Microwaves

Anja Skrivervik
anja.skrivervik@epfl.ch, 021 693 4635

Summary (microwaves)

- Introduction and applications
- A short reminder transmission line theory
- An introduction to waveguides
- Microwave circuit theory
- Microwave components
- Microwave filters
- An introduction to microwave measurements

Course form

- ex cathedra
- supervised and unsupervised exercises
- handouts and corrections on the web (Moodle)
- Two tests (16th of November and 14th of December)

History

1872	Publication of "a treatise on electricity and magnetism" by James Clerk Maxwell
1887	Publication of Oliver Heaviside's comments on Maxwell's work
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1938	First Portable phone (Motorola)

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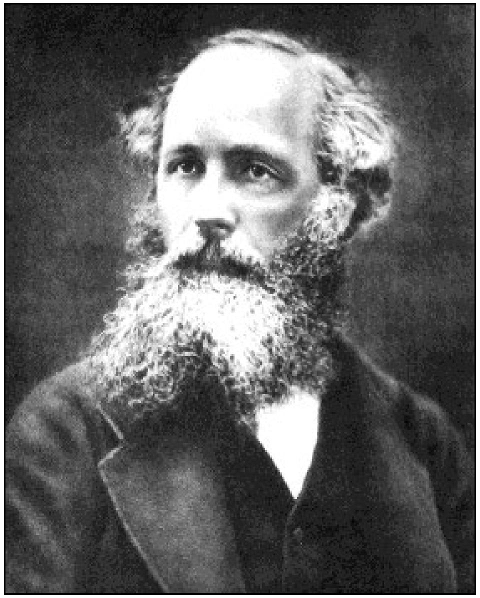
Maxwell's equations (Telecom style)

$$\nabla \times \mathbf{H} = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}$$



Electric currents Varying in space and time

acting in a specific medium create

electromagnetic waves

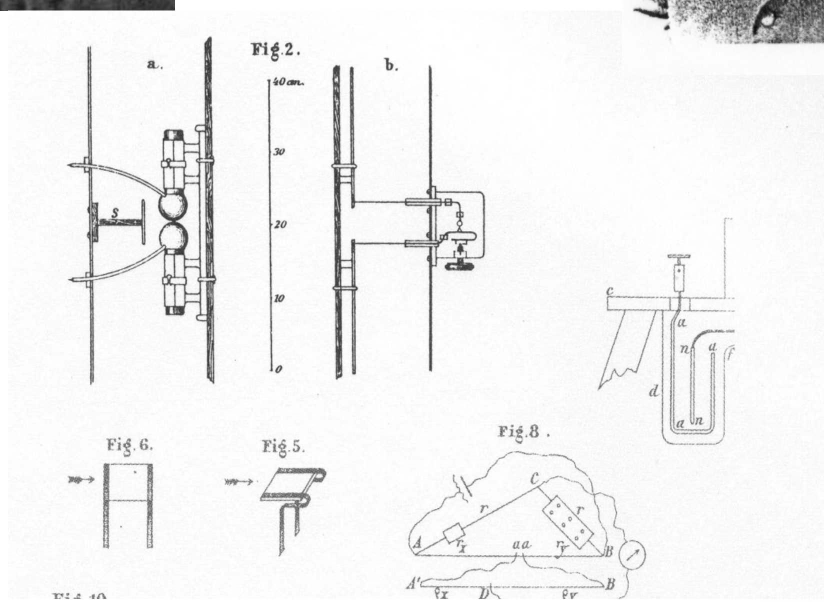
Maxwell - Heaviside

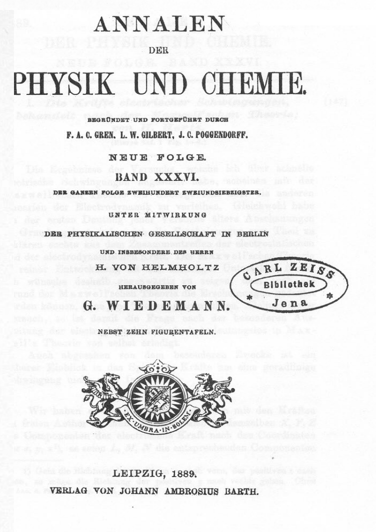
$$\left.\begin{aligned}\frac{dQ}{dz}-\frac{dR}{dy}&=\mu\frac{d\alpha}{dt}\\ \frac{dP}{dy}-\frac{dQ}{dx}&=\mu\frac{d\gamma}{dt}\\ \frac{dR}{dx}-\frac{dP}{dz}&=\mu\frac{d\beta}{dt}\end{aligned}\right\}\quad \nabla\times\mathbf{E}=-\frac{\partial\mathbf{B}}{\partial t}$$

$$\left.\begin{aligned}p&=\frac{1}{4\pi}\left(\frac{d\gamma}{dy}-\frac{d\beta}{dz}-\frac{1}{\varepsilon^2}\frac{dP}{dt}\right)\\ q&=\frac{1}{4\pi}\left(\frac{d\alpha}{dz}-\frac{d\gamma}{dx}-\frac{1}{\varepsilon^2}\frac{dQ}{dt}\right)\\ r&=\frac{1}{4\pi}\left(\frac{d\beta}{dx}-\frac{d\alpha}{dy}-\frac{1}{\varepsilon^2}\frac{dR}{dt}\right)\end{aligned}\right\}\quad \nabla\times\mathbf{H}=\frac{\partial\mathbf{D}}{\partial t}+\mathbf{J}$$

From Maxwell (1865) to Hertz (1888)

Heinrich Hertz (1857–1894). (Photograph courtesy of Deutsches Museum, Munich.)





ANNALEN
DER
PHYSIK UND CHEMIE.

BEGRÜNDET UND FORTGEFÜHRT DURCH
F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF.

NEUE FOLGE.
BAND XXXVI.
DER GANZEN FOLGE ZWEIHUNDERT ZWEIUNDSIEBZIGSTER.

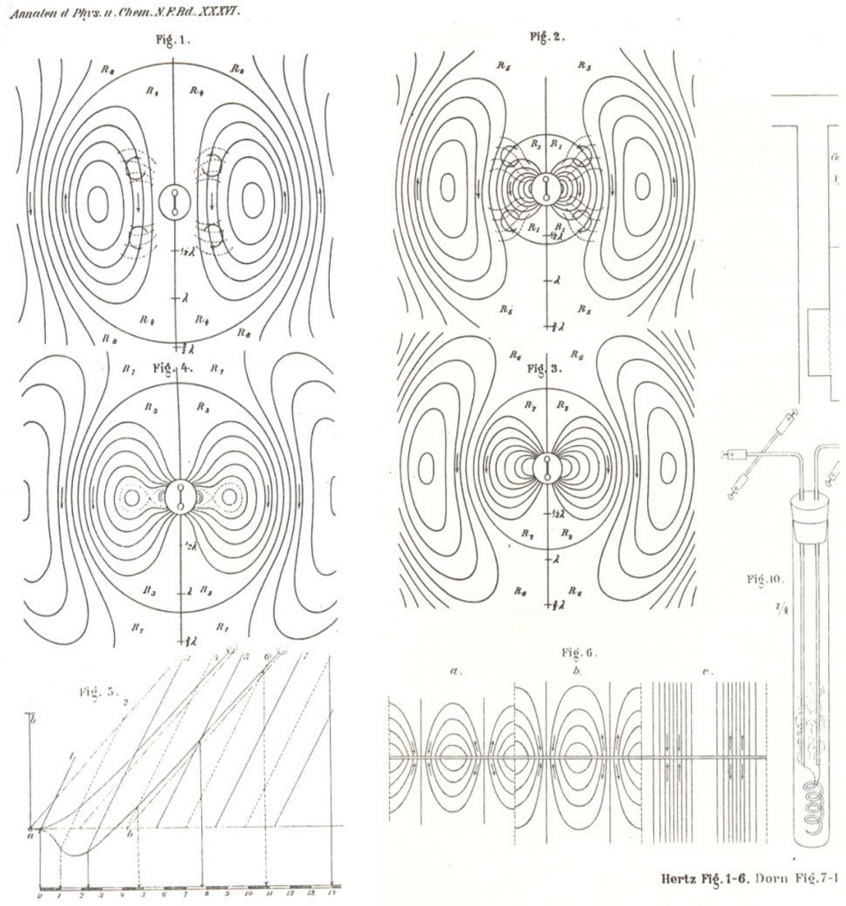
UNTER MITWIRKUNG
DER PHYSIKALISCHEN GESELLSCHAFT IN BERLIN
UND INSBESONDERE DES HERRN
H. VON HELMHOLTZ
HERAUSGEGEBEN VON
G. WIEDEMANN.

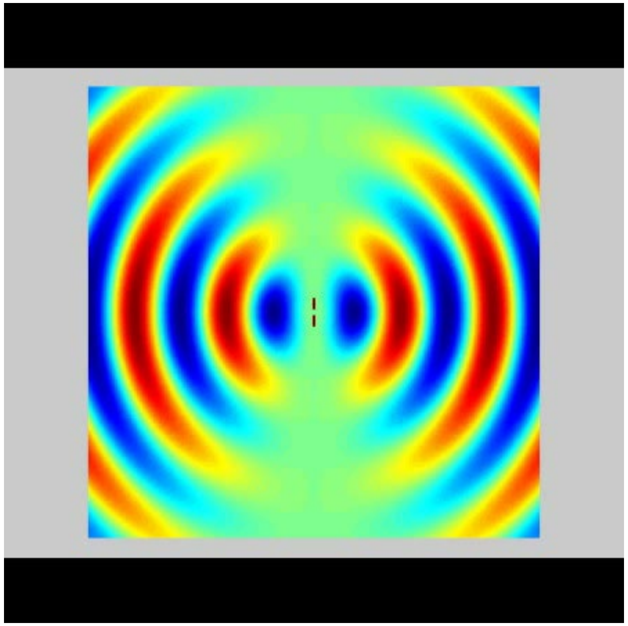
NEBST ZEHN FIGURENTAFELN.

LEIPZIG, 1889.
VERLAG VON JOHANN AMBROSIUS BARTH.

