

Lecture 2

2025/2026

Microwave Devices and Circuits for Radiocommunications

2025/2026

- 2C/1L, **MDCR**
- Attendance at minimum 7 sessions (course or laboratory)
- Lectures- **associate professor Radu Damian**
 - Tuesday **12-14, P2**
 - E – 50% final grade
 - problems + (2p atten. lect.) + (3 tests) + (bonus activity)
 - first test L1: 24.02.2026 (t2 and t3 not announced, lecture)
 - 3att.=+0.5p
 - all materials/equipments authorized

2025/2026

- Laboratory – **associate professor Radu Damian**
 - Monday 14-16, Il.13 / (even weeks)
 - L – 25% final grade
 - ADS, 4 sessions
 - Attendance + **personal results**
 - P – 25% final grade
 - ADS, 3 sessions (-1? 24.02.2026)
 - personal homework

Materials

■ <https://rf-opto.etti.tuiasi.ro>

The screenshot shows a web browser window with the URL https://rf-opto.etti.tuiasi.ro/microwave_cd.php?chg_lang=0. The page features a dark blue navigation bar with links for Main, Courses, Master, Staff, Research, Students, and Admin. Below this is a secondary navigation bar with links for Microwave CD, Optical Communications, Optoelectronics, Internet, Antennas, Practica, Networks, and Educational software. The main content area is titled "Microwave Devices and Circuits for Radiocommunications (English)" and includes details for the "Course: MDCR (2017-2018)".

Microwave Devices and Circuits for Radiocommunications (English)

Course: MDCR (2017-2018)

Course Coordinator: Assoc.P. Dr. Radu-Florin Damian
Code: EDOS412T
Discipline Type: DOS; Alternative, Specialty
Credits: 4
Enrollment Year: 4, Sem. 7

Activities

Course: Instructor: Assoc.P. Dr. Radu-Florin Damian, 2 Hours/Week, Specialization Section, Timetable:
Laboratory: Instructor: Assoc.P. Dr. Radu-Florin Damian, 1 Hours/Week, Group, Timetable:

Evaluation

Type: Examen

A: 50%, (Test/Colloquium)
B: 25%, (Seminary/Laboratory/Project Activity)
D: 25%, (Homework/Specialty papers)

Grades

[Aggregate Results](#)

Attendance

[Course](#)
[Laboratory](#)

Lists

[Bonus-uri acumulate \(final\)](#)
[Studenti care nu pot intra in examen](#)

Materials

Course Slides

[MDCR Lecture 1](#) (pdf, 5.43 MB, en, [↗](#))
[MDCR Lecture 2](#) (pdf, 3.67 MB, en, [↗](#))
[MDCR Lecture 3](#) (pdf, 4.76 MB, en, [↗](#))
[MDCR Lecture 4](#) (pdf, 5.58 MB, en, [↗](#))

The right side of the image shows a zoomed-in view of the website's header and navigation. It features the "RF-OPTO" logo, the ETTI logo, and the University of Tuiasi logo. A red circle highlights the language selection menu, which includes "English" (with a UK flag) and "Romana" (with a Romanian flag). Below the language menu is a navigation bar with links for Main, Courses, Master, Staff, and Research. A secondary navigation bar includes links for Grades, Student List, Exams, and Photos. The main content area is titled "Online Exams" and includes the text "In order to participate at online exams you must get ready following".

Materials

- RF-OPTO
 - <https://rf-opto.etti.tuiasi.ro>
- **David Pozar, “Microwave Engineering”,**
Wiley; 4th edition , 2011
 - 1 exam problem ← Pozar
- Photos
 - sent by **online exam**
 - used at lectures/laboratory

Online exam manual

- The online exam app used for:
 - ~~lectures (attendance)~~
 - laboratory
 - project
 - ~~examinations~~

Materials

Other data

[Manual examen on-line](#) (pdf, 2.65 MB, ro, 🇷🇴)

[Simulare Examen](#) (video). (mp4, 65.12 MB, ro, 🇷🇴)

Microwave Devices and Circuits (Englis

Online exam

- always against a **timetable**
 - long period (project submission/laboratory results)
 - ~~short period (tests: 15min, exam: 2h)~~

Announcement 23:59 (10/05/2020)	Support material 00:05 (11/05/2020)	Exam Topics 00:07 (11/05/2020)	Results 00:10 (11/05/2020)	End 00:20 (15/05/2020)	Confirmation 00:20 (16/05/2020)	Next timeframe in: 05 m 43 s Refresh now
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Announcement

This is a "fake" exam, introduced to familiarize you with the server interface and to perform the necessary actions during an exam: thesis scan, selfie, use email for co

Server Time

All exams are based on the server's time zone (it may be different from local time). For reference time on the server is now:

10/05/2020 23:59:16

Online results submission

- many numerical values/files

Schema finala	Rezultate - castig	Rezultate - zgomot	Fisier justificare calcul (factor andrei)	Fisier zap (optional)	T1, fisier parametri S	T2, fisier parametri S	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Ze1	Zo1	Ze2	Zo2	Ze3	Zo3	Ze4	Zo4	Ze5	Zo5	Ze6
86 - 5428 - 259 ...	86 - 5428 - 260 ...	86 - 5428 - 261 ...	86 - 5428 - 316 ...	-	86 - 5428 - 314 ...	86 - 5428 - 315 ...	148.33	155.88	202.12	164.35	180.91	30.29	185.19	79.9	37	68.89	45.14	61.83	45.05	57.97	46.02	61.85	45.05	68.8
86 - 5622 - 259 ...	86 - 5622 - 260 ...	86 - 5622 - 261 ...	86 - 5622 - 316 ...	86 - 5622 - 262 ...	86 - 5622 - 314 ...	86 - 5622 - 315 ...	26.97	153.5	34.64	35.79	55.56	26.212	10.693	0	0	0	0	0	0	0	0	0	0	0
86 - 5488 - 259 ...	86 - 5488 - 260 ...	86 - 5488 - 261 ...	86 - 5488 - 316 ...	86 - 5488 - 262 ...	86 - 5488 - 314 ...	86 - 5488 - 315 ...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86 - 5391 - 259 ...	86 - 5391 - 260 ...	86 - 5391 - 261 ...	86 - 5391 - 316 ...	-	-	-	50	50	50	50	50	50	50	70.14	40.39	61.85	44.59	55.7	45.2	54.89	45.38	58.65	45.8	70.0
86 - 5664 - 259 ...	86 - 5664 - 260 ...	86 - 5664 - 261 ...	86 - 5664 - 316 ...	-	86 - 5664 - 314 ...	86 - 5664 - 315 ...	168.02	150.5	178.28	133.75	92.12	121.67	144.48	94.36	36.19	70.77	42.56	65.69	42.05	55.17	42.29	65.59	42.05	70.7
86 - 5665 - 259 ...	86 - 5665 - 260 ...	86 - 5665 - 261 ...	86 - 5665 - 316 ...	-	86 - 5665 - 314 ...	86 - 5665 - 315 ...	162.2	80.8	209.2	140.85	135.1	183.7	167.6	94.58	36.15	78.16	39.77	65.57	45.05	65.57	45.05	78.16	39.77	94.5
86 - 5433 - 259 ...	86 - 5433 - 260 ...	86 - 5433 - 261 ...	86 - 5433 - 316 ...	-	86 - 5433 - 314 ...	86 - 5433 - 315 ...	165.138	106.228	226.157	130.134	72.71	180.177	164.616	101.36	36.11	77.22	42.49	68.02	45.62	60	45.42	68.02	45.62	77.2
86 - 5608 - 259 ...	86 - 5608 - 260 ...	86 - 5608 - 261 ...	86 - 5608 - 316 ...	-	86 - 5608 - 314 ...	86 - 5608 - 315 ...	150.84	152.5	30.94	32.37	54.36	19.837	29.85	64.14	40.145	54.32	46.32	53.8	46.7	53.8	46.7	54.32	46.32	54.9
86 - 5555 - 259 ...	86 - 5555 - 260 ...	86 - 5555 - 261 ...	86 - 5555 - 316 ...	-	86 - 5555 - 314 ...	86 - 5555 - 315 ...	168.001	150.288	178.399	133.115	92.491	121.257	144.126	97.05	36.16	71.13	43.09	65.45	42.12	55.66	42.18	65.45	42.12	71.1

Online results submission

- many numerical values

	Z1	Z2	Z3	Z4	Z5	Z6	Z7
	148.33	155.88	202.12	164.35	180.91	30.29	185.19
	25.97	153.5	34.64	35.79	55.56	26.212	10.692
	0	0	0	0	0	0	0
	50	50	50	50	50	50	50



Online results submission

**Grade = Quality of the work +
+ Quality of the submission**

Attendance, Lists

Grades

[Aggregate Results](#)

Attendance

[Course](#)
[Laboratory](#)

Lists

[Studenti care nu pot intra in examen](#)
[Bonus-uri acumulate \(final\)](#)
[Punctaj laborator](#)

Materials

- Attendance
- minimum 7 sessions
- Activity bonus
- Homework
- individual data
- etc.

Bonus

Group	Course attendance	B. attendance	B. supplemental	B. photo	B. T1	B. T2	B. T3	Total Bonus	Obs.
5411	4.6	0.5		1		0	0.1	1.6	-
5411	17	2.5		1	0.75	0	0.5	4.75	-
5411	12.6	2		1		0	0.1	3.1	-
5411	9.6	1.5		1	0.25		0	2.75	-
5411	5.2	0.5		1		0	0	1.5	-
5411	12	2		0.5		0		2.5	-
5411	16.15	2.5		0.5	0.5	0.3		3.8	-
5411	18	2.5	1.5	1	0		0.1	5.1	-
5411	15.725	2.5		1	0.75	0	0	4.25	-
5411	18	2.5	1.75	1	0.63	0	1	6.88	-
5411	1.2	0		1				1	-
5411	13	2	0.5	1	0.13	0	0	3.63	-
5411	15.375	2.5		1	1	0		4.5	-
5411	5.075	0.5	0.05	0				0.55	-
5411	1.8	0		0.5			0.1	0.6	-
5411	17.5	2.5	0.4	1	1		0.2	5.1	-

Previous years

Optoelectronics

Course: OPTO (2019-2020)

Course Coordinator: Assoc.P. Dr. Radu-Florin Damian

Code: DID405M

Discipline Type: DID; Required, Domain

Credits: 4

Enrollment Year: 4, Sem. 8

Activities

Course: Instructor: Assoc.P. Dr. Radu-Florin Damian, 2 Hours/Week, Specialization Section, Timetable:

Laboratory: Instructor: Assist.P. Dr. Petre-Daniel Matasaru, 1 Hours/Week, Group, Timetable:

Evaluation

Type: **Colloquium**

A: 50%, (Test/Colloquium)

B: 30%, (Seminary/Laboratory/Project Activity)

C: 20%, (Tests during semester)

Previous years

2018-2019

2017-2018

2016-2017

2015-2016

2014-2015

More years...

Server-ul "rf-opto" pastreaza istoricul materialelor pentru anii anteriori
Alegeti anul recent corespunzator pentru vizualizare sau "More years" pentru a afisa mai multi ani din istoric

Previous years

[Microwave CD](#)

[Optical Communications](#)

[Optoelectronics](#)

[Internet](#)

[Antennas](#)

[Practica](#)

[Networks](#)

[Educational software](#)

[Examen DCMR 10 feb 2019](#) (pdf, 934.2 KB, ro, 🇷🇴)

[Rezolvări DCMR 10 feb 2019](#) (pdf, 825.2 KB, ro, 🇷🇴)

[Detalii notare DCMR/MDCR 2018 2019](#) (htm, 13.05 KB, ro, 🇷🇴)

Other data

[Factorul "Andrei"](#) (pdf, 15.85 MB, ro, 🇷🇴)

Previous years

2017-2018

2016-2017

2015-2016

2014-2015

2013-2014

More years...

