Class 9

Wednesday, March 22, 2023 10:08 AM

ENGI-1500
Physics -2

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Winter 2023

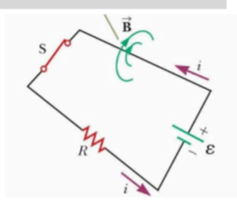
HUMBER

Reminder of the previous week

Self induction / inductance

$$\mathcal{E}_L = -L\frac{di}{dt}$$

$$L = \frac{N\Phi_B}{i}$$

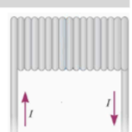


SI Unit: Henry (H), 1 H = 1 V · s/A

Energy in Magnetic Field

Stored energy in inductor:

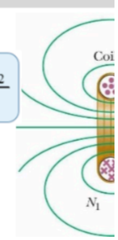
$$U_B = \frac{1}{2}Li^2$$



$$u_B = \frac{B^2}{2\mu_0}$$

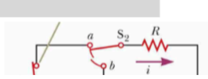
Mutual Inductance

$$M_{12} = \frac{N_2\Phi_{12}}{i_1}$$

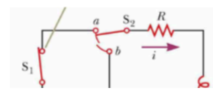


RL Circuits

Charging [switch → a]



Discharging [switch → b]

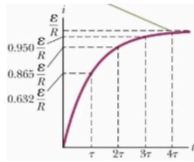


LC Circuit

$$i = \frac{\varepsilon}{R}\left(1 - e^{-Rt/L}\right)$$

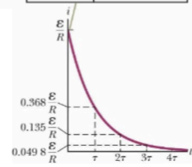
$$\tau = \frac{L}{R}$$

$$\Rightarrow i = \frac{\varepsilon}{R}\left(1 - e^{-t/\tau}\right)$$



$$i = \frac{\varepsilon}{R} e^{-t/\tau} = I_i e^{-t/\tau}$$

$$(\tau = \frac{L}{R})$$



$$q = Q_{\max} \cos(\omega t + \phi)$$

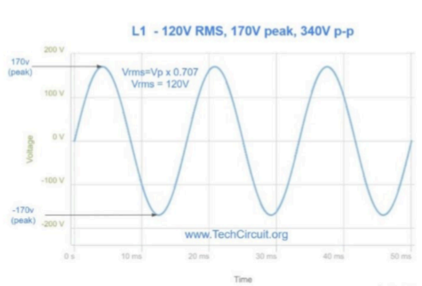
$$\omega = \frac{1}{\sqrt{LC}}$$ ω: natural freq

$$i = \frac{dq}{dt} = -\omega Q_{\max} \sin(\omega t + \phi)$$

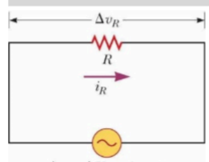
Source: Serway, Raymond A., a *scientists and engineers.* 10th E

Reminder of the previous week

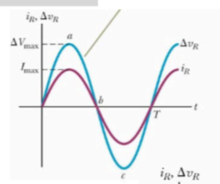
AC Circuits

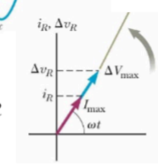


Resistors in AC Circuits



$\Delta v = \Delta V_{\max} \sin \omega t$

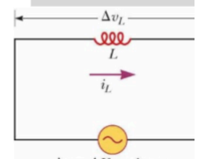




$$I_{\text{rms}} = \frac{I_{\max}}{\sqrt{2}} = 0.707 I_{\max}$$

$$P_{\text{avg}} = I_{\text{rms}}^2 R$$

Inductors in A

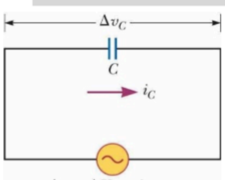


$\Delta v = \Delta V_{\max} \sin \omega t$

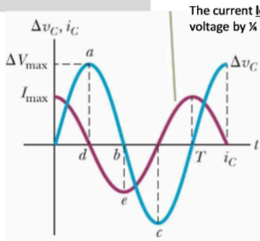
$$i_L = \frac{\Delta V_{\max}}{\omega L} \sin\left(\omega t\right.$$

$$X_L \equiv \omega L$$

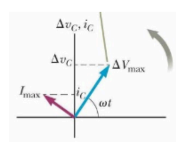
Capacitors in AC Circuits



$\Delta v = \Delta V_{\max} \sin \omega t$



The current **leads** the voltage by ¼ of a cycle



$$i_C = \omega C \Delta V_{\max} \sin\left(\omega t + \frac{\pi}{2}\right)$$

$$X_C \equiv \frac{1}{\omega C}$$

$$I_{\max} = \frac{\Delta V_{\max}}{X_C}$$

Source: Serway, Raymond A., a *scientists and engineers.* 10th E

Week 11 / Class 9

Electromagnetic Waves (Ch. 33)

Outline of Week 11 / Class 9

- Reminder of the previous week
- Electromagnetic Waves (Ch. 33)
  - Displacement Current and General Form of Ampere's Law
  - Maxwell's Equations and Hertz's Discoveries
  - Plane Electromagnetic Waves
  - Energy Carried by Electromagnetic Waves
  - Momentum and Radiation Pressure
  - Production of Electromagnetic Waves by an Antenna
  - The Spectrum of Electromagnetic Waves
- Applied EM & Emerging Technologies
- Examples
- Next week's topic

Electromagnetic Waves (Ch. 3

Displacement Current and General Form of Ampere's Law

March 15, 2023

Prof. Faruk Erkmen, PhD PEng MBA PMP

Displacement Current and General Form of Ampere's L

- Earlier, we discussed using Ampère's law to analyze the magnetic fields created by currents:

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0 I$$

- In this equation, the line integral is over any closed path through which ***conduction current*** passes (current carried by charge carriers in wire).

- Ampere's law is fundamental in electromagnetics but ***James Clerk Maxwell*** recognized its limitation and modified Ampère's law to include time-varying electric fields.

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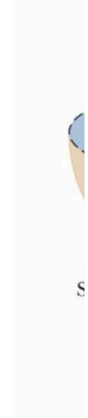
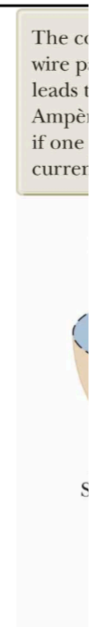


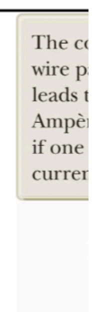
Displacement Current and General Form of Ampere's L



- Consider a capacitor being charged as illustrated in the figure. When a conduction current is present, the charge on the positive plate changes, but no conduction current exists in the gap between the plates because there are no charge carriers in the gap.
- Now consider the two surfaces S_1 and S_2 in the figure, bounded by the same path P.
- Ampère's law states that $\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}}$ around this path must equal $\mu_0 I$, where I is the total current through ***any*** surface bounded by the path ***P***.
  - When the path ***P*** is considered to be the boundary of S_1, we get $\mu_0 I$ no problem because the conduction current I passes through S_1.
  - When the path is considered to be the boundary of S_2, however, we get ***0*** because no conduction current passes through S_2.
- Therefore, we have a contradictory situation that arises from the discontinuity of the current!

March 15, 2023 Prof. Faruk Erkmen, PhD PEng MBA PMP

Displacement Current and General Form of Ampere's L



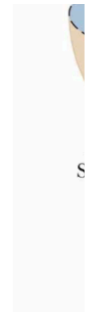
Maxwell solved this problem by postulating an ***additional term*** on the right side of Ampère's law, which includes a factor called the ***displacement current I_d*** defined as:

$$I_d \equiv \epsilon_0 \frac{d\Phi_E}{dt}$$

where ε_0 is the permittivity of free space $\Phi_E \equiv \int \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}}$ is the electric flux through the surface bounded by the path of integration surface bounded by the path of integration.

With the addition of the displacement current, the generalized Ampere's law can be expressed as follows:

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0(I + I_d) = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$



Displacement Current and General Form of Ampere's L

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0(I + I_d) = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

We can better understand the meaning of this expression by looking at the displacement current in the figure:

$$\Phi_E = EA = \frac{q}{\epsilon_0}$$ (E = σ/ε_0 = (q/A)/ε_0 [See Ch. 25])

$$I_d = \epsilon_0 \frac{d\Phi_E}{dt} = \frac{dq}{dt}$$

Therefore, the displacement current I_d through ***S*** is precisely equal to the conduction current ***I*** in the wires connected to the capacitor!

