Lecture 2

2017/2018

Microwave Devices and Circuits for Radiocommunications

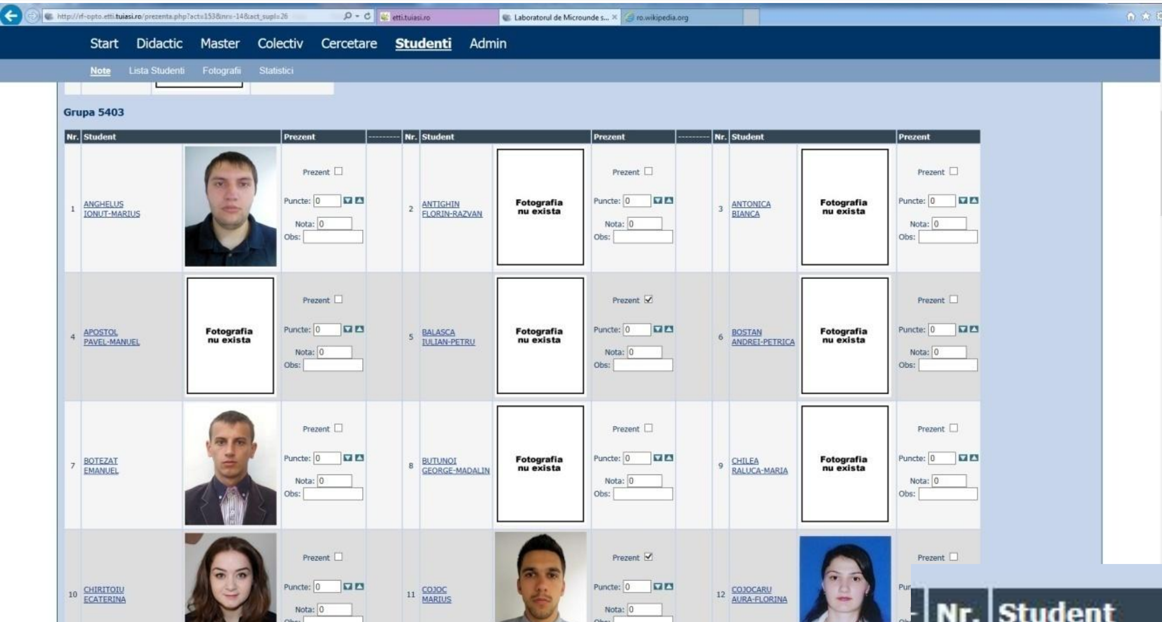
2017/2018

- 2C/1L, MDCR
- Attendance at minimum 7 sessions (course + laboratory)
- Lectures- assistant professor Radu Damian
  - Monday 16-18, P2
  - E – 50% final grade
  - problems + (? 1 topic teory) + (2p atten. lect.) + (3 tests) + (bonus activity)
    - 3p=+0.5p
  - all materials/equipments authorized
- Laboratory – assistant professor Radu Damian
  - Monday 18-20 II.12 even weeks
  - Thursday 8-14 odd weeks II.12 ?
  - L – 25% final grade
  - P – 25% final grade

Materials

- RF-OPTO
  - **http://rf-opto.etti.tuiasi.ro**
- **David Pozar, "Microwave Engineering"**, Wiley; 4th edition , 2011
  - 1 exam problem ← Pozar
- Photos
  - sent by email: rdamian@etti.tuiasi.ro
  - used at lectures/laboratory

Photos



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Student
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ANTIGHIN FLORIN-RAZVAN
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APOSTOL PAVEL-MANUEL
BALASCA IULIAN-PETRU
BOSTAN ANDREI-PETRICA
BOTEZAT EMANUEL
BUTUNOI GEORGE-MADALIN
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Access

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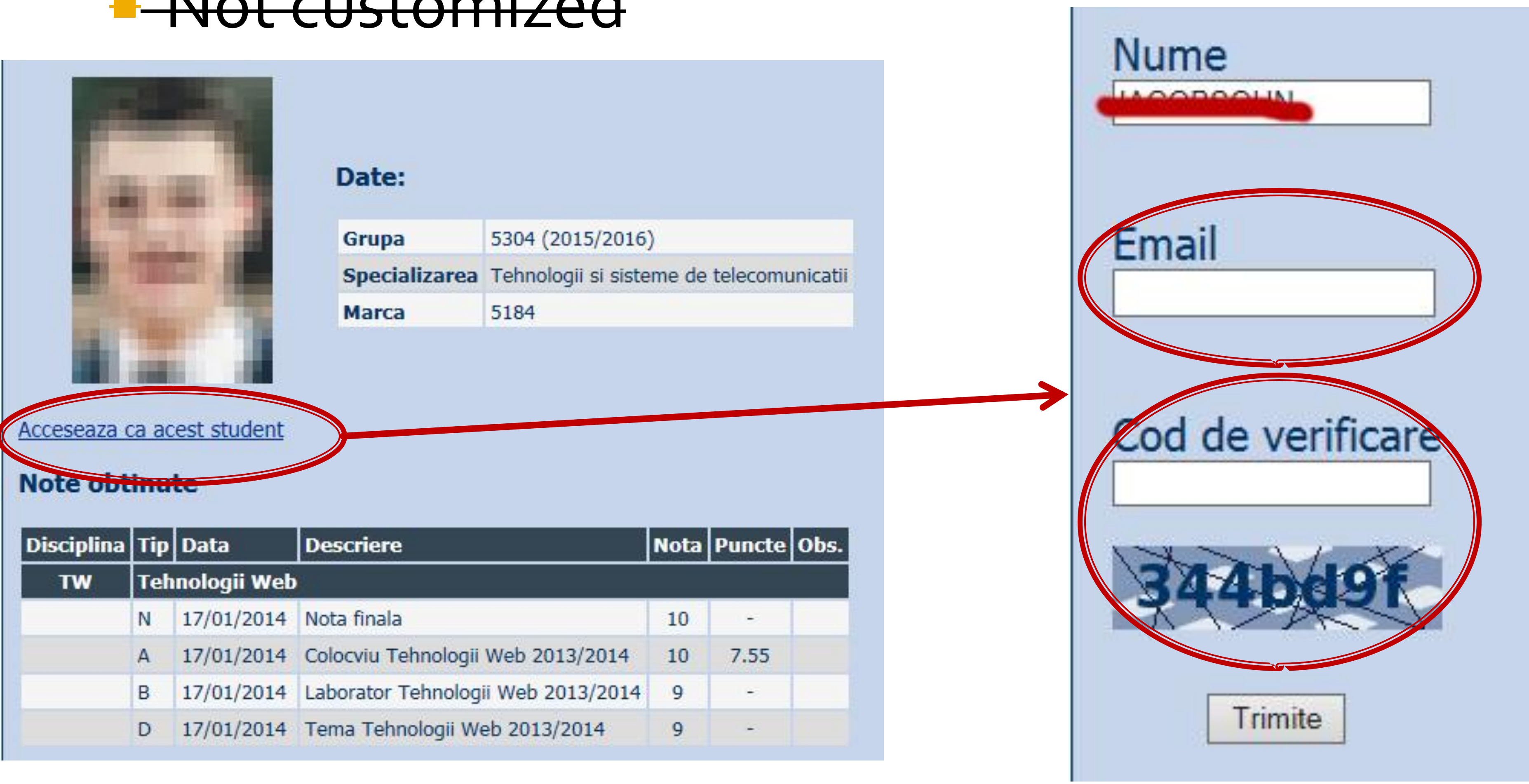

Disciplina	Tip	Data	Descriere	Nota	Puncte	Obs.
TW	Tehnologii Web					
	N	17/01/2014	Nota finala	10	-	
	A	17/01/2014	Colocviu Tehnologii Web 2013/2014	10	7.55	
	B	17/01/2014	Laborator Tehnologii Web 2013/2014	9	-	
	D	17/01/2014	Tema Tehnologii Web 2013/2014	9	-	

Software

- ADS 2016
- EmPro 2015
- pe baza de IP din exterior

Software


Advanced Design System
Premier High-Frequency and High Speed Design Platform
2016.01
KEYSIGHT TECHNOLOGIES
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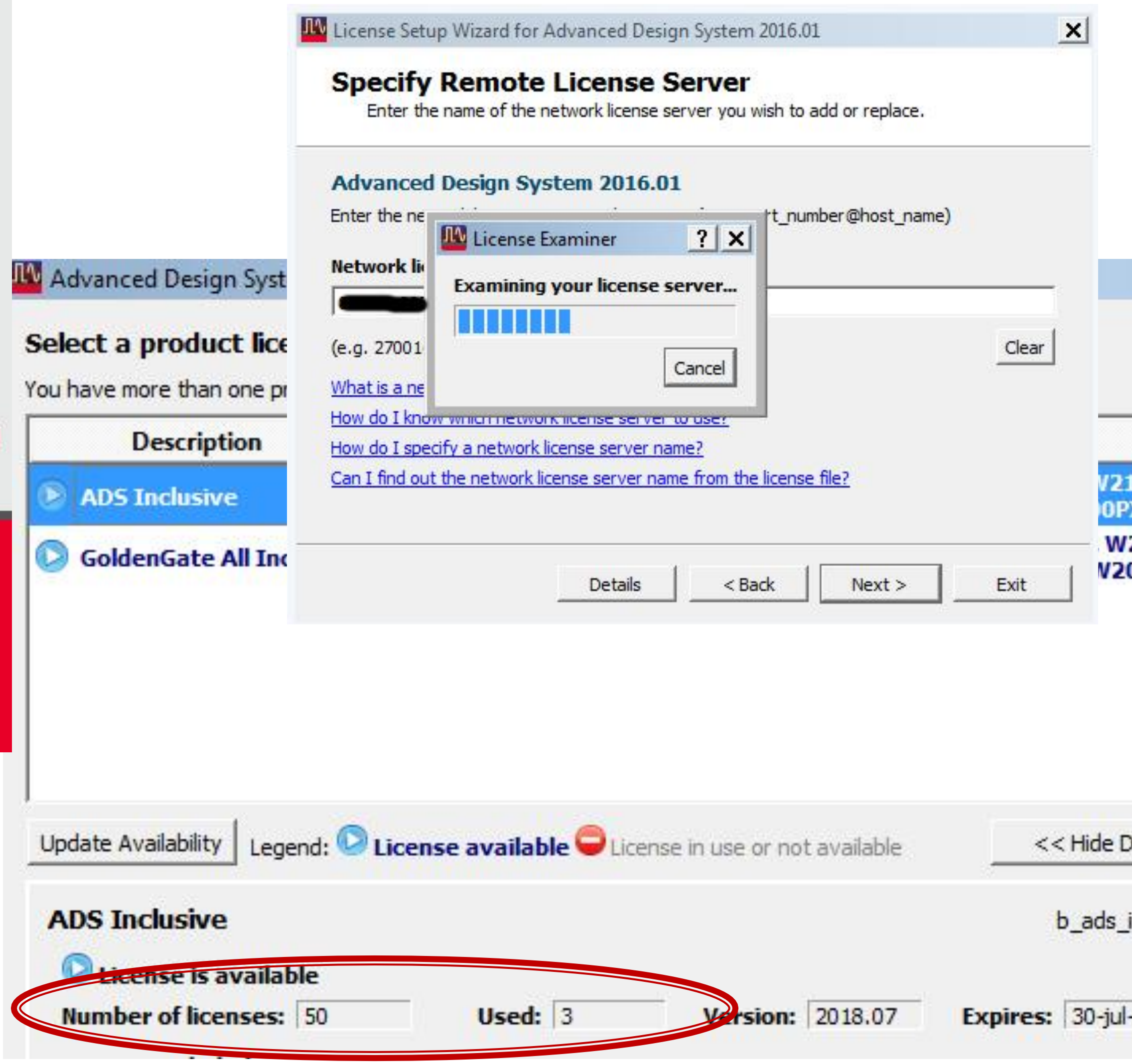
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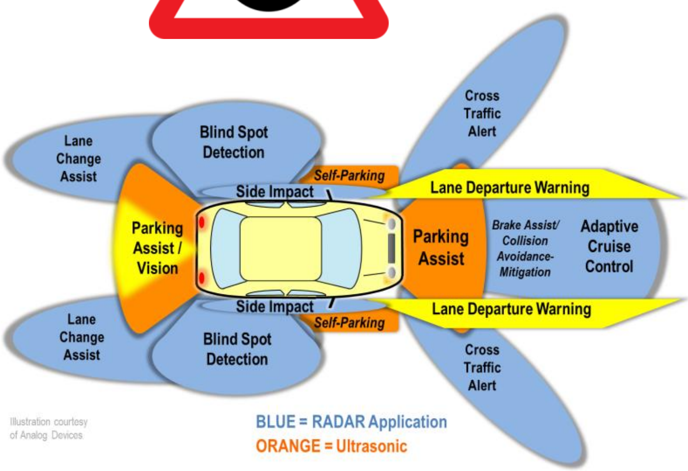
Version: 2018.07
Expires: 30-jul-

Course Objectives 4

"Engineering" Sinapses

Technology

> 2010



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Examen

- Complex numbers arithmetic**!!!!**
- $z = a + j \cdot b$; $\mathbf{j^2 = -1}$

Polar representation

- standard unit for angles – radians
- microwaves traditional unit for angles – **degrees in decimal form** (55.89°)

$$\varphi = \arg(z) = \begin{cases} \arctan\left(\frac{b}{a}\right), & a > 0 \\ \arctan\left(\frac{b}{a}\right) + \pi, & a < 0, b \geq 0 \\ \arctan\left(\frac{b}{a}\right) - \pi, & a < 0, b < 0 \\ \frac{\pi}{2}, -\frac{\pi}{2}, nedefinit & a = 0 \end{cases}$$

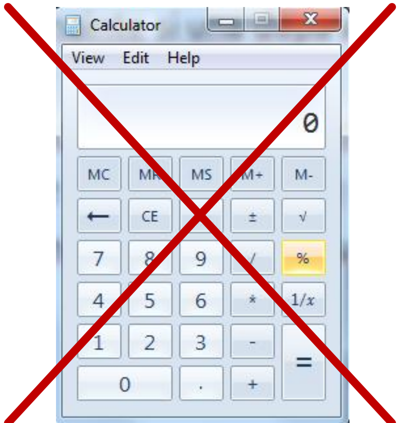
$$\varphi[°] = 180° \cdot \frac{\varphi[rad]}{\pi} \qquad \varphi[rad] = \pi \cdot \frac{\varphi[°]}{180°}$$

