Microwave Engineering

ETE 415

LECTURE 1

INTRODUCTION TO MICROWAVE

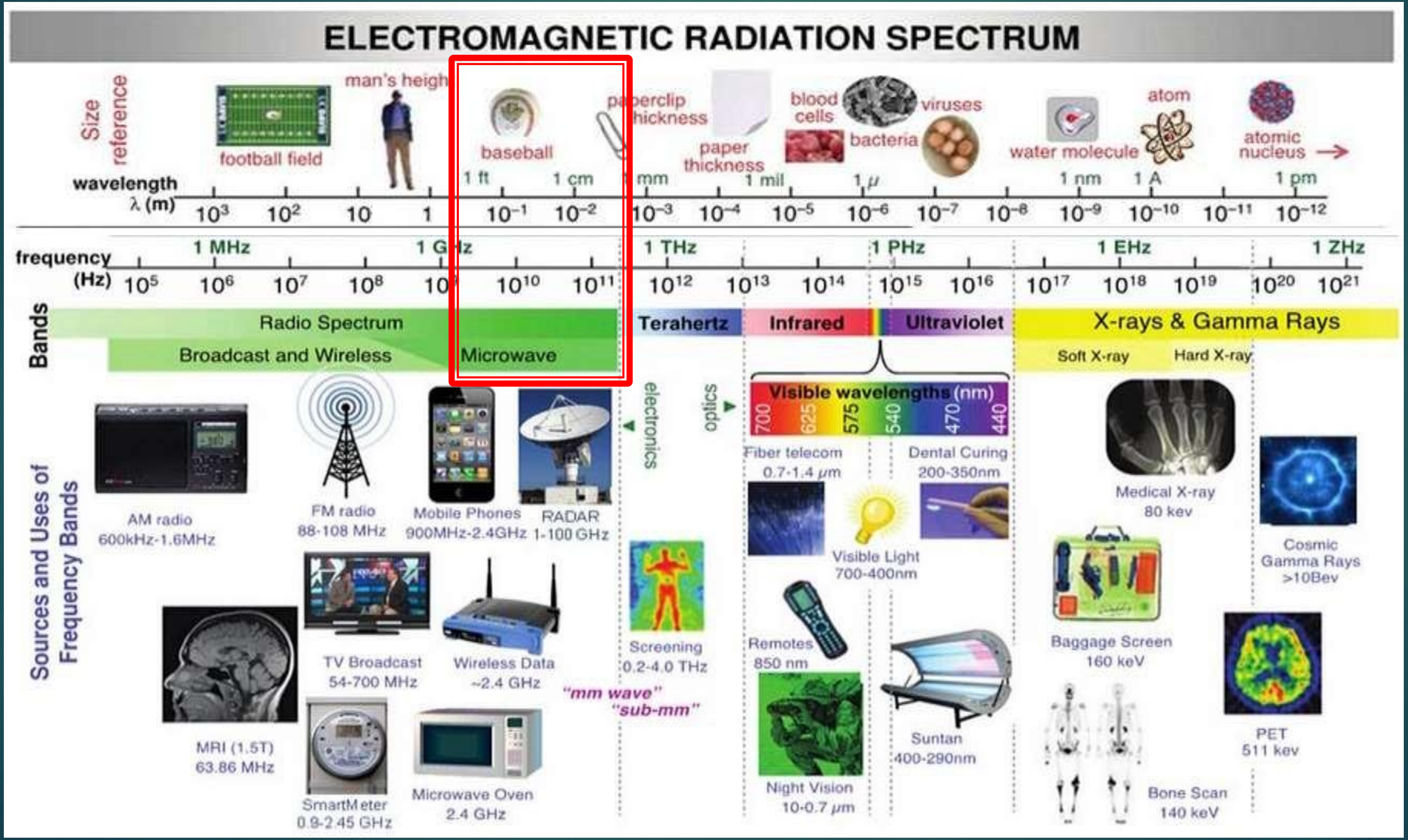
Microwaves

- Microwaves term is used to describe the electromagnetic waves with wavelengths ranging from 10 cm – 1 mm.
- The corresponding frequency range is 3 – 300 GHz (IEEE: from 1 GHz).
- ***RF bands***: from 30 MHz to 3 GHz
- ***Microwave bands***: from 3 GHz to 30 GHz (cm wavelengths)

$$\boxed{\lambda_{[\mathrm{cm}]} = \frac{c}{f} \approx \frac{30}{f_{[\mathrm{GHz}]}}}$$

- ***Millimeter-wave bands***: from 30 GHz to 300 GHz
- Why are cm-waves called microwaves?

Electromagnetic Frequency Spectrum



Frequency Spectrum Designations

n	Frequency band	Wavelength	Designation	Services
4	3 – 30 kHz	100 – 10 km	Very Low Frequency (VLF)	Navigation, sonar, submarine
5	30 – 300 kHz	10 – 1 km	Low Frequency (LF)	Radio beacons, navigation
6	300 – 3000 kHz	1000 – 100 m	Medium Frequency (MF)	AM broadcast, maritime/coast-guard radio
7	3 – 30 MHz	100 – 10 m	High Frequency (HF)	Telephone, telegraph, fax, amateur radio, ship-to-coast, ship-to-aircraft communication
8	30 – 300 MHz	10 – 1 m	Very High Frequency (VHF)	TV, FM broadcast, air traffic control, police, taxicab mobile radio
9	300 – 3000 MHz	100 – 10 cm	Ultrahigh Frequency (UHF)	TV, satellite, radiosonde, radar, bluetooth, PCS, wireless LAN
10	3 – 30 GHz	10 – 1 cm	Super High Frequency (SHF)	Airborne & automotive radar, microwave relay, satellite, mobile communication, local wireless networks.
11	30 – 300 GHz	10 – 1 mm	Extremely High Frequency (EHF)	Radar, experimental, security systems

IEEE MW Band Designations

RF Region

Microwave Region

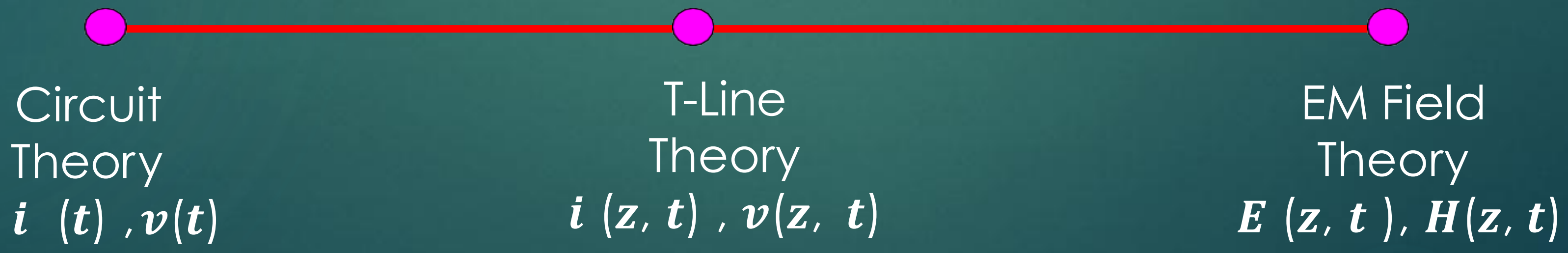
(λ = 30 cm to 8 mm)