Microwave Devices and Circuits for Radiocommunications

Course: DCMR (2017-2018)

Course Coordinator: Assoc.P. Dr. Radu-Florin Damian

Code: DOS412T

Discipline Type: DOS; Alternative, Specialty

Credits: 4

Enrollment Year: 4, Sem. 7

Activities

Course: Instructor: Assoc.P. Dr. Radu-Florin Damian, 2 Hours/Week, Specialization Section, Timetable:

Laboratory: Instructor: Assoc.P. Dr. Radu-Florin Damian, 1 Hours/Week, Group, Timetable:

Previous years, 2004-2025

Previous years

2018-2019

2017-2018

2016-2017

2015-2016

2014-2015

More years...

Optoelectronics

Course: OPTO (2018-2019)

Course Coordinator: Assoc.P. Dr. Radu-Florin Damian

Code: DIS405M

Discipline Type: DID; Required, Domain

Credits: 3

Enrollment Year: 4, Sem. 8

Activities

Course: Instructor: Assoc.P. Dr. Radu-Florin Damian, 2 Hours/Week, Specialization S
Laboratory: Instructor: Assist.P. Dr. Petre-Daniel Matasaru, 1 Hours/Week, Group, T

Evaluation

Type: Colloquium

A: 50%, (Test/Colloquium)

B: 30%, (Seminary/Laboratory/Project Activity)

C: 20%, (Tests during semester)

Grades

[Aggregate Results](#)

Attendance

Previous years

2018-2019

2017-2018

2016-2017

2015-2016

2014-2015

2013-2014

2012-2011

Optoelectronics, Structures, Technologies, Circuits

Course: OSTC (2013-2014)

Course Coordinator: Assoc.P. Dr. Radu-Florin Damian

Code: DIS405M

Discipline Type: DIS; Required, Specialty

Credits: 4

Enrollment Year: 4, Sem. 7

Activities

Course: Instructor: Assoc.P. Dr. Radu-Florin Damian, 2 Hours/Week, Specialization Section, Timetable:
Laboratory: Instructor: Assist.P. Dr. Petre-Daniel Matasaru, 1 Hours/Week, Half Group, Timetable:

Evaluation

Type: Colloquium

A: 66%, (Test/Colloquium)

B: 17%, (Seminary/Laboratory/Project Activity)

D: 17%, (Homework/Specialty papers)

Grades

[Aggregate Results](#)

Materials

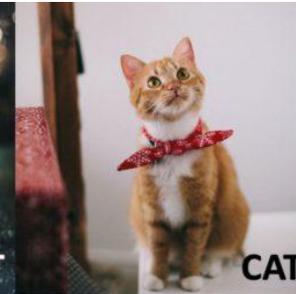
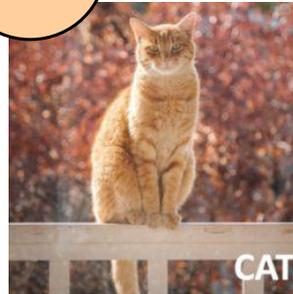
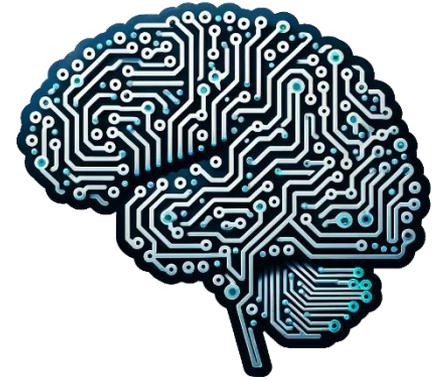
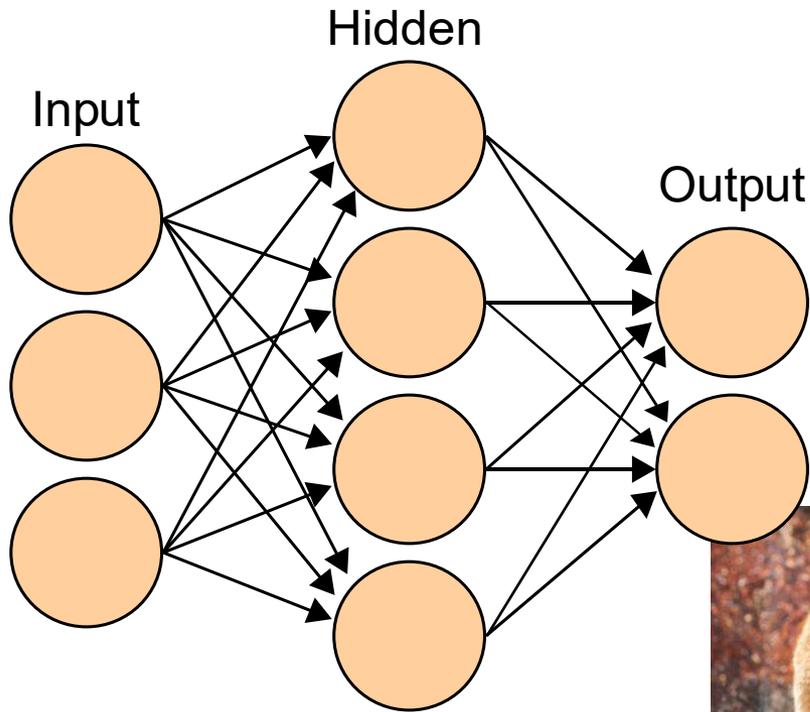
Course Objectives 4



**“Engineering”
Sinapses**



IA/AI



Examen: Logarithmic scales

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

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

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

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 μ W
-30 dBm	= 1 μ W
-60 dBm	= 1 nW

$$[\text{dBm}] + [\text{dB}] = [\text{dBm}]$$

$$[\text{dBm/Hz}] + [\text{dB}] = [\text{dBm/Hz}]$$

$$[x] + [\text{dB}] = [x]$$

Computing Loss/Gain in circuits

$$\text{Gain/Loss} = \frac{P_{out}}{P_{in}}$$

$$\text{Loss[dB]} = [-] 10 \cdot \log_{10} \left(\frac{P_{out}}{P_{in}} \right)$$


$$\text{Loss[dB]} = [-] 10 \cdot \log_{10} \left(\frac{P_{out}}{P_0} \cdot \frac{P_0}{P_{in}} \right)$$

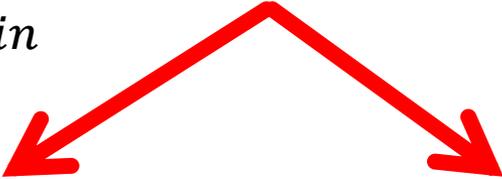
$$\text{Loss[dB]} = [-] 10 \cdot \left[\log_{10} \left(\frac{P_{out}}{P_0} \right) - \log_{10} \left(\frac{P_{in}}{P_0} \right) \right]$$

$$\text{Loss[dB]} = [-] (P_{out}[\text{dBm}] - P_{in}[\text{dBm}])$$



Computing Loss/Gain in circuits

$$\text{Loss} = \frac{P_{out}}{P_{in}} < 1 \qquad \text{Loss[dB]} = 10 \cdot \log_{10} \left(\frac{P_{out}}{P_{in}} \right) < 0$$


$$\text{Loss/Attenuation[dB]} = [-] 10 \cdot \log_{10} \left(\frac{P_{out}}{P_{in}} \right)$$

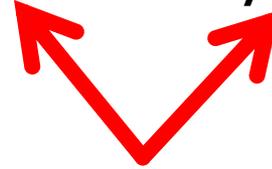
$$\text{Gain} = \frac{P_{out}}{P_{in}} > 1 \qquad \text{Gain[dB]} = 10 \cdot \log_{10} \left(\frac{P_{out}}{P_{in}} \right) > 0$$

$$\text{Attenuation[dB/km]} = \frac{\text{Loss[dB]}}{\text{Length[km]}}$$

Computing Loss/Gain in circuits

Loss/Attenuation $\rightarrow P_{out} < P_{in} \rightarrow P_{out}[\text{dBm}] < P_{in}[\text{dBm}]$

$$P_{out}[\text{dBm}] = P_{in}[\text{dBm}] - \text{Loss/Attenuation}[\text{dB}]$$



Gain/Amplification $\rightarrow P_{out} > P_{in} \rightarrow P_{out}[\text{dBm}] > P_{in}[\text{dBm}]$

$$P_{out}[\text{dBm}] = P_{in}[\text{dBm}] + \text{Gain/Amplification}[\text{dB}]$$

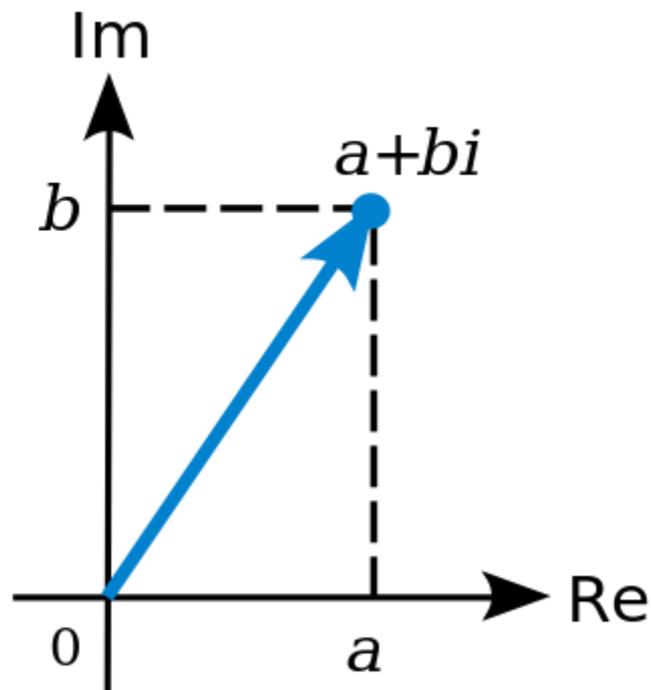


Exam

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

Complex plane

- abscissa – real part
- ordinate – imaginary part
- any of them can be negative, whole plane, 4 quadrants



Elementary operations

- Addition

$$z + w = (a + j \cdot b) + (c + j \cdot d) = (a + c) + j \cdot (b + d)$$

- Subtraction

$$z - w = (a + j \cdot b) - (c + j \cdot d) = (a - c) + j \cdot (b - d)$$

- Multiplication

$$z \cdot w = (a + j \cdot b) \cdot (c + j \cdot d) = (a \cdot c - b \cdot d) + j \cdot (b \cdot c + a \cdot d)$$

- Division

$$z / w = \frac{a + j \cdot b}{c + j \cdot d} = \frac{(a + j \cdot b) \cdot (c - j \cdot d)}{(c + j \cdot d) \cdot (c - j \cdot d)} = \left(\frac{a \cdot c + b \cdot d}{c^2 + d^2} \right) + j \cdot \left(\frac{b \cdot c - a \cdot d}{c^2 + d^2} \right)$$