Polar representation

- **Attention to angle numerical values!!**
  - math software – work in standard unit: radians
    - a **conversion** is necessary before and after using a trigonometric function (sin, cos, tan, atan, tanh)
  - scientific calculators have the built-in option of choosing the angle unit
    - always **double check** current working unit

$$\varphi[^\circ] = 180^\circ \cdot \frac{\varphi[rad]}{\pi}$$

$$\varphi[rad] = \pi \cdot \frac{\varphi[^\circ]}{180^\circ}$$



Logarithmic scales

dB $= 10 \bullet \log_{10} (P_2 / P_1)$

0 dB	= 1
+ 0.1 dB	= 1.023 (+2.3%)
+ 3 dB	= 2
+ 5 dB	= 3
+ 10 dB	= 10
-3 dB	= 0.5
-10 dB	= 0.1
-20 dB	= 0.01
-30 dB	= 0.001

dBm $= 10 \bullet \log_{10} (P / 1\ \text{mW})$

0 dBm	= 1 mW
3 dBm	= 2 mW
5 dBm	= 3 mW
10 dBm	= 10 mW
20 dBm	= 100 mW
-3 dBm	= 0.5 mW
-10 dBm	= 100 µW
-30 dBm	= 1 µW
-60 dBm	= 1 nW

[dBm] + [dB] = [dBm]

[dBm/Hz] + [dB] = [dBm/Hz]

→ [x] + [dB] = [x]

Introduction

Maxwell's Equations

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = \frac{\partial D}{\partial t} + J$$

$$\nabla \cdot D = \rho$$

$$\nabla \cdot B = 0$$

$$\nabla \cdot J = -\frac{\partial \rho}{\partial t}$$

- Constitutive equations

$$D = \varepsilon \cdot E$$

$$B = \mu \cdot H$$

$$J = \sigma \cdot E$$

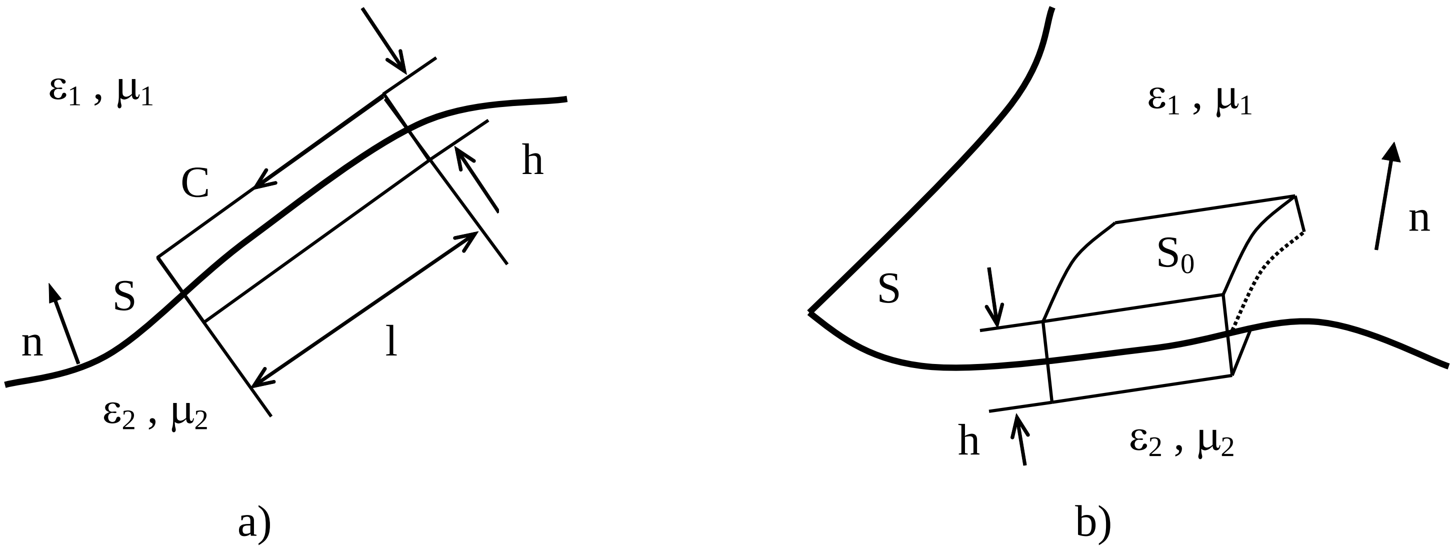
- Vacuum

$$\mu_0 = 4\pi \times 10^{-7}\ H/m$$

$$\varepsilon_0 = 8{,}854 \times 10^{-12}\ F/m$$

$$c_0 = \frac{1}{\sqrt{\varepsilon_0 \cdot \mu_0}} = 2{,}99790 \cdot 10^8\ m/s$$

Interface conditions on the interface between two different media



$$n \times (E_1 - E_2) = 0 \qquad n \cdot (D_1 - D_2) = \rho_S$$

$$n \times (H_1 - H_2) = J_S \qquad n \cdot (B_1 - B_2) = 0$$

- If one of the media is a perfect conductor (metal) all fields are annulled inside

Electromagnetic fields with harmonic time dependence

$$X = X_0 e^{j\cdot\omega\cdot t} \qquad \frac{\partial X}{\partial t} = j\cdot\omega\cdot X$$

$$g(\omega) = \int_{-\infty}^{\infty} f(t)\cdot e^{-j\omega t}\,dt \qquad f(t) = \int_{-\infty}^{\infty} g(\omega)\cdot e^{j\omega t}\,d\omega$$

- Maxwell's Equations more simple

$$\nabla^2 E + \omega^2 \varepsilon\mu E = j\omega\mu J + \frac{1}{\varepsilon}\nabla\rho$$

$$\nabla^2 H + \omega^2 \varepsilon\mu H = -\nabla\times J$$

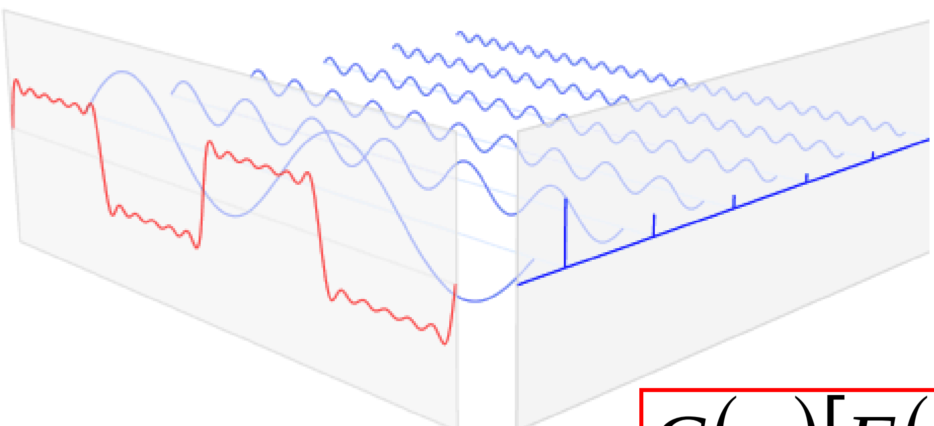
$$\nabla\cdot E = \frac{\rho}{\varepsilon}$$

$$\nabla\cdot H = 0$$

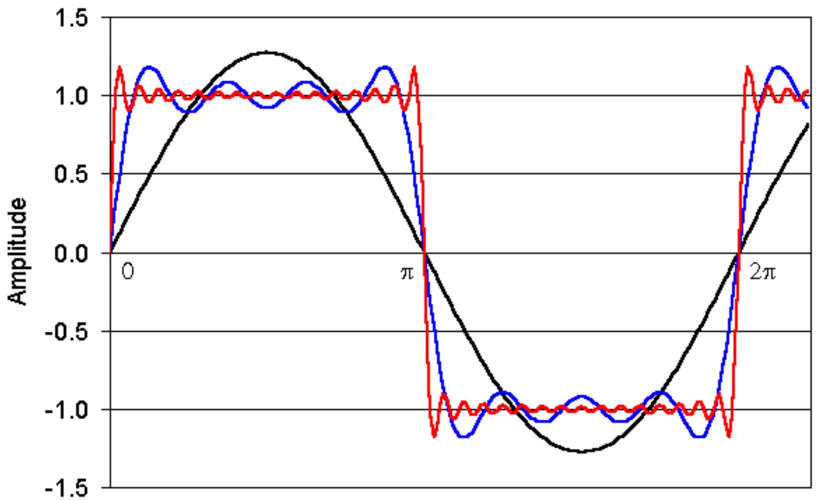
Mathematical models

- particular cases where analytical solution exists
  - harmonic signals, Fourier Transform, frequency spectrum

$$X = X_0 e^{j \cdot \omega \cdot t} \qquad \frac{\partial X}{\partial t} = j \cdot \omega \cdot X \qquad g(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-j\omega t} dt \qquad f(t) = \int_{-\infty}^{\infty} g(\omega) \cdot e^{j\omega t} d\omega$$