Frequency	Old Band	New Band
500 – 1000 MHz	VHF	C
1 – 2 GHz	L	D
2 – 3 GHz	S	E
3 – 4 GHz	S	F
4 – 6 GHz	C	G
6 – 8 GHz	C	H
8 – 10 GHz	X	I
10 – 12.4 GHz	X	J
12.4 – 18 GHz	Ku	J
18 – 20 GHz	K	J
20 – 26.5 GHz	K	K
26.5 – 40 GHz	Ka	K

Circuit Theory vs. EM Field Theory

- When the size of a structure is much smaller than a wavelength, there is negligible variation in the electric/magnetic fields (voltages/currents) across the structure
    - Can apply circuit theory (KCL, KVL, …)
    - lumped-parameter circuit components

- As the structure gets large/wavelength gets small, such that this is no longer true, circuit theory is no longer applicable
    - Need EM field theory to analyze the system
    - distributed-parameter circuit components

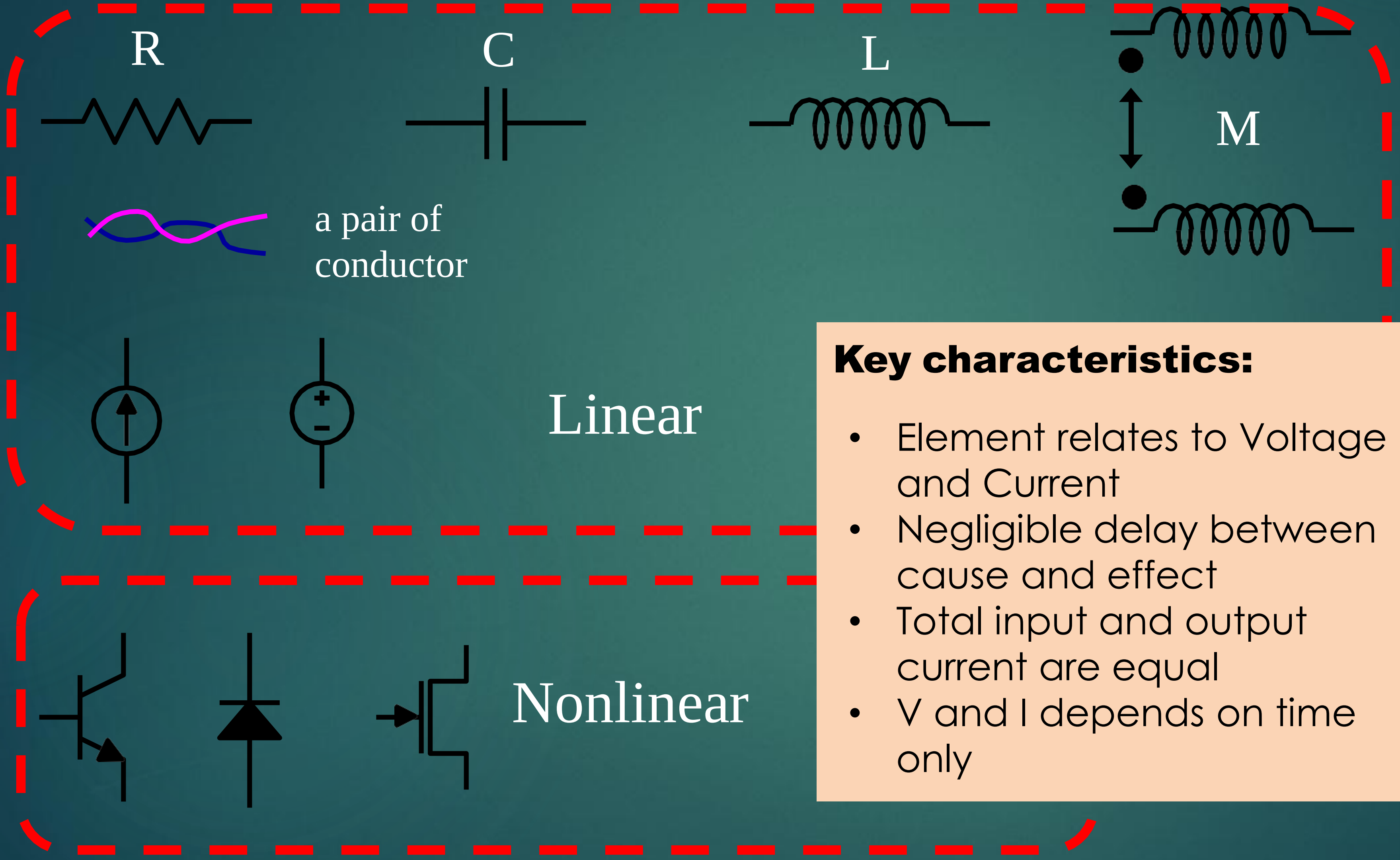


Circuit Theory
$\boldsymbol{i}(\boldsymbol{t}), \boldsymbol{v}(\boldsymbol{t})$

T-Line Theory
$\boldsymbol{i}(\boldsymbol{z}, \boldsymbol{t}), \boldsymbol{v}(\boldsymbol{z}, \boldsymbol{t})$

EM Field Theory
$\boldsymbol{E}(\boldsymbol{z}, \boldsymbol{t}), \boldsymbol{H}(\boldsymbol{z}, \boldsymbol{t})$

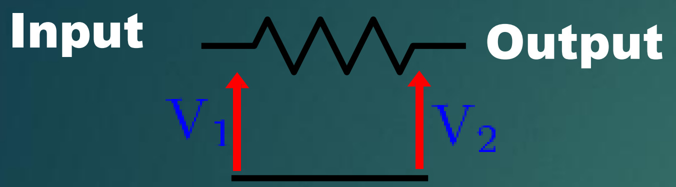
Lumped Elements (1)

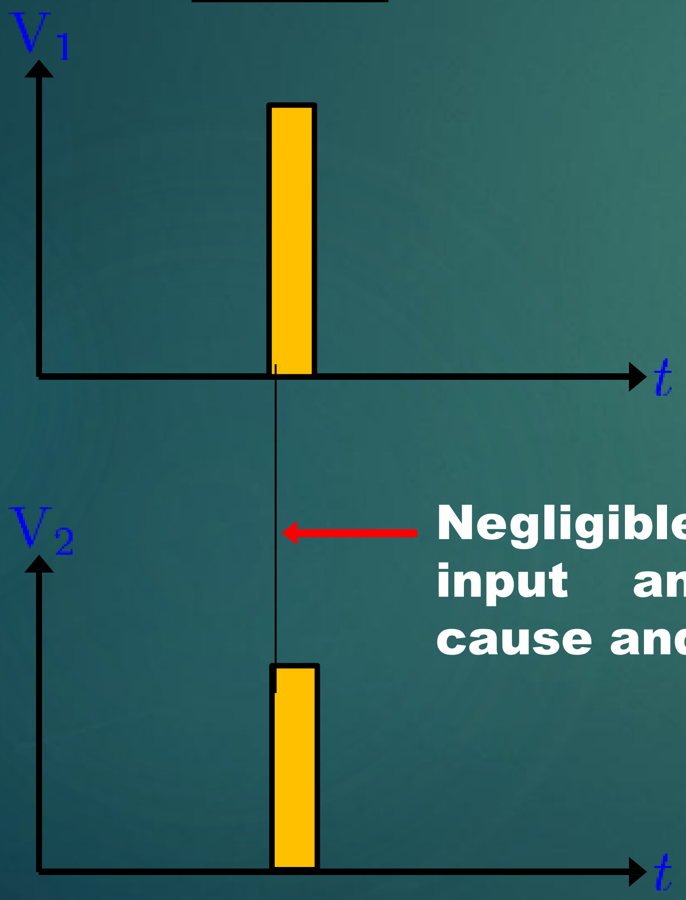


Key characteristics:

- Element relates to Voltage and Current
- Negligible delay between cause and effect
- Total input and output current are equal
- V and I depends on time only

Lumped Elements (2)



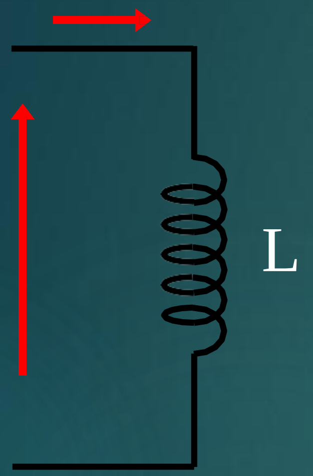


Negligible delay between input and output, e.g., cause and effect.