CARL ZEISS Bibliothek Jena

Herzian dipole





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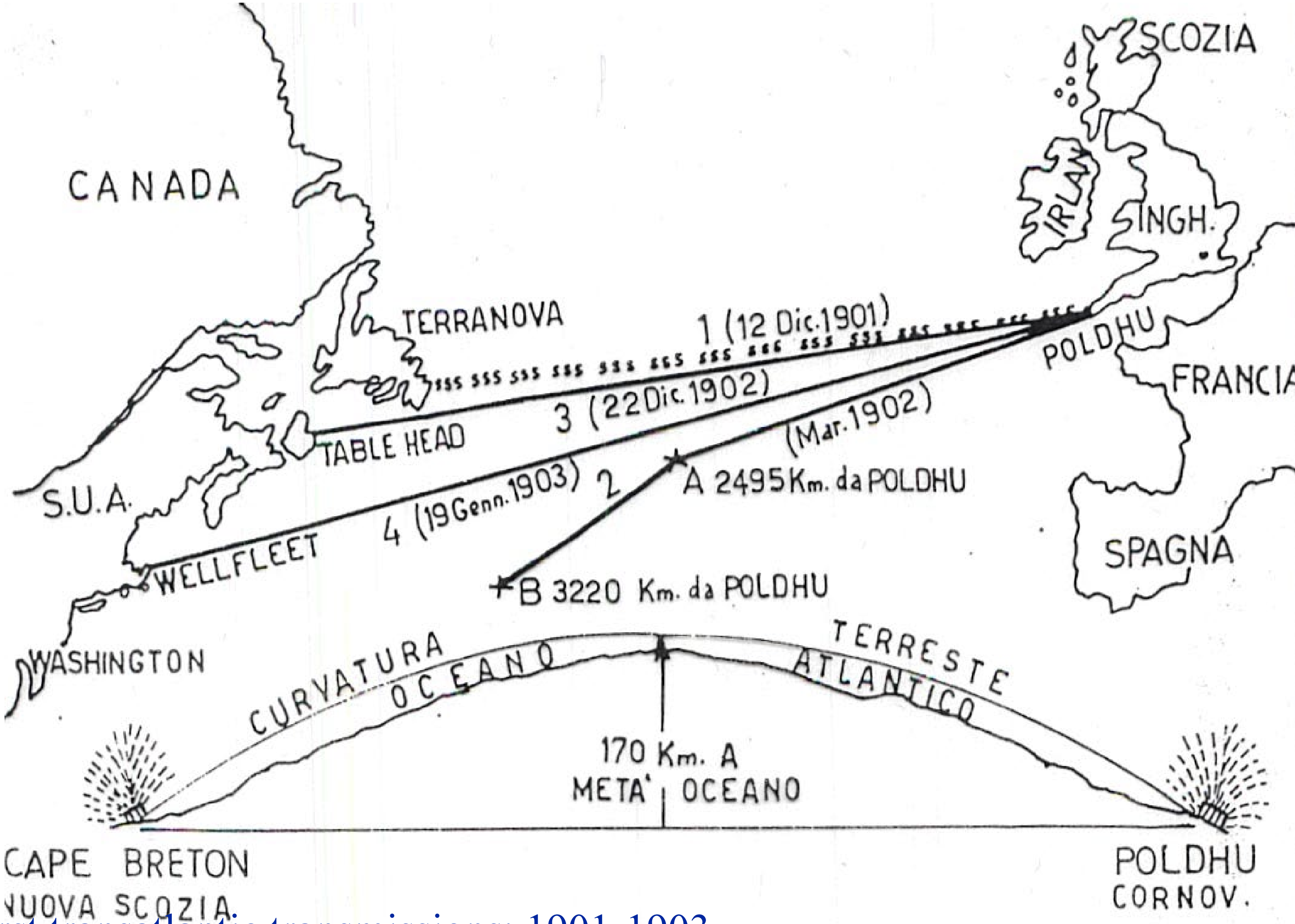
Marconi : A pioneer's work

EPFL



First transatlantic transmissions: 1901-1903

1- Poldhu St. John 12 December 1901 3400 km

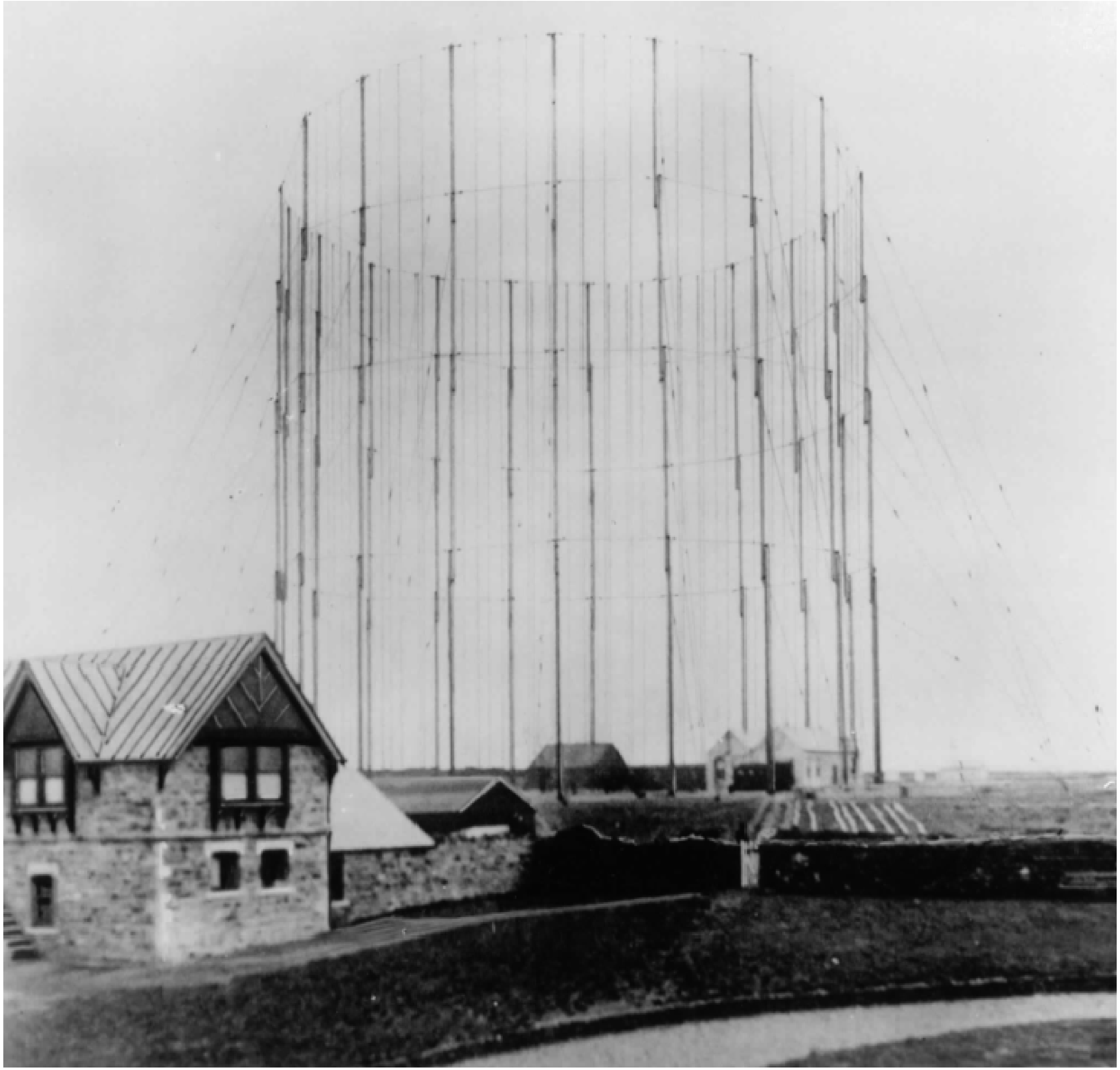
2- Poldhu - Philadelphia (ship) March 1902 discovery of night effect

3- Activation of the link Glace Bay Poldhu 22 December 1902

4- Activation of the link Cape Cod Poldhu 19 January 1903

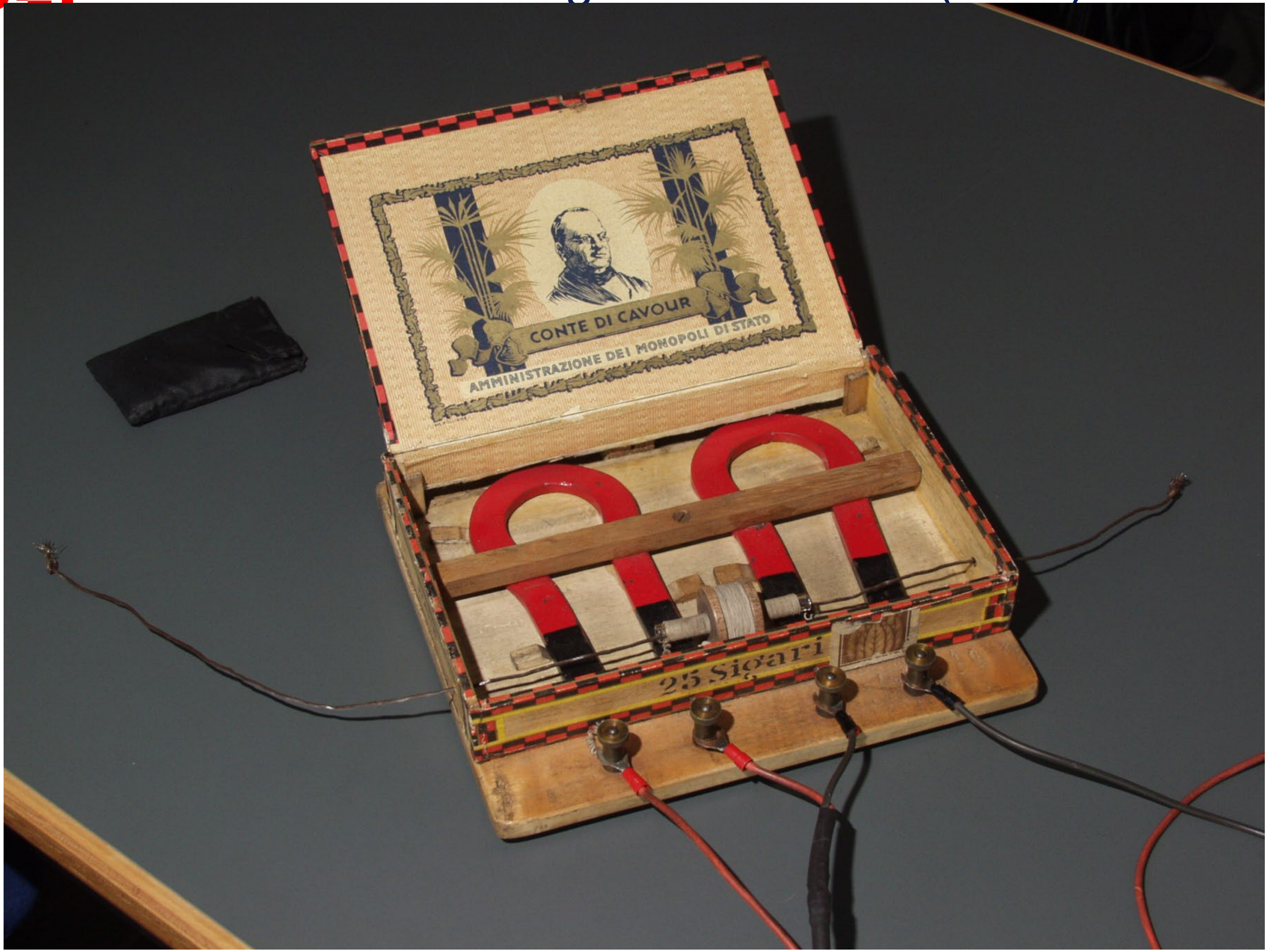
Marconi :

Despite the opposition which I had received from many quarters, often that of most eminent men, it was still my opinion that electric waves would not be stopped by the curvature of the earth, and therefore could be made to travel any distance, separating any two places on our planet. From the very first of my experiments, I was sincerely convinced of this (Jacot and Collier, 1935: 64).