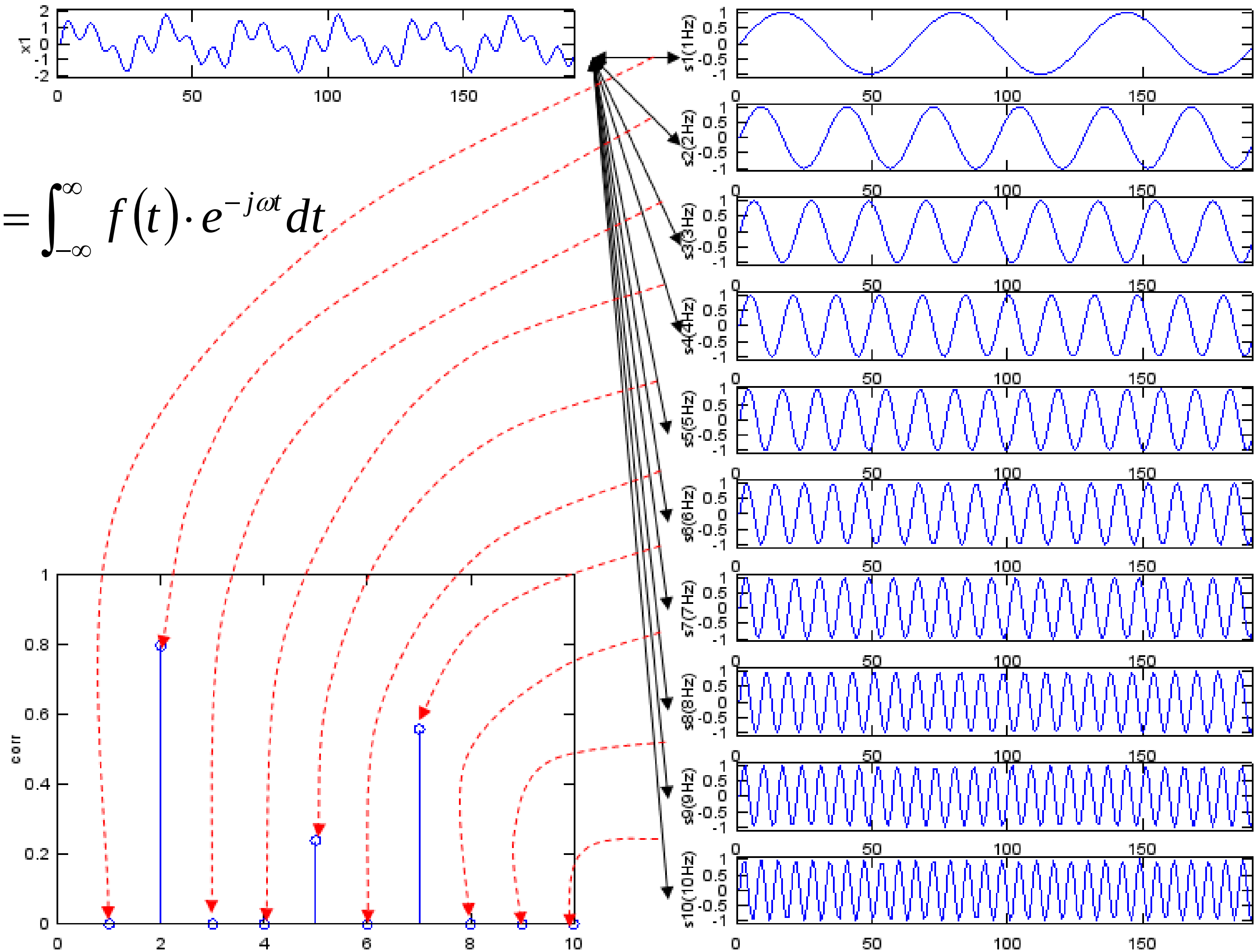


$$G(\omega)[F(\omega)]$$

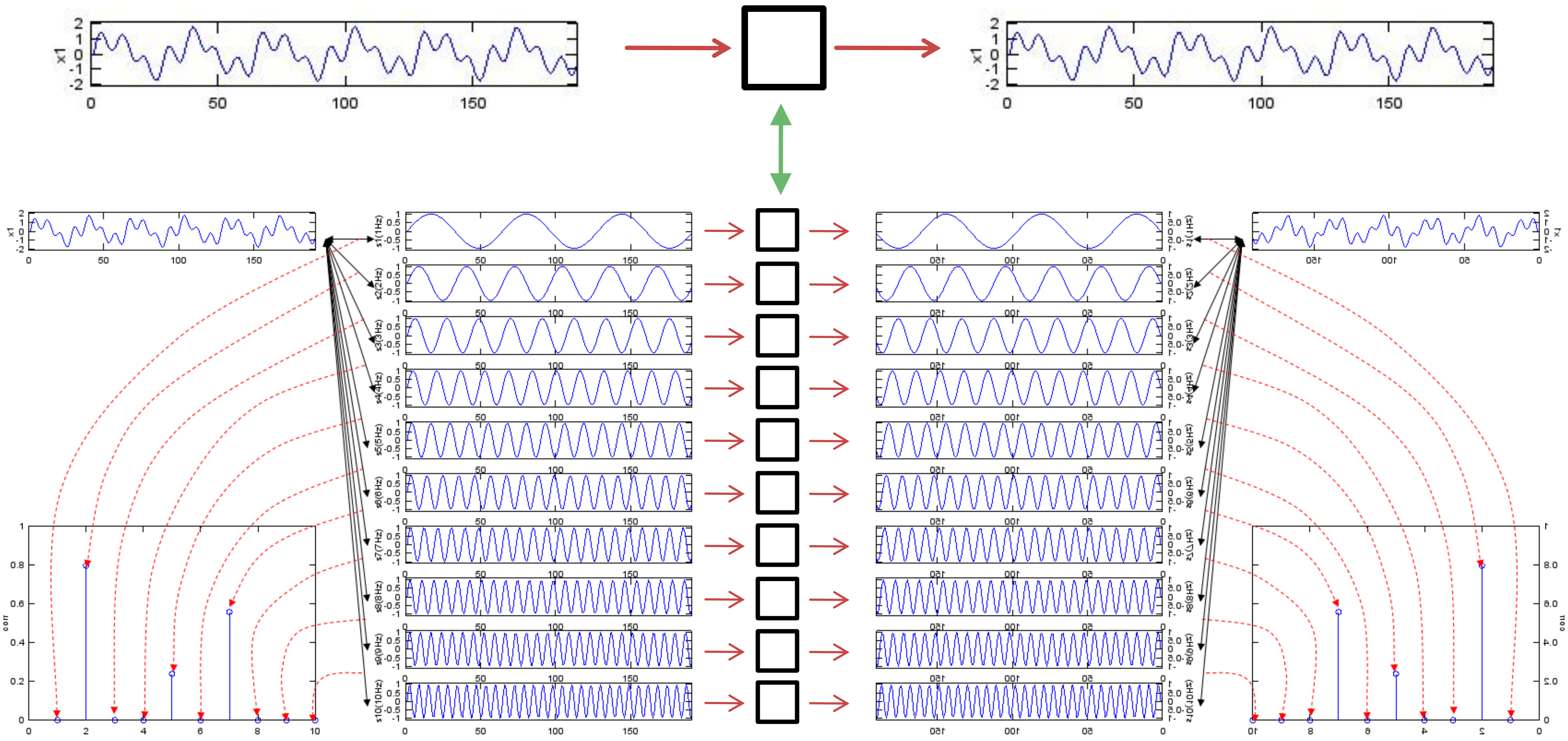


Mathematical models

$$g(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-j\omega t} dt$$



Mathematical models



$$F(\omega)=\int_{-\infty}^{\infty} f(t)\cdot e^{-j\omega t}dt \qquad G(\omega)[F(\omega)] \qquad g(t)=\int_{-\infty}^{\infty} G(\omega)\cdot e^{j\omega t}d\omega$$

Wave equations

- Helmoltz equations or Wave equations

Medium void of free electric charges

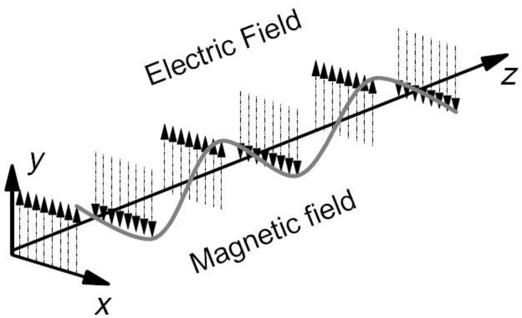
$$\nabla^2 E - \gamma^2 E = 0$$

$$\nabla^2 H - \gamma^2 H = 0$$

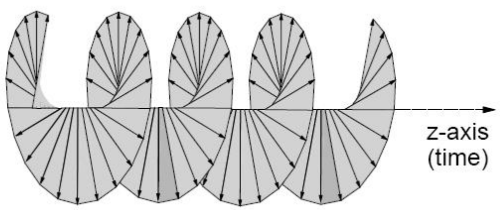
$$\gamma^2 = -\omega^2 \varepsilon\mu + j\omega\mu\sigma$$

γ – propagation constant (known also as phase constant or wave number)

Solutions of the wave equations



Wave Propagation



Circular Polarization

Electric field only in Oy direction, ← through judicious choice
wave traveling after Oz direction ← of the coordinate system

$$E_y = E_+ e^{-\gamma \cdot z} + E_- e^{\gamma \cdot z}$$

$$\gamma = \sqrt{-\omega^2 \varepsilon\mu + j\omega\mu\sigma} = \alpha + j \cdot \beta$$

If we have only the positive direction wave $E_+ \Rightarrow A$

$$E_y = Ae^{-(\alpha + j \cdot \beta) \cdot z}$$

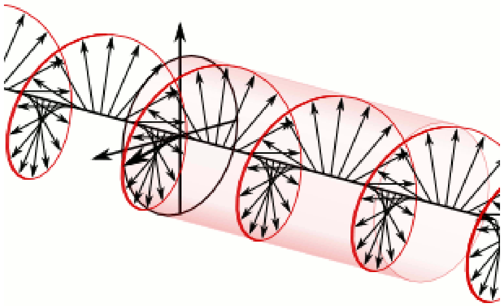
Harmonic Field

$$E_y = A \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t - \beta \cdot z)}$$

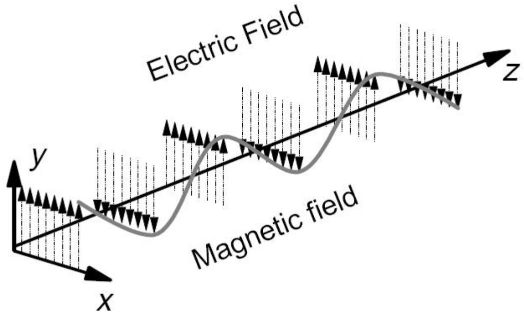
Amplitude

Attenuation

Wave Propagation (simultaneous space and time variation)



Plane wave parameters



$$\nabla \times E = -j\omega\mu \cdot H$$

$$H_x = \frac{j\gamma \cdot E_y}{\omega\mu}$$

Lossless Medium, $\sigma = 0$ $\gamma = j\omega \cdot \sqrt{\varepsilon\mu}$

$$\eta = \frac{E_y}{H_x} = \sqrt{\frac{\mu}{\varepsilon}}$$ intrinsic impedance of the medium

$$E_y = A \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t - \beta \cdot z)}$$

constant phase points: $(\omega \cdot t - \beta \cdot z) = \text{const}$

Phase velocity $v_p = \frac{dz}{dt} = \frac{\omega}{\beta} = \frac{1}{\sqrt{\varepsilon\mu}}$

Group velocity $v_g = \frac{dz}{dt} = \frac{d\omega}{d\beta}$ in dispersive media where $\beta = \beta(\omega)$

Plane wave parameters

- In vacuum

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\Omega \qquad v = v_g = c_0 \qquad c_0 = \frac{1}{\sqrt{\varepsilon_0 \cdot \mu_0}} = 2{,}99790 \cdot 10^8 \ m/s$$

$$\lambda_0 = \frac{2\pi}{\beta} = \frac{c_0}{f} \qquad T = \frac{2\pi}{\omega} = \frac{1}{f}$$

Space periodicity — Time periodicity

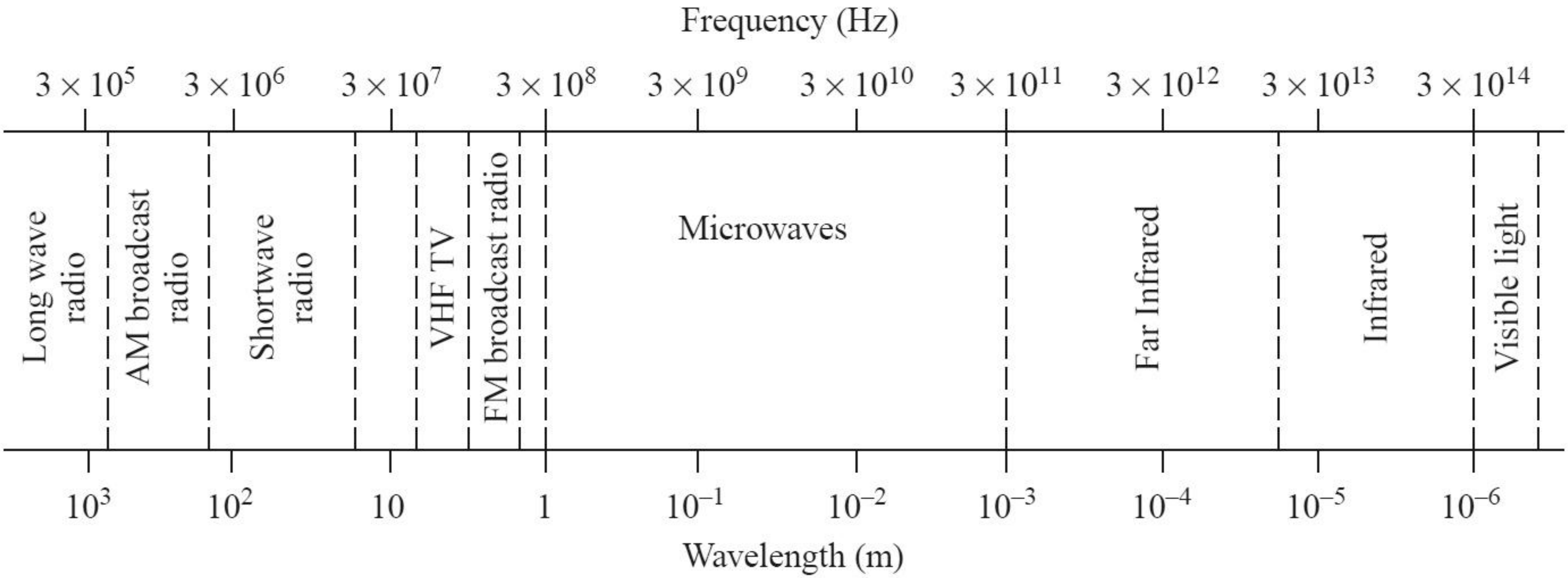
- In a non-dispersive medium, ε_r

$$c = \frac{1}{\sqrt{\varepsilon \cdot \mu_0}} = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_r \cdot \mu_0}} = \frac{c_0}{\sqrt{\varepsilon_r}}$$

$n = \sqrt{\varepsilon_r}$ refractive index of a medium $\qquad c = \frac{c_0}{n}$

$$T = \frac{2\pi}{\omega} = \frac{1}{f} \qquad \lambda = \frac{2\pi}{\beta} = \frac{c}{f} \qquad \lambda = \frac{c_0}{\sqrt{\varepsilon_r} \cdot f} = \frac{\lambda_0}{\sqrt{\varepsilon_r}}$$

Microwaves



- typically
  - $f \approx 1 \div 3\text{GHz} - 300\text{GHz}$
  - $\lambda \approx 1\text{mm} - 10\text{cm}$

Microunde

Typical Frequencies

AM broadcast band	535–1605 kHz
Short wave radio band	3–30 MHz
FM broadcast band	88–108 MHz
VHF TV (2–4)	54–72 MHz
VHF TV (5–6)	76–88 MHz
UHF TV (7–13)	174–216 MHz
UHF TV (14–83)	470–890 MHz
US cellular telephone	824–849 MHz
	869–894 MHz
European GSM cellular	880–915 MHz
	925–960 MHz
GPS	1575.42 MHz
	1227.60 MHz
Microwave ovens	2.45 GHz
US DBS	11.7–12.5 GHz
US ISM bands	902–928 MHz
	2.400–2.484 GHz
	5.725–5.850 GHz
US UWB radio	3.1–10.6 GHz

Approximate Band Designations

Medium frequency	300 kHz–3 MHz
High frequency (HF)	3 MHz–30 MHz
Very high frequency (VHF)	30 MHz–300 MHz
Ultra high frequency (UHF)	300 MHz–3 GHz
L band	1–2 GHz
S band	2–4 GHz
C band	4–8 GHz
X band	8–12 GHz
Ku band	12–18 GHz
K band	18–26 GHz
Ka band	26–40 GHz
U band	40–60 GHz
V band	50–75 GHz
E band	60–90 GHz
W band	75–110 GHz
F band	90–140 GHz

~ Microunde

- Electrical Length (Phase Length)
  - l – physical length
  - E = β·l – electrical Length

$$E = \beta \cdot l = \frac{2\pi}{\lambda} \cdot l = 2\pi \cdot \left(\frac{l}{\lambda} \right)$$

$$E = \beta \cdot l = \frac{2\pi}{c_0} \cdot \left(l \cdot f \cdot \sqrt{\varepsilon_r} \right)$$

