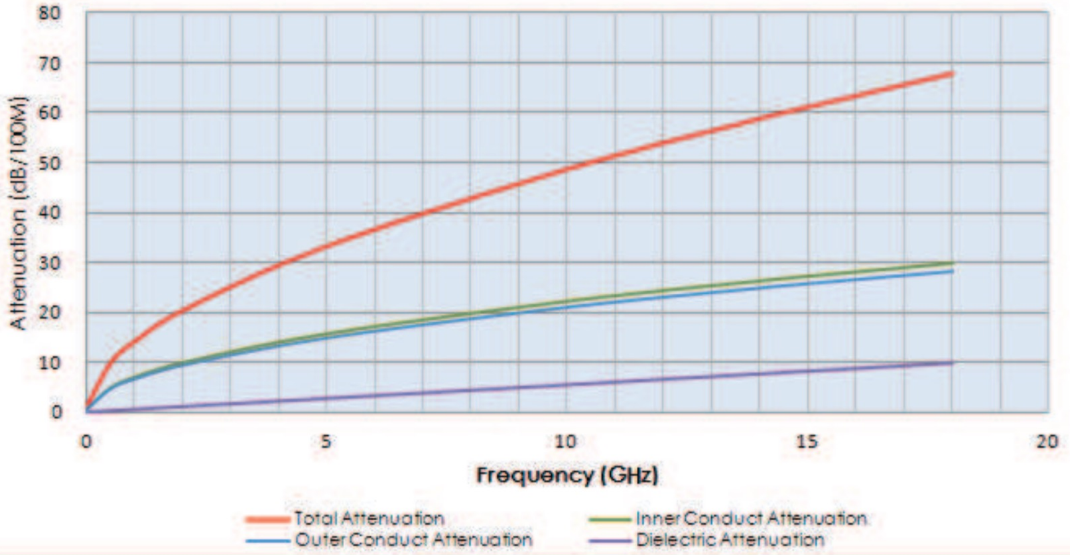
(Part 1): TD1 Coxial cable



- Coaxial cable of 50 m measurement $\Delta t = 0.25\mu S$
- Characteristic impedance could be approximated with $Z_c = \frac{138\, log(d_1/d_2)}{\sqrt{\varepsilon_r}}$ with $d_1 = 4.95\, mm\ and\ d_2 = 0.75\, mm\ and\ \varepsilon_r$ (or k): Relative Permittivity



- Attenuation of the coaxial is given vs frequency (dielect = 5dB/100m and conductor losses 21 and 22 dB/100m)



- Give secondary parameters of this coaxial cable @10GHz ($v_\varphi, \lambda, \beta, Z_c$ and α)
- Deduce the associated primary parameters (L, C, R, G)
- Verify low-loss condition and explain losses vs frequency

(Part1) Wireless - Maxwell's equations

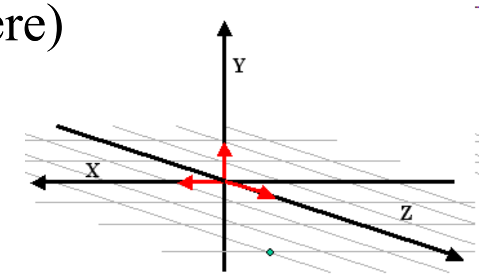
- The theory of propagation is described by the 4 Maxwell-Lorentz equations.
- These equations describe electromagnetic parameters:

$\vec{E}$ (electric field V/m), $\vec{H}$ (magnetic field A/m) linked in time and space

Relationship between time and space (x,y,z) of the two fields

$$\begin{cases} div\left(\vec{E}\right) = \rho/\varepsilon \approx 0 & \text{(1-Maxwell Gauss)} \\ \overrightarrow{rot}\left(\vec{E}\right) = -\mu\dfrac{\partial\vec{H}}{\partial t} & \text{(2-Maxwell Faraday)} \\ div\left(\vec{H}\right) = 0 & \text{(3-Maxwell Thomson)} \\ \overrightarrow{rot}\left(\vec{H}\right) = \varepsilon\dfrac{\partial\vec{E}}{\partial t} + \vec{j} & \text{(4-Maxwell Ampère)} \end{cases}$$