Photograph of the original conical antenna system installed at Poldhu, Cornwall (after **BAE Systems Marconi Research Centre, Chelmsford, Essex**)

Une antenne de Guglielmo Marconi (1901)



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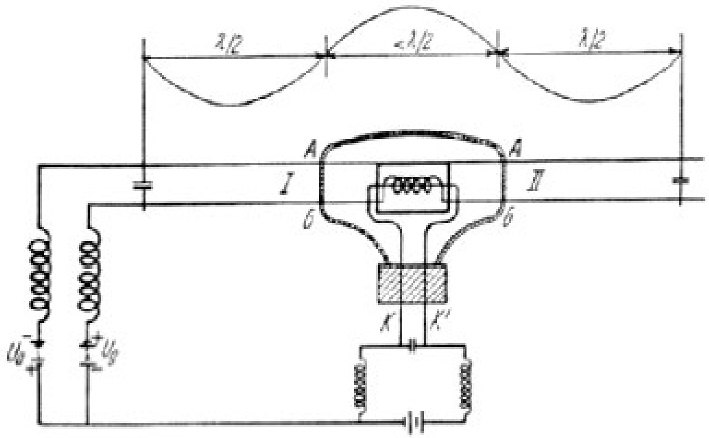
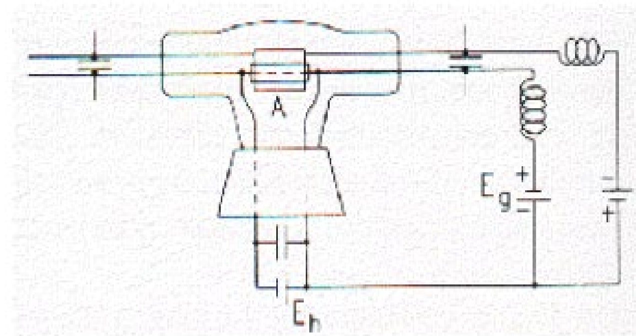
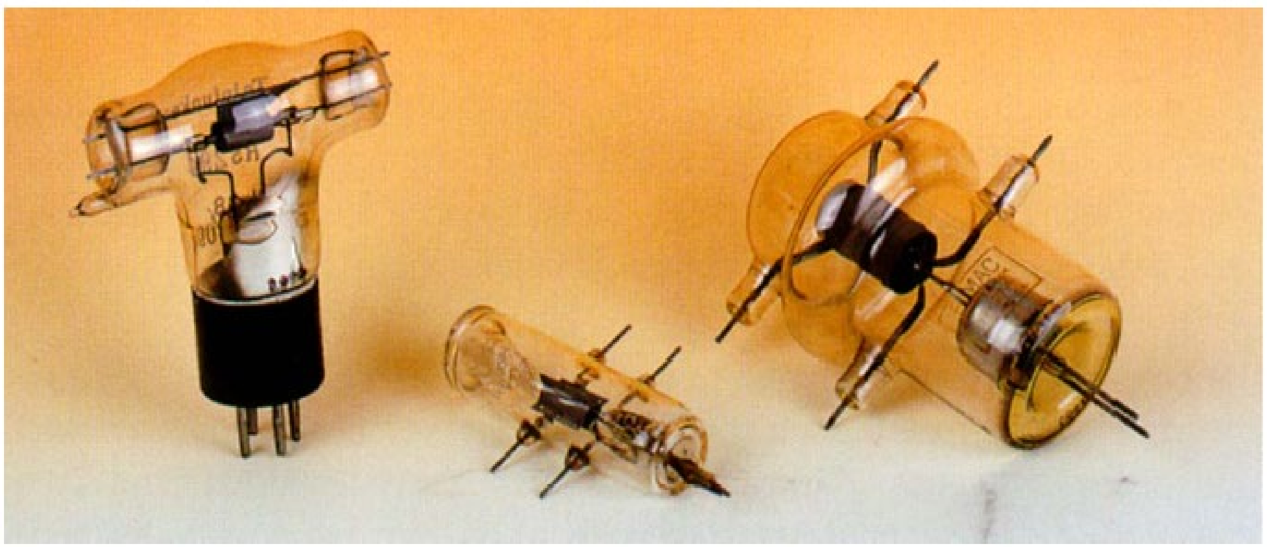
Microwave tubes







Retarding-field tube RS296 and its circuit (Kühle 1932 at Telefunken)
"Hammer Tube" [8,11]. The photograph also shows the retarding field tubes 8012 of RCA (middle) and VT 127 A of Eimac (right)

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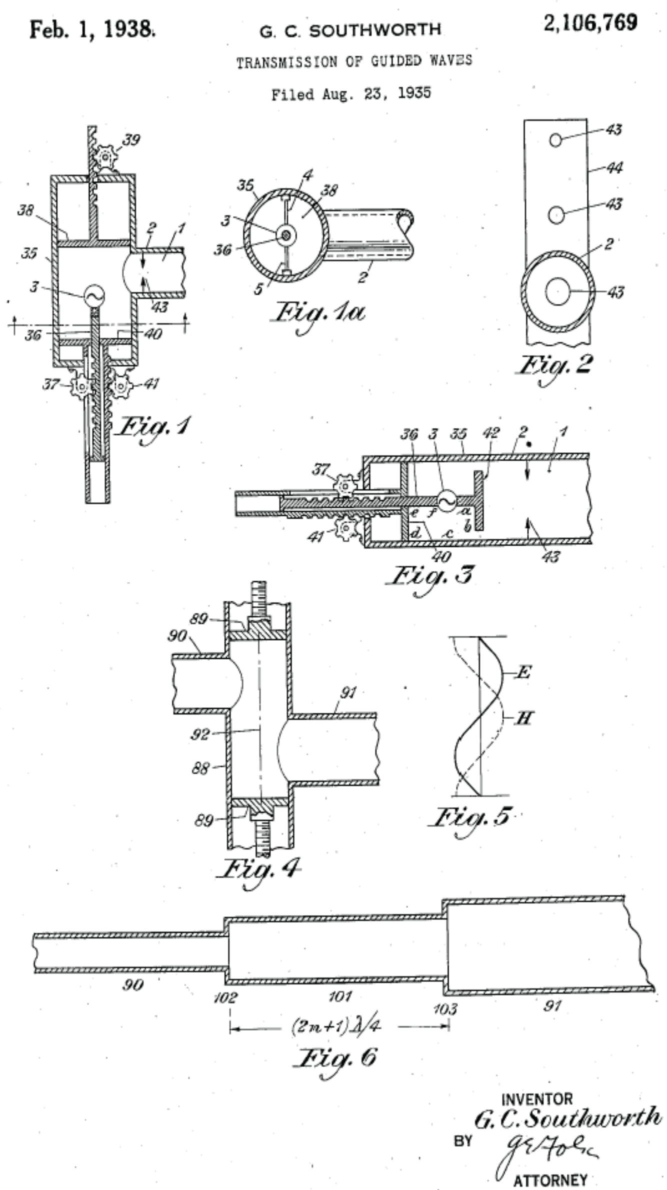

1st page of patent by Southworth

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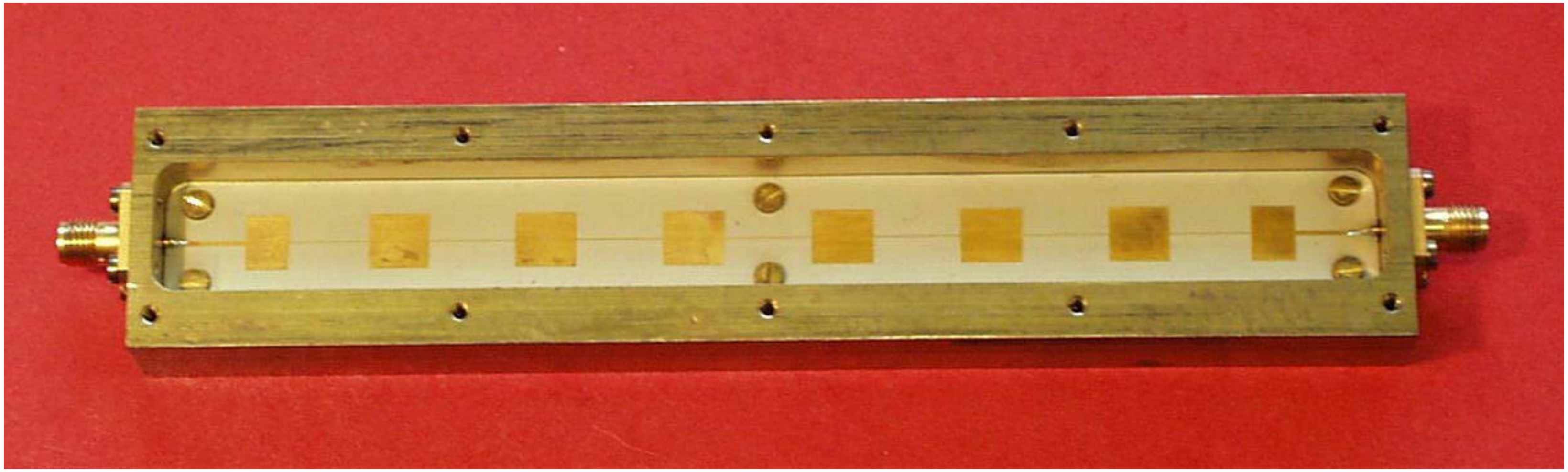
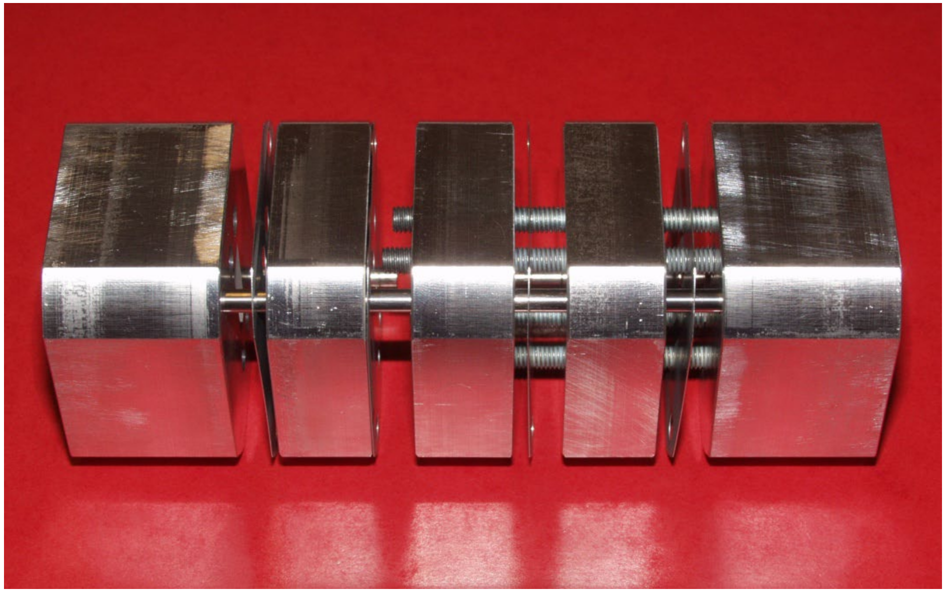
EPFL

example of distributed filter:
LPF realized in microstrip technology

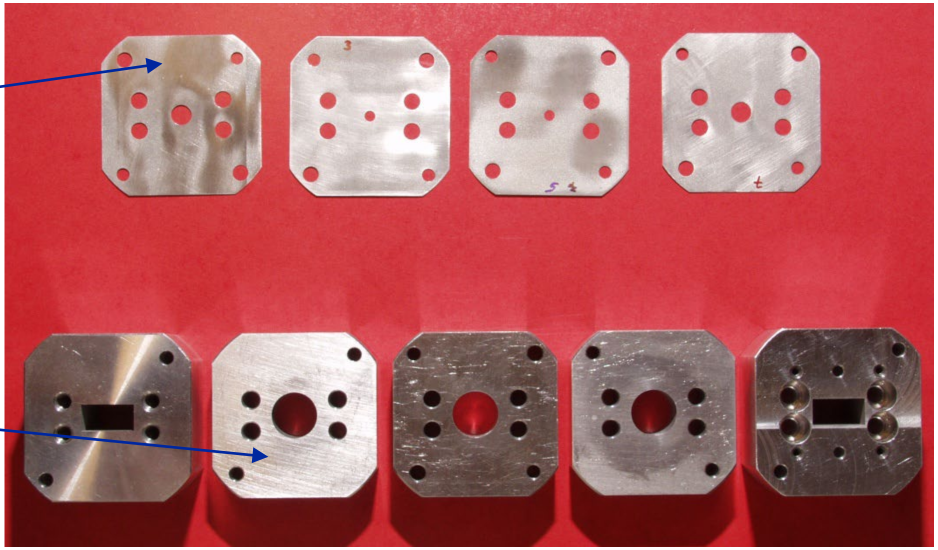


cavity filter
(exploded)

