Introduction

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

1887  Lord Rayleigh proves theoretically the concept of waveguides

1891  Experimental verification of Maxwell's theory by Heinrich Herz (experiment at 1 GHz)

1901  First transatlantic wireless link by Guglielmo Marconi

1903  Regular wireless telegraphic service

1918  First tubes and continuous wave generators

1920  First use of frequency shifters in detectors, mixers, and receivers

1938  First Portable phone (Motorola)
1936 Simultaneous rediscovery of the waveguide concept by G.C. Southworth and W.L. Barrow
1938-1945: intensive research on RADAR
1948 Distributed filter theory by Richards
1950 First cavity filters
1950 Introduction of planar microwave transmission lines (first stripline, then microstrip)
1950 Apparition of TWT amplifiers
1960 Apparition of the first microwave transistors
1970 First MMICs
1971 First CAD tools
1990 Start of wireless communication boom
Photograph of the original conical antenna system installed at Poldhu, Cornwall (after BAE Systems Marconi Research Centre, Chelmsford, Essex)

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)
example of distributed filter: LPF realized in microstrip technology
cavity filter (exploded)

irises

waveguide sections

example of microstrip circuit: complete 2.45 GHz transceiver
### Definitions of microwaves

<table>
<thead>
<tr>
<th>Property</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (f)</td>
<td>300 MHz - 300 GHz</td>
</tr>
<tr>
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- **Gamma rays**
- **X rays**
- **Ultraviolet**
- **Visible**
- **Infrared**
- **Microwaves**
- **Television**
- **Radio**
### Properties of microwaves

#### Bandwidth
- 1% of 10 GHz = 100 MHz, but 1% of 100 MHz = 1 MHz

#### 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
\[ \varepsilon_0 = 8.854 \times 10^{-12} \text{ As/Vm} \] : permittivity of free space.

\[ \omega \ll \omega_p \]

\[ \varepsilon_e \to -\infty \]

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \to j0 \]
Ionosphere

\[ \omega = \omega_p \]

\[ \varepsilon_e \rightarrow 0 \quad k = \omega \sqrt{\varepsilon \mu} = 0 \]

\[ \omega = \omega_p \]

penetration and absorption

absorption

plasma

\[ \omega \gg \omega_p \]

Ionosphere

\[ \omega \gg \omega_p \]

\[ \varepsilon_e \rightarrow 1 \quad k = \omega \sqrt{\varepsilon \mu} = k_o \]

\[ \omega \gg \omega_p \]

\[ \omega > \omega_p \]

air

plasma

air
Properties of microwaves

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

Atmosphere

strategic use of the atmospheric absorption!

detection of pollution from satellites

Fig.3.2.1 Microwave absorption due to atmospheric gases
Atmosphere

Noise
Propagation

Friis formula:

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

Link with Mars

- Mars Pathfinder Mission: 1996
- Distance Earth-Mars: 228’000’000 km
From Earth to Mars

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

From Mars to Earth

- Frequency: 8.425 GHz ($\lambda = 35.6$ 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: $7 \times 10^{-18}$ W
  - (nothing !!)
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 !!!

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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

At high frequencies, antennas are directive
Arecibo dish antenna

diameter: 305 m!

Arecibo feed
Arecibo beamwidth

- 50 MHz, $\lambda=6m$ and $\alpha=1.12^\circ$
- 10GH, $\lambda=3cm$ and $\alpha=0.0056^\circ$
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Interaction with matter: microwave heating

The waves penetrate into the matter and generate heat inside.

- **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.

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

Properties of microwaves

- Directivity of the antennas
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Biological effects: ionization

molecular cohesion energy

<table>
<thead>
<tr>
<th>Type</th>
<th>kJ/mole</th>
<th>eV/atom</th>
</tr>
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<tbody>
<tr>
<td>ionic</td>
<td>750</td>
<td>7800</td>
</tr>
<tr>
<td>dipolar</td>
<td>~20</td>
<td>207</td>
</tr>
<tr>
<td>Van der Waals</td>
<td>10</td>
<td>103</td>
</tr>
<tr>
<td>covalent</td>
<td>2,5</td>
<td></td>
</tr>
</tbody>
</table>

In microwaves, the energy of a photon is:
\(1,2 \times 10^{-6}\) to \(1,2 \times 10^{-3}\) eV
Biological effects: Thermal effects

- Limits exist since many years
  - USA: \( \sim 10 \text{ mW/cm}^2 = 100 \text{ W/m}^2 \)
  - Russia: \( \sim 10 \text{ µW/cm}^2 = 0.1 \text{ W/m}^2 \)
- Diathermy: 1-10 kW/m² !!
- Solar flux: 1 kW/m² (at ground level)

Are electromagnetic waves dangerous?

(1)

Energy at a MICROSCOPIC level

\[ E = hf \]

(Planck's constant times frequency)

<table>
<thead>
<tr>
<th>Source</th>
<th>Frequency</th>
<th>Wavelength</th>
<th>Protection factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio FM</td>
<td>100 MHz</td>
<td>3 m</td>
<td>800'000</td>
</tr>
<tr>
<td>Natel</td>
<td>1 GHz</td>
<td>30 cm</td>
<td>80'000</td>
</tr>
<tr>
<td>TV Sat</td>
<td>10 GHz</td>
<td>3 cm</td>
<td>8000</td>
</tr>
<tr>
<td>Radar</td>
<td>100 GHz</td>
<td>3 mm</td>
<td>800</td>
</tr>
<tr>
<td>Infrared</td>
<td>10 THz</td>
<td>3 microns</td>
<td>8</td>
</tr>
<tr>
<td>Visible light</td>
<td>500 THz</td>
<td>600 nm</td>
<td>4</td>
</tr>
<tr>
<td>Ultraviolet UVA</td>
<td>1000 THz</td>
<td>300 nm</td>
<td>2</td>
</tr>
<tr>
<td>Ultraviolet UVB</td>
<td>10000 THz</td>
<td>30 nm</td>
<td>0.2</td>
</tr>
<tr>
<td>X Rays</td>
<td>Million THz</td>
<td>0.3 nm</td>
<td>0.0002</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>more</td>
<td>less</td>
<td>less</td>
</tr>
</tbody>
</table>
Are electromagnetic waves dangerous?

(2)

Power density at a MACROSCOPIC Level

\[ P = \vec{E} \cdot \vec{H} = \text{electric field} \times \text{magnetic field} \]

\[ \text{[mW/cm}^2\text{]} \]

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

Analogy: Electromagnetic waves = Rain

Frequency = size of drops; Power = density of drops

- Low frequency, Low intensity: Telecoms
- Low frequency, High density: Microwave oven
- High frequency, low density: Radiography
- High frequency, High density: Tchernobyl
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