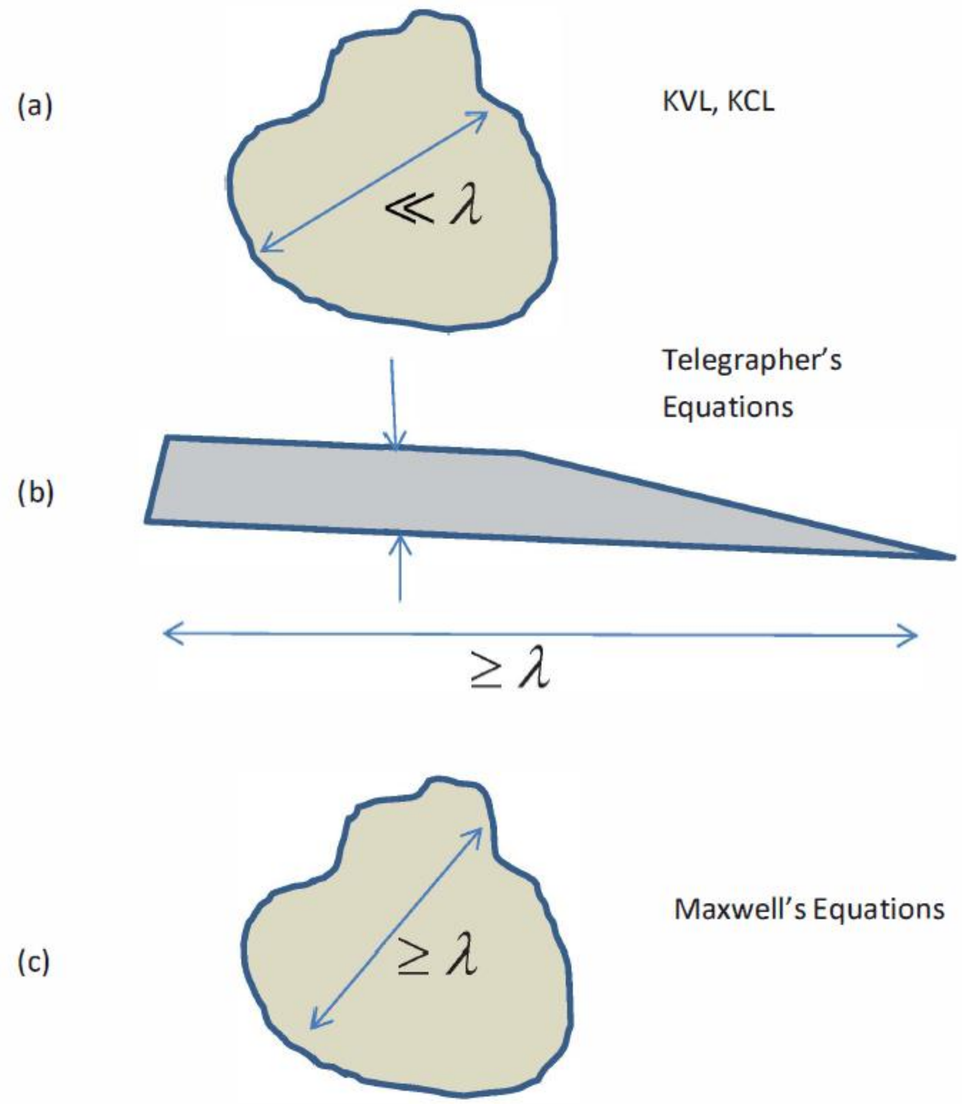
V, I vary
~ useless

- Dependency
  - antenna gain
  - Radar cross-section

Electrical Length

- Behavior (and description) of any circuit depends on his electrical length at the particular frequency of interest
  - E≈0 → Kirchhoff
  - E>0 → wave propagation

$$E = \beta \cdot l = \frac{2\pi}{\lambda} \cdot l = 2\pi \cdot \left(\frac{l}{\lambda}\right)$$



Solutions of the wave equations

$$E_y = E^+ e^{-\gamma \cdot z} + E^- e^{\gamma \cdot z}$$

Electric field only in Oy direction, ← **through judicious choice**
wave traveling after Oz direction ← **of the coordinate system**

$$\gamma = \sqrt{-\omega^2 \varepsilon \mu + j \omega \mu \sigma} = \alpha + j \cdot \beta$$

- wave
  - incident
  - reflected
- wave
  - direct
  - inverse

$$E_y = E^+ \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega t - \beta \cdot z)}$$

$$(\omega \cdot t - \beta \cdot z) = \text{const}$$

$$E_y = E^- \cdot e^{\alpha \cdot z} \cdot e^{j(\omega t + \beta \cdot z)}$$

$$(\omega \cdot t + \beta \cdot z) = \text{const}$$

points of constant phase

Solutions of the wave equations

- wave
  - incident
  - reflected
- wave
  - direct
  - inverse

$$E_y = E^+ \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t - \beta \cdot z)} + E^- \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t + \beta \cdot z)}$$

$$H_z = H^+ \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t - \beta \cdot z)} + H^- \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t + \beta \cdot z)}$$

$$V(z) = V^+ \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t - \beta \cdot z)} + V^- \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t + \beta \cdot z)}$$

$$I(z) = I^+ \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t - \beta \cdot z)} + I^- \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t + \beta \cdot z)}$$

$$V(z) = V^+ \cdot e^{j(\omega \cdot t - \beta \cdot z)} + V^- \cdot e^{j(\omega \cdot t + \beta \cdot z)}$$

Moduri in medii delimitate

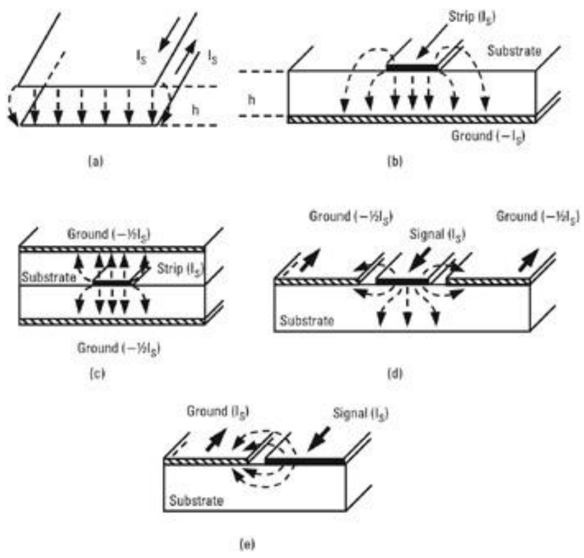
- Câmpuri electromagnetice cu variație armonică în timp
  - simplificarea ecuatiilor lui Maxwell

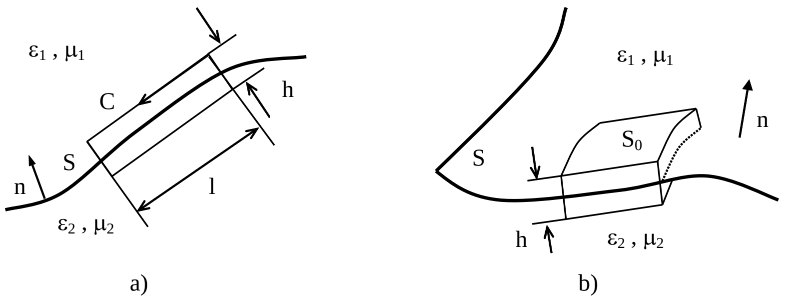
$$X = X_0 e^{j \cdot \omega \cdot t} \qquad \frac{\partial X}{\partial t} = j \cdot \omega \cdot X \qquad g(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-j\omega t} dt \qquad f(t) = \int_{-\infty}^{\infty} g(\omega) \cdot e^{j\omega t} d\omega$$

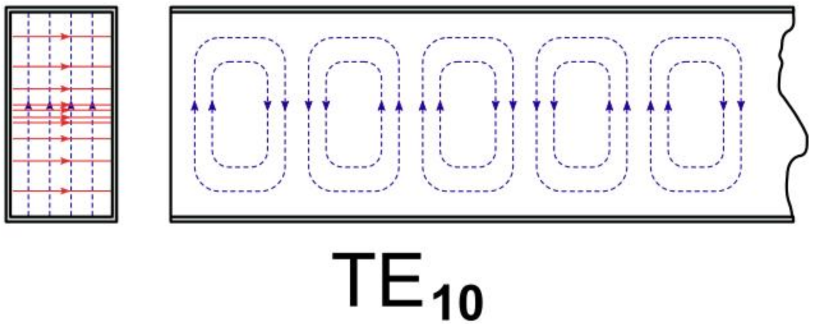
- In medii delimitate solutiile ecuatiilor lui Maxwell trebuie sa verifice conditiile la limita
  - solutiile trebuie sa respecte anumite conditii suplimentare

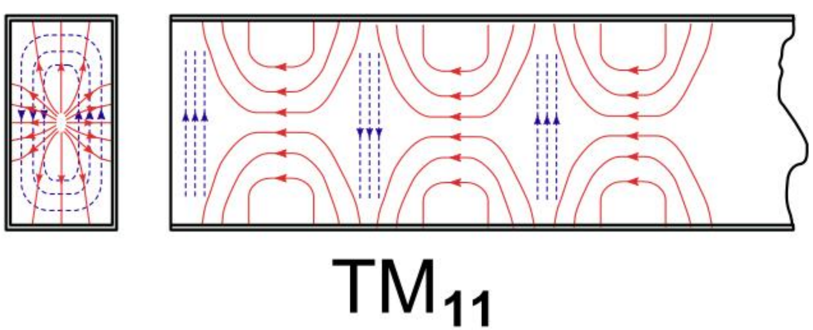
Moduri in medii delimitate

- Campul electric trebuie sa fie perpendicular pe un perete metalic sau nul
- Campul magnetic trebuie sa fie tangent la un perete metalic sau nul

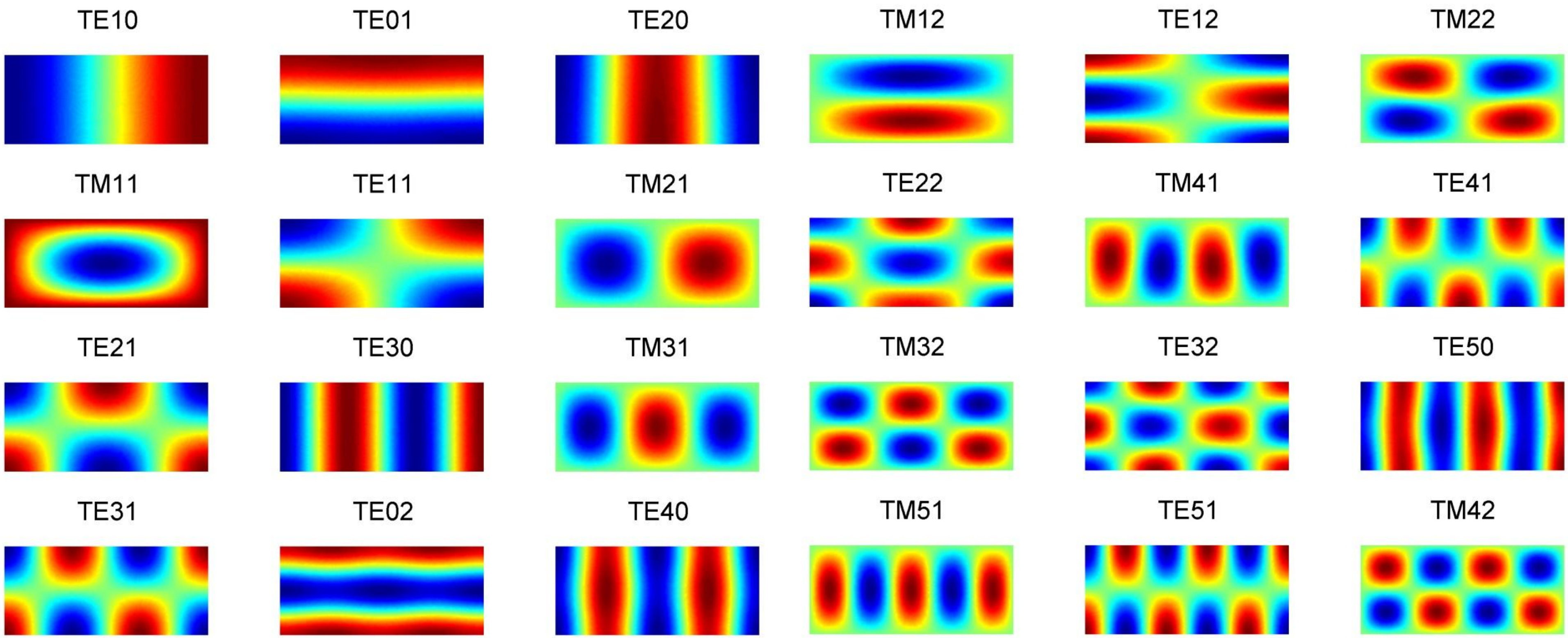








Moduri in medii delimitate



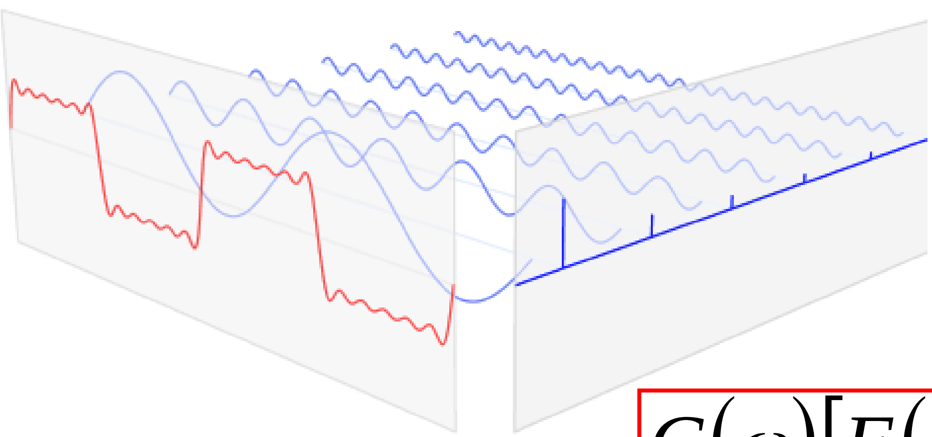
- Similar cu transformata Fourier $g(\omega)=\int_{-\infty}^{\infty} f(t)\cdot e^{-j\omega t}dt \quad f(t)=\int_{-\infty}^{\infty} g(\omega)\cdot e^{j\omega t}d\omega$

$$E^{+},E^{-}=\sum_{1}^{\infty} A_i \cdot Mod_i \qquad A_i=\langle E, Mod_i \rangle$$

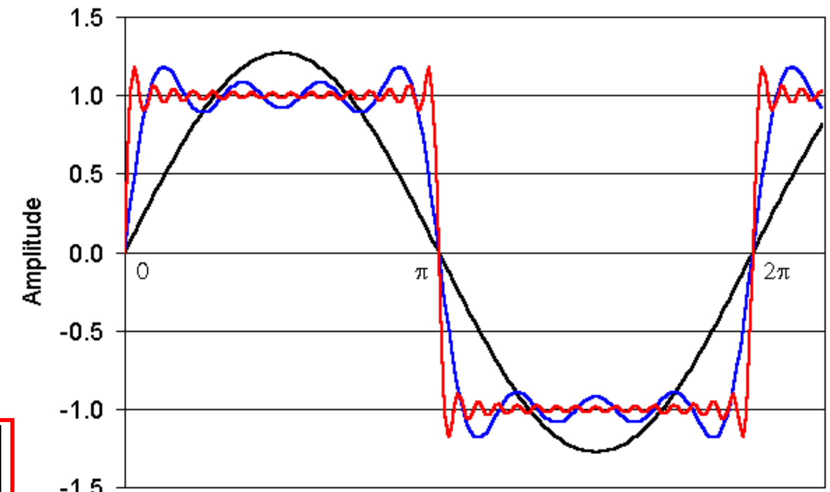
Mathematical modeling

- particular cases where analytical solution exists
  - harmonic signals, Fourier Transform, frequency spectrum

$$X = X_0 e^{j\cdot\omega\cdot t} \qquad \frac{\partial X}{\partial t} = j\cdot\omega\cdot X \qquad g(\omega)=\int_{-\infty}^{\infty} f(t)\cdot e^{-j\omega t}dt \qquad f(t)=\int_{-\infty}^{\infty} g(\omega)\cdot e^{j\omega t}d\omega$$