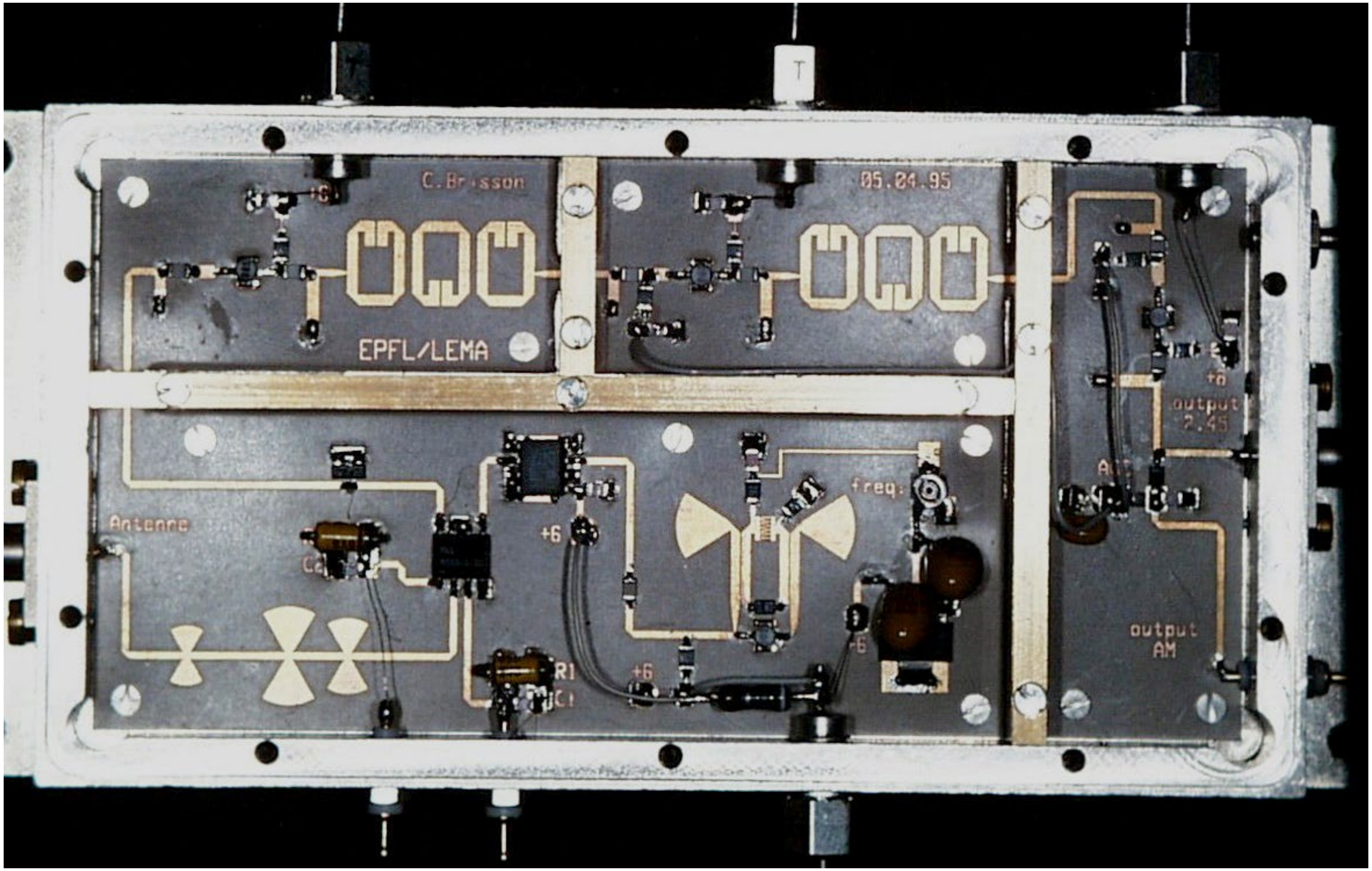


irises

waveguide sections

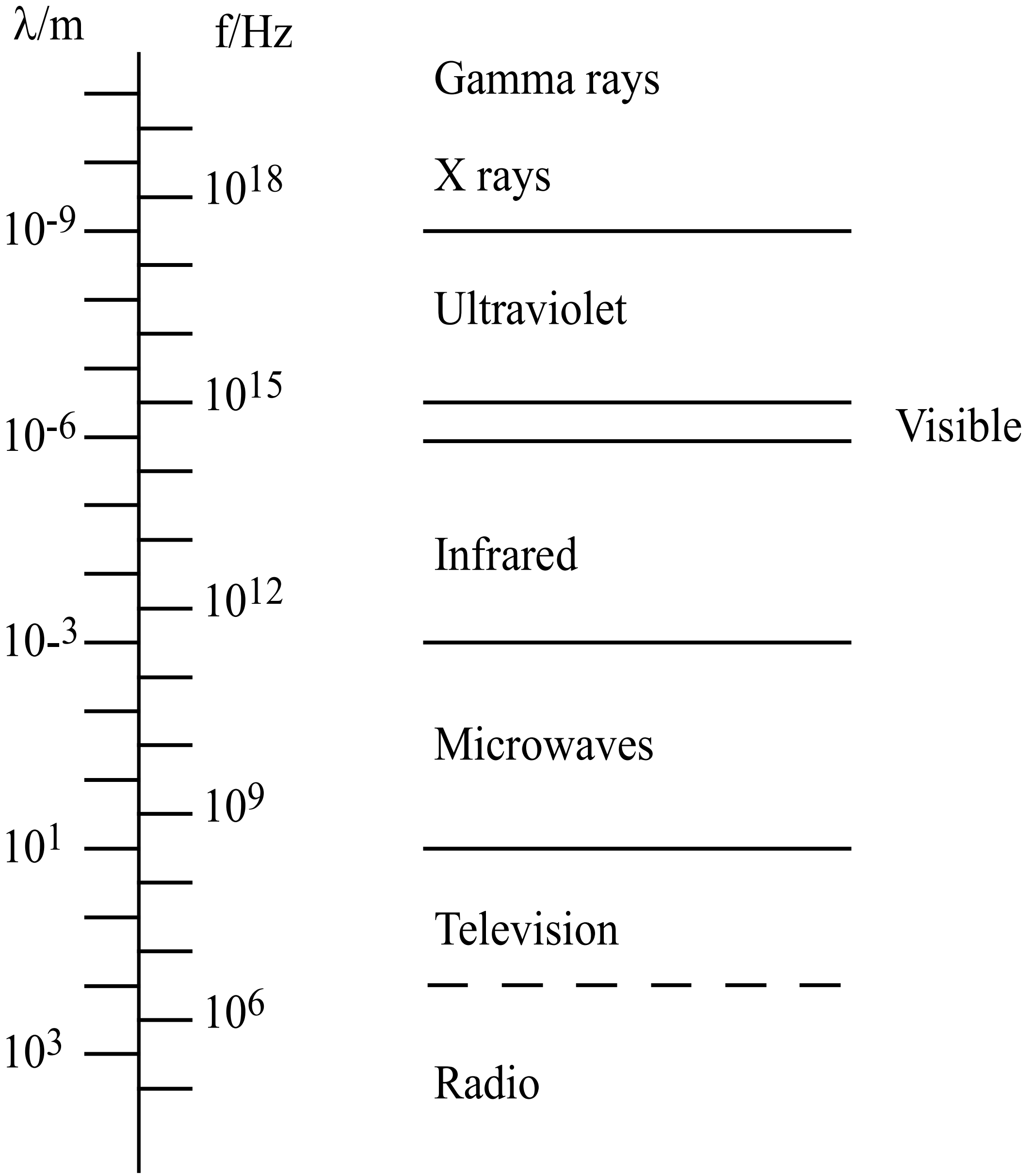


example of microstrip circuit: complete 2.45 GHz transceiver



Definition of microwaves

Frequency (f)	300 MHz-300 GHz
Period (T)	3 ns - 3 ps
Wavelength (λ)	1 m - 1 mm
Energy (hf)	1.2 10^{-6}eV - 1.2 10^{-3}eV


λ/m
f/Hz
Gamma rays
X rays
10^{18}
10^{-9}
Ultraviolet
10^{15}
Visible
10^{-6}
Infrared
10^{12}
10^{-3}
Microwaves
10^{9}
10^{1}
Television
10^{6}
10^{3}
Radio

Band	Frequency
L	1-2 GHz
S	2-4 GHz
C	4-8 GHz
X	8-12 GHz
Ku	12-18 GHz
K	18-26 GHz
Ka	26-40 GHz
Q	40-60 GHz
E	60-90 GHz

Properties of microwaves

- Bandwidth
  - 1% of 10 GHz = 100 MHz, but 1% of 100 MHz = 1MHz
- Transparency of the Ionosphere
  - Satellites

Ionosphere

4 layers: D, E, F1, F2
altitude: circa 70-800 km

$$\varepsilon_e = \varepsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2} \right)$$

$$\omega_p = \sqrt{\frac{Nq^2}{m\varepsilon_0}}$$

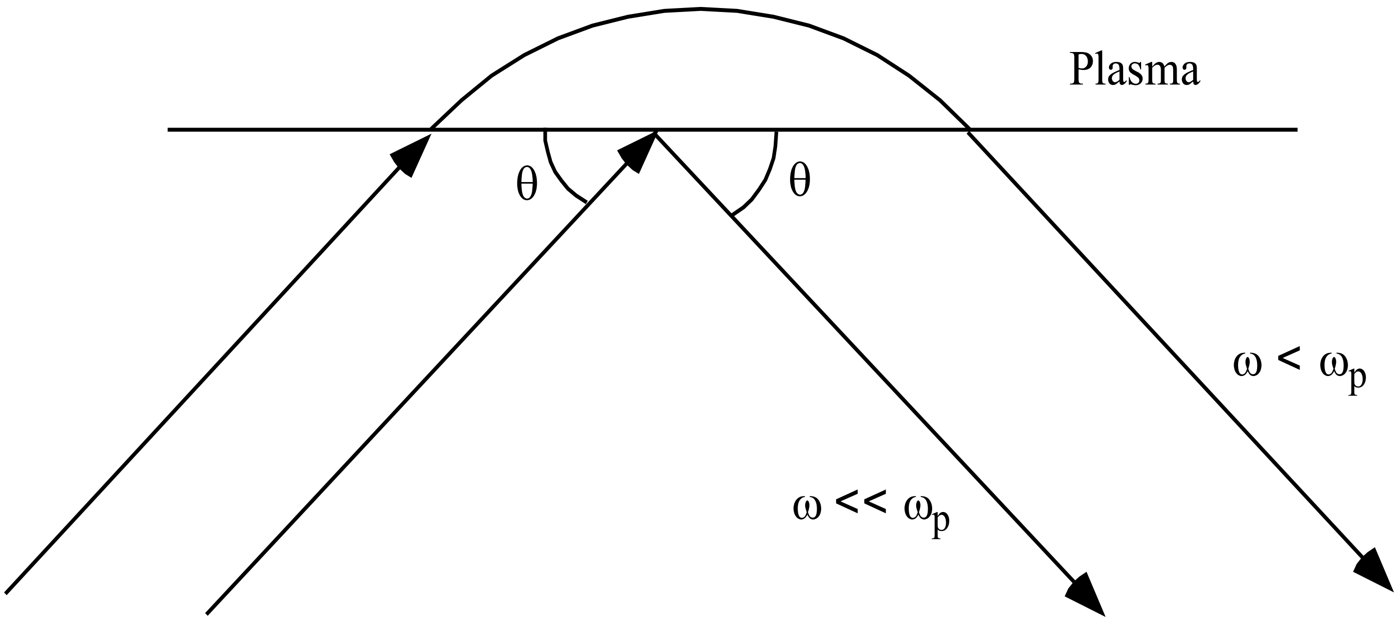
N : number of ions/volume
q : charge of the electron
m : mass of the electron
ε0 = 8.854 10-12 As/Vm : permittivity of free space.