Electromagnetic Waves (Ch. 3

Maxwell's Equations and Hertz's Discoveries

Maxwell's Equations and Hertz's Discove

Maxwell's Equations

Maxwell's four equations are regarded as the basis of all electrical and magnetic phenomena:

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{q}{\epsilon_0}$$ ◀ Gauss's law

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$ ◀ Gauss's law in magnetism

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$ ◀ Faraday's law

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0 I + \epsilon_0 \mu_0 \frac{d\Phi_E}{dt}$$ ◀ Ampère–Maxwell law

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Maxwell’s Equations and Hertz’s Discove

Lorentz Force Law

Once the electric and magnetic fields are known at some point in space, the force acting on a particle of char calculated from the electric and magnetic versions of the particle in a field model:

$$\vec{\mathbf{F}} = q\vec{\mathbf{E}} + q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$$

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{q}{\epsilon_0}$$ ◀ Gauss's law

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$ ◀ Gauss's law in magnetism

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$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0 I + \epsilon_0 \mu_0 \frac{d\Phi_E}{dt}$$ ◀ Ampère–Maxwell law

This relationship is called the ***Lor*** Maxwell’s equations, together wi law, completely describe all classi electromagnetic interactions in a

Maxwell’s Equations and Hertz’s Discove

Lorentz Force Law

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$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$ ◀ Faraday's law

Maxwell's equations can be combi to obtain a wave equation for botl the magnetic field.

Equations suggest that electric an exist in charge-free, current-free s where ***q=0*** and ***I=0,*** the solution t shows that the speed at which ele travel equals the measured speed

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0 I + \epsilon_0 \mu_0 \frac{d\Phi_E}{dt}$$

◀ Ampère–Maxwell law

This result led Maxwell to predict form of electromagnetic radiation.

Sou scie

Maxwell's Equations and Hertz's Discove

Hertz's Experiment

Hertz performed experiments that verified Maxwell's prediction.

The transmitter: two spherical electrodes separated by a narrow gap

- Spark generated between spheres when electric field surpasses the dielectric strength for air (3x10^6 V/m)
- Free electrons in strong electric field accelerate and gain enough energy to ionize any molecules they strike, and the ionization provides more electrons which can accelerate and cause further ionizations.
- As air in gap ionized → becomes much better conductor.
- Discharge between electrodes exhibits oscillatory behavior at very high frequency
- The experimental apparatus is equivalent to LC circuit.
    - Inductance of coil
    - Capacitance due to spherical electrodes
- L and C small in Hertz's apparatus → frequency of oscillation ($\omega = 1/\sqrt{LC}$) high (~ 100 MHz).
- Electromagnetic waves are radiated as a result of oscillation of free charges in the transmitter circuit.

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Maxwell's Equations and Hertz's Discove

Hertz's Experiment

Hertz was able to detect waves by resonance using a single loop of wire with its own spark gap (receiver).

- Receiver loop (m's from the transmitter) has its own effective *L* and *C*, and thus natural frequency of oscillation

- Sparks induced across gap of electrodes with the receiver's frequency adjusted to match that of the transmitter
  - → Oscillating current induced in the receiver was produced by electromagnetic waves radiated by the transmitter
- Series of experiments showed: radiation generated by spark-gap device exhibited wave properties of interference, diffraction, reflection, refraction, and polarization - all the properties exhibited by light, only with difference in frequency and wavelength
- Measured speed of radiation:
  - Waves of known frequency reflected from metal sheet and created standing-wave interference pattern: using the distance between nodal points to determine wavelength λ
  - Using relationship $\boldsymbol{v = \lambda f}$ → $\boldsymbol{v}$ **close to** $\mathbf{3 \times 10^8}$ **m/s**: known speed $\boldsymbol{c}$ of the visible light

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Maxwell's Equations and Hertz's Discove

Hertz's Experiment

https://www.youtube.com/watch?v=FWCN_uI5ygY [0-0:59]

https://www.youtube.com/watch?v=9gDFll6Ge7g [4:09]

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Electromagnetic Waves (Ch. 3

Plane Electromagnetic Waves

Plane Electromagnetic Waves

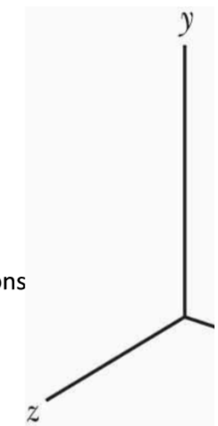
- Properties of electromagnetic waves can be deduced from Maxwell's equations.
- One approach: solve second-order differential equation obtained from Maxwell's third and fourth equations.
  - Assuming vectors for electric and magnetic fields in the electromagnetic wave have specific space–time behavior:
    - Simple but consistent with Maxwell equations
- Figure: changing electric field as an effective current
  - Generates circular magnetic field lines around electric field lines
- Magnetic field generated by the changing electric field is perpendicular to the electric field

Plane Electromagnetic Waves

- Let's consider a simple electromagnetic wave (figure)
  - Electric field **E** in ***y*** direction
  - Magnetic field **B** in ***z*** direction
    - Referred to as ***linearly polarized*** waves
- Assume field magnitudes **E** and **B** depend on ***x*** and ***t*** only
  - Not on ***y*** or ***z*** coordinate

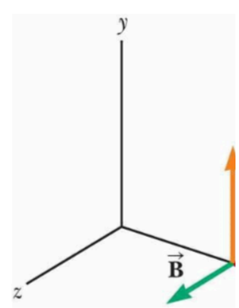
- Field vectors for wave propagating along ***x*** axis (vector c)
  - Magnitude ***c*** (speed of light)
- Imagine source in the ***yz*** plane that emits large number of such waves from all positions in the plane - not just the origin
- All waves travel in ***x*** direction

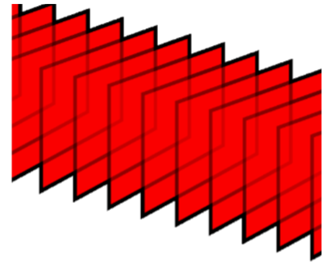
- Define ***ray*** as line along which wave travels →
  - All rays for these waves are parallel
- Entire collection of waves: ***plane wave***



Plane Electromagnetic Waves

A plane wave is a special case of wave or field: a physical quantity whose value, at any moment, is constant over any plane that is perpendicular to a fixed direction in space





Plane Electromagnetic Waves

The Wave Equation

To generate the prediction of plane electromagnetic waves, we start with Faraday's Law;

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$

Consider a rectangle of width ***dx*** and height ***l***, lying in the **xy** plane as shown in the figure. Skipping some steps (pls refer to textbook), evaluating the line integral yields:

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = [E(x + dx)]\ell - [E(x)]\ell \approx \ell\left(\frac{\partial E}{\partial x}\right) dx$$

Because the magnetic field is in the ***z*** direction, the magnetic flux through the rectangle of area, ***ldx*** is approximately $\boldsymbol{\phi_B = Bldx}$. Taking the time derivative yields:

$$\frac{d\Phi_B}{dt} = \ell\, dx \frac{dB}{dt}\bigg|_{x\,\text{constant}} = \ell\, dx \frac{\partial B}{\partial t}$$

Plane Electromagnetic Waves

The Wave Equation

Substituting the previously found gives:

$$\ell\left(\frac{\partial E}{\partial x}\right)dx = -\ell\,dx\,\frac{\partial B}{\partial t}$$

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

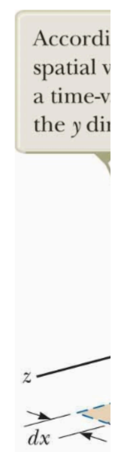
Plane Electromagnetic Waves

The Wave Equation

Similarly, we can derive a second equation by starting with Maxwell's fourth equation in empty space. In this case, the line integral is evaluated around a rectangle lying in the ***xz*** plane and having width ***dx*** and length ***l***. Skipping some steps, one can find:

$$-\ell\left(\frac{\partial B}{\partial x}\right)dx = \mu_0\,\epsilon_0\,\ell\;dx\left(\frac{\partial E}{\partial t}\right)$$

$$\frac{\partial B}{\partial x} = -\mu_0\epsilon_0\,\frac{\partial E}{\partial t}$$



Plane Electromagnetic Waves

The Wave Equation

Combining the equations:

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t} \qquad \frac{\partial B}{\partial x} = -\mu_0\epsilon_0\frac{\partial E}{\partial t}$$