Input and output currents are similar at any instant in time.

Lumped Elements (3)

Example of lumped components:

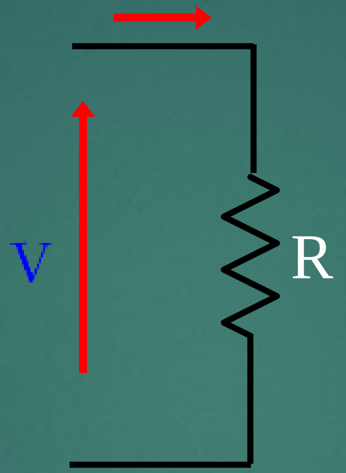


Time-Domain

$$v(t) = L\frac{di(t)}{dt}$$

Frequency-Domain

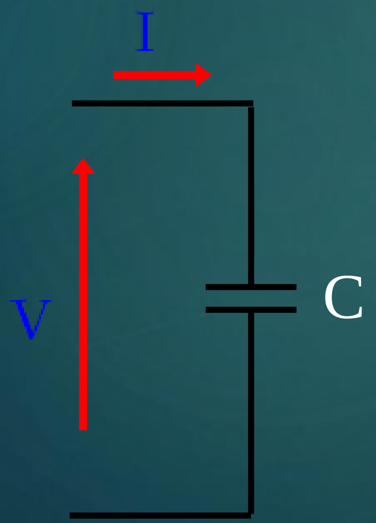
$$V(w) = jwLI(w)$$



Time-Domain

$$v(t) = Ri(t)$$

$$V(w) = RI(w)$$



Time-Domain

$$i(t) = C\frac{dv(t)}{dt}$$

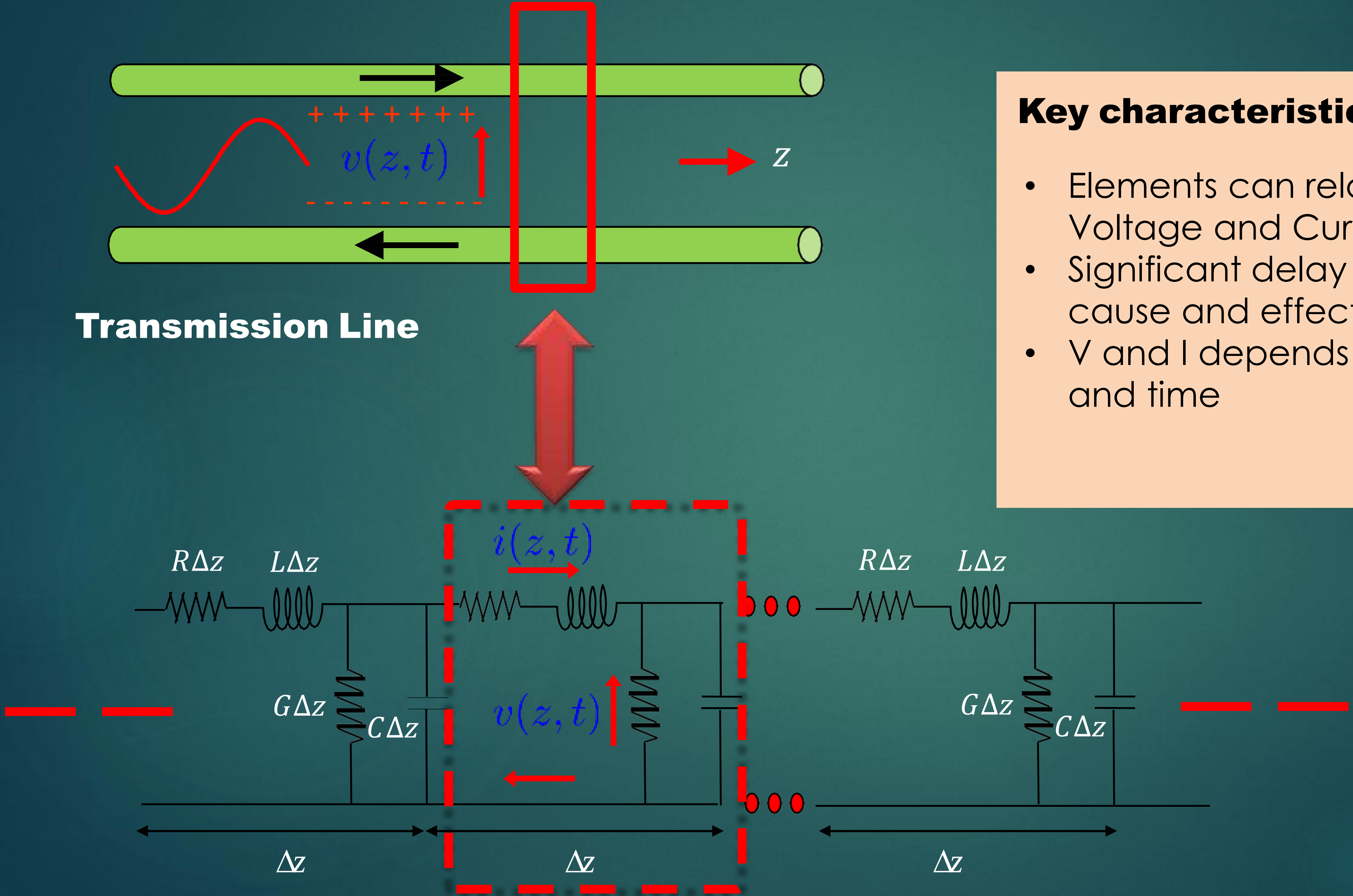
Frequency-Domain

$$V(w) = \frac{1}{jwC}I(w)$$

Voltage phasor

Current phasor

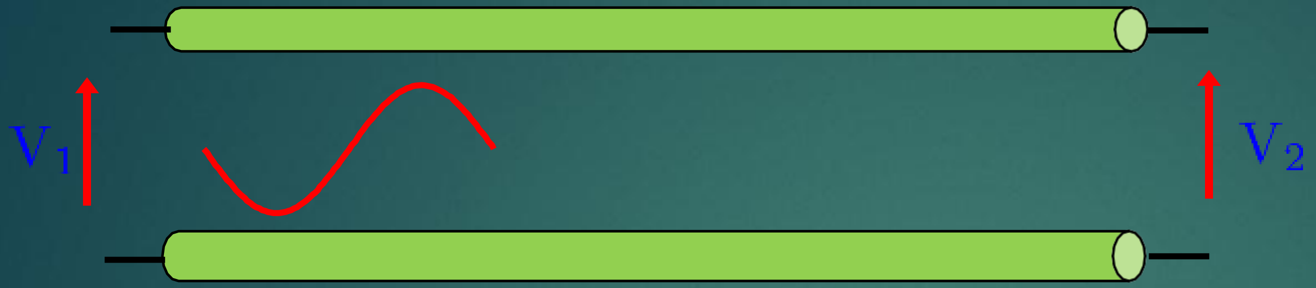
Distributed Elements (1)