Ionosphere

ω << ωp

$$\varepsilon_e \to -\infty$$

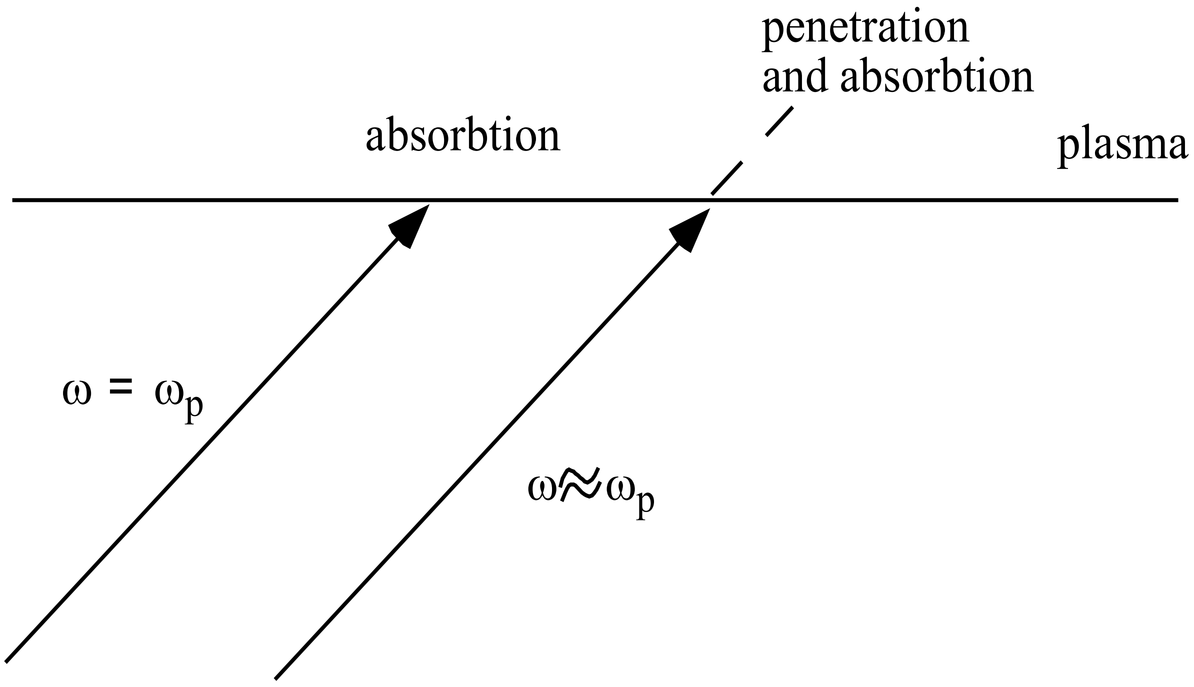
$$Z = \sqrt{\frac{\mu}{\varepsilon}} \to j0$$



Ionosphere

$\omega = \omega p$

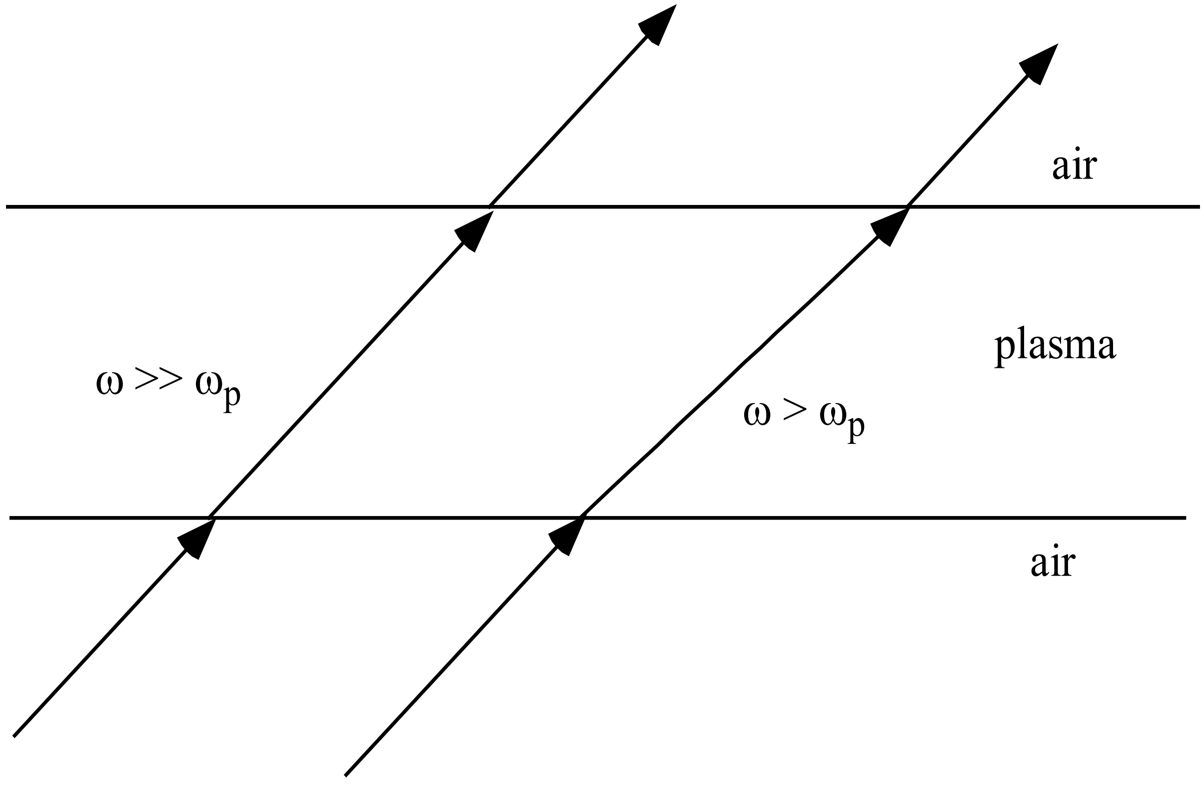
$$\varepsilon_e \rightarrow 0 \qquad k = \omega\sqrt{\varepsilon\mu} = 0$$



Ionosphere

ω >> ωp

$$\varepsilon_{\mathrm{e}} \rightarrow 1 \qquad k = \omega\sqrt{\varepsilon\mu} = k_o$$



Properties of microwaves

- Transparency of the atmosphere up to 10 GHz
- Electromagnetic noise Minimum between 1 and 10 GHz, + low noise amps

Atmosphere

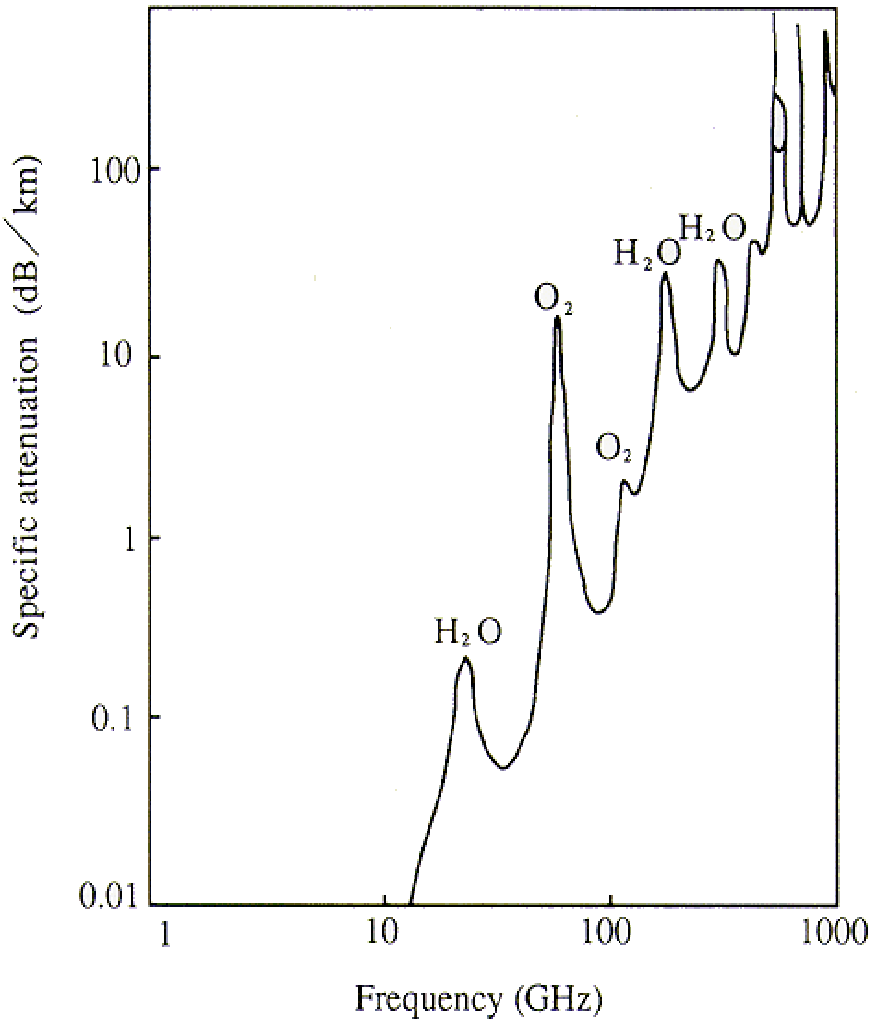
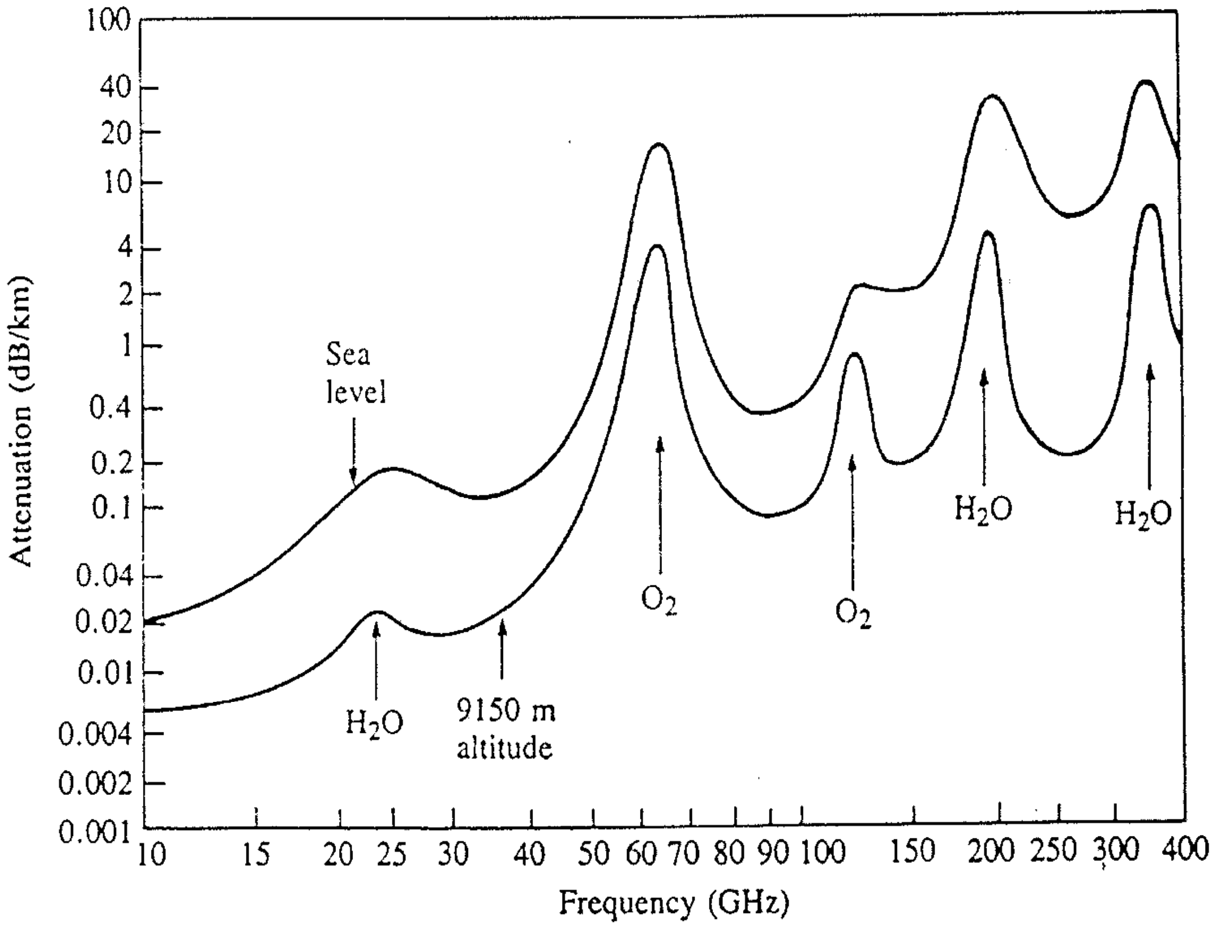