Conjugate

- z $z = a + j \cdot b$
- z^* $z^* = a - j \cdot b$
- Symmetry over the real axis

$$\operatorname{Re}(z) = a = \frac{1}{2} \cdot (z + z^*)$$

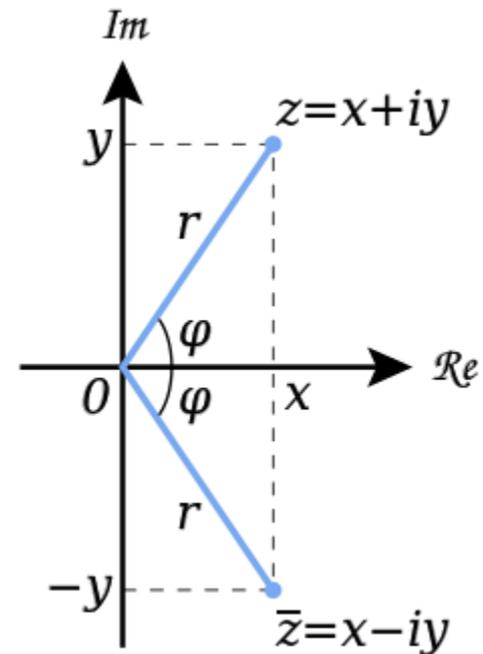
$$\operatorname{Im}(z) = b = \frac{1}{2 \cdot j} \cdot (z - z^*) = \frac{j}{2} \cdot (z^* - z)$$

$$(z + w)^* = z^* + w^*$$

$$(z - w)^* = z^* - w^*$$

$$(z \cdot w)^* = z^* \cdot w^*$$

$$(z / w)^* = z^* / w^*$$



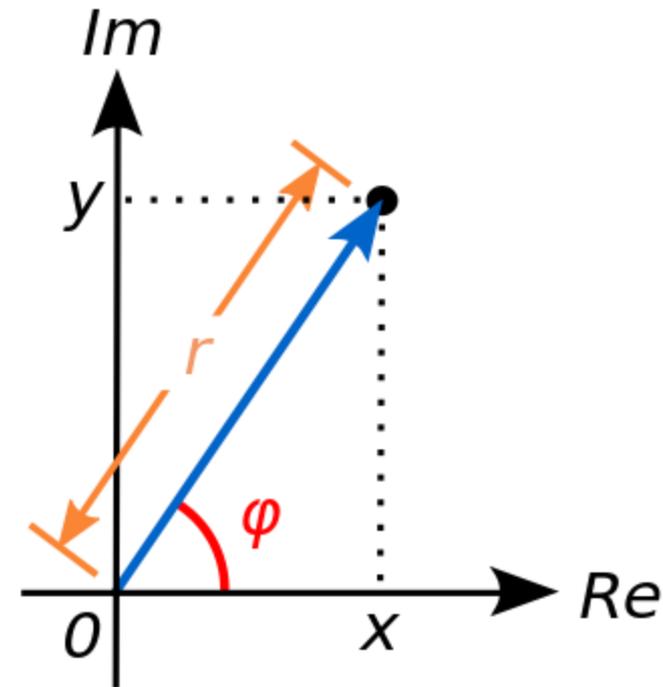
Polar representation

- Polar representation
 - modulus
 - phase relative to the real axis

$$z = a + j \cdot b = |z| \cdot (\cos \varphi + j \cdot \sin \varphi)$$

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

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



Polar representation

- Euler's formula

$$e^{j \cdot x} = \cos x + j \cdot \sin x; \forall x \in R$$

- Polar representation

$$z = a + j \cdot b = |z| \cdot e^{j \cdot \varphi}$$

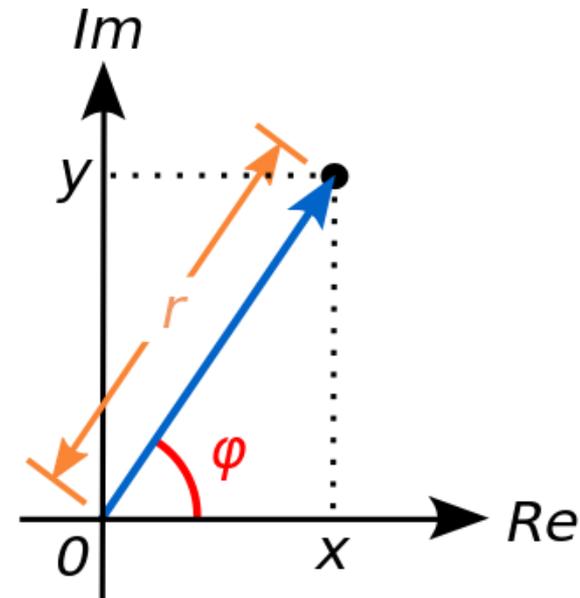
$$z = a + j \cdot b = |z| \cdot (\cos \varphi + j \cdot \sin \varphi)$$

$$z^n = (|z| \cdot e^{j \cdot \varphi})^n = |z|^n \cdot e^{j \cdot n \cdot \varphi} = |z|^n \cdot [\cos(n \cdot \varphi) + j \cdot \sin(n \cdot \varphi)]$$

→
$$\sqrt{z} = (|z| \cdot e^{j \cdot \varphi})^{1/2} = \sqrt{|z|} \cdot e^{j \cdot \frac{\varphi}{2}} = \sqrt{|z|} \cdot \left(\cos \frac{\varphi}{2} + j \cdot \sin \frac{\varphi}{2} \right)$$

$$z \cdot w = |z| \cdot e^{j \cdot \varphi} \cdot |w| \cdot e^{j \cdot \theta} = |z| \cdot |w| \cdot e^{j \cdot (\varphi + \theta)} = |z| \cdot |w| \cdot [\cos(\varphi + \theta) + j \cdot \sin(\varphi + \theta)]$$

$$z/w = \frac{|z| \cdot e^{j \cdot \varphi}}{|w| \cdot e^{j \cdot \theta}} = \frac{|z|}{|w|} \cdot e^{j \cdot \varphi} \cdot e^{-j \cdot \theta} = \frac{|z|}{|w|} \cdot [\cos(\varphi - \theta) + j \cdot \sin(\varphi - \theta)]$$



Polar representation

- Polar representation

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

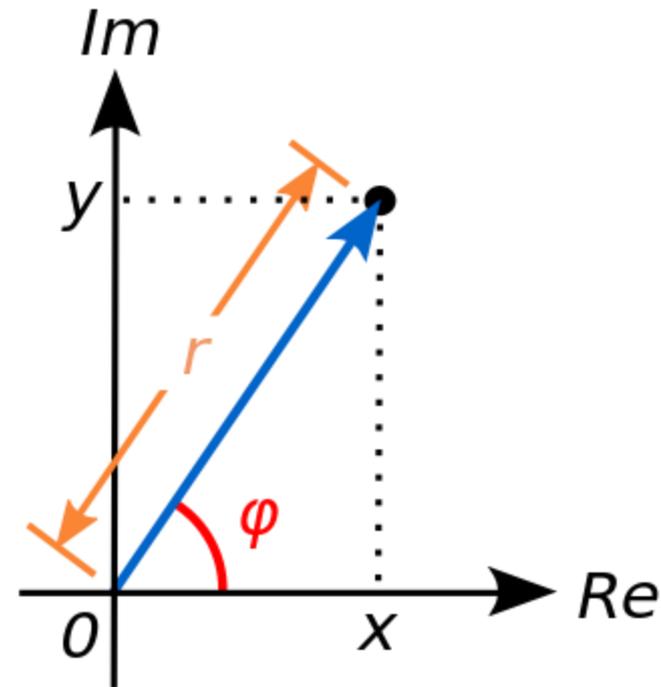
$$|z|^2 = z \cdot z^*$$

⇒ ⇒

$$|e^{j \cdot x}| = |\cos x + j \cdot \sin x| = \sqrt{\cos^2 x + \sin^2 x} = 1$$

$$|e^{j \cdot x}| = 1; \quad \forall x \in R$$

$$\begin{aligned} z^* &= (|z| \cdot e^{j \cdot \varphi})^* = |z| \cdot (\cos \varphi + j \cdot \sin \varphi)^* = |z| \cdot (\cos \varphi - j \cdot \sin \varphi) = \\ &= |z| \cdot [\cos(-\varphi) + j \cdot \sin(-\varphi)] = |z| \cdot e^{-j \cdot \varphi} \end{aligned}$$

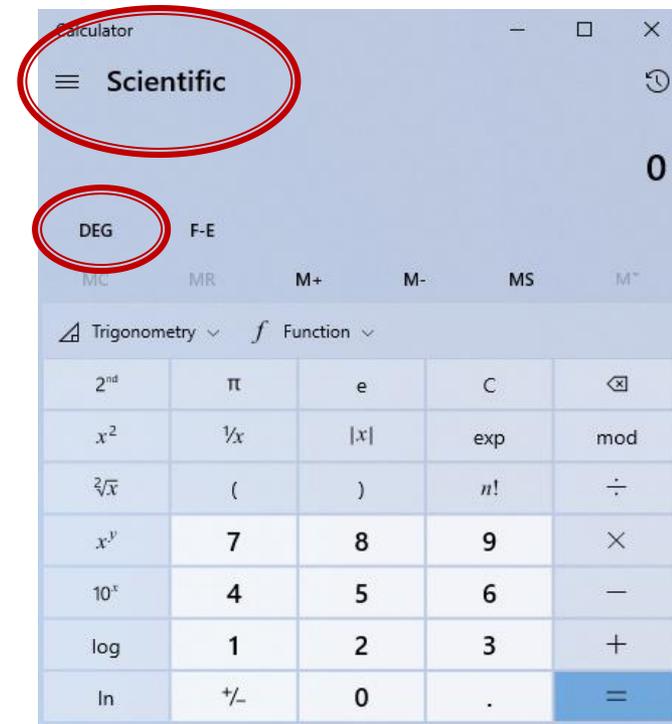


Polar representation

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

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

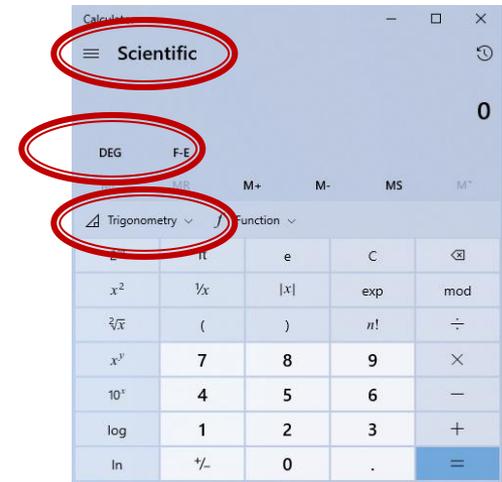
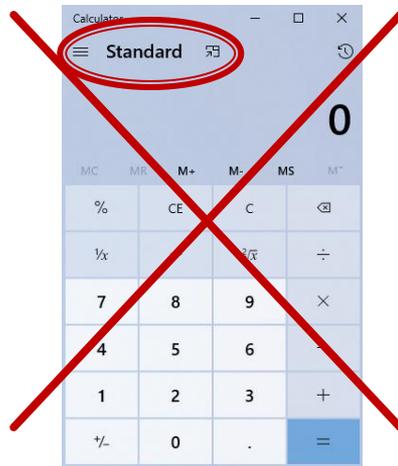
$$\varphi[^\circ] = 180^\circ \cdot \frac{\varphi[\text{rad}]}{\pi} \qquad \varphi[\text{rad}] = \pi \cdot \frac{\varphi[^\circ]}{180^\circ}$$