Two current densities
- displacement
- of conduction



Reminder on the operators of the divergence and the rotational

$$div\left(\vec{A}\right) = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$

$$\overrightarrow{rot}\left(\vec{A}\right) = \left(\frac{\partial A_y}{\partial z} - \frac{\partial A_z}{\partial y}\right)\overrightarrow{u_x} + \left(\frac{\partial A_z}{\partial x} - \frac{\partial A_x}{\partial z}\right)\overrightarrow{u_y} + \left(\frac{\partial A_x}{\partial y} - \frac{\partial A_y}{\partial x}\right)\overrightarrow{u_z}$$

(Part1) Wireless - Equations of Helmholtz & d'Alembert

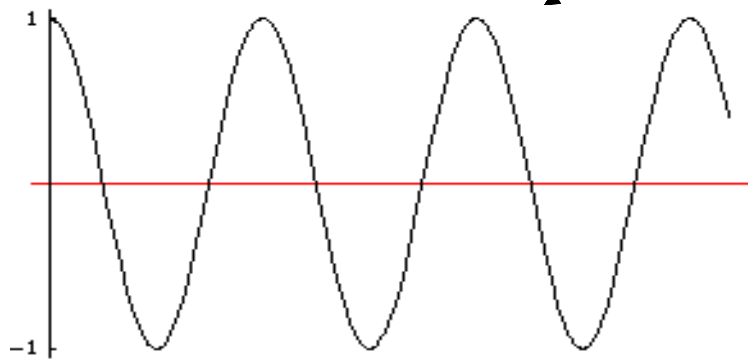
- In case of 1D lossless propagation differential equation could be expressed as

$$\frac{\partial^2 E}{\partial x^2} - \varepsilon\mu \frac{\partial^2 E}{\partial t^2} = \frac{\partial^2 E}{\partial x^2} - \left(\frac{1}{{v_p}^2}\right)\frac{\partial^2 E}{\partial t^2} = 0$$

Same équation for H

- The solution of the d'Alembert equation is a combination of to propagation waves (progressive and regressive) in both directions of the x axis

$$E(x,t) = E_i cos(\omega t - kx) + E_r cos(\omega t + kx)$$



the speed of propagation v_φ (m/s) and signal frequency f (Hz)

or pusation ω (rd/s)