Fig.3.2.1 Microwave absorption due to atmospheric gases

strategic use
of the atmospheric
absorption!

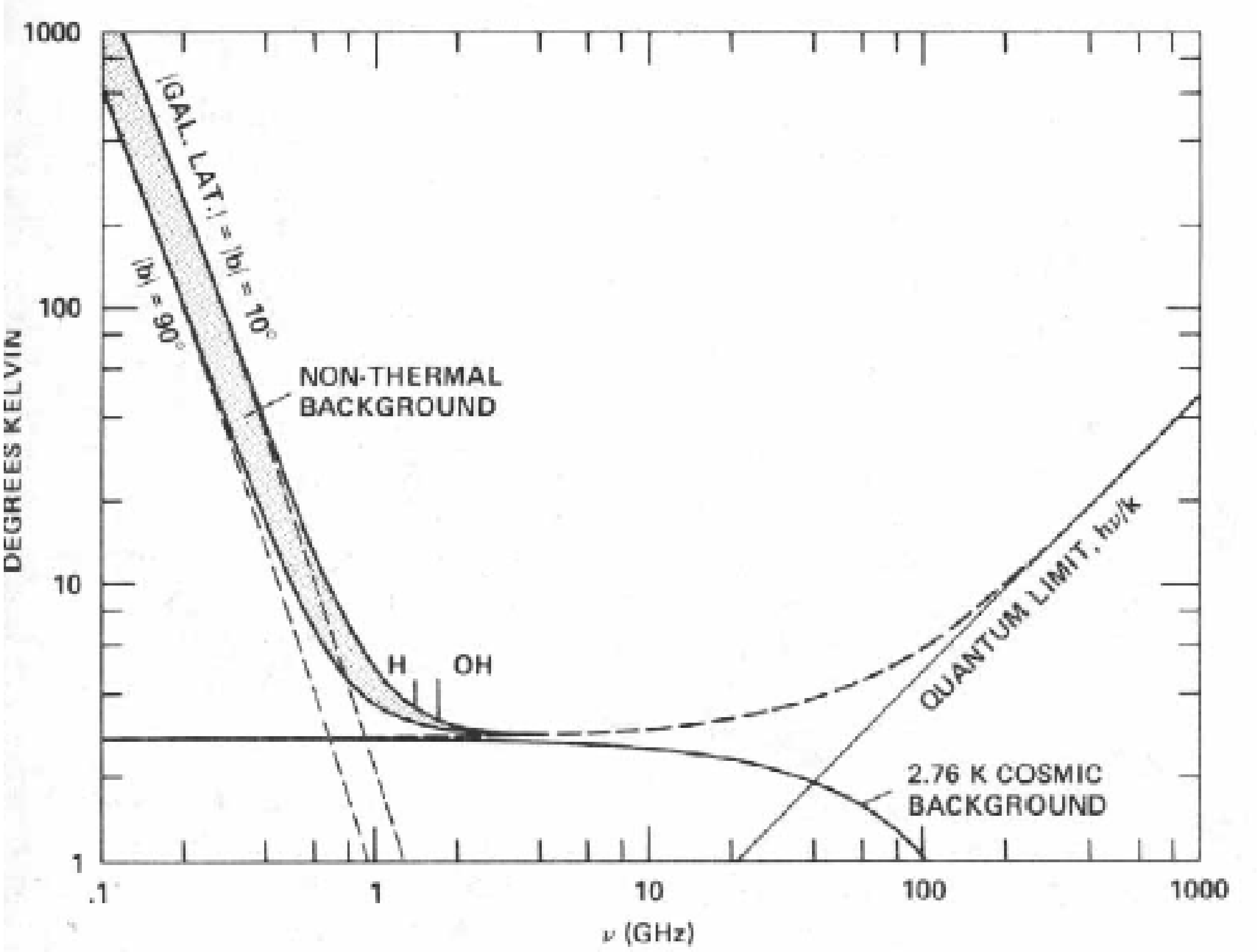
detection of
pollution from
satellites

Atmosphere

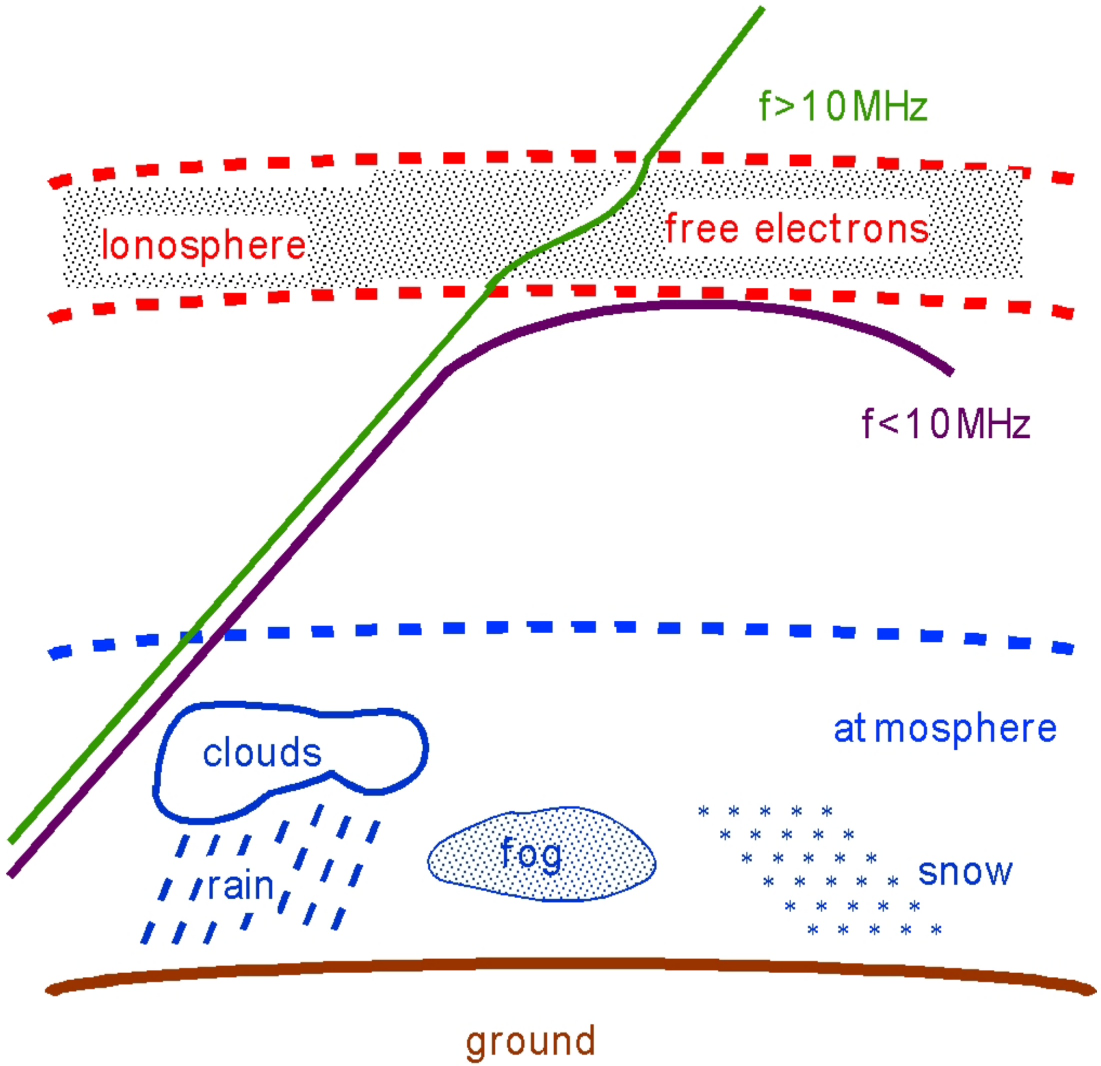


100
40
20
10
4
2
1
0.4
0.2
0.1
0.04
0.02
0.01
0.004
0.002
0.001
Attenuation (dB/km)
10
15
20
25
30
40
50
60
70
80
90
100
150
200
250
300
400
Frequency (GHz)
Sea level
H_2O
9150 m altitude
O_2
O_2
H_2O
H_2O

Noise


1000
100
10
1
DEGREES KELVIN
.1
1
10
100
1000
ν (GHz)
|GAL. LAT.| = |b| = 10°
|b| = 90°
NON-THERMAL
BACKGROUND
H
OH
QUANTUM LIMIT, hν/k
2.76 K COSMIC
BACKGROUND

Propagation



Link with Mars

- Mars Pathfinder Mission : 1996
- Distance Earth-Mars : 228'000'000 km

Friis formula:

$$P_r = P_f \cdot G_1 \cdot G_2 \cdot (\lambda/4\pi L)^2$$

From Earth to Mars

- Frequency : 7.175 GHz (λ = 41.8 mm)
- Terrestrial Antenna Gain : 4’265’795
  - Ø = 70 m
- Satellite Antenna Gain : 13.8
- Emitted Power on Earth : 22 kW
  - (a very small car)
- Received power on Mars : $3.16\ 10^{-16}$ W
  - (Not really much)

From Mars to Earth

- Frequency : 8.425 GHz (λ = 35.6 mm)