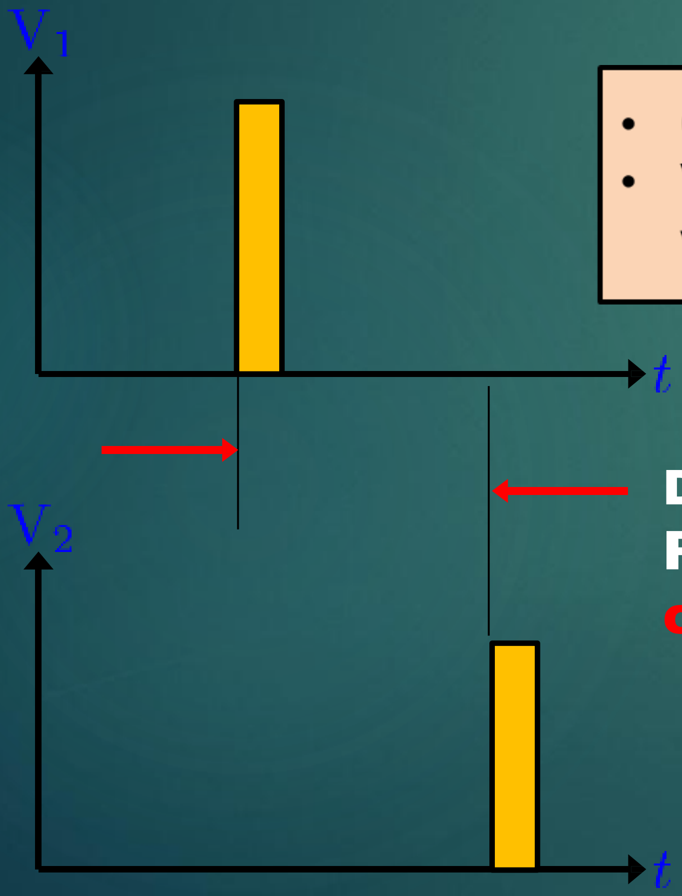


Key characteristics:

- Elements can relate to Voltage and Current
- Significant delay between cause and effect
- V and I depends on location and time

Distributed Elements (2)





- **Current varies along conductors and elements**
- **Voltage across points along conductor or within elements varies**