the wave vector : $k = \frac{\omega}{v_\varphi} = \frac{2\pi}{\lambda}$ (rd/m),

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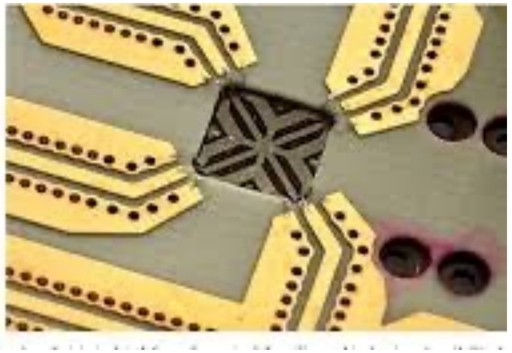
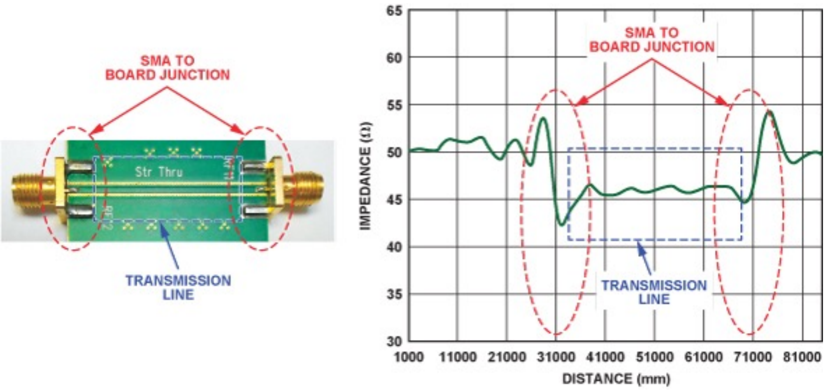
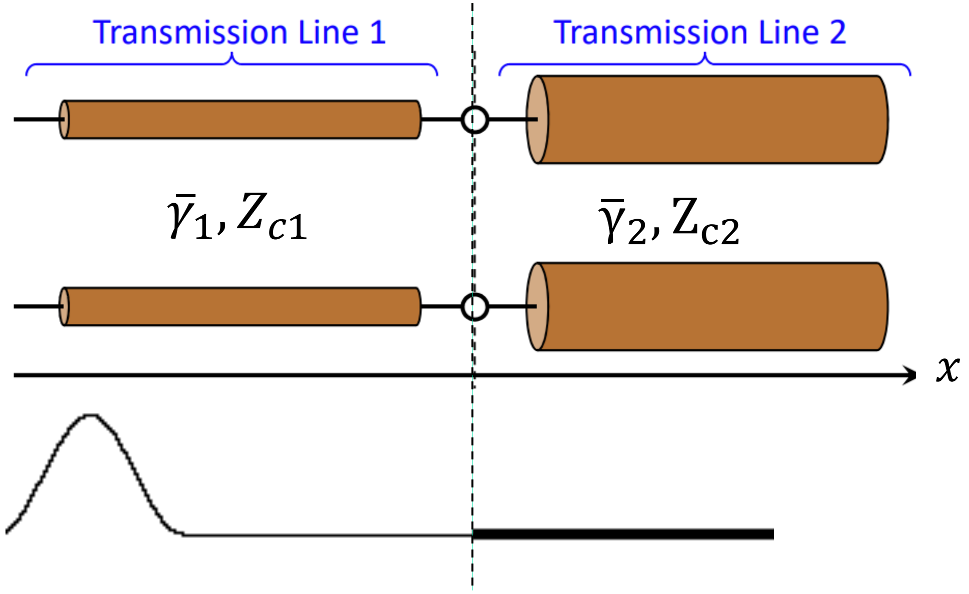




(Part 1) : Matching and reflection- Pulse reflection

- There is propagation in a transmission line in both directions but what happens at the ends of the line?
- At a end, if the characteristic impedances (ratio $\frac{v_+(x,t)}{i_+(x,t)}$) are different there will be a partial transmission of the power the rest being reflected
- Reflection Coefficient $$\Gamma = \frac{v_-(x,t)}{v_+(x,t)} = \frac{Z_{c2} - Z_{c1}}{Z_{c2} + Z_{c1}}$$



$Z_{c2} = Z_{c1} \rightarrow \Gamma = 0$ (matched)

$Z_{c2} = 0 \rightarrow \Gamma = -1$ (short circuit)

$Z_{c2} = \infty \rightarrow \Gamma = +1$ (open circuit)