Similar procedure re

$$\frac{\partial^2 E}{\partial x^2} = -\frac{\partial}{\partial x}\left(\frac{\partial B}{\partial t}\right) = -\frac{\partial}{\partial t}\left(\frac{\partial B}{\partial x}\right) = -\frac{\partial}{\partial t}\left(-\mu_0\epsilon_0\frac{\partial E}{\partial t}\right)$$

$$\boxed{\frac{\partial^2 E}{\partial x^2} = \mu_0\epsilon_0\frac{\partial^2 E}{\partial t^2}}$$

$$\frac{\partial^2 B}{\partial x^2} = \mu_0\epsilon_0$$

Sou scie

Plane Electromagnetic Waves

The Wave Equation

Combining the equations:

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t} \qquad \frac{\partial B}{\partial x} = -\mu_0\epsilon_0\frac{\partial E}{\partial t}$$

Similar procedure re

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$$\boxed{\frac{\partial^2 E}{\partial x^2} = \mu_0\epsilon_0\frac{\partial^2 E}{\partial t^2}}$$

Both equations are said to have the form of linear wave equation.

$$\frac{\partial^2 B}{\partial x^2} = \mu_0\epsilon_0$$

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2} \quad (v\text{: wave speed})$$

Plane Electromagnetic Waves

The Wave Equation & Speed of Light

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 B}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 B}{\partial t^2}$$

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2} \quad (v\text{: wave speed})$$

v* replaced by *c

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

Evaluating the wave speed nume

$$c = \frac{1}{\sqrt{(4\pi \times 10^{-7}\,\mathrm{T\cdot m/A})(8.854\,19 \times 10^{-12}\,\mathrm{C^2/N}}}$$
$$= 2.997\,92 \times 10^8\ \mathrm{m/s}$$

Because this speed is precisely the same as the speed of light in empty space, we are led to believe (correctly) that light is an electromagnetic wave.

Plane Electromagnetic Waves

Solutions to the Wave Equation

The simplest solution to the wave equations is a sinusoidal wave for which the field magnitudes **E** and **B** vary with ***x*** and ***t*** according to the following expressions:

$$E = E_{\max} \cos(kx - \omega t)$$
$$B = B_{\max} \cos(kx - \omega t)$$

∂x

The angular wave number is **k=2π/λ**, where λ is the wavelength. The angular frequency is **ω=2πf**, where ***f*** is the wave frequency. According to the traveling wave model, the ratio **ω/k** equals the speed of an electromagnetic wave, **c**:

$$\frac{\omega}{k}=\frac{2\pi f}{2\pi/\lambda}=\boxed{\lambda f=c}$$

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Plane Electromagnetic Waves

Solutions to the Wave Equation

$$E=E_{\max}\cos(kx-\omega t)$$

$$B=B_{\max}\cos(kx-\omega t)$$

We can generate other mathematical representations of the traveling wave model for electromagnetic waves. Taking partial derivatives of above equations:

$$\frac{\partial E}{\partial x}=-kE_{\max}\sin(kx-\omega t)$$

$$\frac{\partial B}{\partial t}=\omega B_{\max}\sin(kx-\omega t)$$

$$kE_{\max}=\omega B_{\max}$$

$$\frac{E_{\max}}{B_{\max}}=\frac{\omega}{k}=c$$

$$\frac{E_{\max}}{B_{\max}}=\frac{E}{B}=c$$

At every instant, the ratio of the magnitude of the electric field to the magnitude of the magnetic field in an electromagnetic wave equals the speed of light.

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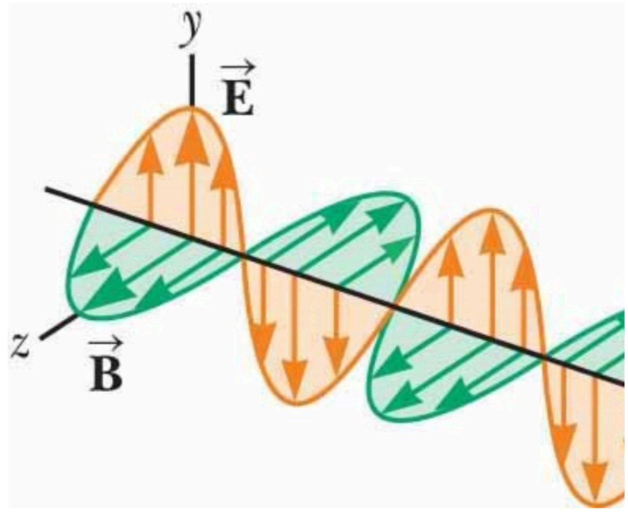
Plane Electromagnetic Waves

Plane Electromagnetic Waves

Linear Polarization

- Figure provides pictorial representation, at one instant, of a sinusoidal electromagnetic wave moving in the positive x direction.
- Such a wave (in which electric and magnetic fields are parallel to a pair of perpendicular axes) is said ***linearly polarized***.



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Quick Quiz

Quick Quiz

An electromagnetic wave propagates in the negative *y* direction. The electric field at a point in space is momentarily oriented in the positive *x* direction. In which direction is the magnetic field at that point momentarily oriented?

(a) the negative *x* direction
(b) the positive *y* direction
(c) the positive *z* direction
(d) the negative *z* direction

Quick Quiz

Quick Quiz

An electromagnetic wave propagates in the negative *y* direction. The electric field at a point in space is momentarily oriented in the positive *x* direction. In which direction is the magnetic field at that point momentarily oriented?

(a) the negative *x* direction
(b) the positive *y* direction
(c) the positive *z* direction
(d) the negative *z* direction

Right Hand rule

An EM Wave

Example 33.2

A sinusoidal electromagnetic wave of frequency **40.0 MHz** travels in free space in the **x** direction as in the figure.

(A) Determine the wavelength and period of the wave.
(B) At some point and at some instant, the electric field has its maximum value of **750 N/C** and is directed along the ***y*** axis. Calculate the magnitude and direction of the magnetic field at this position and time.

An EM Wave

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Solution

Part A:

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^8 \text{ m/s}}{40.0 \times 10^6 \text{ Hz}} = \boxed{7.50 \text{ m}}$$

$$T = \frac{1}{f} = \frac{1}{40.0 \times 10^6 \text{ Hz}} = \boxed{2.50 \times 10^{-8} \text{ s}}$$

An EM Wave

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Part B:

$$B_{\text{max}} = \frac{E_{\text{max}}}{c} = \frac{750 \text{ N/C}}{3.00 \times 10^8 \text{ m/s}} = \boxed{2.50 \times 10^{-6} \text{ T}}$$

Electromagnetic Waves (Ch. 3

Energy Carried by Electromagnetic Waves

Energy Carried by Electromagnetic Wave

Poynting Vector

- Electromagnetic radiation is one method of energy transfer across the boundary of a system.

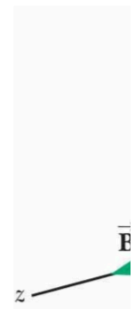
- The rate of transfer of energy by an electromagnetic wave is described by a vector $\vec{\mathbf{S}}$, called the ***Poynting vector***, which is defined by the expression:

$$\vec{\mathbf{S}} \equiv \frac{1}{\mu_0}\vec{\mathbf{E}} \times \vec{\mathbf{B}}$$

- The magnitude of the Poynting vector represents the rate at which energy passes through a unit surface area perpendicular to the direction of wave propagation. Therefore, the magnitude of $\vec{\mathbf{S}}$ represents ***power per unit area***. The direction of the vector is along the direction of wave propagation.