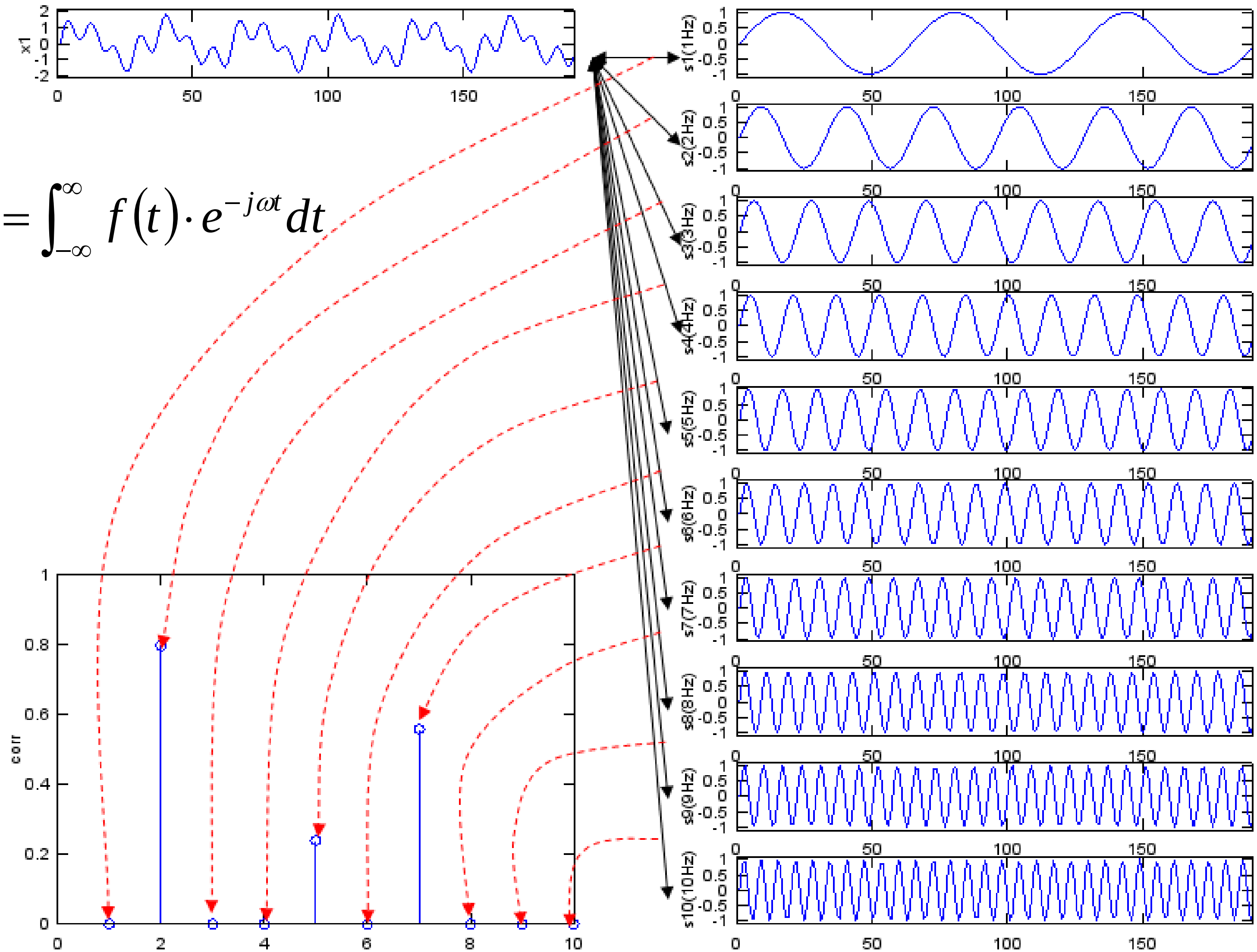


$$G(\omega)[F(\omega)]$$

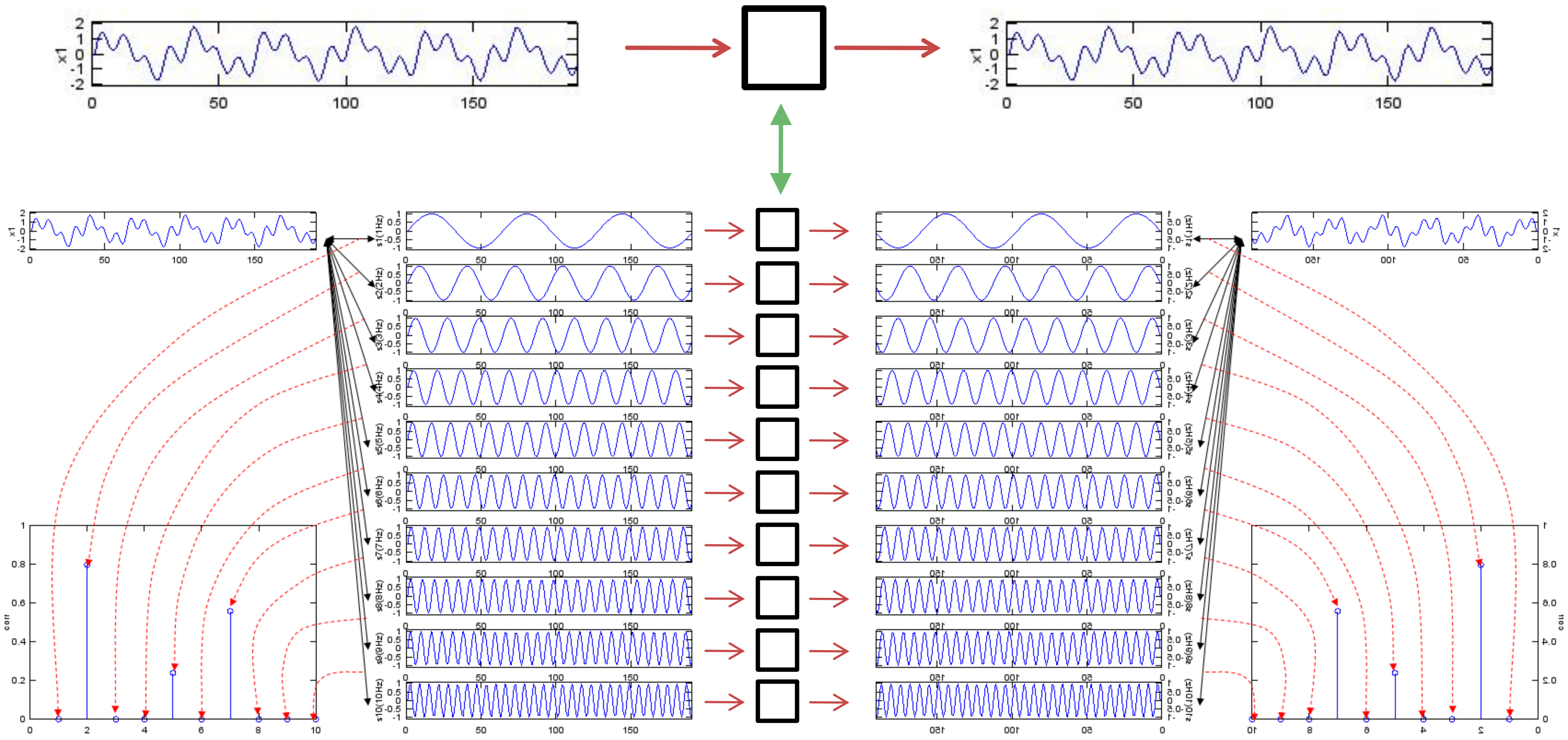


Mathematical modeling

$$g(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-j\omega t} dt$$



Mathematical modeling

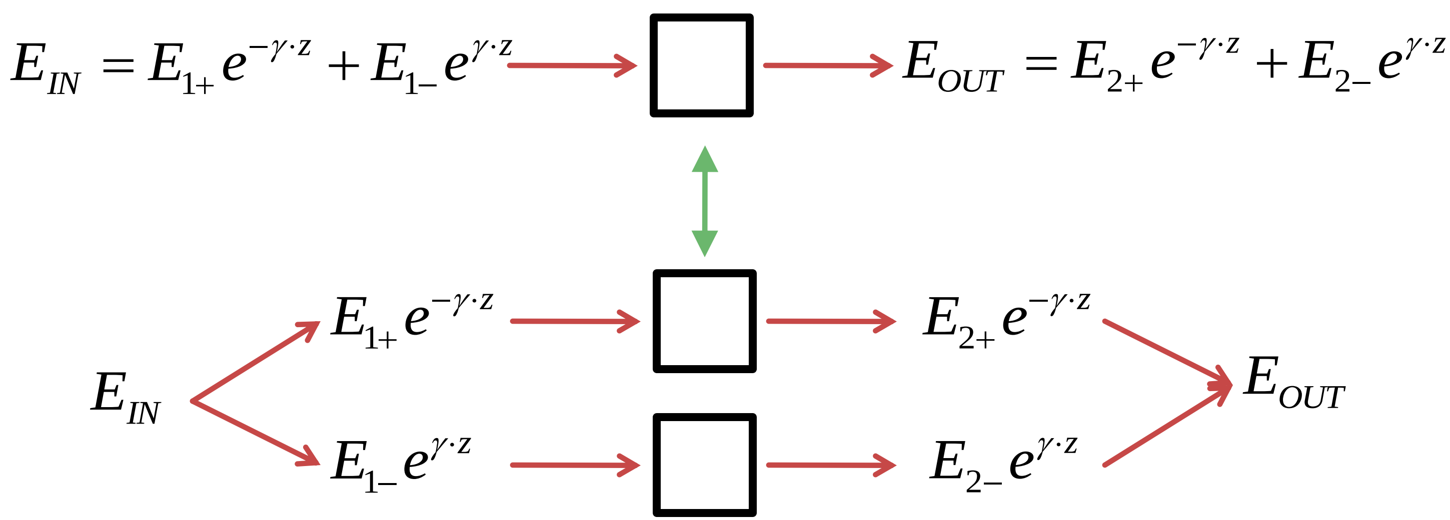


$$F(\omega)=\int_{-\infty}^{\infty} f(t)\cdot e^{-j\omega t}dt \qquad G(\omega)\left[F(\omega)\right] \qquad g(t)=\int_{-\infty}^{\infty} G(\omega)\cdot e^{j\omega t}d\omega$$

Mathematical modeling

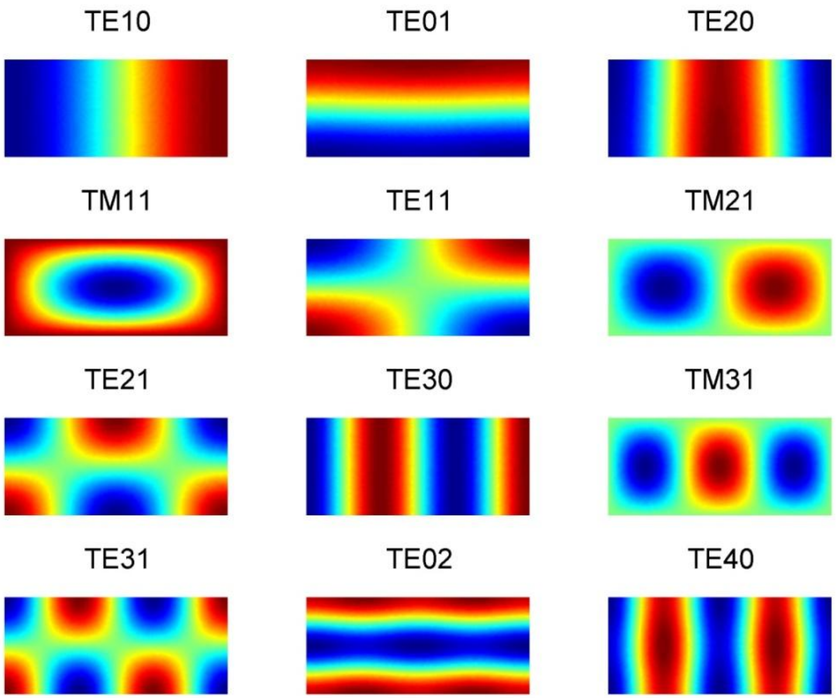
- particular cases where analytical solution exists
  - wave
    - incident
    - reflected
  - wave
    - direct
    - inverse

$$E_y = E^+ \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t - \beta \cdot z)} + E^- \cdot e^{-\alpha \cdot z} \cdot e^{j(\omega \cdot t + \beta \cdot z)}$$