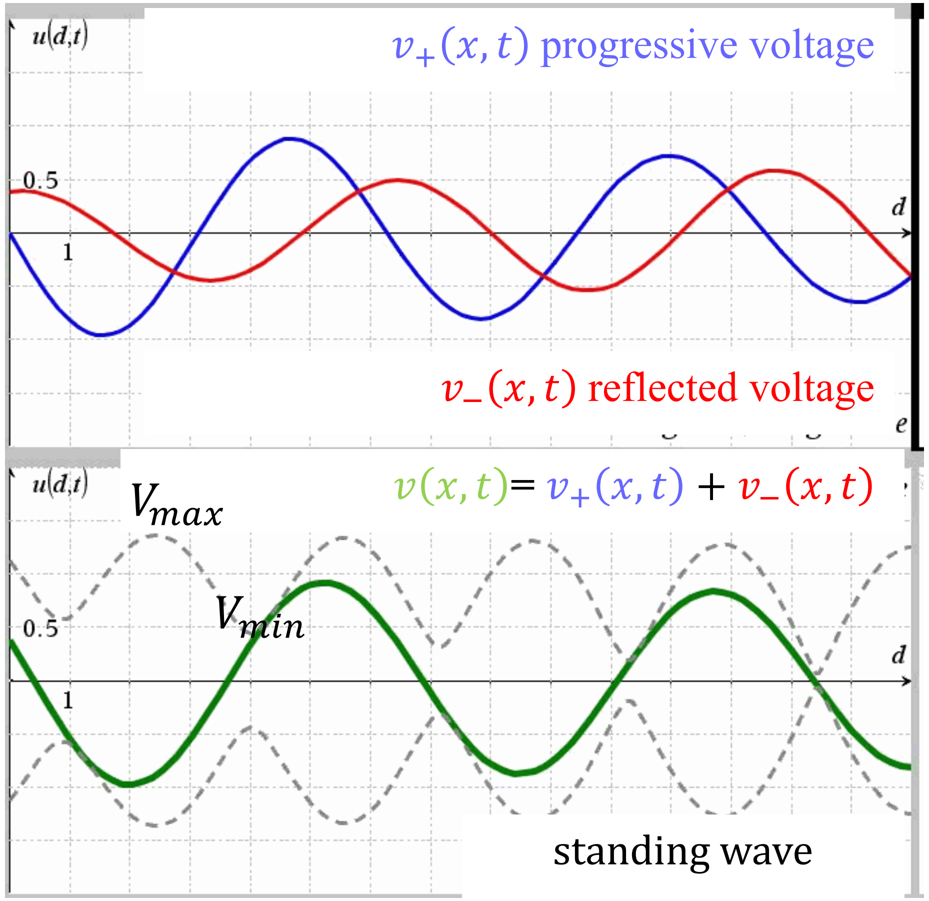
$Z_{c2} > Z_{c1} \rightarrow \Gamma > 0 \rightarrow v_-(x,t)\ v_+(x,t)$ same sign

$Z_{c2} < Z_{c1} \rightarrow \Gamma < 0 \rightarrow v_-(x,t)\ v_+(x,t)$ opposite sign

(Part 1) : Matching and reflection- Reflection with sinewave

- Standing waves are created by reflections (non-transmitted power P_- return to generator).
- This can lead to overvoltage of a mismatched load (maximum and minimum are located each $\frac{\lambda}{4}$)
- Except in the case of a resonator (filter or antenna), mismatching impedance and therefore reflection will be avoided
- Standing wave ratio (SWR)

$$SWR = \frac{V_{max}}{V_{min}} = \frac{1 + \sqrt{\frac{P_-}{P_+}}}{1 - \sqrt{\frac{P_-}{P_+}}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