- The SI units of $\vec{\mathbf{S}}$ are **J/s·m² = W/m²**

$$\left[\vec{\mathbf{S}}\right] \equiv \frac{\left[\vec{\mathbf{E}}\right]\left[\vec{\mathbf{B}}\right]}{\left[\mu_0\right]} = \frac{(\mathrm{N/C})(\mathrm{T})}{\mathrm{T\cdot m/A}} = \frac{\mathrm{N\cdot m}}{\mathrm{m^2\cdot s}} = \frac{\mathrm{J}}{\mathrm{m^2\cdot s}} = \frac{\mathrm{W}}{\mathrm{m^2}}$$

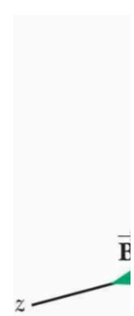


Energy Carried by Electromagnetic Wave

Poynting Vector

- For a plane EM wave:

$$\vec{\mathbf{S}} \equiv \frac{1}{\mu_0}\vec{\mathbf{E}} \times \vec{\mathbf{B}} \xrightarrow{|\vec{\mathbf{E}} \times \vec{\mathbf{B}}| = EB} S = \frac{EB}{\mu_0} \xrightarrow{B = E/c} S = \frac{E^2}{\mu_0 c} = \frac{cB^2}{\mu_0}$$



- Instantaneous rate at which energy passing through a unit area in terms of instantaneous values of **E** and **B**

Energy Carried by Electromagnetic Wave

Poynting Vector

The time average of **S** over one or more cycles is called the wave intensity **I**.

$$I = S_{\text{avg}} = \frac{E_{\text{max}} B_{\text{max}}}{2\mu_0} = \frac{E_{\text{max}}^2}{2\mu_0 c} = \frac{c B_{\text{max}}^2}{2\mu_0}$$

[Time average of $\cos^2(kx - \omega t) = ½$]

Energy density per unit volume associated with an electric field:

$$u_E = \tfrac{1}{2}\epsilon_0 E^2$$

Energy density per unit volume associated with a magnetic field:

$$u_B = \frac{B^2}{2\mu_0}$$

$B = E/c$ and $c = 1/\sqrt{\mu_0 \epsilon_0}$

$$u_B = \frac{(E/c)^2}{2\mu_0} = \frac{\mu_0 \epsilon_0}{2\mu_0} E^2 = \tfrac{1}{2}\epsilon_0 E^2$$

$$u_B = u_E = \tfrac{1}{2}\epsilon_0 E^2 = \frac{B^2}{2\mu_0}$$

Energy Carried by Electromagnetic Wave

Poynting Vector

The total instantaneous energy density **u** is equal to the sum of the energy densities associated with the electric and magnetic fields:

$$u = u_E + u_B = \epsilon_0 E^2 = \frac{B^2}{\mu_0}$$

When averaged over one or more cycles, we again obtain a factor of ½. Hence, for any electromagnetic wave, the total average energy per unit volume is:

$$u_{\text{avg}} = \epsilon_0(E^2)_{\text{avg}} = \tfrac{1}{2}\epsilon_0 E_{\text{max}}^2 = \frac{B_{\text{max}}^2}{2\mu_0}$$

We can rewrite the average value of S as:

$$I = S_{\text{avg}} = \frac{E_{\text{max}} B_{\text{max}}}{2\mu_0} = \frac{E_{\text{max}}^2}{2\mu_0 c} = \frac{c B_{\text{max}}^2}{2\mu_0}$$

In other words, the intensity of an electro
wave equals the average energy density
by the speed of light.

$$I = S_{\text{avg}} = c u_{\text{avg}}$$

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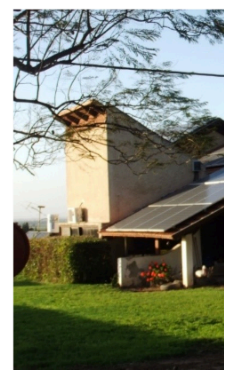
Energy Carried by Electromagnetic Wave

Energy from the Sun

- The Sun delivers about **10^3 W/m^2** of energy to the Earth's surface via electromagnetic radiation. Let's calculate the total power that is incident on the roof of a home.
- The roof's dimensions are **8.00m x 20.0m**. We assume the average magnitude of the Poynting vector for solar radiation at the surface of the Earth is **S_{avg} = 1,000 W/m^2**.
- Assuming the radiation is incident normal to the roof:

$$P_{\text{avg}} = S_{\text{avg}} A = (1\,000\ \text{W/m}^2)(8.00\ \text{m} \times 20.0\ \text{m}) = 1.60 \times 10^5\ \text{W}$$

- Power more than enough for average home needs!



The average U.S. hou
kilowatthours (kWh)

~30 kWh per day

Source: Serway, Raymond A.

https://www.eia.gov/ene

Energy Carried by Electromagnetic Wave

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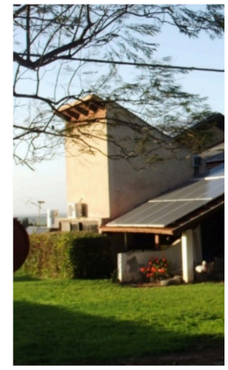
- Power more than enough for average home needs!

- However;
  - Efficiency of conversion from solar energy typically 12–18% for photovoltaic cells
  - Radiation likely not incident normal to roof
  - No energy available for about half of each day during nighttime
  - Cloudy days further reduce available energy
  - Energy must be stored for later use
    - Requiring batteries or other storage devices (further inefficiencies)

- Despite all of the above; conversion of homes to solar operation can be cost-effective



The average U.S. hou
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https://www.eia.gov/ene

Electromagnetic Waves (Ch. 3

Momentum and Radiation Pressure

Momentum and Radiation Pressure

Electromagnetic waves transport linear momentum as well as energy. As this momentum is absorbed by som
pressure is exerted on the surface.

Let's assume the electromagnetic wave strikes the surface at normal incidence and transports a total energy
surface in a time interval Δt.

If the surface absorbs all the incident energy in this time interval, the total momentum $\vec{\mathbf{p}}$ transported to the s
has a magnitude:

$$p = \frac{T_{\mathrm{ER}}}{c}$$

Pressure ***P*** exerted on surface (force per unit area F/A) combining Newton's second law:

$$P = \frac{F}{A} = \frac{1}{A}\frac{dp}{dt} \rightarrow P = \frac{1}{A}\frac{dp}{dt} = \frac{1}{A}\frac{d}{dt}\left(\frac{T_{\mathrm{ER}}}{c}\right) = \frac{1}{c}\frac{(dT_{\mathrm{ER}}/dt)}{A} \rightarrow P = \frac{S}{c} \qquad ($$

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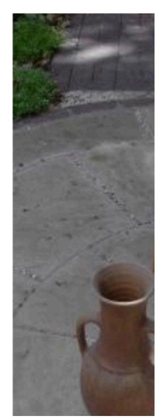
Momentum and Radiation Pressure

- With a perfect surface reflector (e.g., mirror) and normal incidence, momentum transported to surface is **d**
  - Momentum transferred to surface by incoming light: ***p = T_{ER}/c***
  - Momentum transferred by reflected light also ***p = T_{ER}/c***



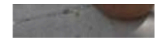
$$p = \frac{2T_{\mathrm{ER}}}{c} \qquad \text{(complete reflection)}$$

Radiation pressure exerted on perfectly reflecting surface for normal incidence of wave:

$$P = \frac{2S}{c} \qquad \text{(complete reflection)}$$

For surface neither perfect absorber nor perfect reflector:

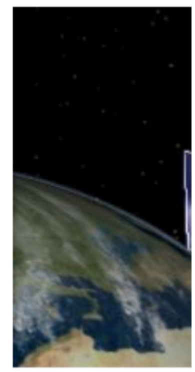
$$P = \left(1 + f\right)\frac{S}{c}$$ (f : fraction of incident light reflected from surface)



Source: Serway, R

Momentum and Radiation Pressure

Energy from the Sun



- Radiation pressures very small ≈ 5×10^{-6} N/m^2 for direct sunlight), however:
  - ***Solar sailing*** → low-cost means of sending spacecraft to planets
  - Large sheets experience radiation pressure from sunlight
    - Similar to sails on sailboats

Source: Serway, R

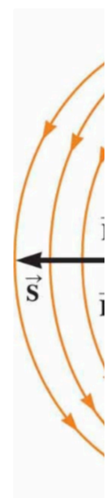
https://comm

Electromagnetic Waves (Ch. 33)

Production of Electromagnetic Waves by an Antenna

Production of Electromagnetic Waves by an Ante

- Stationary charges and steady currents cannot produce electromagnetic waves. If the current in a wire ***changes with time***, however, the wire emits electromagnetic waves.
- Let's consider the production of electromagnetic waves by a ***half-wave dipole antenna***. In this arrangement, two conducting rods are connected to a source of alternating voltage.
- The length of each rod is equal to one-quarter the wavelength of the radiation emitted when the oscillator / AC voltage operates at frequency ***f***.
- The oscillator forces charges to accelerate back and forth between the two rods. The current representing the movement of charges between the ends of the antenna produces magnetic field lines.
- At the two points where the magnetic field is shown in the figure, the Poynting vector ***S*** is directed radially outward, indicating that energy is flowing away from the antenna at this instant.