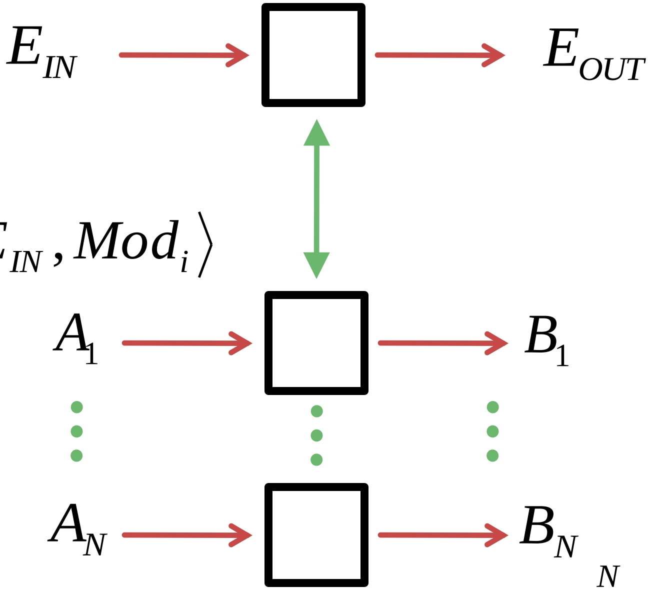


Mathematical modeling

- particular cases where analytical solution exists
  - modes in delimited media



$$E = \sum_{1}^{\infty} A_i \cdot Mod_i \qquad A_i = \langle E, Mod_i \rangle$$

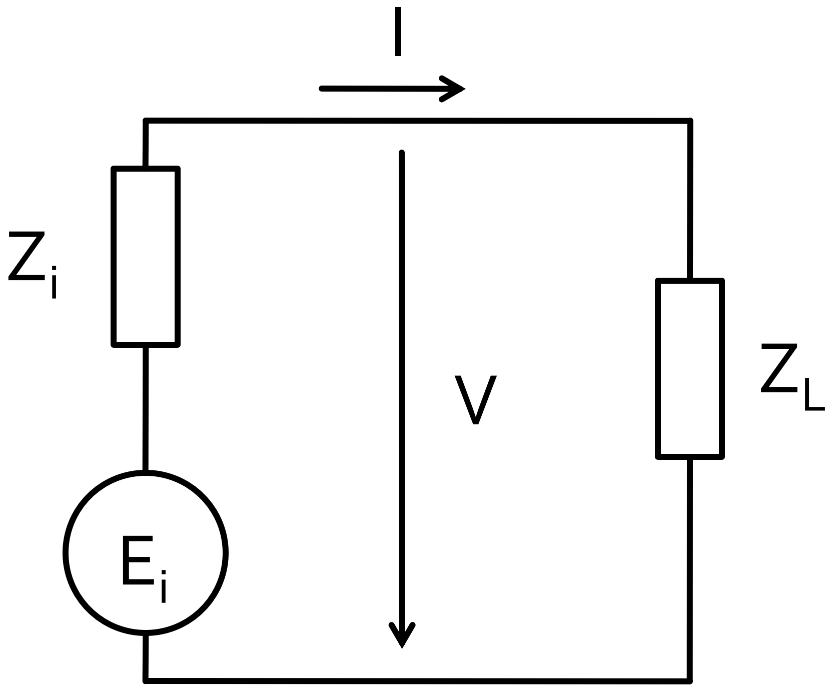


$$A_i = \langle E_{IN}, Mod_i \rangle$$

$$E_{OUT} = \sum_{1}^{N} B_i \cdot Mod_i$$

Matching

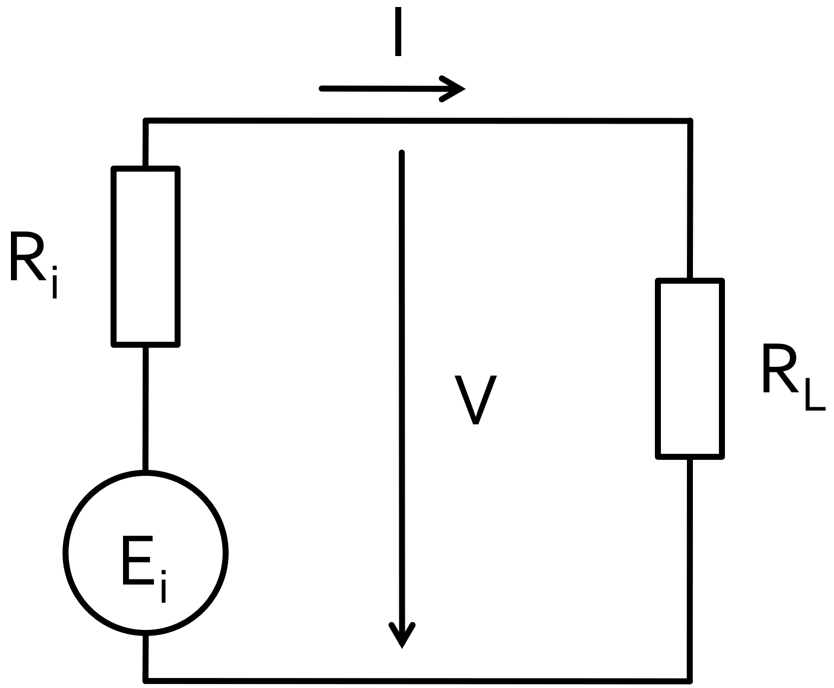
- Source **matched** to load ?



- impedance values ?
- existence of reflections ?

Matching, real impedances

- Source matched to load



$$I = \frac{E_i}{R_i + R_L}$$

$$V = \frac{E_i \cdot R_L}{R_i + R_L}$$

$$P_L = R_L \cdot I^2$$

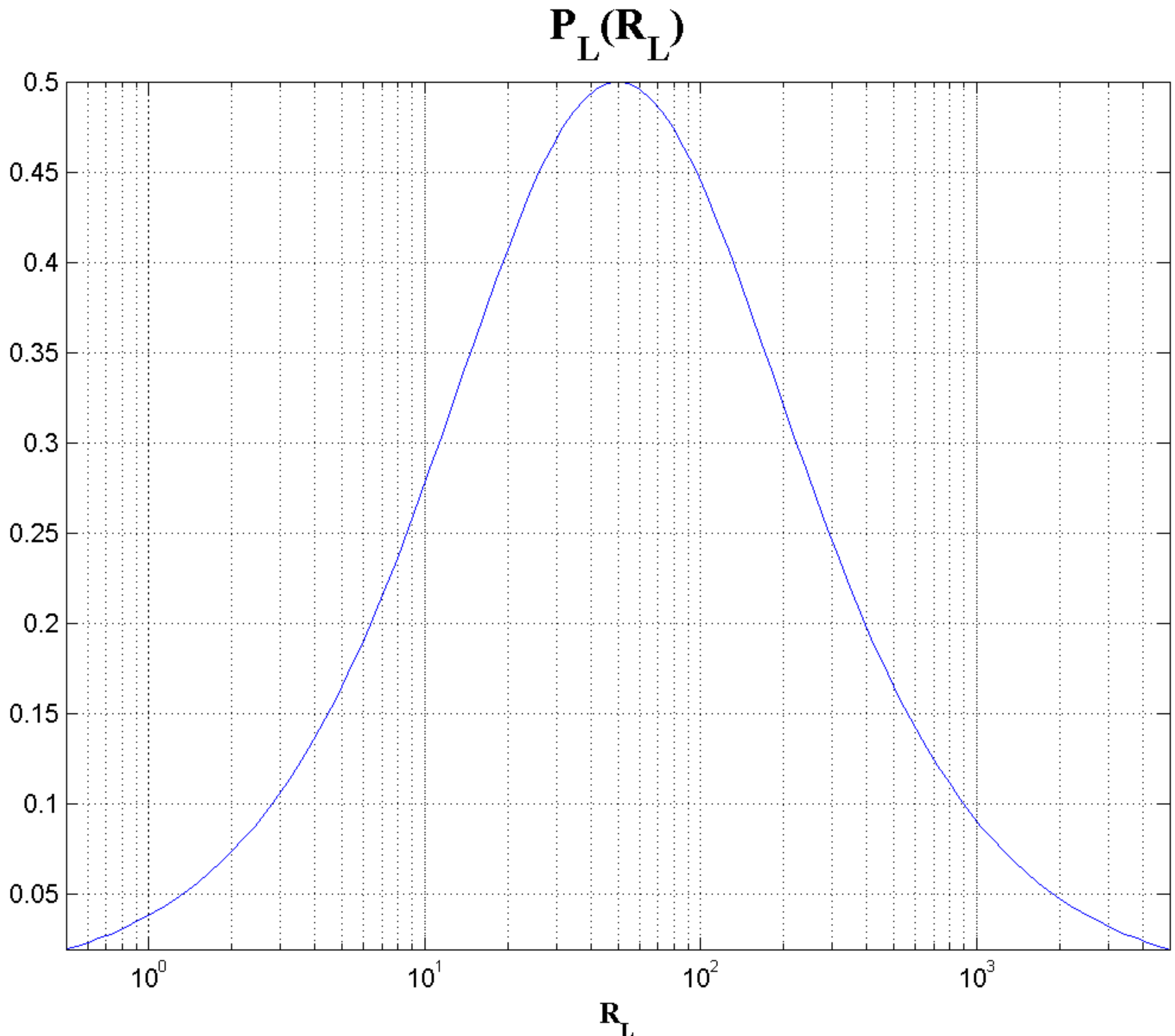
$$P_L = \frac{R_L \cdot E_i^2}{(R_i + R_L)^2}$$

Matching, real impedances

$$P_L = R_L \cdot I^2 \qquad P_L = \frac{R_L \cdot E_i^2}{(R_i + R_L)^2}$$

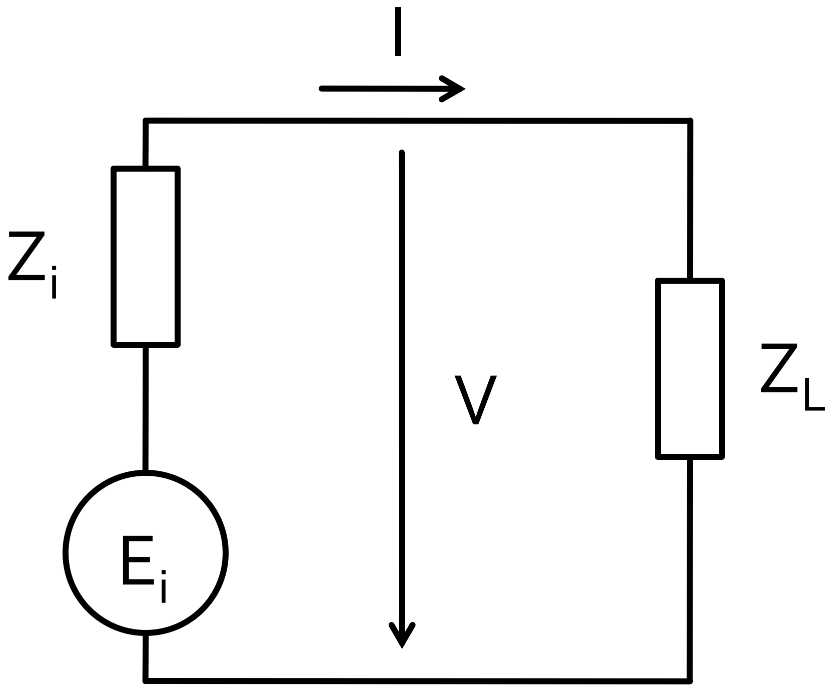
- Power dissipated on load
  - $R_i = 50\Omega$
  - $R_L = 0 \rightarrow P_L = 0$
  - $R_L = \infty \rightarrow P_L = 0$

Matching, real impedances



Matching, complex impedances

- Source matched to load



$$I = \frac{E_i}{Z_i + Z_L}$$

$$V = \frac{E_i \cdot Z_L}{Z_i + Z_L}$$

$$P_L = \operatorname{Re} Z_L \cdot |I|^2$$

$$P_L = \operatorname{Re} Z_L \cdot \left| \frac{E_i}{Z_i + Z_L} \right|^2$$

Matching

$$P_L = \frac{R_L \cdot |E_i|^2}{|Z_i + Z_L|^2} = \frac{R_L \cdot |E_i|^2}{|(R_i + R_L) + j \cdot (X_i + X_L)|^2}$$

$$|a + j \cdot b| = \sqrt{a^2 + b^2}$$

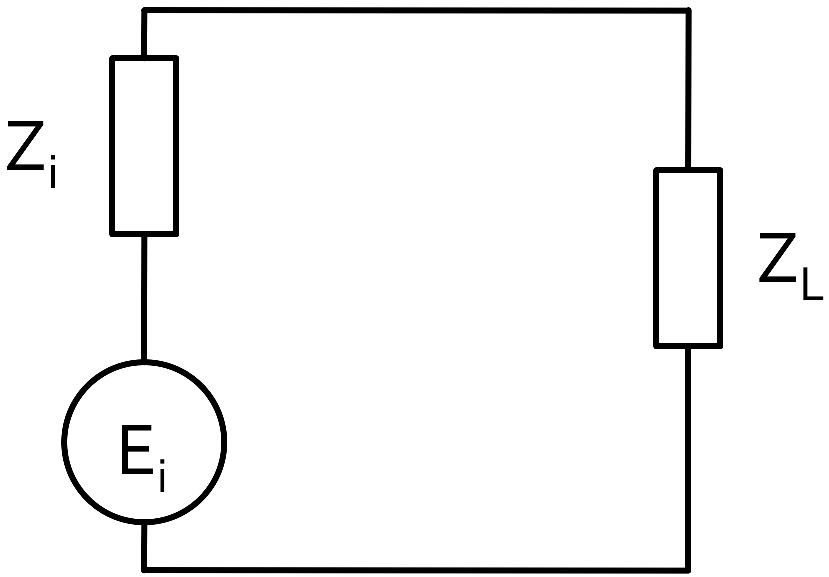
$$P_L = \frac{R_L \cdot |E_i|^2}{(R_i + R_L)^2 + (X_i + X_L)^2}$$

- Adaptare
  - putere maxima transmisa sarcinii
  - conditie?