Polar representation

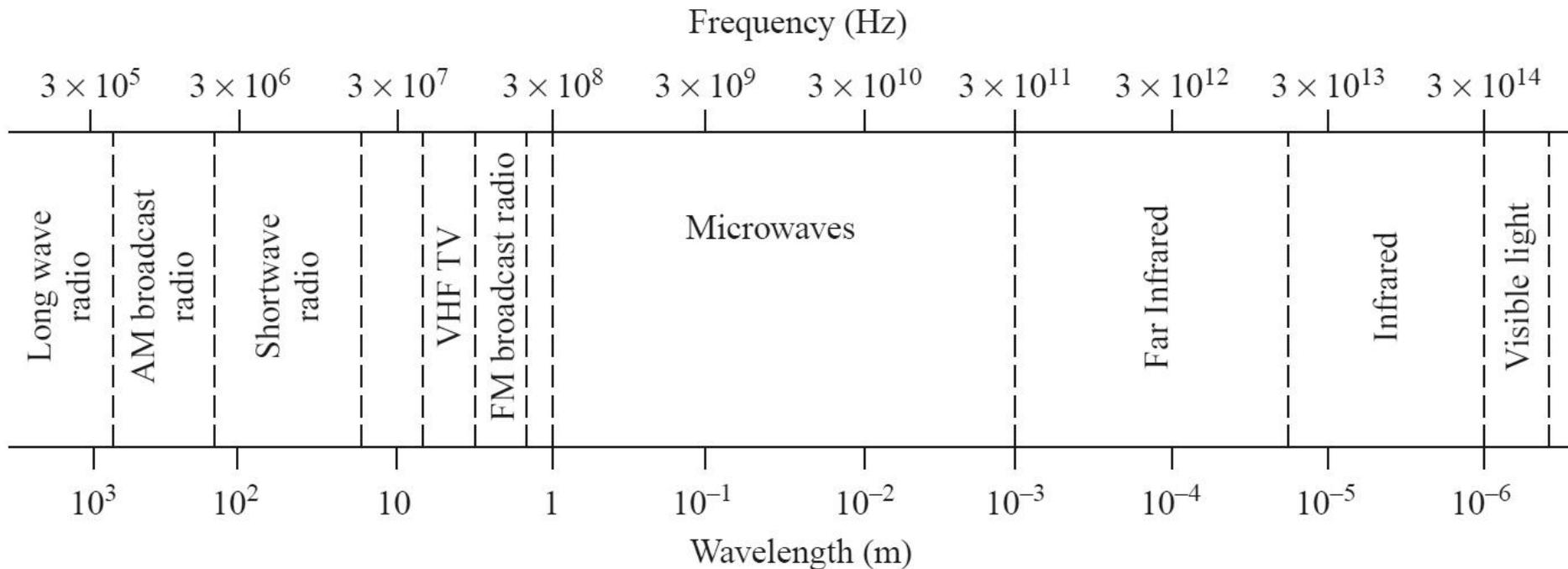
- **Attention to angle numerical values!!**
 - math software – work in standard unit: radians
 - a **conversion** is necessary before and after using a trigonometric function (sin, cos, tan, atan, tanh)
 - scientific calculators have the built-in option of choosing the angle unit
 - always **double check**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

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



Introduction

Microwaves



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

Microwaves

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

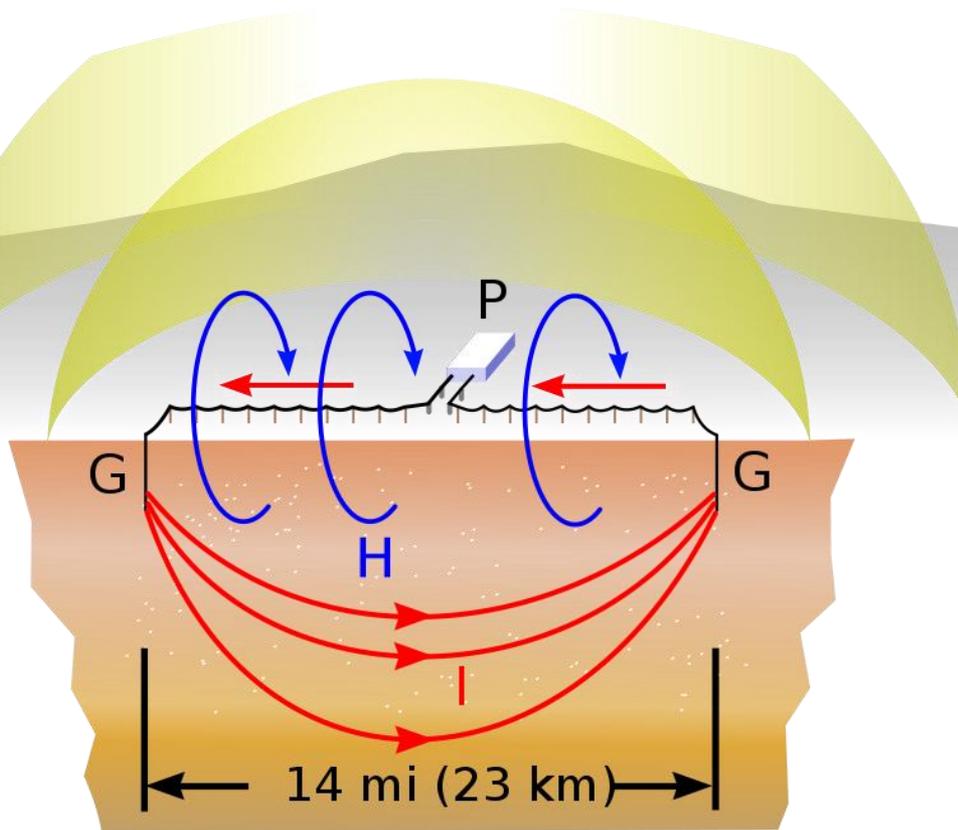
CPU

- Intel® Core™ 14th Gen i9-14900KS
- 6.2 GHz
- overclock 9.043 GHz



ELF, VLF

- Extremely low frequency, 3 - 30 Hz
- Very low frequency, 3 - 30 kHz



~ Microwaves

- Electrical Length (Phase Length)
 - l – physical length
 - $E = \beta \cdot l$ – electrical Length

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

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

V, I vary
~ useless

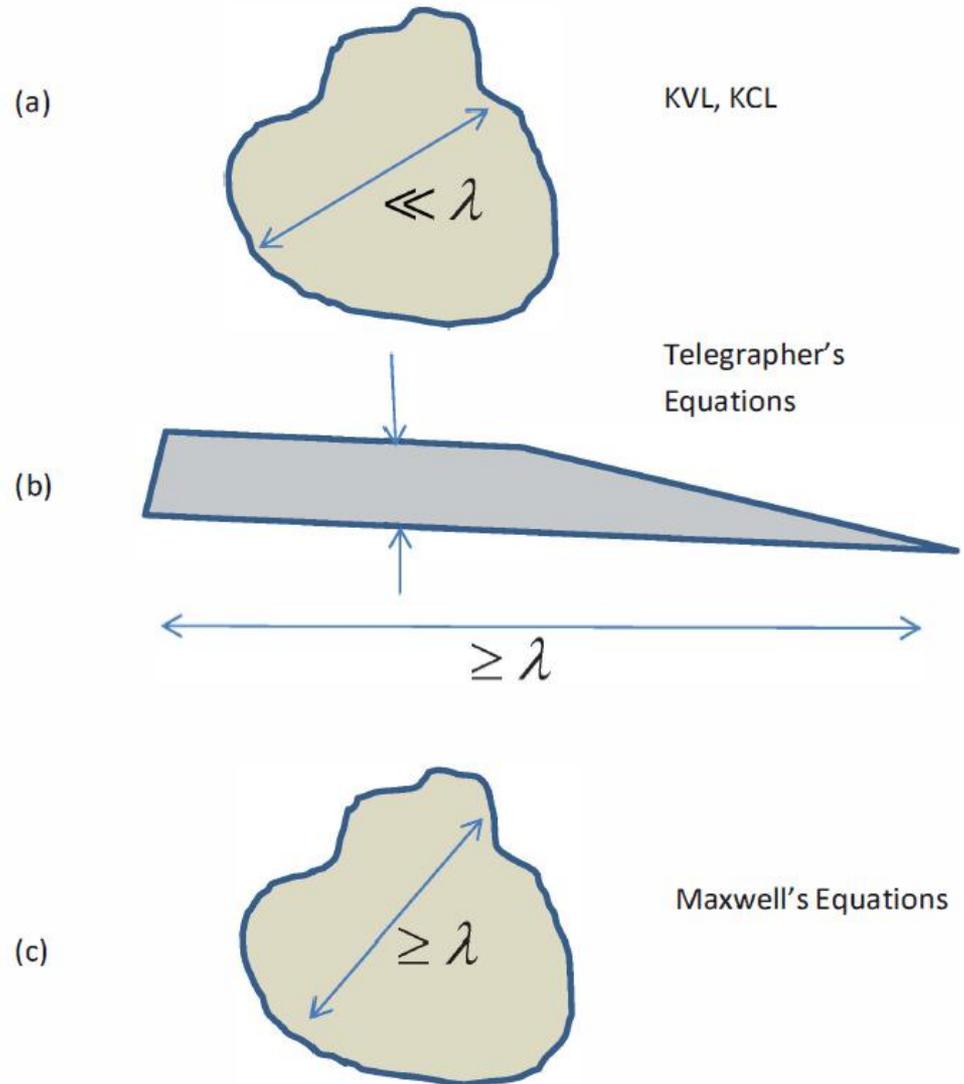
- Dependency
 - antenna gain
 - radar cross-section

Electrical Length

- Behavior (and description) of any circuit depends on his electrical length at the particular frequency of interest

- $E \approx 0 \rightarrow$ Kirchhoff
- $E > 0 \rightarrow$ wave propagation

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



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

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

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

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

Electromagnetic fields with harmonic time dependence

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

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

- Maxwell's Equations more simple

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

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

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

$$\nabla \cdot H = 0$$

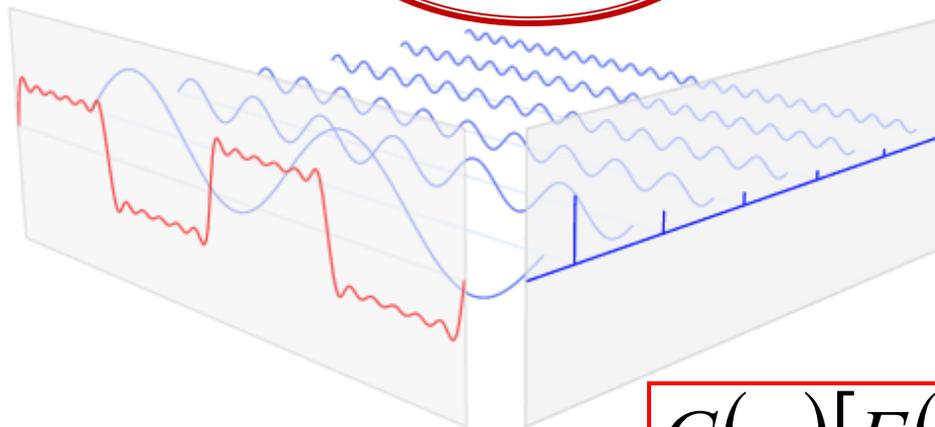
Mathematical models

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

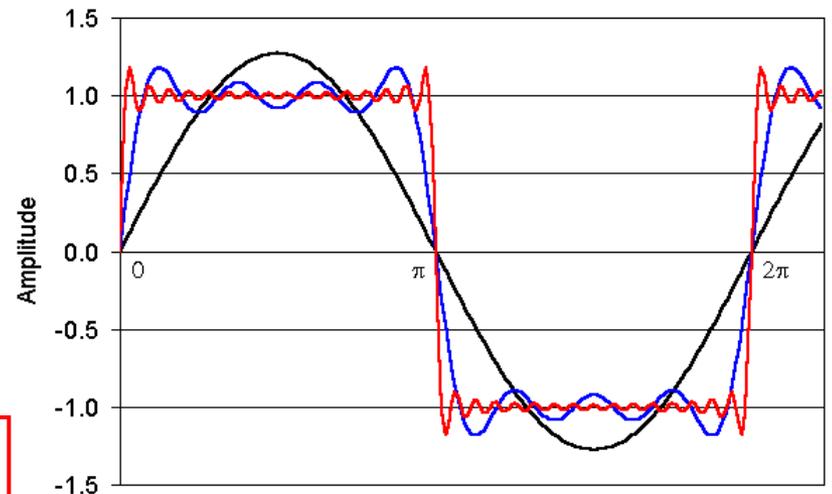
$$X = X_0 e^{j \cdot \omega \cdot t} \quad \frac{\partial X}{\partial t} = j \cdot \omega \cdot X$$