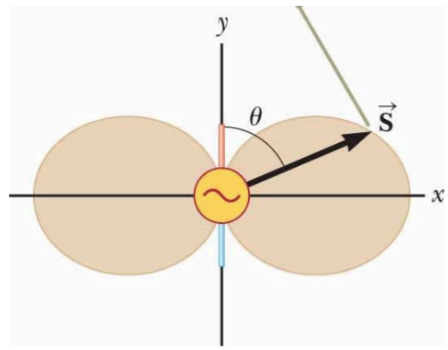


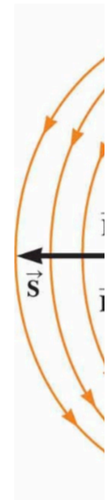
Production of Electromagnetic Waves by an Ante

- At great distances (far-field → plane waves)
  - Continuous induction of electric field by time-varying magnetic field and induction of magnetic field by time-varying electric field.
  - Maxwell's 3rd and 4th equation.

- A mathematical solution to Maxwell's equations for the dipole antenna shows that the intensity of the radiation varies as $(\sin^2\theta)/r^2$, where θ is measured from the axis of the antenna.

- Radiation pattern of a dipole antenna:





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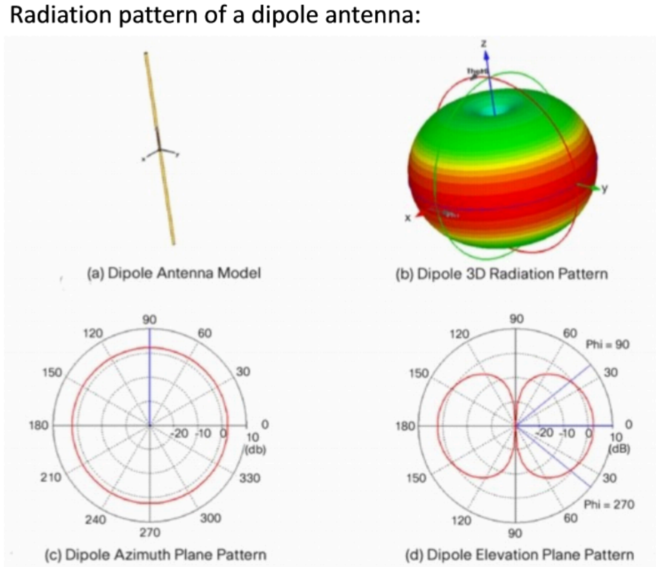
Production of Electromagnetic Waves by an Ante

- Radiation pattern of a dipole antenna:



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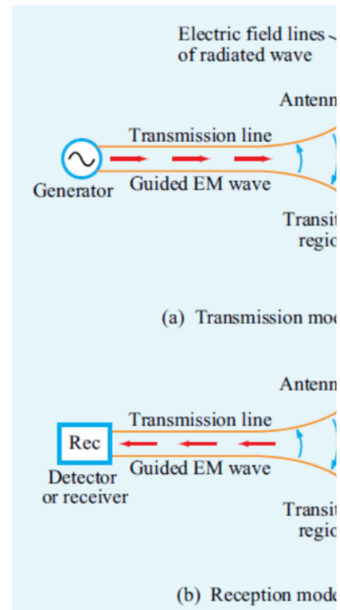
Antennas

Antenna is a means for radiating or receiving radio waves.

The antenna is the transitional structure between free-space and the guiding structure which maybe a coaxial cable or a waveguide.

If the impedance of the antenna is matched to the TL, we can transfer all the power with zero reflection. The accepted power by the antenna is radiated into space. Ideally all of the power should be radiated but in reality the antenna design determines what percentage of the power is actually radiated.



Source:
Ulaby, F. T., & Ravaioli, U. Fundamentals of Appl

Antennas

Types of antennas

Antennas can take so many shapes, sizes and forms.
Here we will introduce and only briefly discuss some of the most prominent antenna types.

- Wire antennas
- Aperture antennas
- Microstrip antennas
- Reflector antennas
- Antenna arrays

Antennas

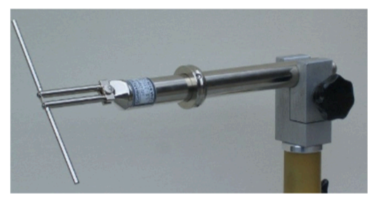
Wire antennas

Wire antennas are some of the oldest, simplest and cheapest antennas.

Wire antennas are familiar to most people because they are widely used as car and TV antennas, sometimes used in buildings and radio communications.

Examples:

- Monopole
  - Quarter wavelength monopole over ground plane
- Dipole
  - Half-wavelength dipole antenna
- Loop antenna
- Yagi-Uda
- Log periodic antennas



Source:
https://en.wikipedia.org/wiki/Dipole_antenna
https://en.wikipedia.org/wiki/Monopole_antenna
https://en.wikipedia.org/wiki/Log-periodic_antenna
https://en.wikipedia.org/wiki/Yagi%E2%80%93Uda_antenna

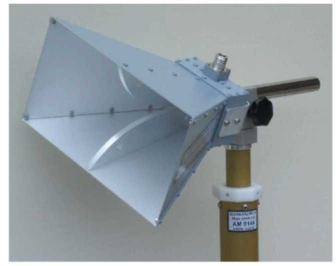
Antennas

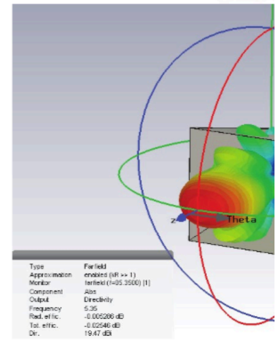
Aperture antennas

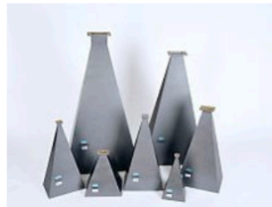
Aperture antennas emit EM waves through an opening / aperture.

Examples:

- Horn antennas
    - Circular
    - Square
    - Other shapes
- Waveguide apertures
    - Circular
    - Square
    - Other shapes



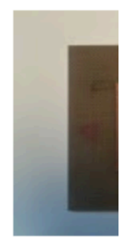




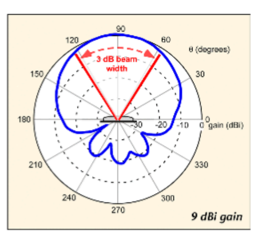
Source:
https://en.wikipedia.org/wiki/Horn_antenna
https://www.researchgate.net/figure/Radiation-patter
with-aperture-of-165x175mm-and-length-415mm-at_fi

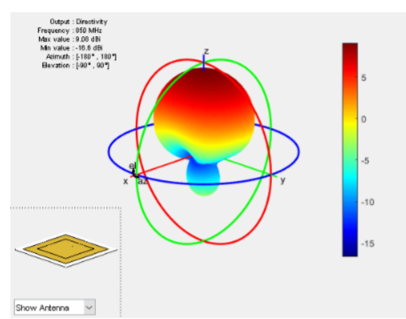
Antennas

Microstrip antennas



- Patch antennas come in various shapes and sizes.
- The construction is a patch of metal / copper directly above a ground plane. Usually a dielectric substrate fills in between.
- Advantages:
    - Low profile, conformal.
    - Easy to integrate with RF circuits
- Disadvantages:
    - Narrow bandwidth
    - Low efficiency





Source:
https://www.researchgate.net/figure/E-field-distribution-for-rectangular-microstrip-patch-antenna-in-single-mode-TE-10-at_fig3_288303417
https://www.researchgate.net/figure/Flexible-printed-monopole-antenna-based-on-Kapton-Polyimide_fig3_275520459
https://it.mathworks.com/help/antenna/gs/design-variations-on-microstrip-patch-antenna-using-pcb-stack.html
https://blog.serverfault.com/2011/12/12/a-studied-approach-at-wifi-part-1/

Antennas

Reflector antennas

Reflector antennas are one of the oldest antenna structures.

Especially the parabolic reflectors are widely used for space communications and radars.

A small horn antenna (sometimes corrugated) is generally used as the feed antenna.

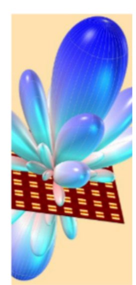
Very high antenna gains are possible with very narrowly focused 'pencil' beams.

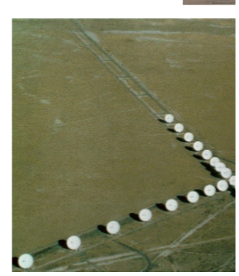
NASA's Special 70m antenna has 83dBi gain at 32GHz.