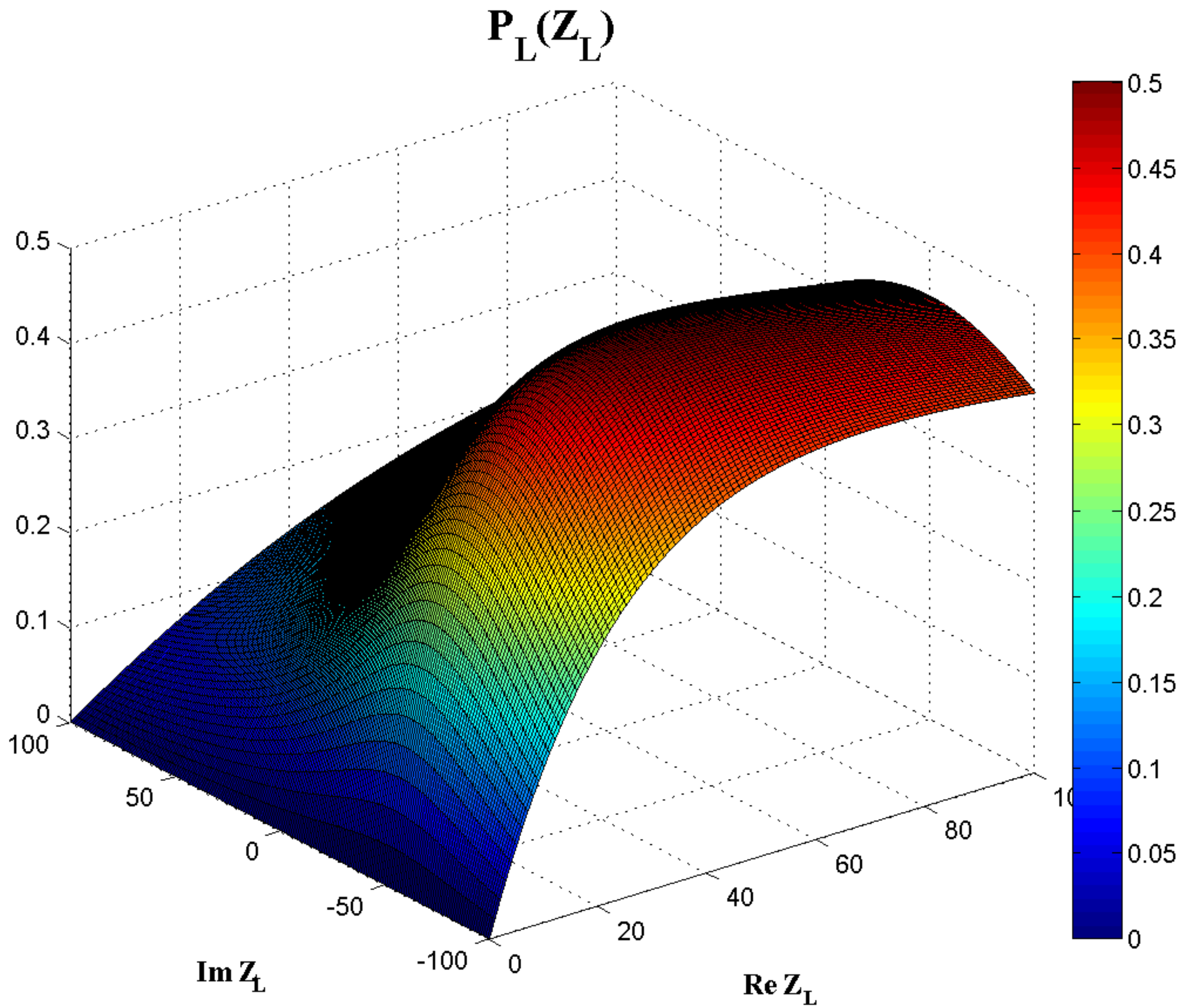
Matching, example

- $E = 10V$
- $Z_i = 50\,\Omega + j\cdot 50\Omega$
- $P_L(Z_L)$?

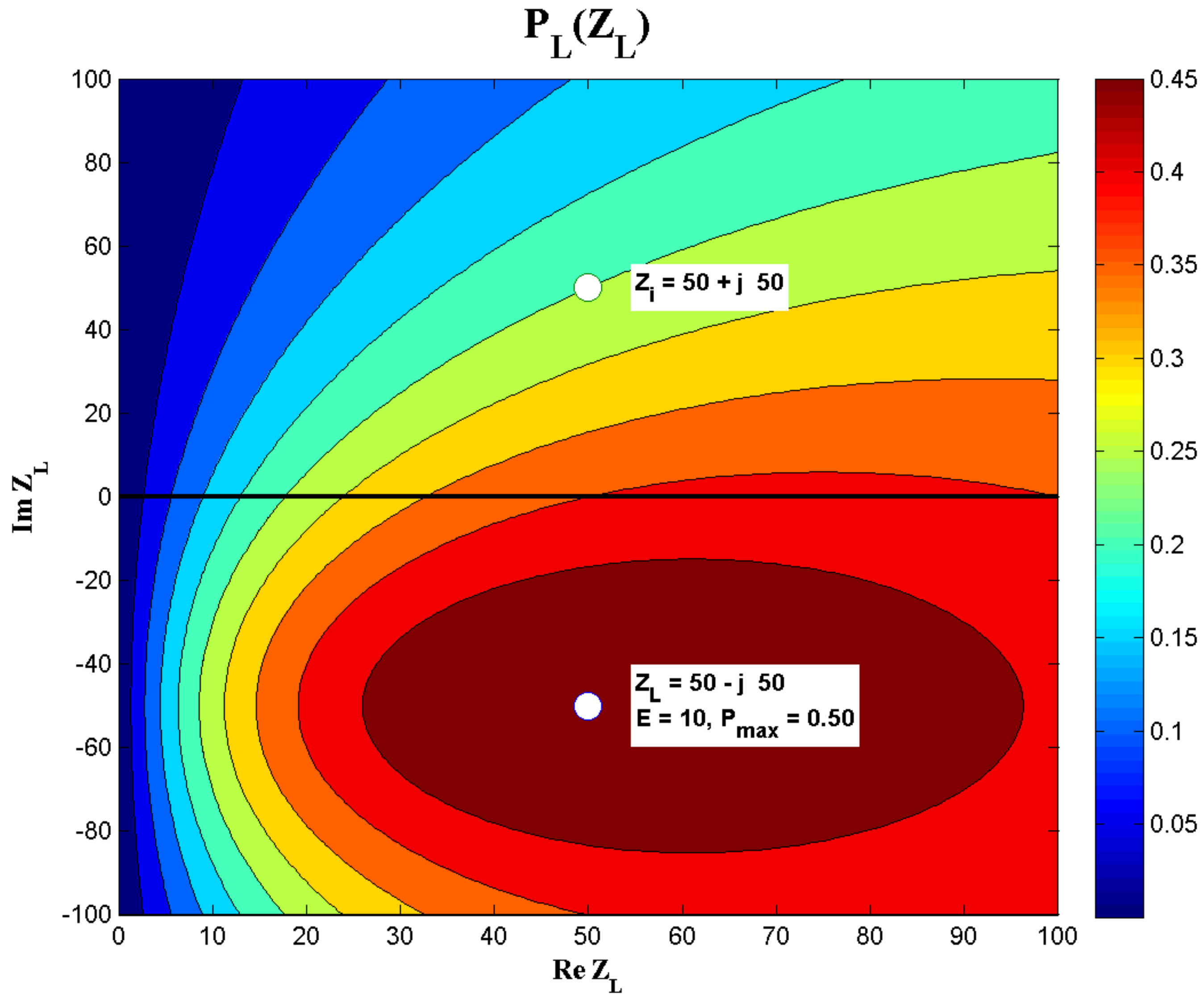
$$P_L = \frac{R_L \cdot |E_i|^2}{(R_i + R_L)^2 + (X_i + X_L)^2}$$



Matching, example



Matching, example



Matching , from the point of view of power transmission

$$R_i > 0,\ R_L > 0 \qquad P_L = \frac{|E_i|^2}{4R_i + \frac{(R_i - R_L)^2}{R_L} + \frac{(X_i + X_L)^2}{R_L}}$$

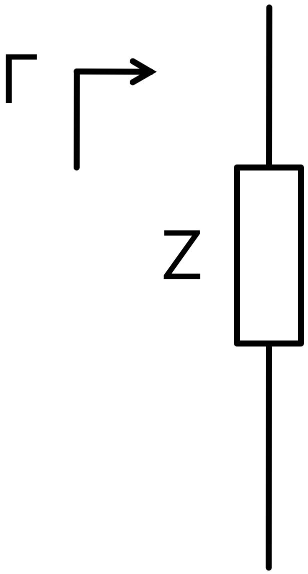
$$P_{L\max} = \frac{|E_i|^2}{4R_i} \equiv P_a \qquad R_L = R_i,\ X_L = -X_i$$

- P_a : Available Power

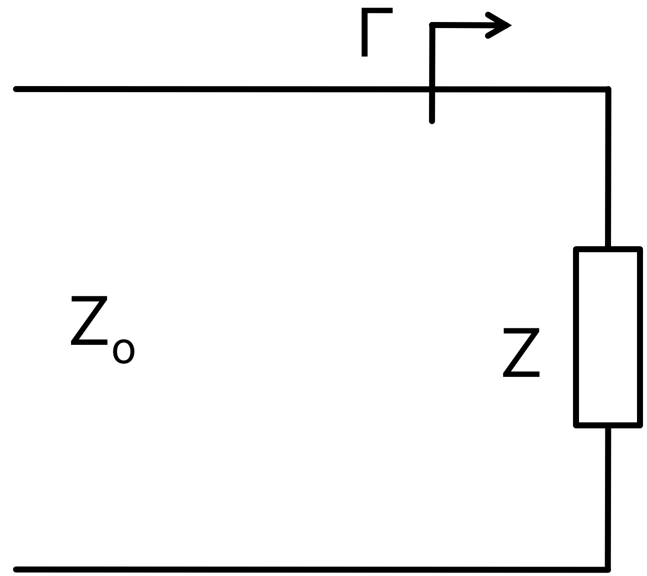
$$Z_L = Z_i^*$$

Reflection coefficient

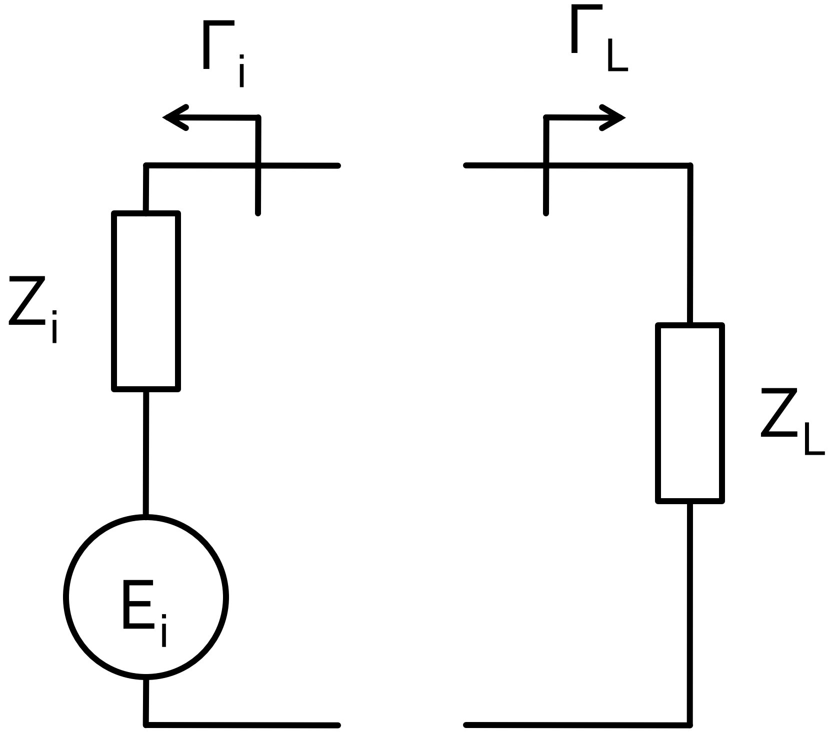
- Any impedance Z_o chosen as reference



$$\Gamma = \frac{Z - Z_0^*}{Z + Z_0}$$



Matching , from the point of view of power transmission



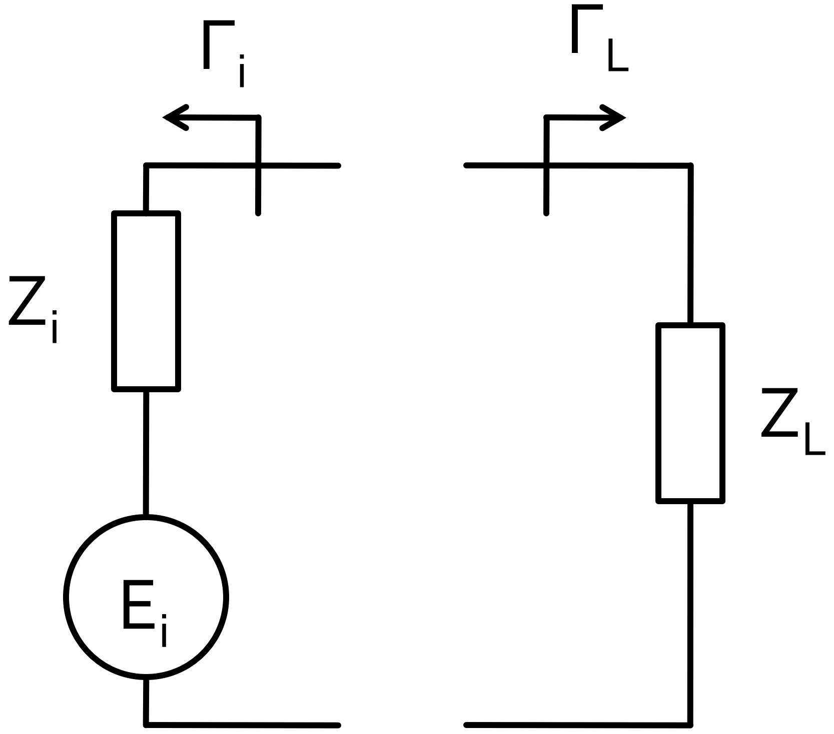
$$\Gamma_i = \frac{Z_i - Z_0^*}{Z_i + Z_0}$$

$$\Gamma_i = \frac{(R_i - R_0) + j \cdot (X_i + X_0)}{(R_i + R_0) + j \cdot (X_i + X_0)}$$

$$\Gamma_L = \frac{Z_L - Z_0^*}{Z_L + Z_0}$$

$$\Gamma_L = \frac{(R_L - R_0) + j \cdot (X_L + X_0)}{(R_L + R_0) + j \cdot (X_L + X_0)}$$

Matching , from the point of view of power transmission



$$\Gamma_i = \frac{Z_i - Z_0^*}{Z_i + Z_0} = 1 - \frac{Z_0 + Z_0^*}{Z_i + Z_0}$$

$$\Gamma_L = \frac{Z_L - Z_0^*}{Z_L + Z_0} = 1 - \frac{Z_0 + Z_0^*}{Z_L + Z_0}$$

$$\Gamma_i^* = 1 - \frac{Z_0^* + Z_0}{Z_i^* + Z_0^*} = 1 - \frac{Z_0^* + Z_0}{Z_L + Z_0^*}$$