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

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

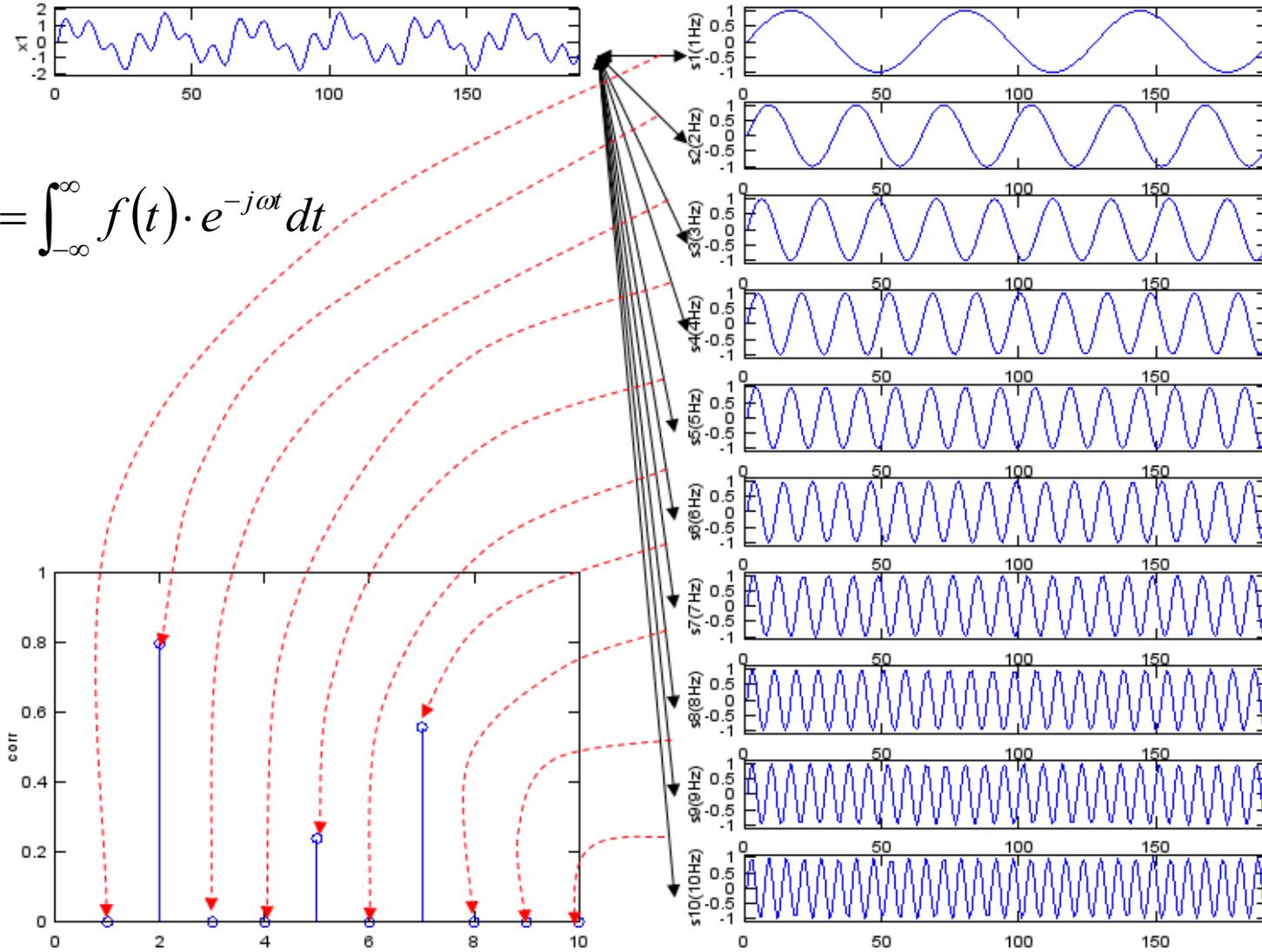


$$G(\omega) [F(\omega)]$$

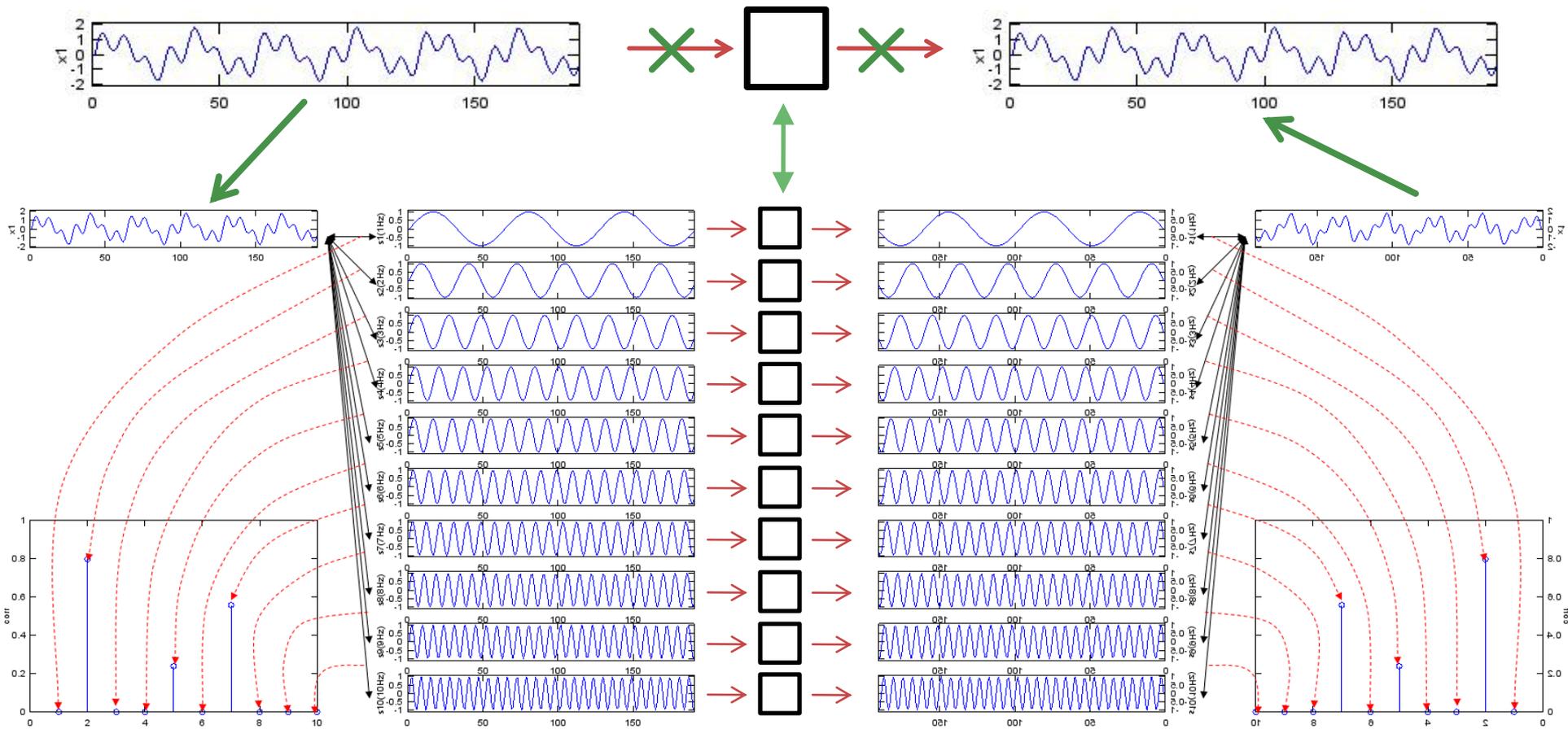


Mathematical models

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



Mathematical models



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

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

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

Wave equations

- Helmholtz equations or Wave equations

Medium void of free electric charges

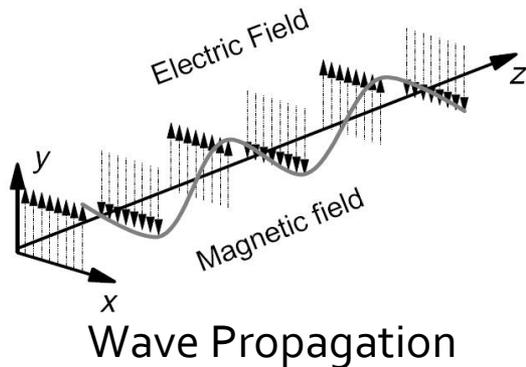
$$\nabla^2 E - \gamma^2 E = 0$$

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

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

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

Solutions of the wave equations



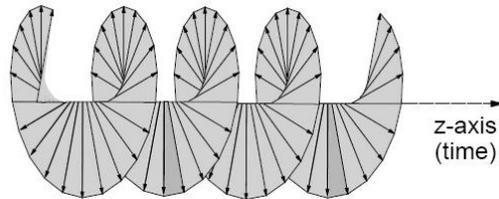
Electric field only in Oy direction, ← through judicious choice
 wave traveling after Oz direction ← of the coordinate system

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

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

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

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



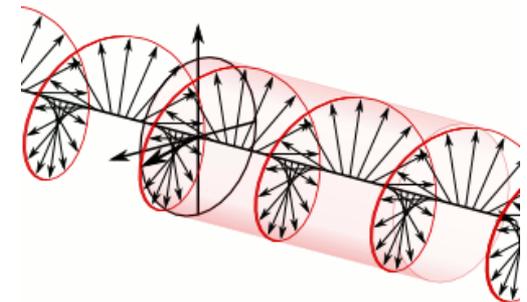
Harmonic Field

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

Amplitude

Attenuation

Wave Propagation
 (simultaneous space and
 time variation)



Attenuation

$$E_y(z_1) = Ct \cdot e^{-\alpha \cdot z_1} \cdot e^{j(\omega t - \beta \cdot z_1)}$$

$$E_y(z_2) = Ct \cdot e^{-\alpha \cdot z_2} \cdot e^{j(\omega t - \beta \cdot z_2)}$$

$$W, P \sim \int E^2$$

$$A = \frac{P_2}{P_1} = \frac{Ct^2 \cdot e^{-2\alpha \cdot z_2}}{Ct^2 \cdot e^{-2\alpha \cdot z_1}} = e^{-2\alpha \cdot (z_2 - z_1)}$$

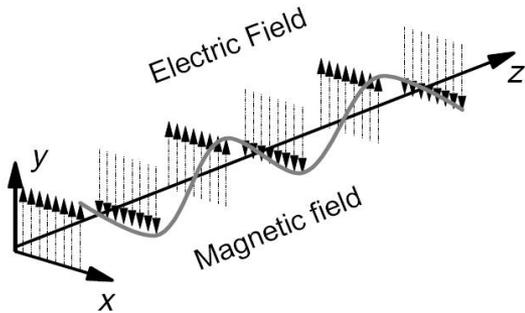
$$A[dB] = 10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \left[e^{-2\alpha \cdot (z_2 - z_1)} \right]$$

$$A[dB] = -20 \cdot \alpha \cdot (z_2 - z_1) \log_{10} e = -8.686 \cdot \alpha \cdot (z_2 - z_1)$$

$$A / L [dB / km] = -8.686 \cdot \alpha < 0$$

- ▶ Attenuation usually expressed in **dB/km**
 - ▶ most of the time a positive value is used
 - ▶ “-” sign = **implied** by the word used