Source:
https://www.britannica.com/technology/parabolic-antenna
https://en.wikipedia.org/wiki/Reflector_(antenna)

Antennas

Antenna arrays





Single element antennas sometimes fall short of the system requirements where high directivity and gain is desired.

Usually enlarging the dimensions of the antenna gives you higher directivity & gain. However another approach to enhance directivity is by specially configuring multiple elements in an array setting.

In most cases, the elements of the antenna array are identical.

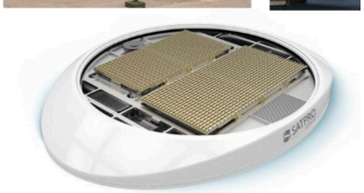
The total field of the array is determined by the vector addition of its elements.

Normally, closely located antennas interfere with each other. In order to obtain a directive radiation pattern, arrays are designed so that this interference (***mutual coupling***) is a constructive interference.

Source:
https://www.nasa.gov/directorates/heo/scan/communicatior
https://www.militaryaerospace.com/rf-analog/article/167201
initiative-on-wideband-phased-array-antennas
https://www.comsol.com/blogs/how-to-synthesize-the-radiat

Antennas

Phased arrays



Phased array
Electronically scanned array
Electronically steered antenna

Refers to the same concept

The elements get the same magnitude from the feed point but their phases are different to create constructive interference.

Phase shifters or beam forming networks are used to provide the elements with the correct phase.

Videos illustrating how arrays work:

https://en.wikipedia.org/wiki/Phased_array#/media/File:Phased_array_animation_with_arrow_10frames_371x400px_100ms.gif

https://en.wikipedia.org/wiki/Phased_array#/media/File:Phasearray.gif

Source:
http://defence-blog.com/news/china-has-developed-a-new-type-of-
https://www.comsol.com/blogs/designing-a-butler-matrix-beamforn
http://satcom-sys.com/assets/images/resources/22/pa450.jpg

Electromagnetic Waves (Ch. 33)

The Spectrum of Electromagnetic Waves

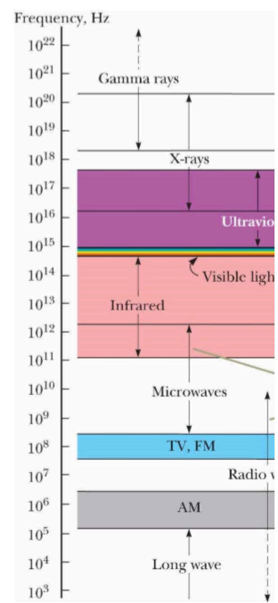
The Spectrum of Electromagnetic Waves

- Various types of electromagnetic waves are listed in the figure - which shows the ***electromagnetic spectrum***.
- Notice the wide ranges of frequencies and wavelengths. No sharp dividing point exists between one type of wave and the next.
- The names given to the types of waves are simply a convenient way to describe the region of the spectrum in which they lie.

TABLE 33.1 Approximate Correspondence Between Wavelengths of Visible Light and Color

Wavelength Range (nm)	Color Description
400–430	Violet
430–485	Blue
485–560	Green
560–590	Yellow
590–625	Orange
625–700	Red

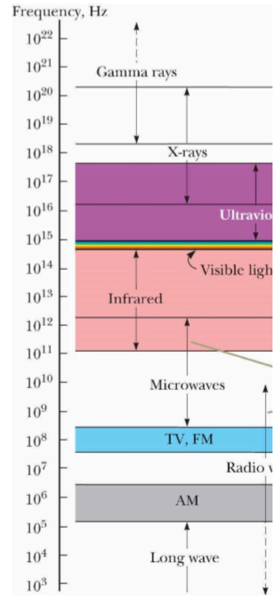
Note: The wavelength ranges here are approximate. Different people will describe colors differently.



The Spectrum of Electromagnetic Waves

The Spectrum of Electromagnetic Waves

- Radio Waves:,
- Microwaves
- Infrared Waves
- Visible Light
- Ultraviolet Waves
- X-rays
- Gamma rays



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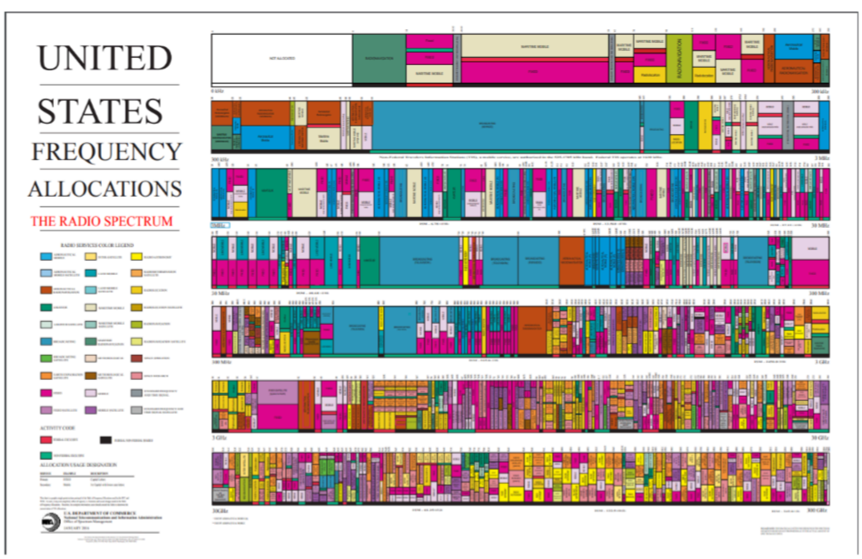
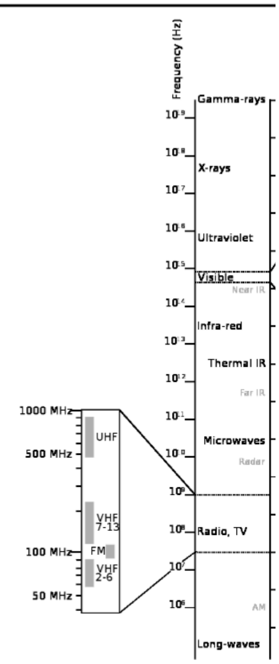
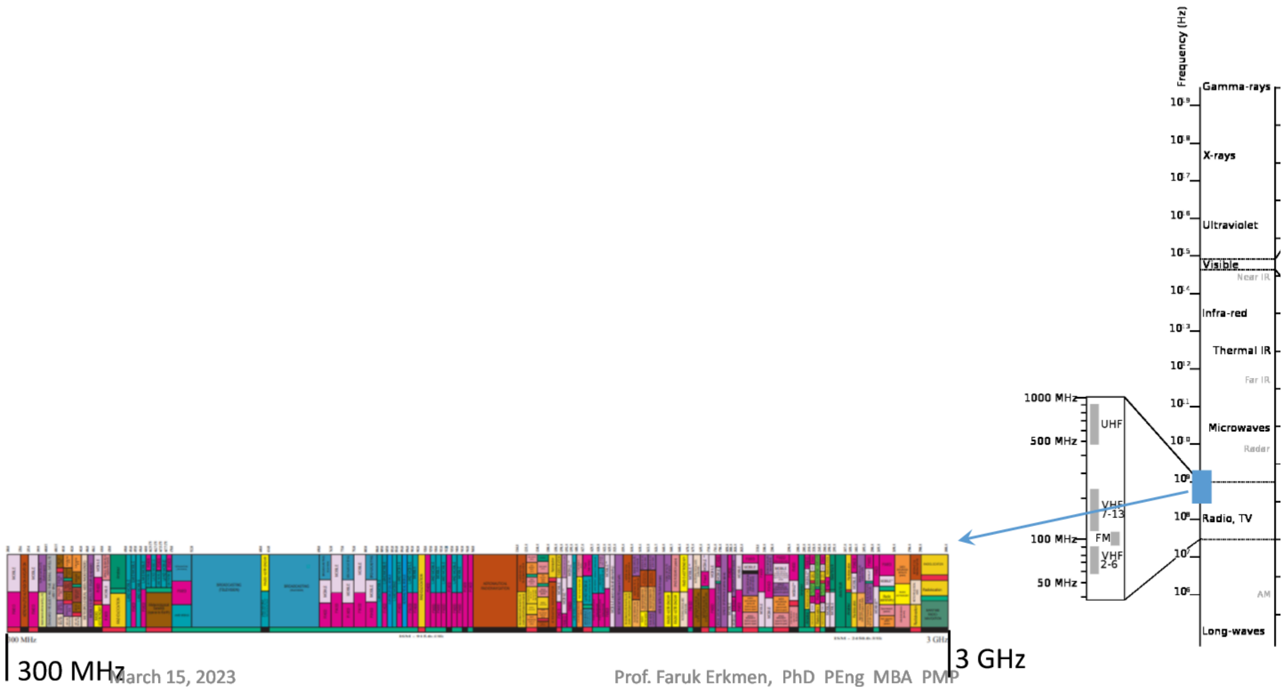
The Spectrum of Electromagnetic Waves