Matching , from the point of view of power transmission

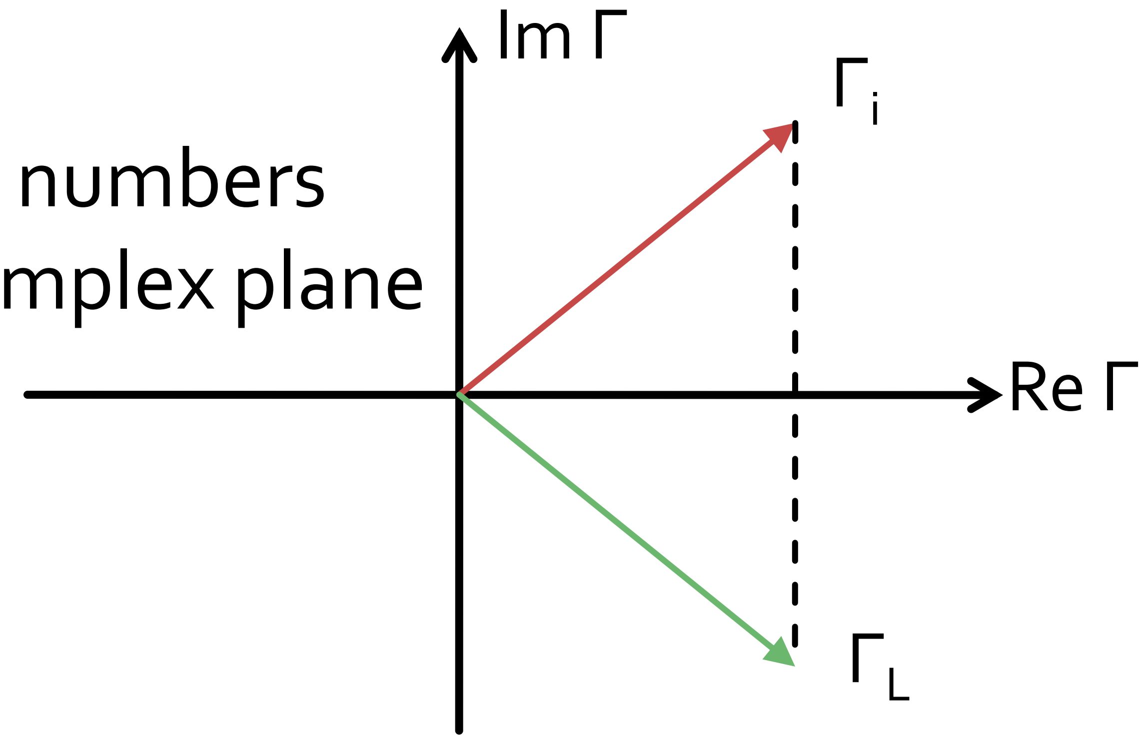
$$Z_L = Z_i^*$$

If we choose a real Zo

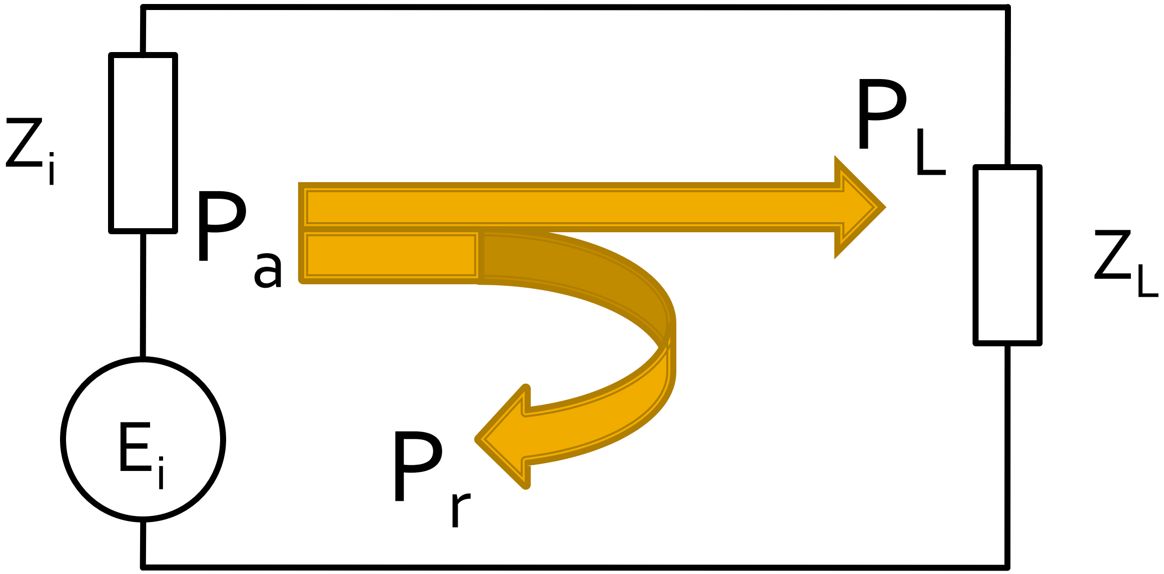
$$\Gamma = \frac{Z - Z_0}{Z + Z_0}$$

$$\Gamma_L = \Gamma_i^*$$

- complex numbers
- in the complex plane



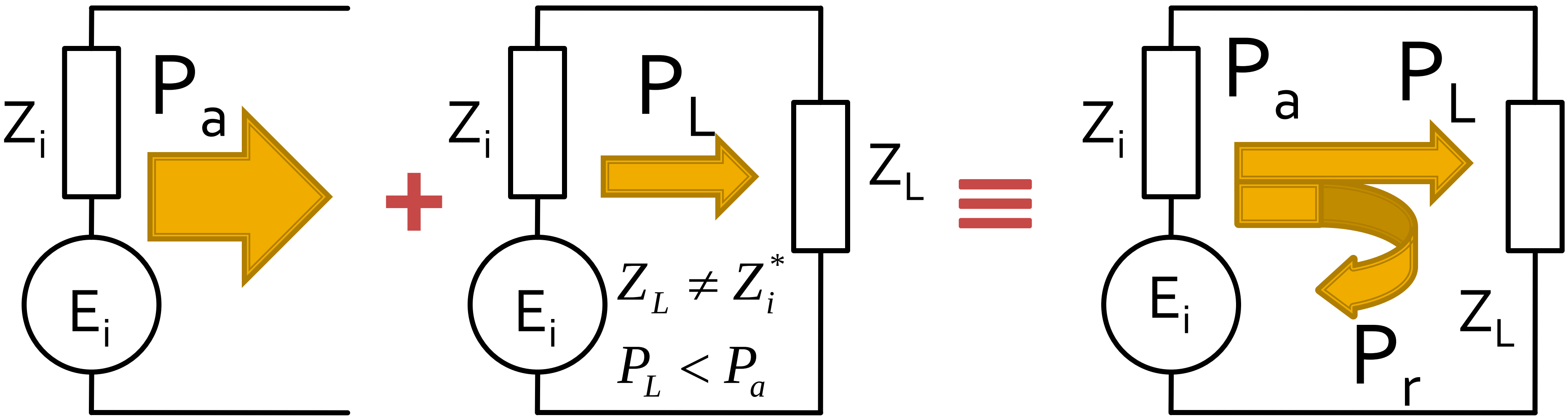
Reflection and power / Model



$$Z_L \neq Z_i^*$$

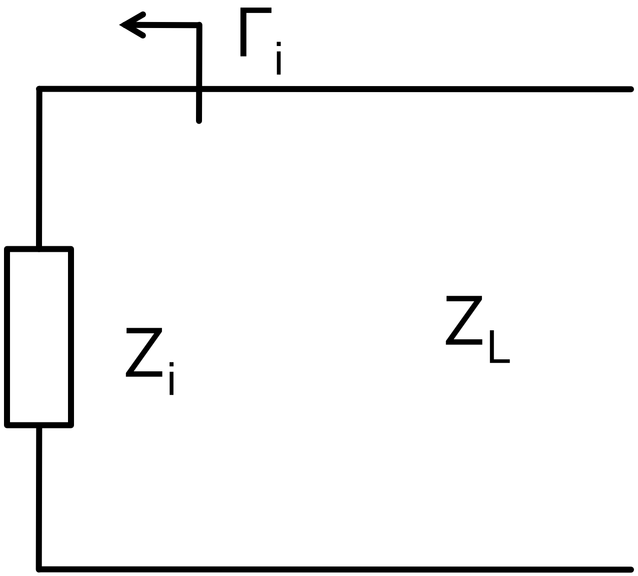
- ~~Power reflection~~
- Power of the reflected wave

Reflection and power / Model

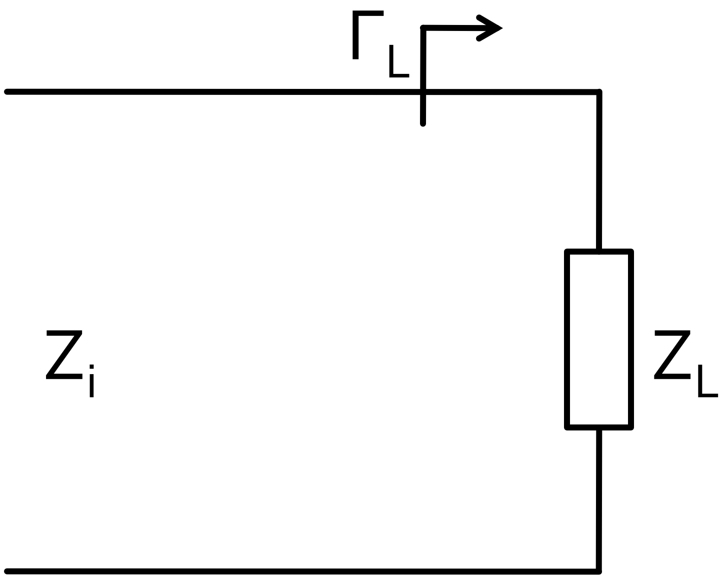


- The source has the ability to sent to the load a certain maximum power (available power) P_a
- For a particular load the power sent to the load is less than the maximum (mismatch) $P_L < P_a$
- The phenomenon is **"as if"** (model) some of the power is reflected $P_r = P_a - P_L$
- The power is a **scalar !**

Reflection coefficient



$$\Gamma_i = \frac{Z_i - Z_L^*}{Z_i + Z_L}$$



$$\Gamma_L = \frac{Z_L - Z_i^*}{Z_L + Z_i}$$

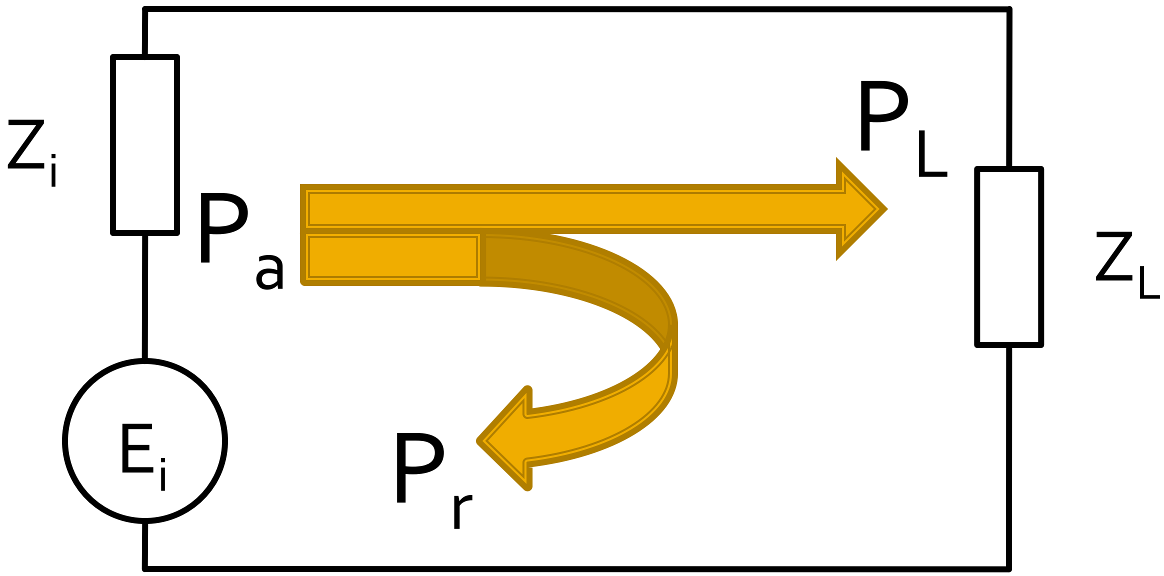
Reflection coefficient

$$\Gamma_i = \frac{(R_i - R_L) + j \cdot (X_i + X_L)}{(R_i + R_L) + j \cdot (X_i + X_L)} \qquad \Gamma_L = \frac{(R_L - R_i) + j \cdot (X_L + X_i)}{(R_L + R_i) + j \cdot (X_L + X_i)}$$

$$|\Gamma_i| = \frac{|(R_i - R_L) + j \cdot (X_i + X_L)|}{|(R_i + R_L) + j \cdot (X_i + X_L)|} = \frac{\sqrt{(R_i - R_L)^2 + (X_i + X_L)^2}}{\sqrt{(R_i + R_L)^2 + (X_i + X_L)^2}} = |\Gamma_L|$$

$$|\Gamma_i| = |\Gamma_L| \equiv |\Gamma|$$

Reflection and power / Model



$$P_a = \frac{|E_i|^2}{4R_i}$$

$$P_L = \frac{R_L \cdot |E_i|^2}{(R_i + R_L)^2 + (X_i + X_L)^2}$$

$$P_r = P_a - P_L = \frac{|E_i|^2}{4R_i} - \frac{R_L \cdot |E_i|^2}{(R_i + R_L)^2 + (X_i + X_L)^2} = \frac{|E_i|^2}{4R_i} \cdot \left[1 - \frac{4R_L \cdot R_i}{(R_i + R_L)^2 + (X_i + X_L)^2} \right]$$

$$P_r = \frac{|E_i|^2}{4R_i} \cdot \left[\frac{(R_i - R_L)^2 + (X_i + X_L)^2}{(R_i + R_L)^2 + (X_i + X_L)^2} \right] = P_a \cdot |\Gamma|^2$$

- $|\Gamma|^2$ is a power reflection coefficient

Contact

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