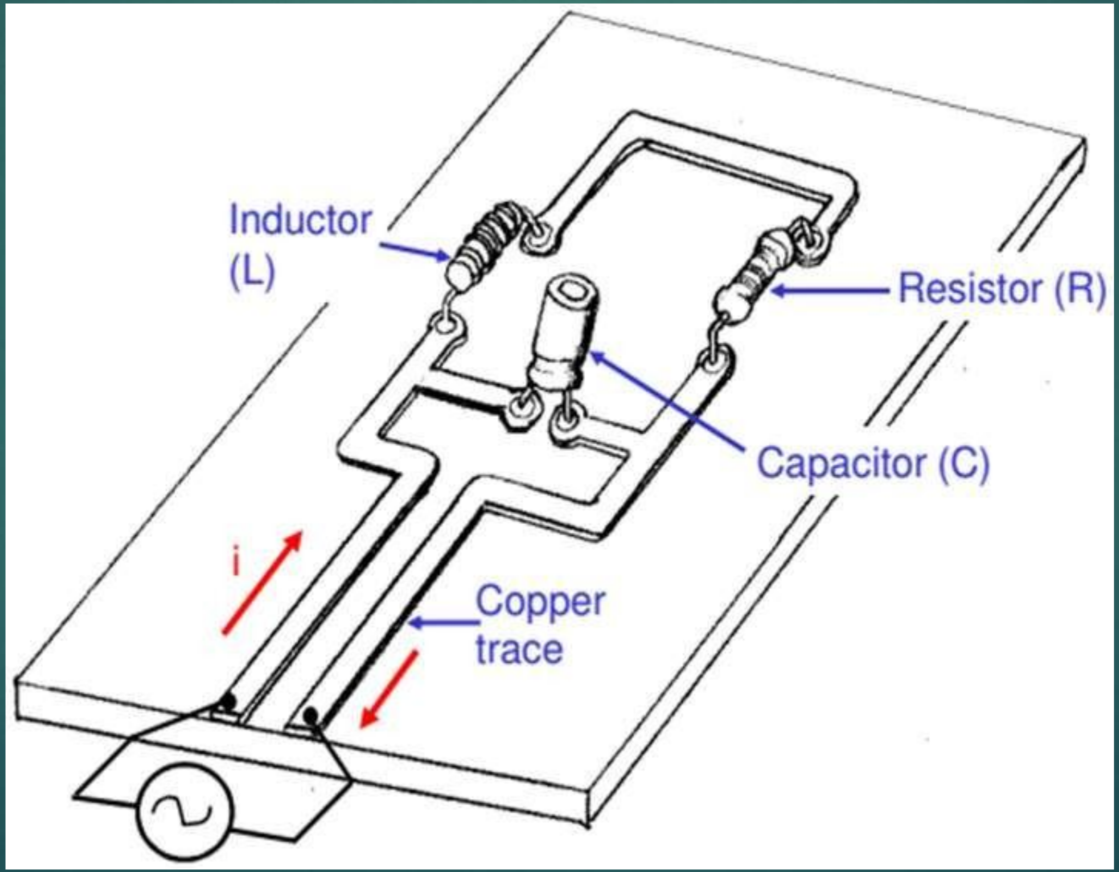
Delay Δt

Phase change or transit time

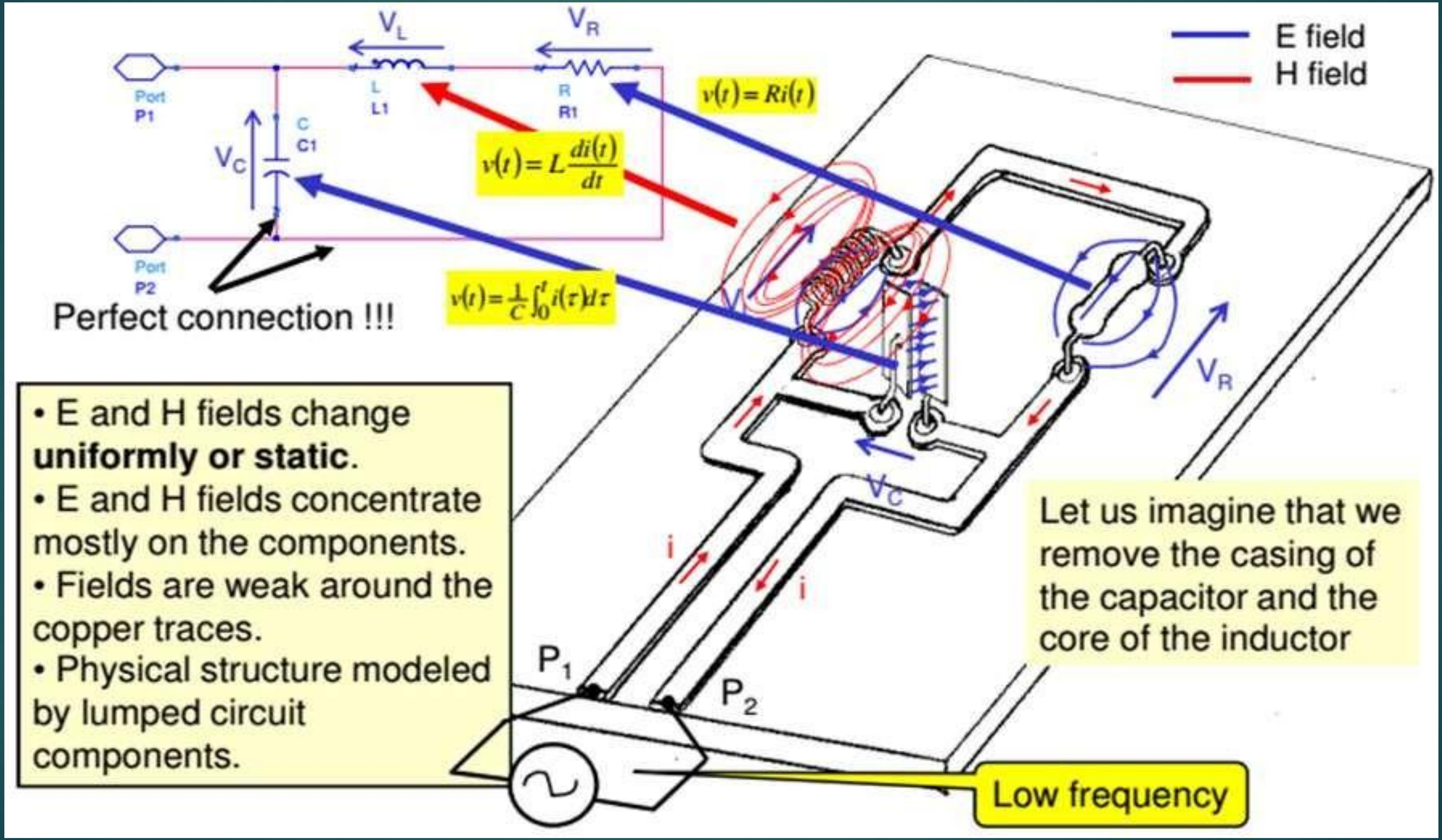
cannot be neglected

Transition from Lumped to Distributed

Consider a simple circuit built on a single-sided printed circuit board (PCB):



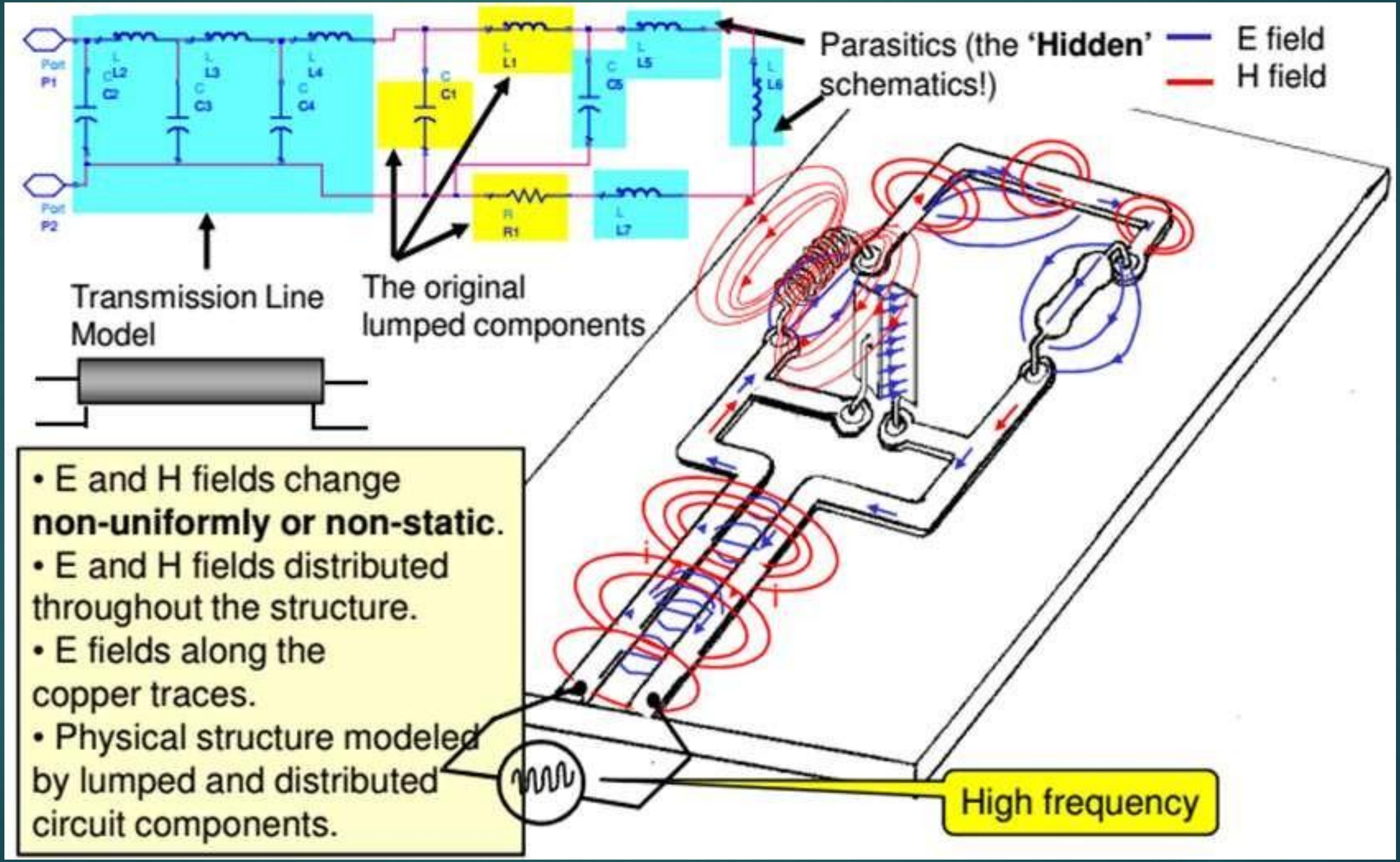
Low-Frequency Condition



- E and H fields change **uniformly or static**.
- E and H fields concentrate mostly on the components.
- Fields are weak around the copper traces.
- Physical structure modeled by lumped circuit components.

Let us imagine that we remove the casing of the capacitor and the core of the inductor

High-Frequency Condition



Parasitics (the '**Hidden**' schematics!)

Transmission Line Model

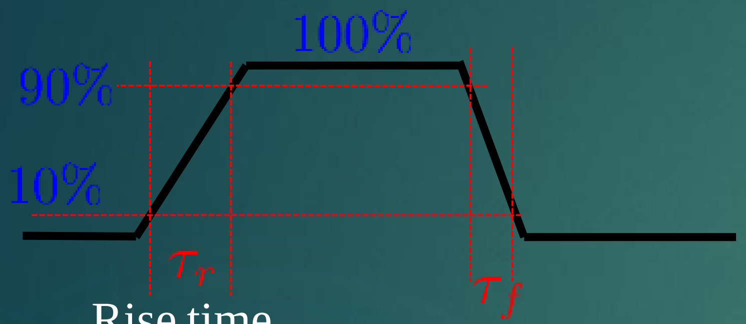
The original lumped components

- E and H fields change **non-uniformly or non-static.**
- E and H fields distributed throughout the structure.
- E fields along the copper traces.
- Physical structure modeled by lumped and distributed circuit components.