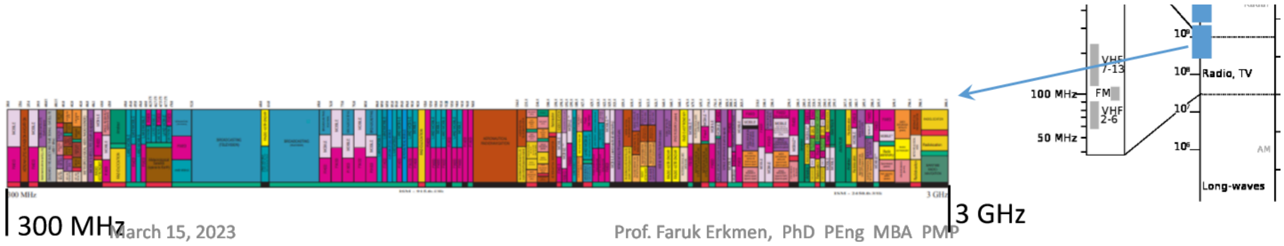




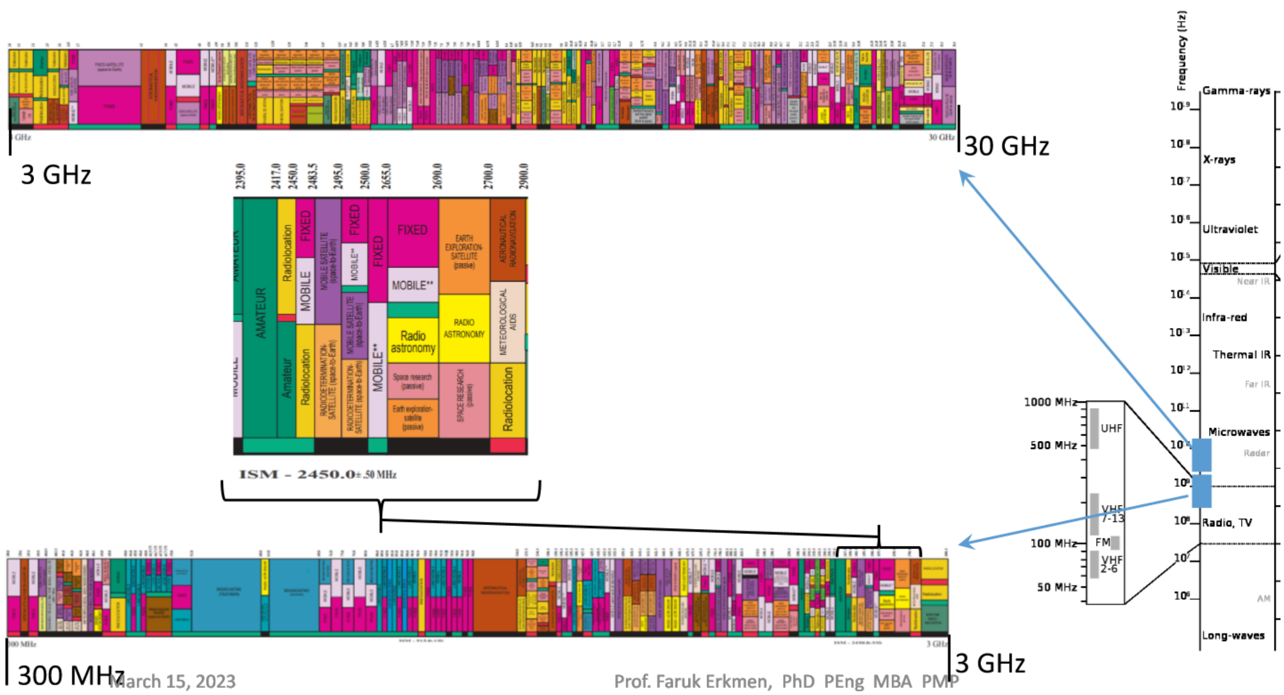
The Spectrum of Electromagnetic Waves



The Spectrum of Electromagnetic Waves



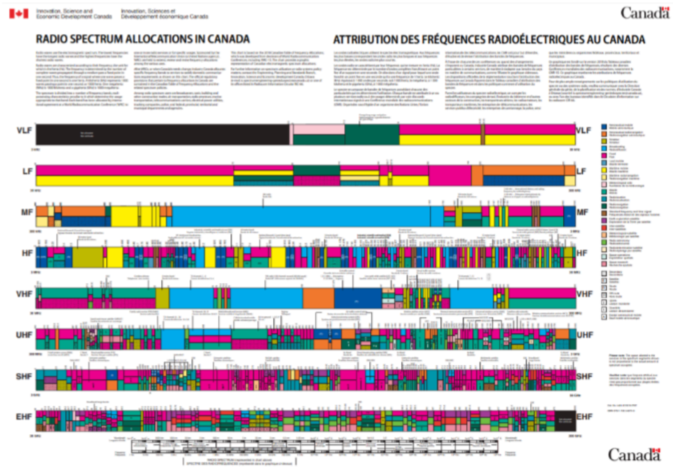
The Spectrum of Electromagnetic Waves



The Spectrum of Electromagnetic Waves

Canadian RF Spectrum

https://www.ic.gc.ca/eic/site/smtgst.nsf/vwapj/2018_Canadian_Radio_Spectrum_Chart.PDF/$FILE/2018_Canadian_Radio_Spect



Applied EM & Emerging Technolo

Applied EM : RF Signal Propagation

Applied Electromagnetics

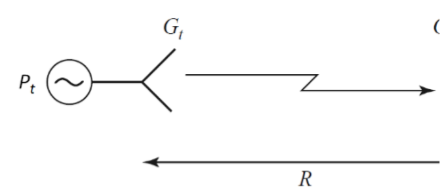
RF Signal Propagation

PREFIX	SYMBOL	MULTIPLIER	EXPONENT FORM
exa	E	1, 000, 000, 000, 000, 000, 000	10^{18}
peta	P	1, 000, 000, 000, 000, 000	10^{15}
tera	T	1, 000, 000, 000, 000	10^{12}
giga	G	1, 000, 000, 000	10^{9}
mega	M	1, 000, 000	10^{6}
kilo	k	1, 000	10^{3}
hecto	h	100	10^{2}
deca	da	10	10^{1}
Basic Unit	Basic Unit	1	10^{0}
deci	d	0.1	10^{-1}
centi	c	0.01	10^{-2}
milli	m	0. 001	10^{-3}
micro	μ	0. 000, 001	10^{-6}
nano	n	0. 000, 000, 001	10^{-9}
pico	p	0. 000, 000, 000, 001	10^{-12}
femto	f	0. 000, 000, 000, 000, 001	10^{-15}
atto	a	0. 000, 000, 000, 000, 000, 001	10^{-18}

Frequency*	λ in free-spa ε_r=1 / VF=1
1 Hz	300'000 km
10 Hz	30'000 km
100 Hz	3'000 km
1 kHz	300 km
10 kHz	30 km
100 kHz	3 km
1 MHz	300 m
10 MHz	30 m
100 MHz	3 m
1 GHz	300 mm
10 GHz	30 mm
100 GHz	3 mm

Applied Electromagnetics

RF Signal Propagation



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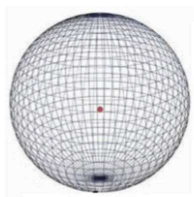
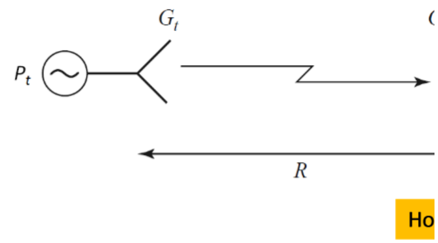
Applied Electromagnetics