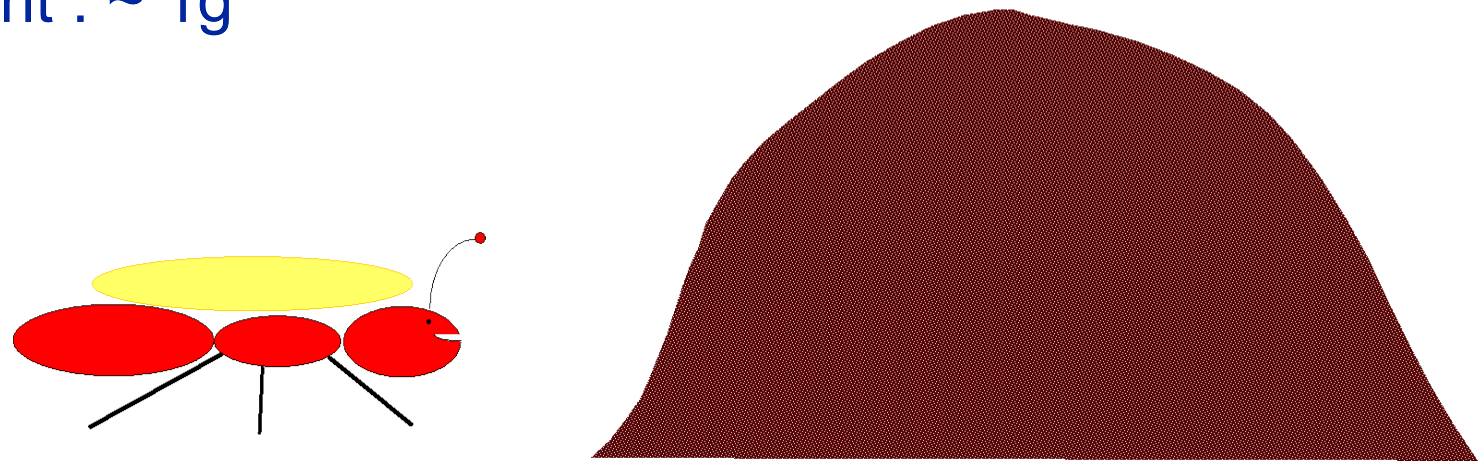
- Terrestrial Antenna Gain : 25'118'864
- Satellite Antenna Gain : 141

- Power emitted on Mars : 13 W
    - (a low consumption halogen lamp)

- Received power on earth : 7 .10^{-18} W
    - (nothing !!)

EPFL

Velocity : 10cm/s
weight : ~ 1g



Power that the ant needs to develop : ~ 10^{-3} W

1 million billions time more than the received power on Earth !!!

Properties of microwaves

- Directivity of the antennas
- Reflections on obstacles
  - Effective surfaces, radar
- Interaction with matter
  - Heating, measurement
- Non ionizing radiation
  - causing no mutation
- Stable oscillation frequencies
  - Atomic clocks and frequency references

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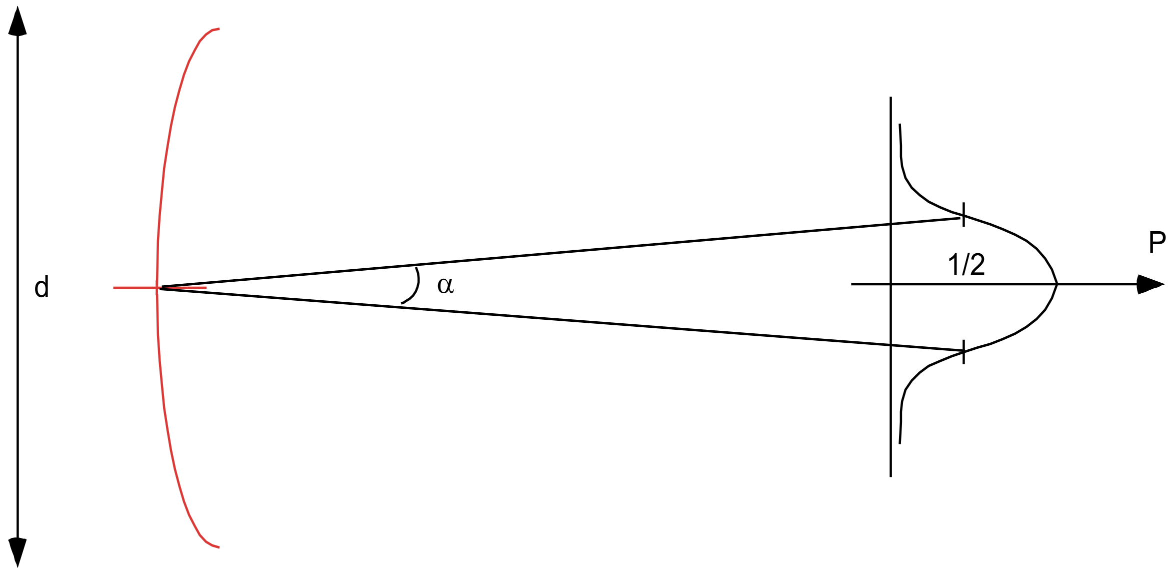
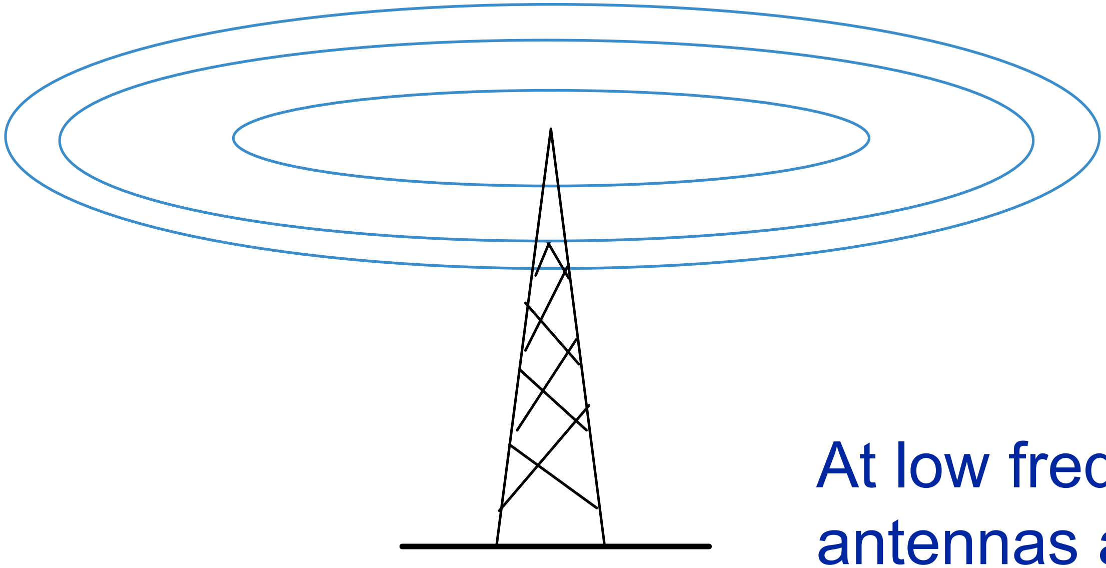
Directivity of antennas



$$\alpha \geq \frac{\lambda}{d}$$

Directivity of antennas



At low frequencies
antennas are omnidirectional

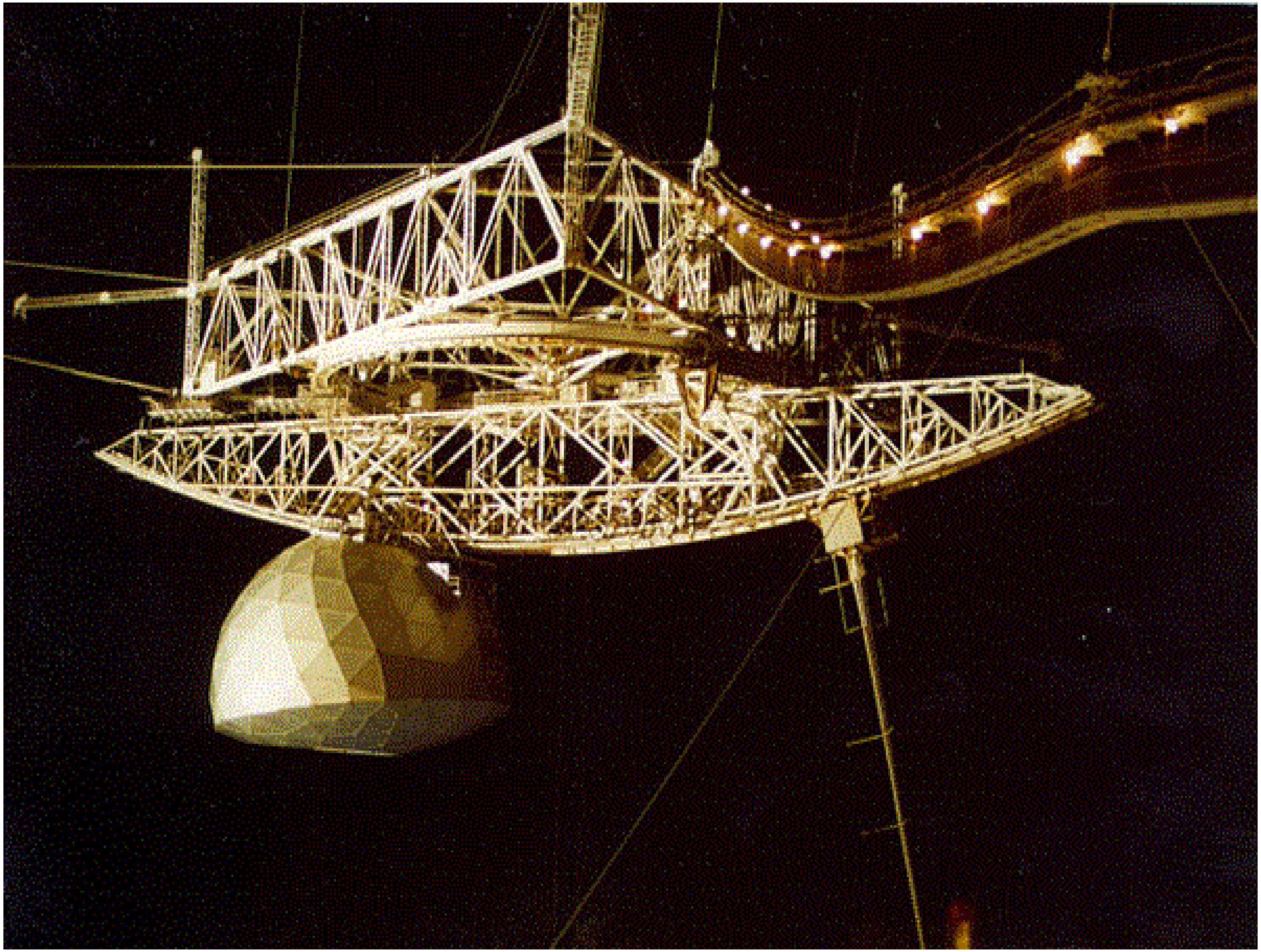
Directivity of antennas

At high frequencies, antennas are directive

Arecibo dish antenna

diameter: 305 m !