Plane wave parameters



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

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

Lossless Medium, $\sigma = 0$

$$\gamma = j\omega \cdot \sqrt{\epsilon\mu}$$

$$\eta = \frac{E_y}{H_x} = \sqrt{\frac{\mu}{\epsilon}}$$

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

$$v_p = \frac{dz}{dt} = \frac{\omega}{\beta} = \frac{1}{\sqrt{\epsilon\mu}}$$

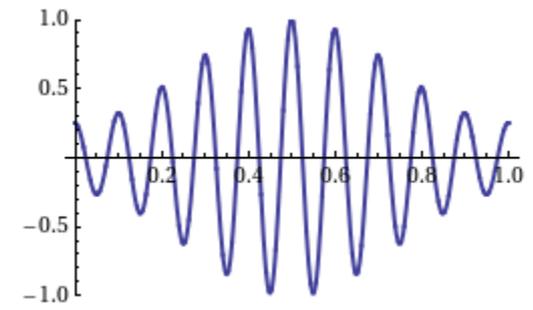
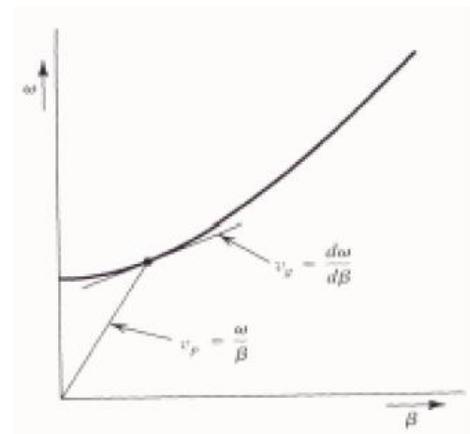
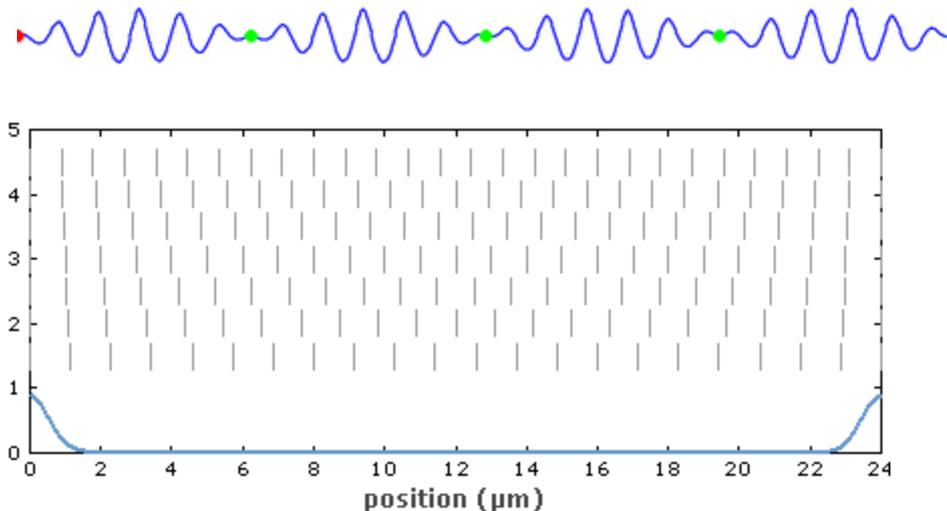
Group velocity

$$v_g = \frac{dz}{dt} = \frac{d\omega}{d\beta}$$

in dispersive media where $\beta = \beta(\omega)$

Group and phase velocities

- Phase velocity – **virtual** speed at which a constant phase point travels (in certain conditions might be greater than the speed of light)
- Group velocity – speed at which the signal (energy, information) propagates (always less or equal to the speed of light in that medium)



Plane wave parameters

- In vacuum

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377\Omega \quad v = v_g = c_0 \quad c_0 = \frac{1}{\sqrt{\epsilon_0 \cdot \mu_0}} = 2,99790 \cdot 10^8 \text{ m/s}$$

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

Space periodicity

Time periodicity

- In non-dispersive medium with ϵ_r

$$c = \frac{1}{\sqrt{\epsilon \cdot \mu_0}} = \frac{1}{\sqrt{\epsilon_0 \epsilon_r \cdot \mu_0}} = \frac{c_0}{\sqrt{\epsilon_r}}$$

$$n = \sqrt{\epsilon_r} \quad \text{refractive index of a medium}$$

$$c = \frac{c_0}{n}$$

$$T = \frac{2\pi}{\omega} = \frac{1}{f}$$

$$\lambda = \frac{2\pi}{\beta} = \frac{c}{f}$$

$$\lambda = \frac{c_0}{\sqrt{\epsilon_r} \cdot f} = \frac{\lambda_0}{\sqrt{\epsilon_r}}$$


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

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

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

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

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

points of
constant
phase

Solutions of the wave equations

- wave

- incident
- reflected

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

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

- wave

- direct
- inverse

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

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

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

Mathematical modeling

- particular cases where analytical solution exists

- wave in **a single direction** $E^+ (E^+)$, $E^- (E^-)$

- wave

- incident

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

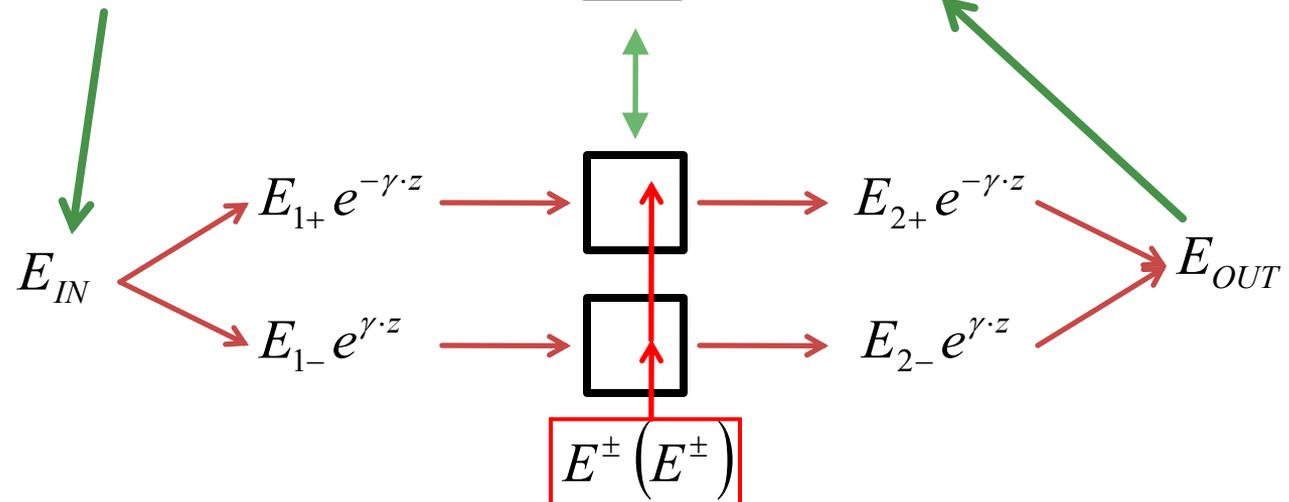
- reflected

$$E_{IN} = E_{1+} e^{-\gamma \cdot z} + E_{1-} e^{\gamma \cdot z} \quad \text{---} \quad \square \quad \text{---} \quad E_{OUT} = E_{2+} e^{-\gamma \cdot z} + E_{2-} e^{\gamma \cdot z}$$

- wave

- direct

- inverse



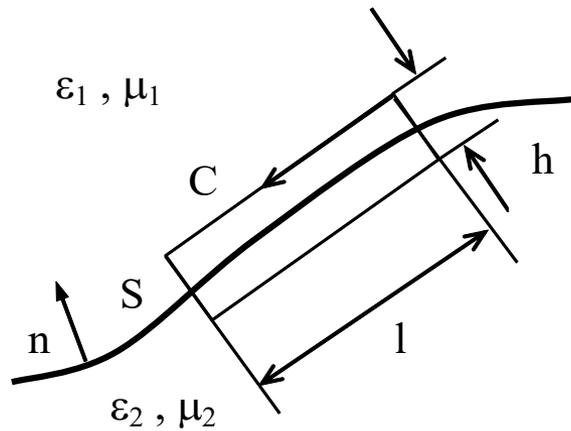
Modes in delimited media

- Electromagnetic fields with harmonic time dependence
 - Maxwell's Equations simplified

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

- In delimited media the solutions of Maxwell's Equations must also verify boundary conditions
 - solutions must respect some supplemental conditions

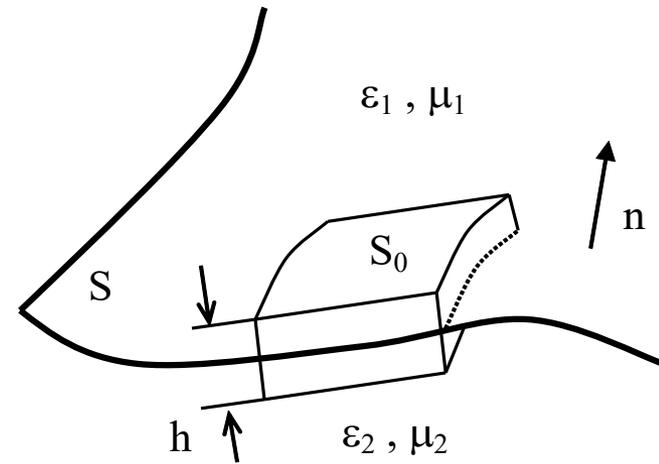
Interface conditions on the interface between two different media



a)

$$n \times (E_1 - E_2) = 0$$

$$n \times (H_1 - H_2) = J_S$$



b)

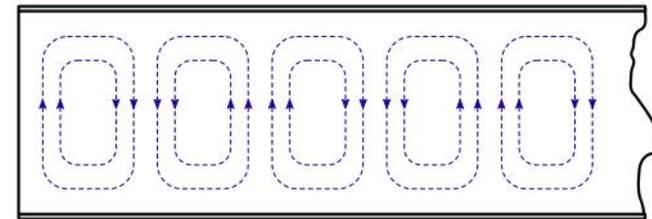
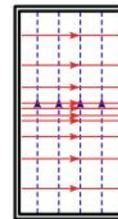
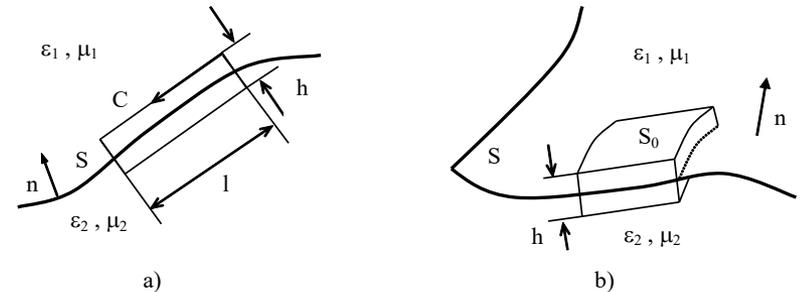
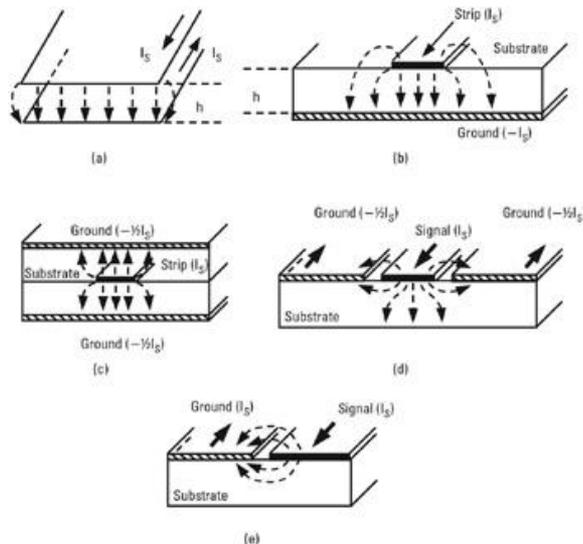
$$n \cdot (D_1 - D_2) = \rho_S$$

$$n \cdot (B_1 - B_2) = 0$$

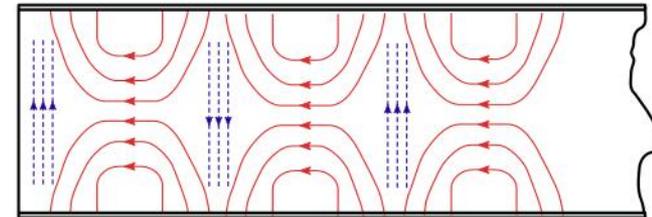
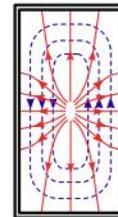
- If one of the media is a perfect conductor (metal) all fields are annulled inside