High frequency

Transition from Lumped to Distributed

Digital domain



Rise time

Fall time

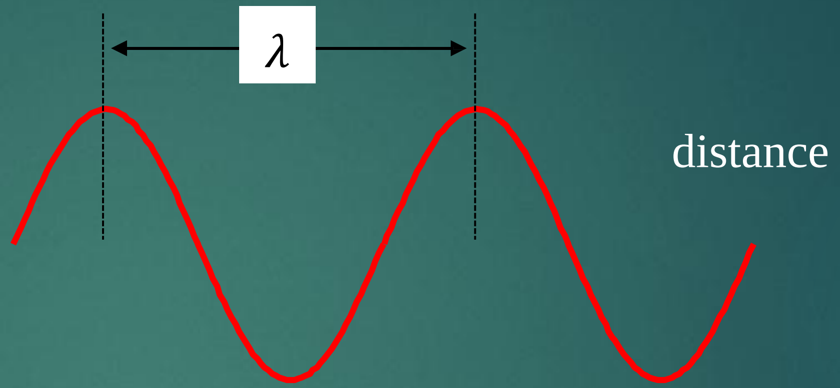
Propagation delay $T_{\text{delay}} = L/v_p$

$$\frac{T_{\text{delay}}}{\tau} \le 0.1$$

Rise/fall time

Short interconnect

Analog domain

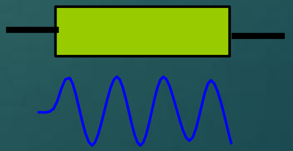


Rule-of-Thumb: if $L < 0.10\lambda$, it is a short interconnect, otherwise it is considered a long interconnect.

$v_p = f\lambda$

Phase velocity


Distributed conductor


Distributed element

Concept: Electrical Length

Electrical length (E) is the portion of a wavelength (λ) that a distance z represents, or simply $\frac{z}{\lambda}$

$$E = 2\pi \frac{z}{\lambda} \quad \text{(in radians)}$$

$$E = 360^\circ \frac{z}{\lambda} \quad \text{(in degrees)}$$

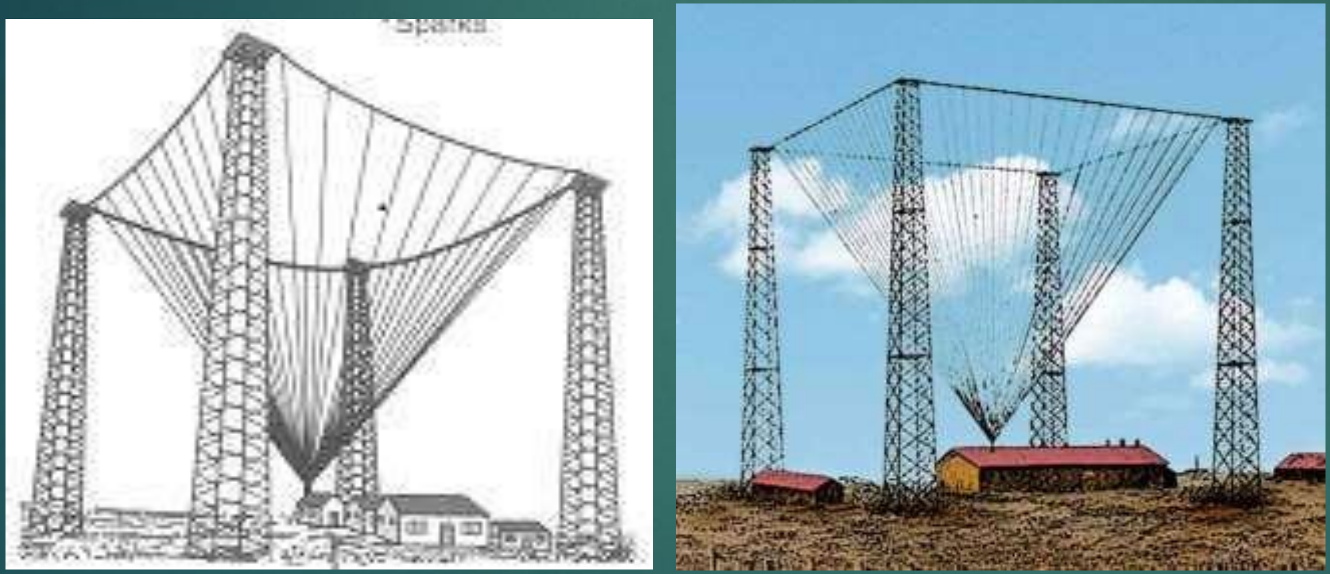
$$E = \frac{z}{\lambda} \quad \text{(as a fraction of a wavelength)}$$

3 ways of expressing the same thing

RF, microwave, and millimeter wave circuit design and construction is **far more complicated** than low frequency work. So why do it?

Advantages of MW-I

1. High gain antennas can be constructed at microwave frequencies that are physically small.



Marconi’s square conical antenna at England in 1905

Modern microwave antennas

Advantages of MW-II

2. More bandwidth:- a 1% bandwidth, for example, provides more absolute frequency range at MW frequencies than that at HF.
3. MW signals travel predominately by line of sight (LOS) and aren't reflected off the ionosphere like HF signals do. Consequently, communication links between (and among) satellites and terrestrial stations are possible.
4. At MW frequencies, the electromagnetic properties of many materials are changing with frequency. This is due to molecular, atomic, and nuclear resonances. This behavior is useful for remote sensing and other applications.
5. There is much less background noise at MW frequencies than at RF.
6. Better resolution for radars due to smaller wavelengths.

Microwave Applications

Cordless telephony

1.9, 2.4, and 5.8 GHz

700 MHz to 2.7 GHz

GSM: two frequency bands of 25 MHz

Uplink: 890-915 MHz (Europe) 1850-1910 MHz (US)

Downlink: 935-960 MHz (Europe) 1930-1990 MHz (US)

2.4 GHz for IEEE 802.11b & 802.11g
5 GHz for IEEE 802.11a

WiMAX

3.5 & 5 GHz
(Middle East & Africa)