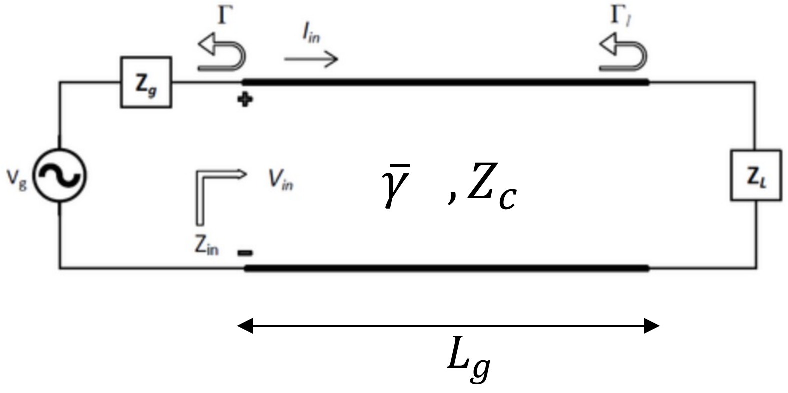


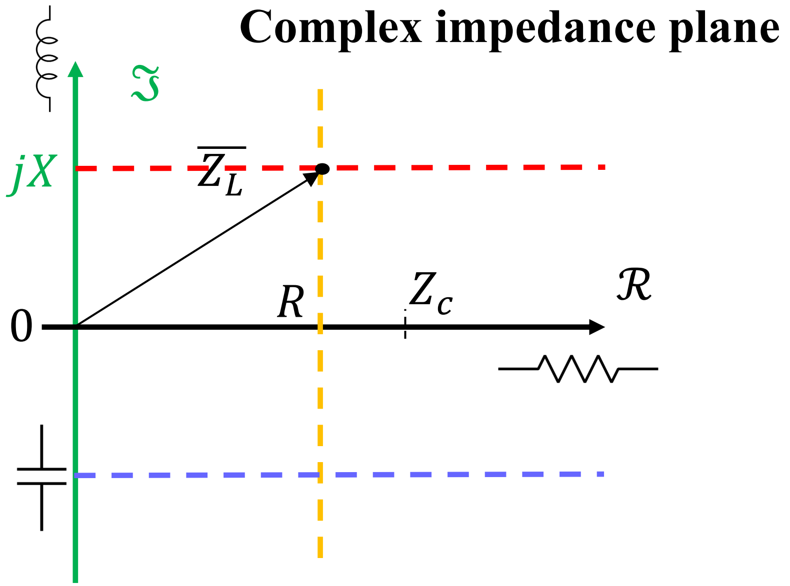
$SWR = 1 \rightarrow |\Gamma| = 0\ (no\ reflection)$ $SWR = \infty \rightarrow |\Gamma| = 1\ (total\ reflection)$

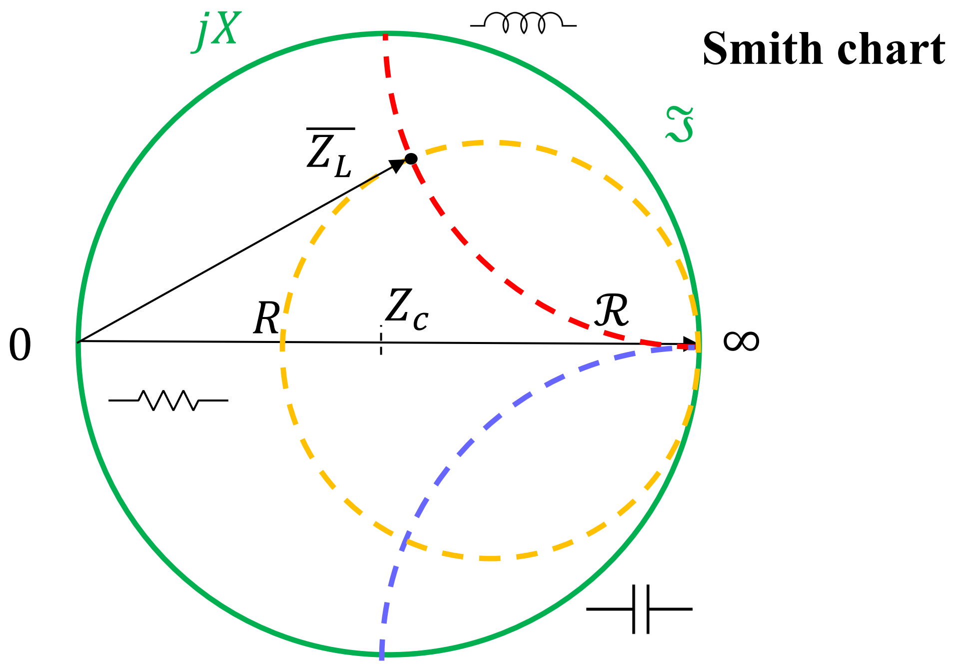
(Part 1) : Matching and reflection– Smith chart

- Transmission line $(\bar{\gamma}, Z_c, Lg)$ loaded by $\overline{Z_L} = R + jX$
- Matching and mismatching are described by Γ (or reduce impedance $z = \overline{Z_L}/Z_c$

$$\Gamma = \frac{\overline{Z_L}/Z_c - 1}{\overline{Z_L}/Z_c + 1} = \frac{z-1}{z+1}$$