Modes in delimited media

- Electric field must always be **normal** on an electric wall or annulled
- Magnetic field must always be **tangent** to an electric wall or annulled

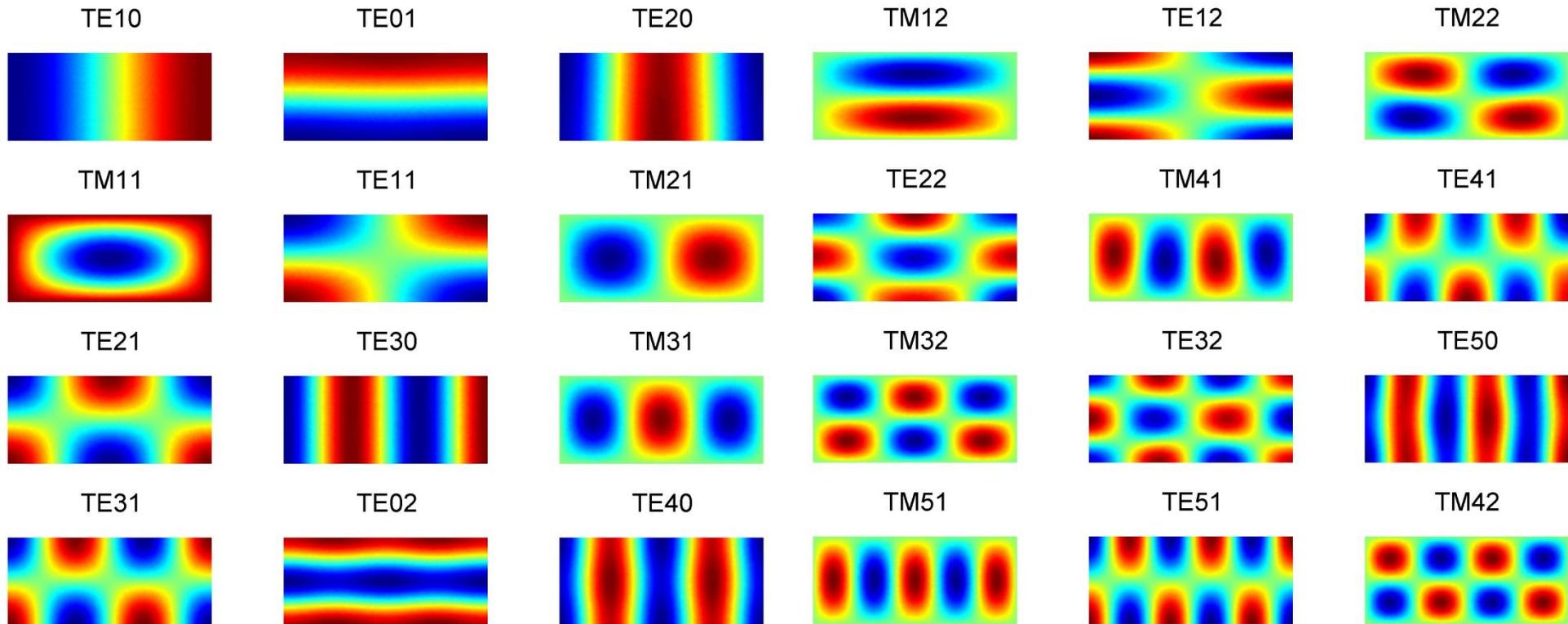


TE₁₀



TM₁₁

Moduri in medii delimitate



- Similar with Fourier Transform

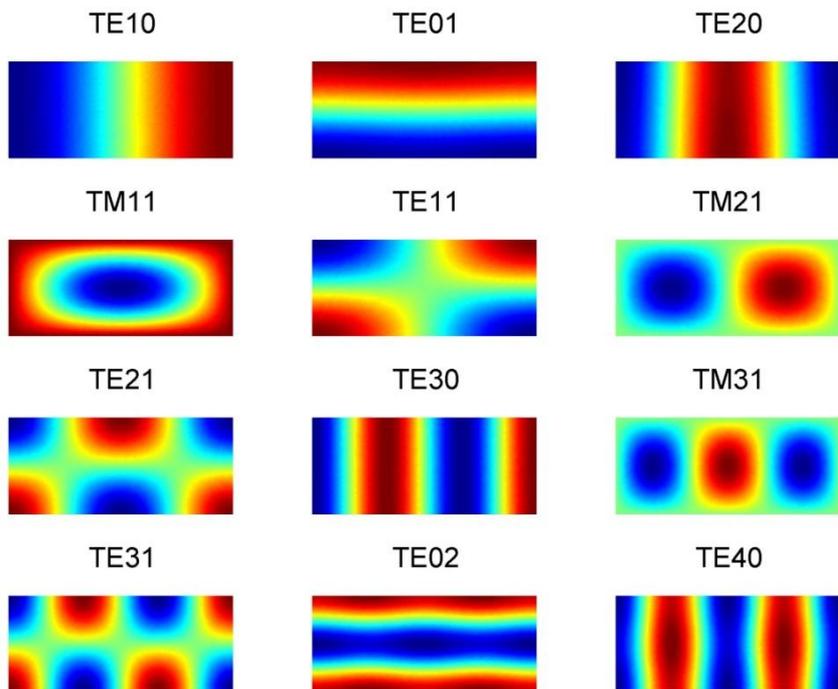
$$g(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-j\omega t} dt \quad f(t) = \int_{-\infty}^{\infty} g(\omega) \cdot e^{j\omega t} d\omega$$

$$E^+, E^- = \sum_1^{\infty} A_i \cdot Mod_i$$

$$A_i = \langle E, Mod_i \rangle$$

Mathematical modeling

- particular cases where analytical solution exists
 - modes in delimited media $B_i(A_i)$



$$E = \sum_1^{\infty} A_i \cdot Mod_i \quad A_i = \langle E, Mod_i \rangle$$



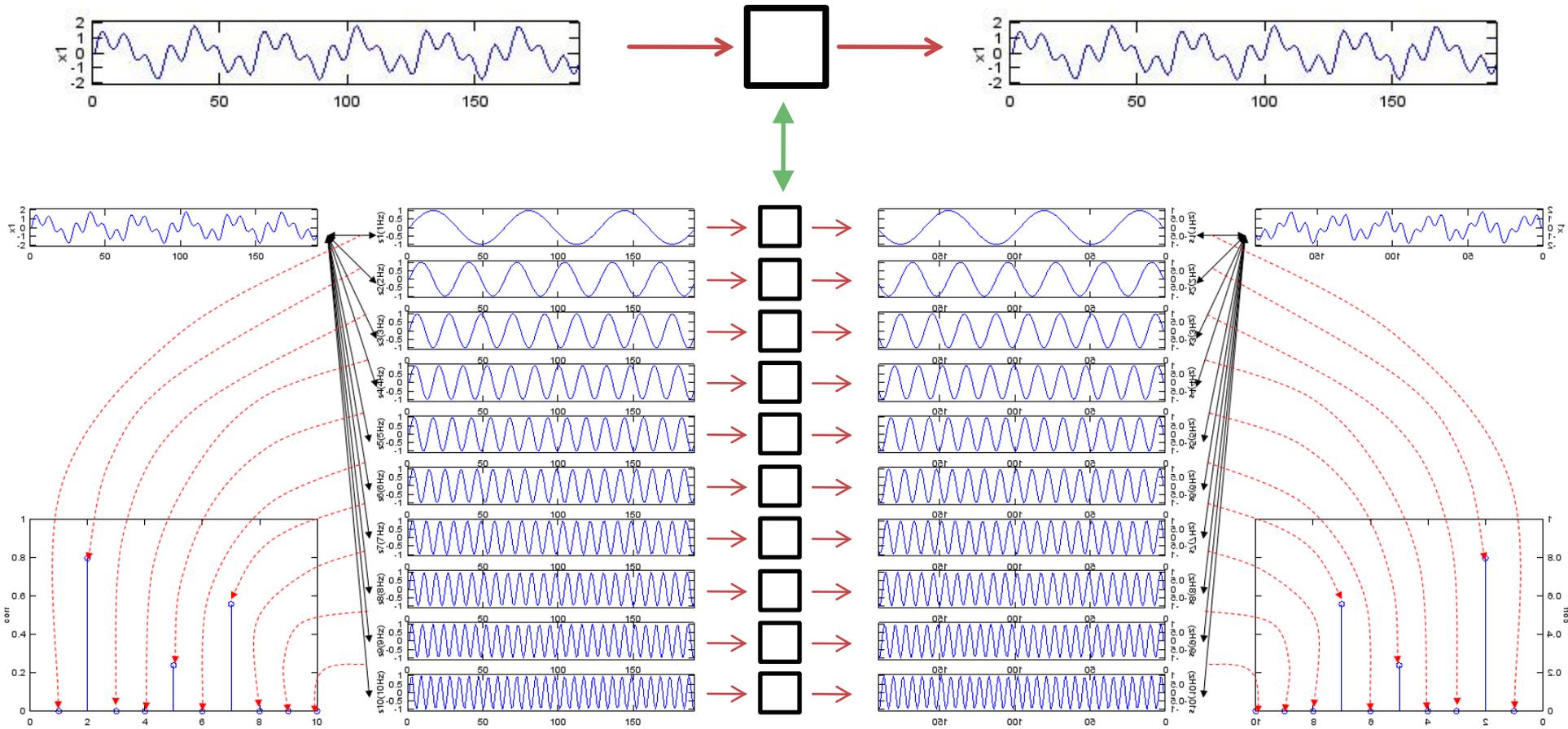
$$A_i = \langle E_{IN}, Mod_i \rangle$$



$$B_i(A_i)$$

$$E_{OUT} = \sum_1^N B_i \cdot Mod_i$$

Mathematical modeling



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

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

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

Mathematical modeling

- particular cases where analytical solution exists

- wave in a single direction $E^+ (E^+)$, $E^- (E^-)$

- wave

- incident

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

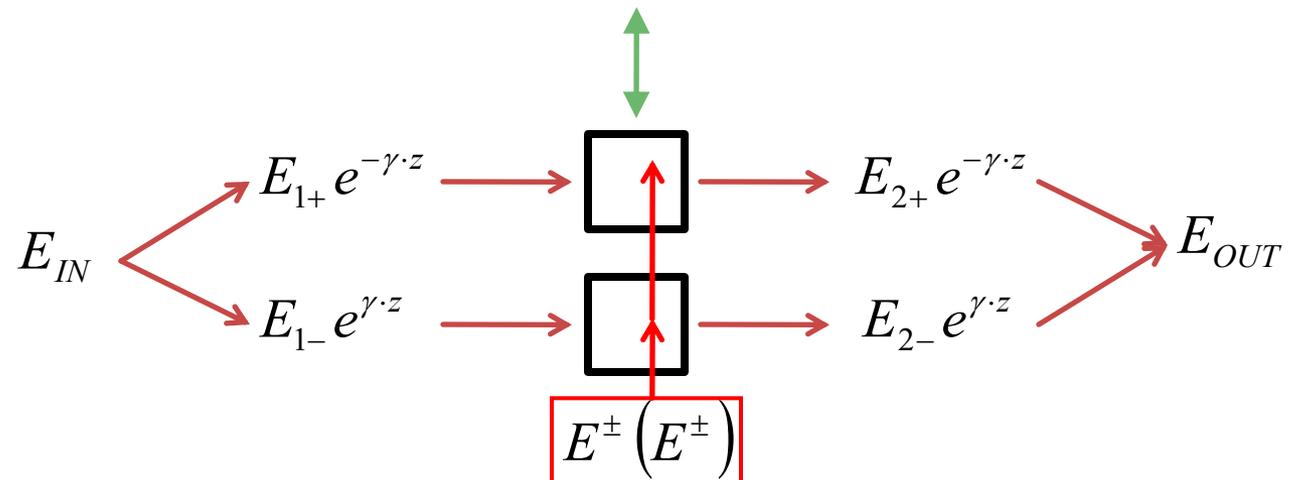
- reflected

$$E_{IN} = E_{1+} e^{-\gamma \cdot z} + E_{1-} e^{\gamma \cdot z} \longrightarrow \boxed{} \longrightarrow E_{OUT} = E_{2+} e^{-\gamma \cdot z} + E_{2-} e^{\gamma \cdot z}$$