Bluetooth®

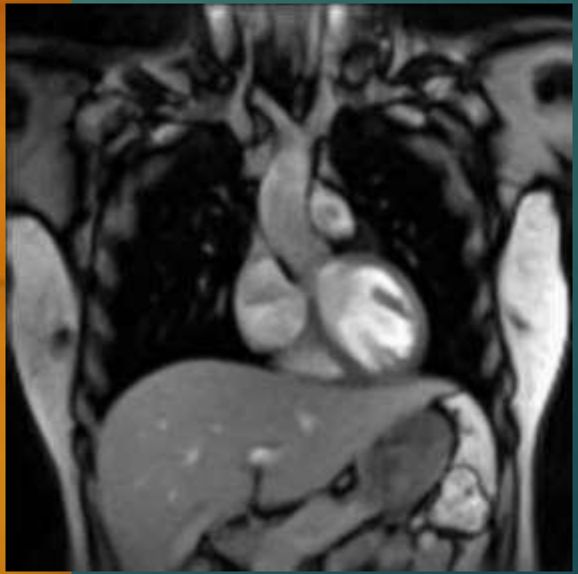
ISM band @ 2.45 GHz

uplink@1.57542 GHz,

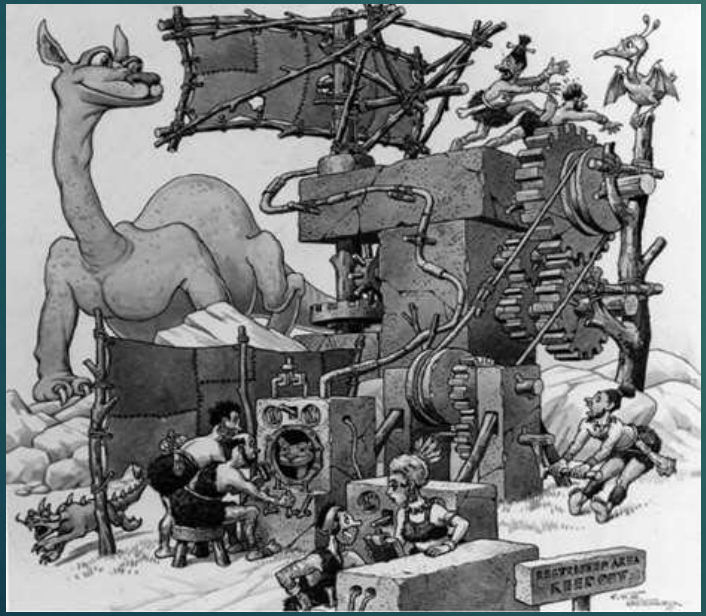
downlink@1.22760 GHz

Personal satellite communications

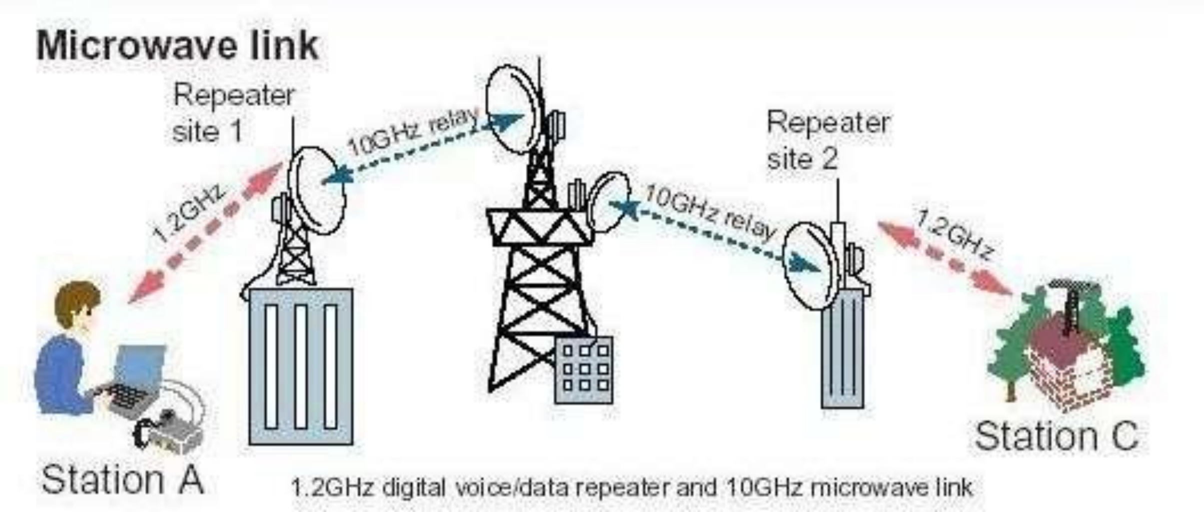
Real-time MRI of a human heart

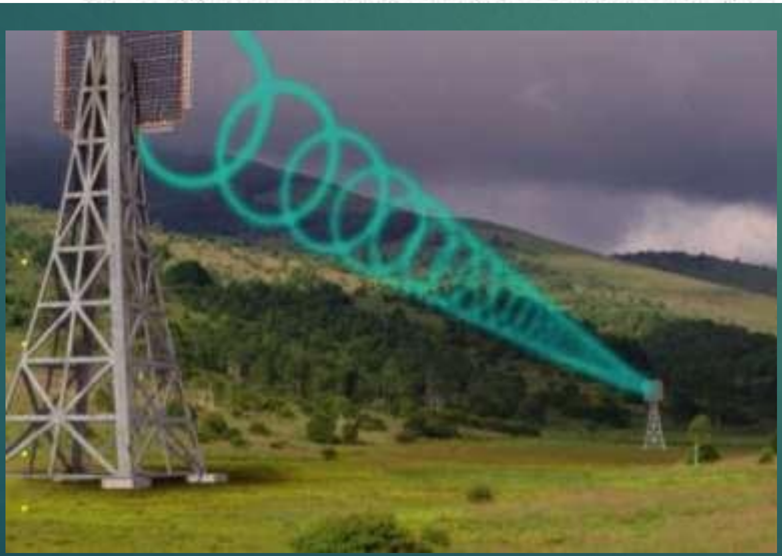


RADAR



Microwave relay links, repeaters

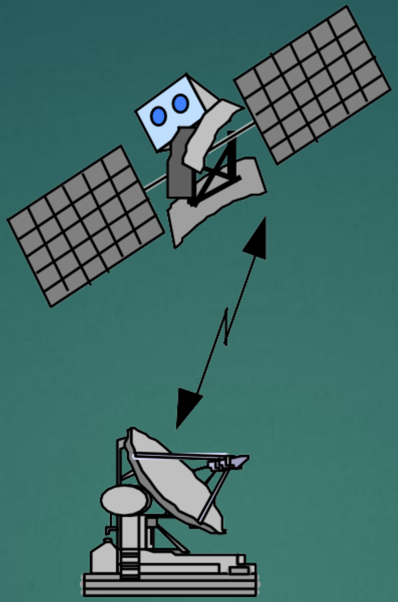




Wireless power transfer

Microwave heating

Microwave Drying of Food and Agricultural Materials

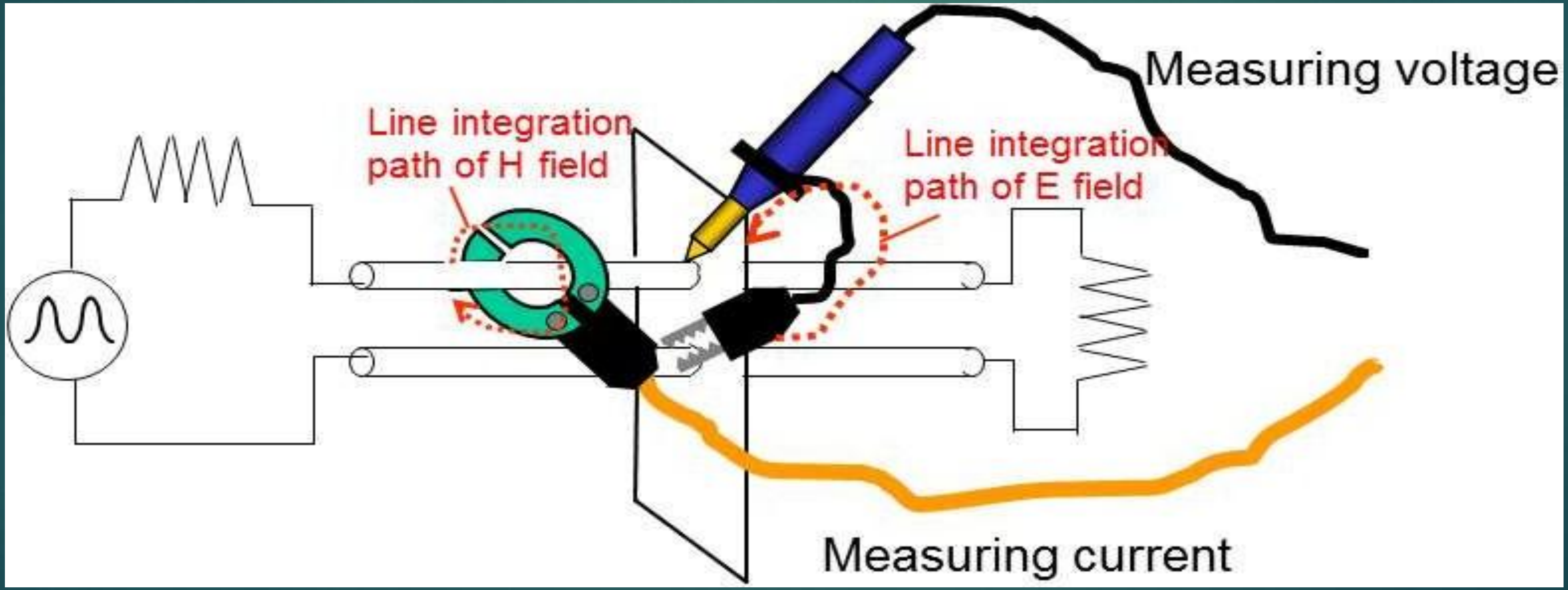


RADIO ASTRONOMY

SATELLITE SYSTEM

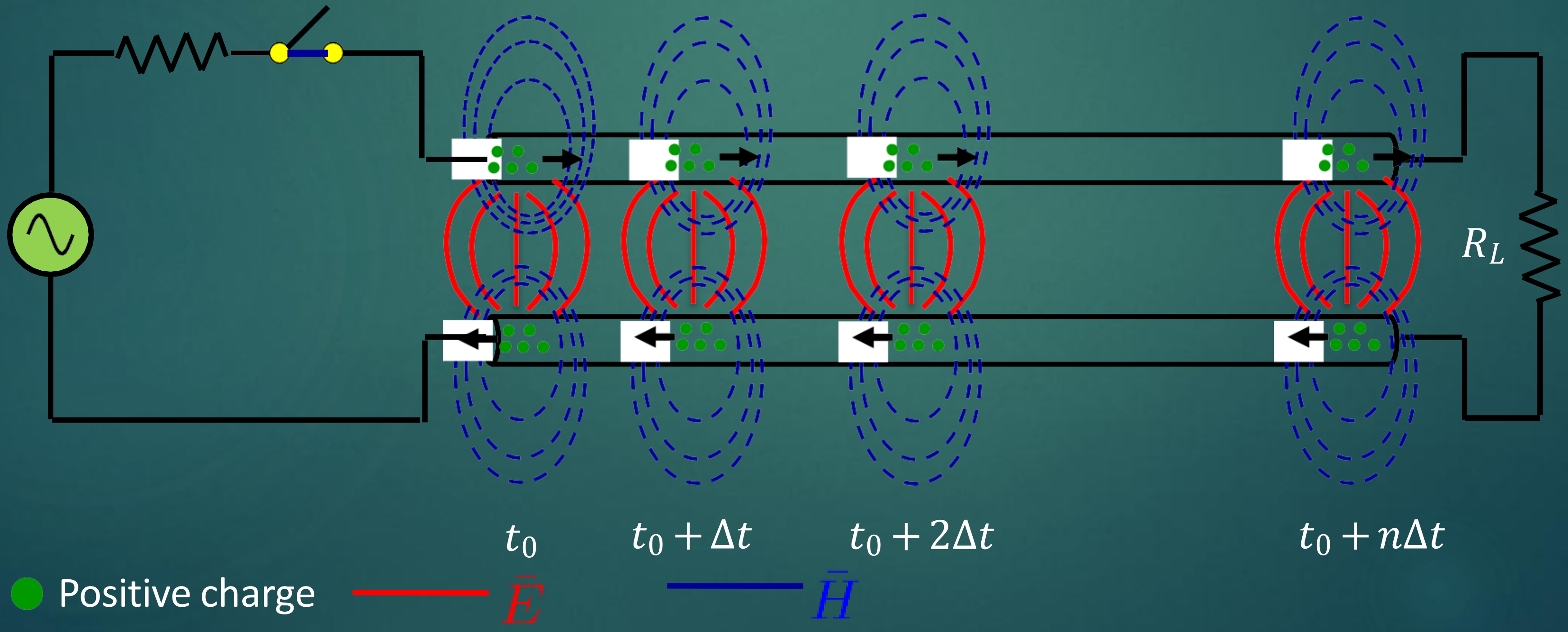
Difficulties

1. Voltage is not well defined if the distance between the two points is not electrically small. At MW frequencies, “electrically large” distances may be just a few millimeters! Moving the probe leads around will also likely affect voltage measurements.



Difficulties

2. More expensive components.
3. One must carefully choose lumped elements (L, C, R, diodes, transistors, etc.) for use in the MW region. Typical low frequency components do not behave as expected.
4. To “transport” electrical signals from one position to another, one must use special “wires.” It is more common to speak of “guiding” signals at these frequencies.



Microwave Engineering

- In UHF band up to around a frequency of 1 GHz, most communications circuits are constructed using lumped-parameter circuit components.
- In the frequency range from 1 – 100 GHz, lumped circuit elements are usually replaced by T-line and waveguide components.
- Microwave engineering: the engineering and design of information-handling systems in the frequency range 1 – 100 GHz (corresponding to wavelengths as long as 30 cm and as short as 3 mm).
- The characteristic feature of microwave engineering is the short wavelengths involved, these being of the same order of magnitude as the circuit elements and devices employed.
- Microwave engineering: is applied electromagnetic fields engineering.

Maxwell’s Equations-I

Perhaps the two most important of the **Maxwell equations** are