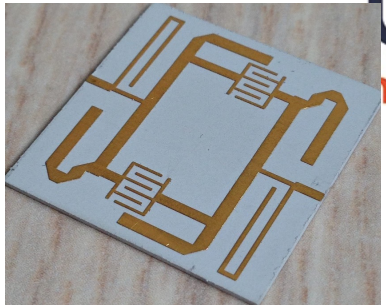






Where to draw infinite $\overline{Z_L}$(open circuit)?

(Part 1) : Matching and reflection- Open stub

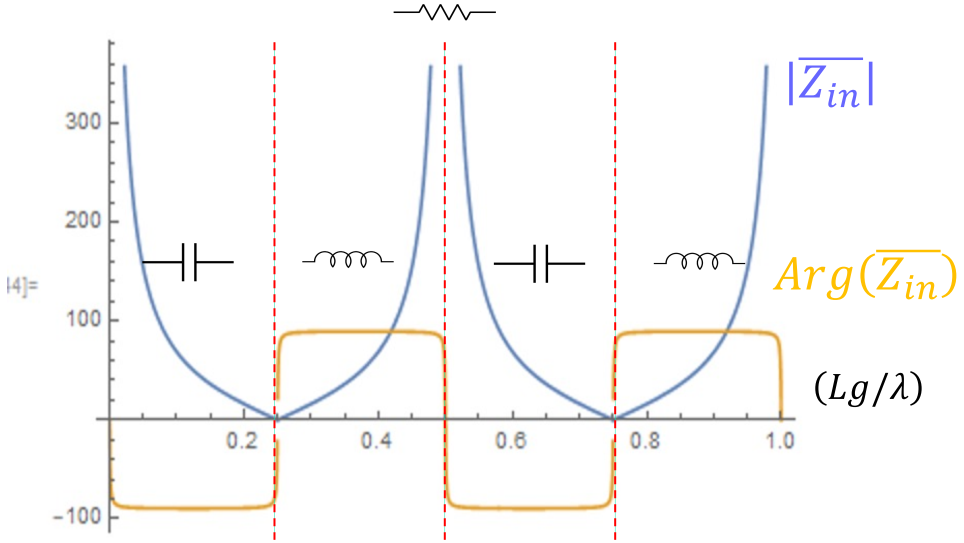


- Input impedance of the transmission line $(\bar{\gamma}, Z_c, Lg)$ loaded by $\overline{Z_L}$ is

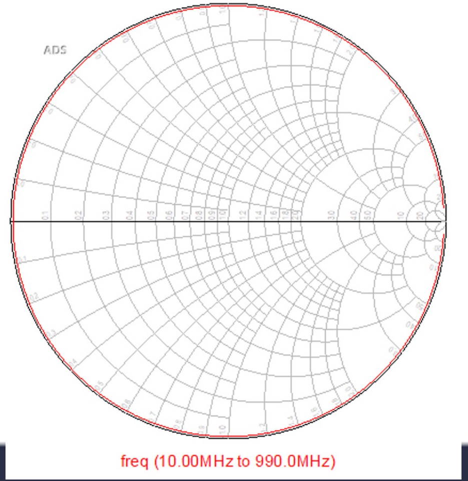
$$\overline{Z_{in}} = Z_c \frac{\bar{Z}_L + Z_c tanh(\bar{\gamma}.Lg)}{Z_c + j\bar{Z}_L tanh(\bar{\gamma}.Lg)}$$

- In low-loss case $\overline{Z_{in}} = Z_c \frac{\bar{Z}_L + \boldsymbol{j} Z_c.tan(\beta.Lg)}{Z_c + \bar{\boldsymbol{j}} \bar{Z}_L.tan(\beta.Lg)} = Z_c \frac{\bar{Z}_L + \boldsymbol{j} Z_c.tan(2\pi.Lg/\boldsymbol{\lambda})}{Z_c + \bar{\boldsymbol{j}} \bar{Z}_L.tan(2\pi.Lg/\boldsymbol{\lambda})}$