- wave

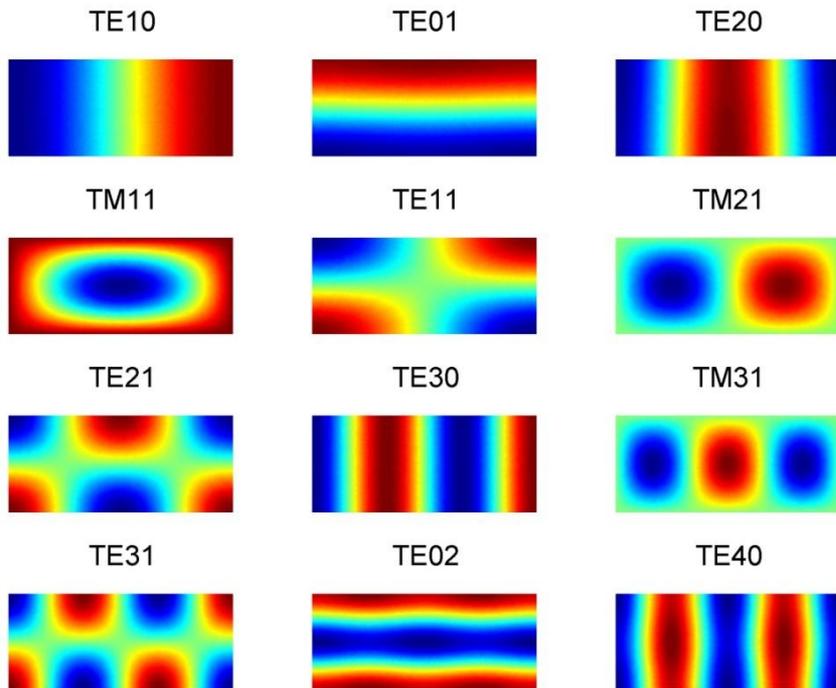
- direct

- inverse



Mathematical modeling

- particular cases where analytical solution exists
 - modes in delimited media $B_i(A_i)$



$$E = \sum_1^{\infty} A_i \cdot \text{Mod}_i \quad A_i = \langle E, \text{Mod}_i \rangle$$



$$A_i = \langle E_{IN}, \text{Mod}_i \rangle$$



$$B_i(A_i)$$

$$E_{OUT} = \sum_1^N B_i \cdot \text{Mod}_i$$

TEM transmission lines

Course Topics

- **Transmission lines**
- Impedance matching and tuning
- Directional couplers
- Power dividers
- Microwave amplifier design
- Microwave filters
- ~~Oscillators and mixers?~~

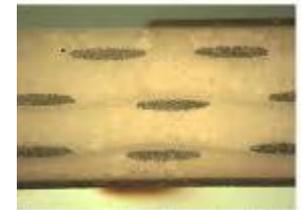
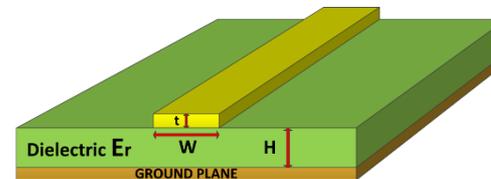
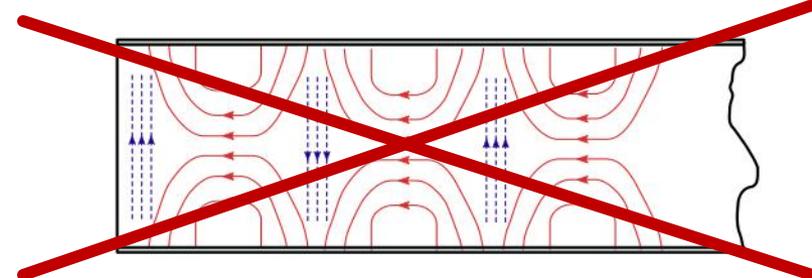
Transmission line

- TEM wave propagation, at least two conductors

$$I(z,t)$$

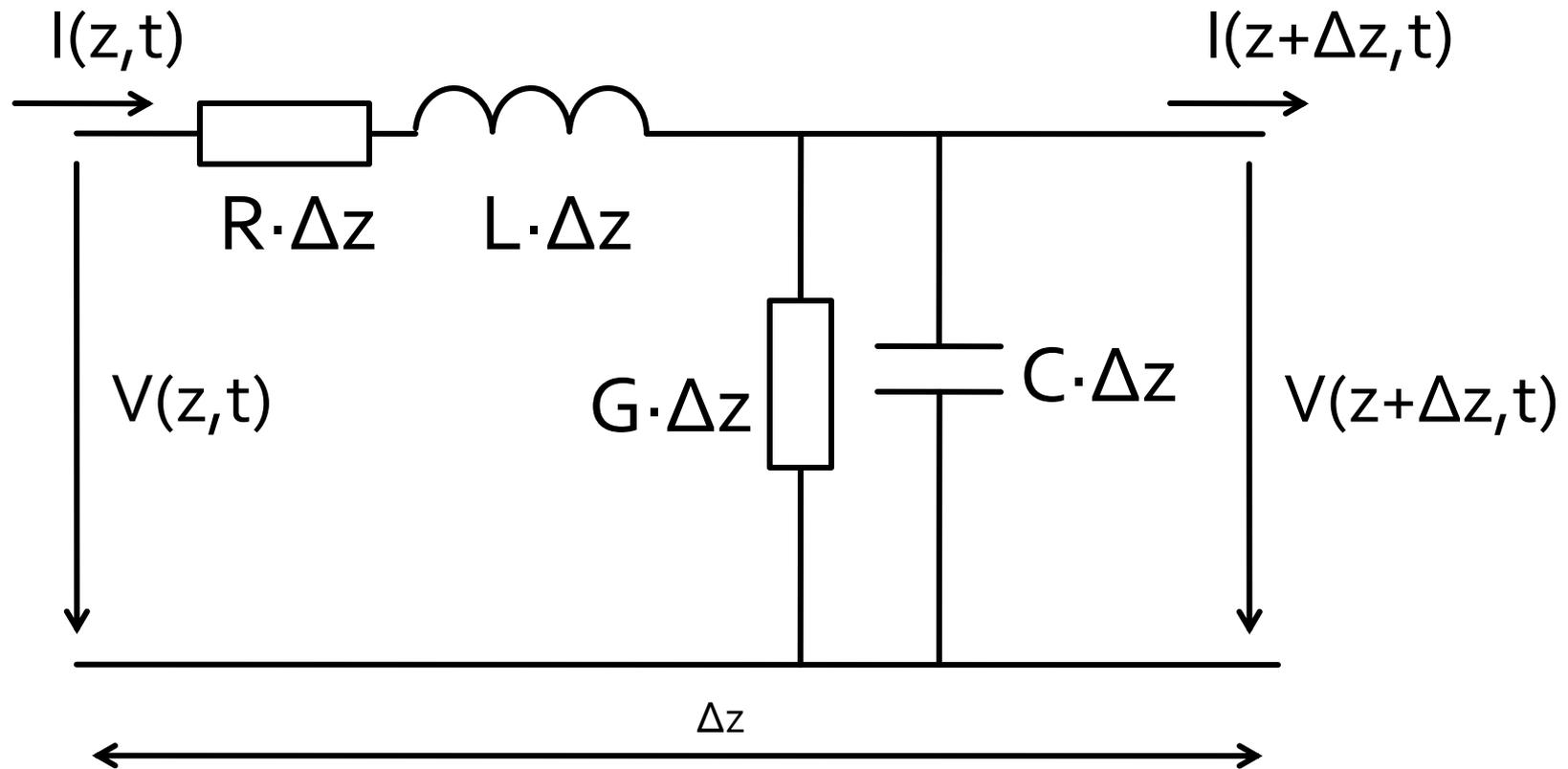


$$V(z,t)$$



Transmission line equivalent model

- TEM wave propagation, at least two conductors



- **distributed** (line) parameters R , L , G , C (eg. Ω/m)

Telegrapher's equations

- time domain

$$\frac{\partial v(z,t)}{\partial z} = -R \cdot i(z,t) - L \cdot \frac{\partial i(z,t)}{\partial t} \quad \text{K II}$$

$$\frac{\partial i(z,t)}{\partial z} = -G \cdot v(z,t) - C \cdot \frac{\partial v(z,t)}{\partial t} \quad \text{K I}$$

- armonic signals (frequency domain)

$$\frac{dV(z)}{dz} = -(R + j \cdot \omega \cdot L) \cdot I(z)$$
$$\frac{dI(z)}{dz} = -(G + j \cdot \omega \cdot C) \cdot V(z)$$

$\left/ \frac{d}{dz} (\dots) \right.$

Solving T's E

$$\frac{d^2 V(z)}{dz^2} - \gamma^2 \cdot V(z) = 0$$

$$\frac{d^2 I(z)}{dz^2} - \gamma^2 \cdot I(z) = 0$$

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


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

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

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

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

Solutions

$$\left\{ \begin{array}{l} V(z) = V_0^+ e^{-\gamma \cdot z} + V_0^- e^{\gamma \cdot z} \\ I(z) = I_0^+ e^{-\gamma \cdot z} + I_0^- e^{\gamma \cdot z} \end{array} \right. \quad \gamma = \alpha + j \cdot \beta = \sqrt{(R + j \cdot \omega \cdot L) \cdot (G + j \cdot \omega \cdot C)}$$

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

$$\frac{dV(z)}{dz} = -(R + j \cdot \omega \cdot L) \cdot I(z)$$

$$Z_0 \equiv \frac{R + j \cdot \omega \cdot L}{\gamma} = \sqrt{\frac{R + j \cdot \omega \cdot L}{G + j \cdot \omega \cdot C}}$$

$$I(z) = \frac{\gamma}{R + j \cdot \omega \cdot L} (V_0^+ e^{-\gamma \cdot z} - V_0^- e^{\gamma \cdot z})$$

- Characteristic impedance of the line

$$\frac{V_0^+}{I_0^+} = Z_0 = -\frac{V_0^-}{I_0^-}$$

$$\lambda = \frac{2\pi}{\beta} \quad v_f = \frac{\omega}{\beta} = \lambda \cdot f$$

The lossless line

- **Lossless:** $R=G=0$

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

$$\alpha = 0 \quad ; \quad \beta = \omega \cdot \sqrt{L \cdot C}$$

$$Z_0 = \sqrt{\frac{R + j \cdot \omega \cdot L}{G + j \cdot \omega \cdot C}} = \sqrt{\frac{L}{C}}$$

- Z_0 is **real**

$$V(z) = V_0^+ e^{-j \cdot \beta \cdot z} + V_0^- e^{j \cdot \beta \cdot z}$$

$$I(z) = \frac{V_0^+}{Z_0} e^{-j \cdot \beta \cdot z} - \frac{V_0^-}{Z_0} e^{j \cdot \beta \cdot z}$$

$$\lambda = \frac{2\pi}{\omega \cdot \sqrt{LC}}$$

$$v_f = \frac{1}{\sqrt{LC}}$$

Contact

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