	Differential form:	**Integral form:**
Faraday’s Law	$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t}$	$\oint_c \bar{E} \cdot d\bar{l} = -\frac{\partial}{\partial t} \int_s \bar{B} \cdot d\bar{s}$
Ampère’s Law	$\nabla \times \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t}$	$\oint_c \bar{H} \cdot d\bar{l} = \int_s \bar{J} \cdot d\bar{s} + \frac{\partial}{\partial t} \int_s \bar{D} \cdot d\bar{s}$

E is the electric field in V/m.

H is the magnetic field in A/m.

D is the electric flux density in Coul/m^2.

B is the magnetic flux density in Wb/m^2.

J is the electric current density in A/m^2.

$$\bar{B} = \mu \bar{H} \qquad \bar{D} = \epsilon \bar{E}$$

$$\mu = \mu_o \mu_r \qquad \epsilon = \epsilon_o \epsilon_r$$

Constitutive relations

Maxwell's Equations-II

Much of our work in this course will be in the **sinusoidal steady state**. With an assumed (and suppressed) e^{jwt} time convention, these curl equations become:

$$\boxed{\frac{\partial}{\partial t} \rightarrow jw}$$

	Differential form:	**Integral form:**
Faraday's Law	$\nabla \times \bar{E} = -jw\bar{B}$	$\oint_c \bar{E} \cdot d\bar{l} = -jw \int_s \bar{B} \cdot d\bar{s}$
Ampere's Law	$\nabla \times \bar{H} = \bar{J} + jw\bar{D}$	$\oint_c \bar{H} \cdot d\bar{l} = \int_s \bar{J} \cdot d\bar{s} + jw \int_s \bar{D} \cdot d\bar{s}$

where E, B, D, H, and J are all **vector phasors**.

Maxwell's Equations-III

Of course, both the differential and integral forms are equally valid.

Which of these to use depends on the problem:

To derive equations to solve for E and H, the **differential forms** are often better.

For circuit approximations of devices (or other physical interpretations), the **integral forms** are often more useful.

Rather than using the full-blown Maxwell's equations in microwave circuit design, **approximations** are often made to simplify the solutions.

Transmission line theory, to be discussed next, is one of these.

We will **not explicitly** be seeing much of Maxwell's equations in this course.

Thank you Very Much !!!