  - If $Lg = \frac{\lambda}{4} \rightarrow tan(\beta.Lg) = \infty$ and $\overline{Z_{in}} = \frac{{Z_c}^2}{\bar{Z}_L}$ impedance transformer function



A transmission line loaded by an open circuit (or open stub) can synthesize all the reactive components : inductors, capacitor but also short-circuit just by changing (Lg/λ)



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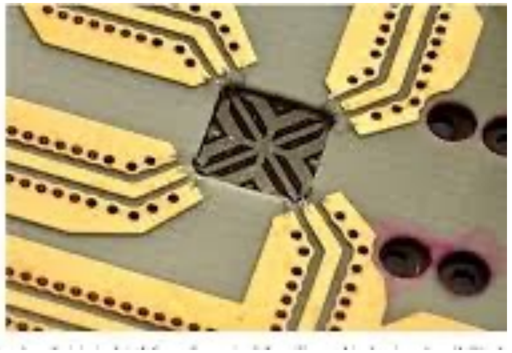
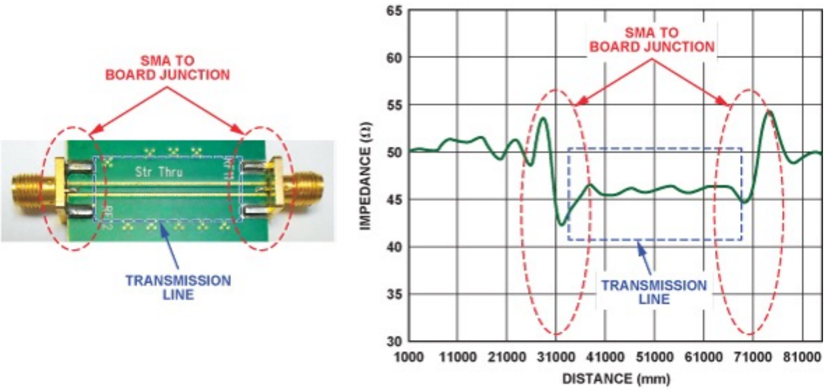


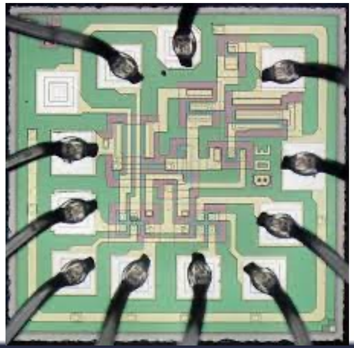


(Part 1) : Conclusion- conditions of use

- These notions of propagation and reflection can be neglected under many conditions
- if the length of a circuit or cable section is less than ($L < \frac{\lambda}{20}$ $or\ 5\%\ of\ \lambda$) then the propagation (or transient) time is negligible and also the reflection phenomena

Application	Lg (m)	Lambda (m)	Freq. (Hz)
Electrical power distribution network	100000	2000000	1,00E+02
Local telephone network	3000	60000	3,33E+03
Printed board in "Europe" format	0,16	3,2	6,25E+07
An integrated circuit in a "Dual in Line" package	0,015	0,3	6,67E+08
An integrated circuit: the chip alone	0,0015	0,03	6,67E+09



(Part 1) Conclusion

- Radio and microwave frequencies (from 100 MHz to 100GHz) are widely used for guided and wireless data transmission to meet the increasing demand for data rate and bandwidth but also for other medical, industrial, military and research applications
- The increase of the frequency induces the necessity to take into account the propagation and reflection phenomena ($L < \frac{\lambda}{20}$ or 5% of λ)
- To describe these phenomena two sets of parameters are available : the primary parameters of a transmission line (RLCG) or the secondary parameters (Zc Vp and Alpha)
- Propagation condition induces also to take into account power reflection