Arecibo feed



Google earth view

Arecibo beamwidth

- 50 MHz, λ=6m and α=1.12°
- 10GH, λ=3cm and α=0.0056°

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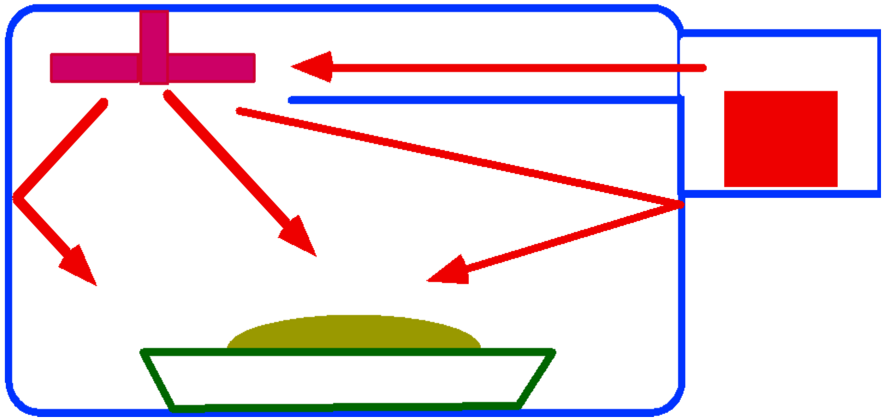
Interaction with matter : microwave heating

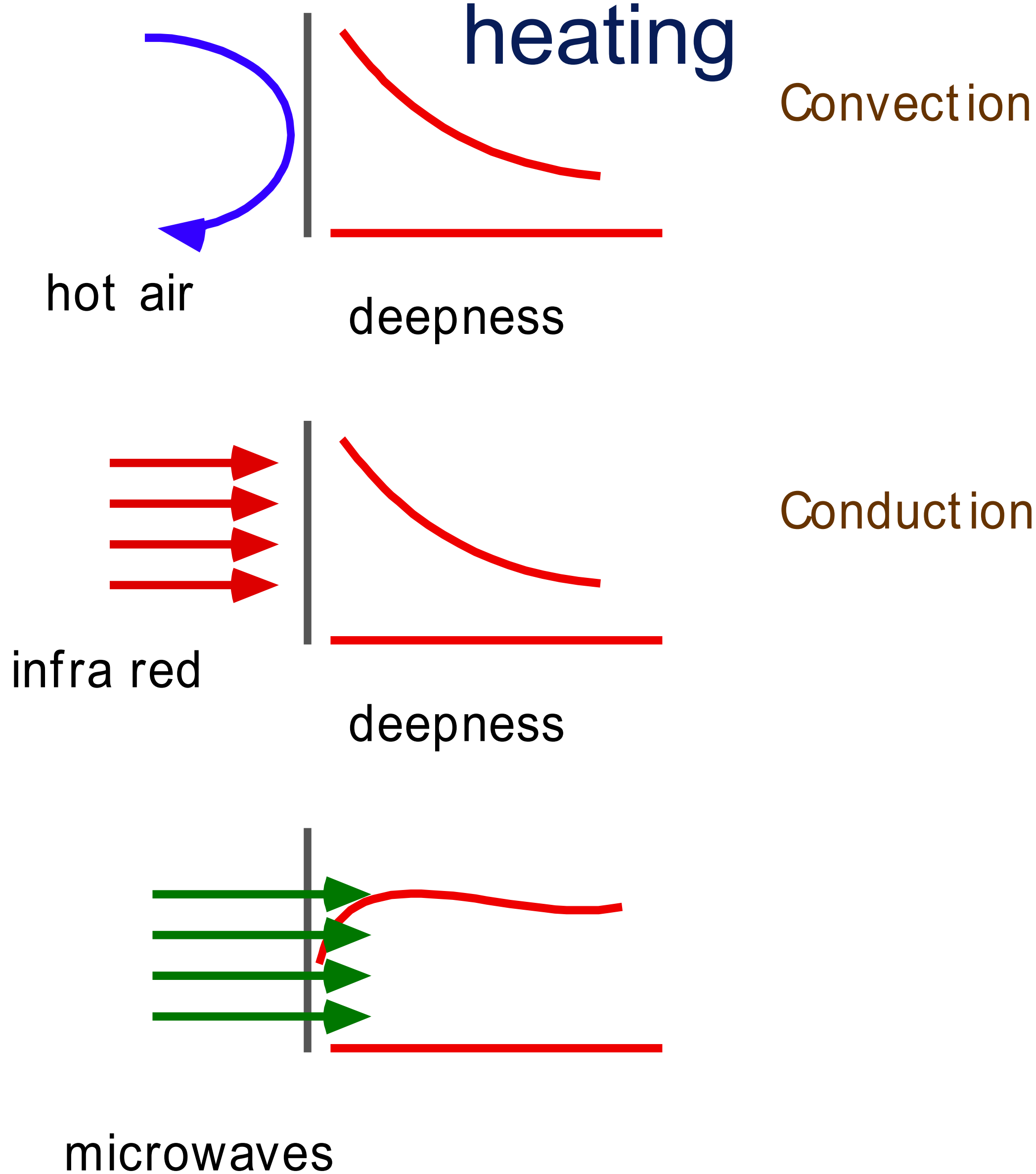


The waves penetrate into the matter and generate heat inside

Interaction with matter : microwave heating

- Applicators :
  - Cavities
  - Progressive Wave
  - Slow wave
  - Antenna
- Principle :
- The wave is absorbed by the water. The absorption decreases when T increases

Interaction with matter : microwave heating



Interaction with matter : microwave heating. Advantages

- Good efficiency (50% of power transfer to the element which is heated)
- Selective heating
  - cereals or insects
  - electrons and ions
- Moderate cost and maintenance
- Less storage room needed as the heating cycle is shorter
- Less losses in the process
- No pre-heating needed

Interaction with matter : microwave heating. Drawbacks

- Costly to develop
- Impossible to grill
- Difficult to evacuate certain solvents needed in the printing industry
- Needs skilled workforce
- High security needed

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Biological effects : ionization

molecular cohesion energy

Type	*kJ/mole*	*eV/atom*
ionic	750	7800
dipolar	~20	207
Van der Waals	10	103
covalent		2,5

In microwaves, the energy of a photon is :
$1{,}2\ 10^{-6}$ to $1{,}2\ 10^{-3}$ eV

Biological effects : Thermal effects

- Limits exist since many years
  - USA : ~10 mW/cm2 = 100 W/m2
  - Russia : ~ 10 µW/cm2 = 0.1 W/m2
- Diathermy : 1-10 kW/m2 !!
- Solar flux : 1 kW/m2 (at ground level)

Are electromagnetic waves dangerous?

(1)

Energy at a <u>MICROSCOPIC level</u>

$E = hf$

(Planck's constant times frequency)

	Frequency	wavelength	protection factor
Radio FM	100 MHz	3 m	800'000
Natel	1 GHz	30 cm	80'000
TV Sat	10 GHz	3 cm	8000
Radar	100 GHz	3 mm	800
Infrared	10 THz	3 microns	8
Visible light	500 THz	600 nm	4
Ultraviolet UVA	1000 THz	300 nm	2
Ultraviolet UVB	10000 THz	30 nm	0.2
X Rays	Million THz	0.3 nm	0.0002
Gamma rays	more	less	less

Are electromagnetic waves dangerous ?

(2)

Power density at a MACROSCOPIC Level

P = E H =

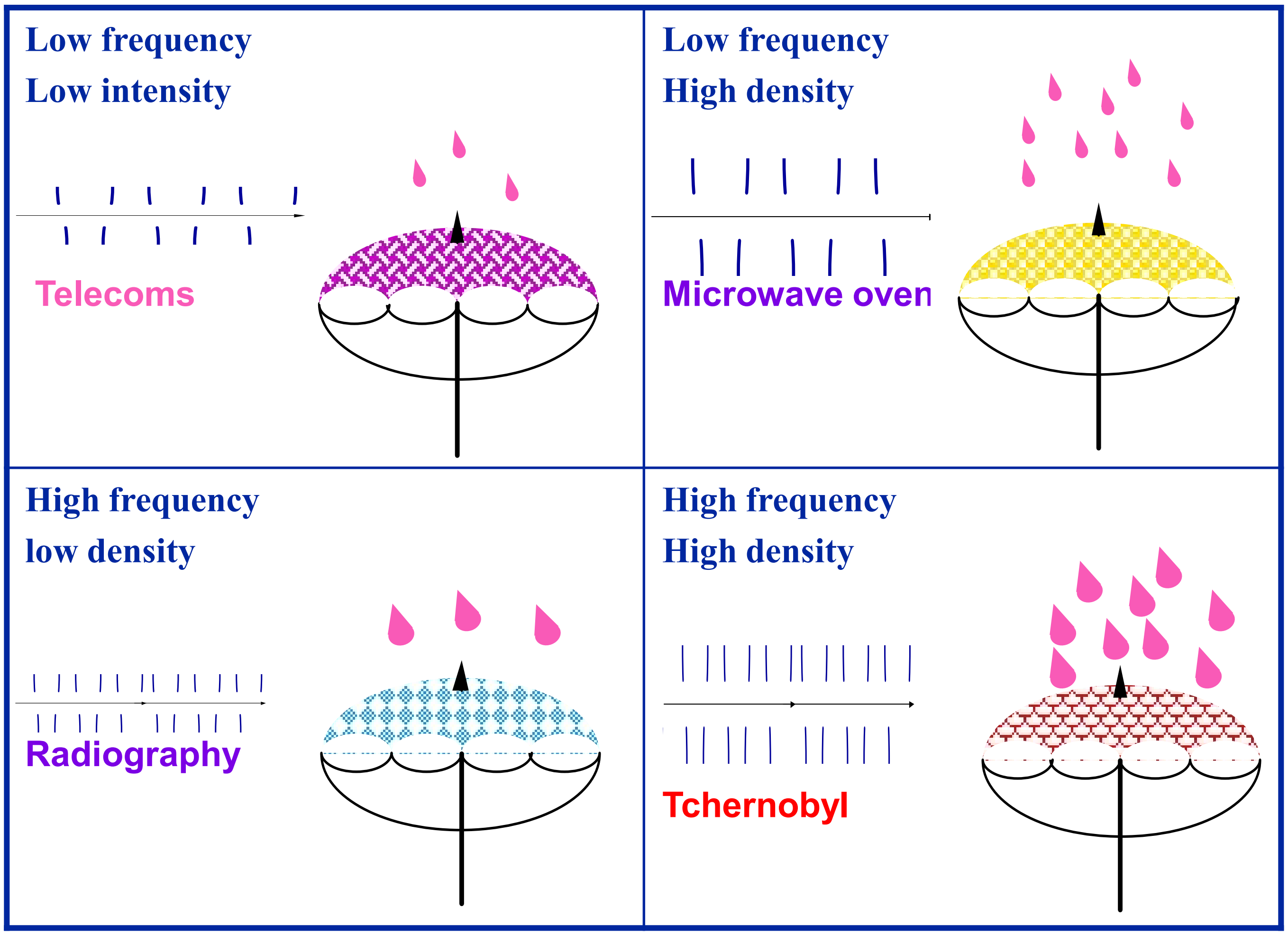
electric field x magnetic field

[mW/cm^2]

In a microwave oven	**500**
Airport RADAR at 10 m	**300**
solar rays outside the atmosphere	**140**
Evident danger	**>100**
Systematic effects	**>50**
Sun during a nice ski day	**10**
FCC Public Exposure Standard	**0.5**
Good cell phone in the head	**0.3**
60 W bulb at 1 m	**0.02**
Good cell phone base station	**5E-04**
FM radio transmitter at 10 Km	**1E-04**
Sat. TV at street level	**1E-06**

Analogy Electromagnetic waves = Rain

Frequency = size of drops ; Puissance = density of drops



Biological effects : non thermal effects

- Controversial since 30 years
  - Do they exist ? (probably yes)
  - Are they harmful ? (probably no)
- In doubt :
- Lower the acceptable limits