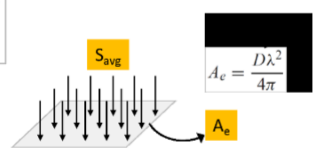
RF Signal Propagation





$$S_{\text{avg}} = \frac{P_t}{4\pi R^2} \ \text{W/m}^2$$

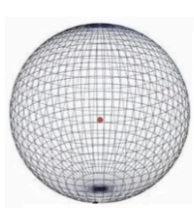
$$S_{\text{avg}} = \frac{G_t P_t}{4\pi R^2} \ \text{W/m}^2$$

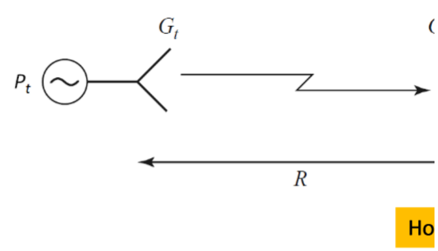


March 15, 2023 Prof. Faruk Erkmen, PhD PEng MBA PMP

Applied Electromagnetics

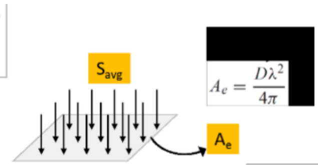
RF Signal Propagation





$$S_{avg} = \frac{P_t}{4\pi R^2} \ \mathrm{W/m^2}$$

$$S_{avg} = \frac{G_t P_t}{4\pi R^2} \ \mathrm{W/m^2}$$

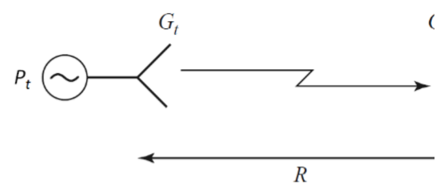


$$P_r = \frac{G_t G_r \lambda^2}{(4\pi R)^2} P_t \ \mathrm{W}$$

- Friis
- Friis

Applied Electromagnetics

RF Signal Propagation



Ho

Observations:

- Friis equation is the fundamental formula to answer how much power is received by an antenna.
- Note the result of this formula gives the absolute maximum possible received power. In practice, there are factors reducing the received power – such as:
  - Impedance mismatch
  - Polarization mismatch
  - Propagation / attenuation effects
  - Multipath effects
- Received power decreases as **$1/R^2$** where R is the distance between Tx and Rx antennas.
- Another important observation is that more power is lost at higher frequencies:
  - c = f x λ
  - λ^2 can be replaced with c^2/f^2 (c is speed of light - constant)
  - Received power is then inversely proportional to the square of frequency. **The higher the frequency, the higher the path loss.**

$$P_r = \frac{G_t G_r \lambda^2}{(4\pi R)^2} P_t \ \mathrm{W}$$

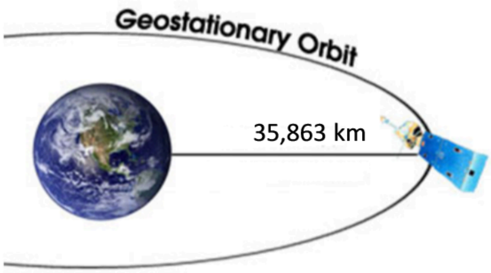
- Friis
- Friis

A basic radio system - Examples

Example

Using Friis transmission formula, calculate the path loss for an L-band signal travelling from earth to a geosyn

- Signal frequency is 1.6 GHz
- Geo Satellites are located above the equator at an approximate distance of 35,863 km.



Source: https://cimss.ssec.wisc.edu/satmet/modules/2_weather_satellites/ws-3.html

A basic radio system - Examples

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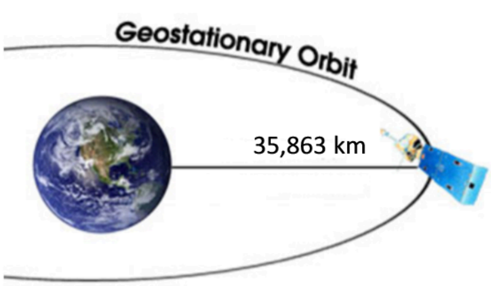

Source: https://cimss.ssec.wisc.edu/satmet/modules/2_weather_satellites/ws-3.html

$$\boxed{P_r} = \frac{\boxed{G_t G_r}\lambda^2}{(4\pi R)^2}\boxed{P_t}\,\mathrm{W}$$

Yellow highlighted information is not given but th rest is enough to calculate the path loss.

$$Path\ Loss = \frac{\lambda^2}{(4\pi R)^2}$$ (expressed in negati

A basic radio system - Examples

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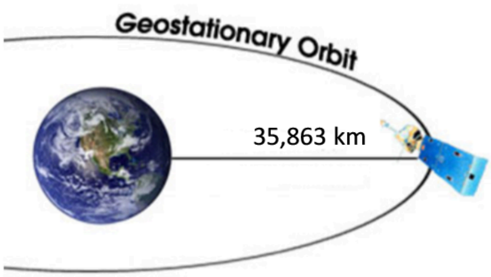


Source: https://cimss.ssec.wisc.edu/satmet/modules/2_weather_satellites/ws-3.html

F = 1.6 GHz

$\lambda = c/f = \dfrac{3x10^8 \text{ m/s}}{1.6x10^9 \text{ 1/s}}$ λ = 0.1875 r

$$Path\ Loss = \frac{\lambda^2}{(4\pi R)^2}$$

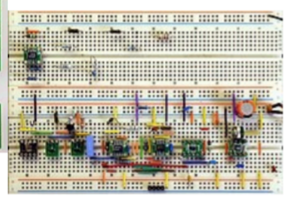
$$Path\ Loss = \frac{(0.1875)^2}{(4x3.14x35{,}863{,}000)^2}$$ = 1

Applied EM & Emerging Technol

Applied EM : Transmission Lines

Microwave Transmission Lines

- For basic electrical circuits, we use wires / conductors to transfer power via electrical current.
- This is achieved by moving electrons over a conductor.



Source:
https://en.wikipedia.org/wiki/Printed_circuit_board
https://en.wikipedia.org/wiki/Breadboard

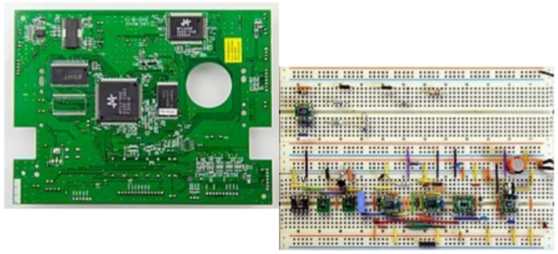
Microwave Transmission Lines

- For basic electrical circuits, we use wires / conductors to transfer power via electrical current.
- This is achieved by moving electrons over a conductor.

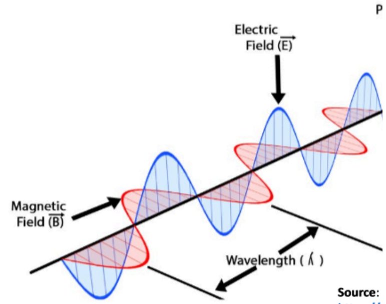
- For microwave circuits, the power is car electromagnetic waves.
- We can't transfer electromagnetic wave We need to guide them in special struct microwave transmission lines.

conductor.

microwave transmission lines.



Source:
https://en.wikipedia.org/wiki/Printed_circuit_board
https://en.wikipedia.org/wiki/Breadboard



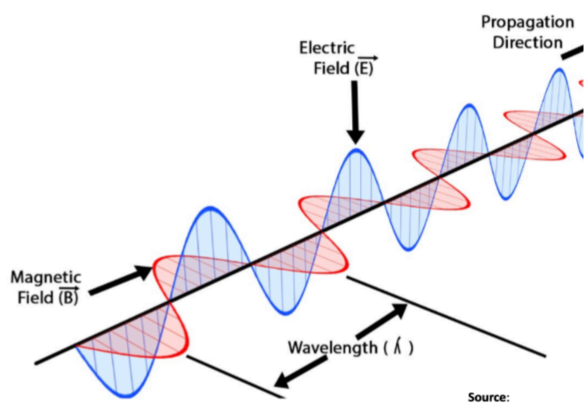
Source:
https://
96/how-

Microwave Transmission Lines

Types of transmission lines

There are a number of different transmission line types available depending on the application.

- Coaxial lines
- Waveguides
- Parallel lines
- Striplines
- Microstrip lines
- Co-planar waveguides

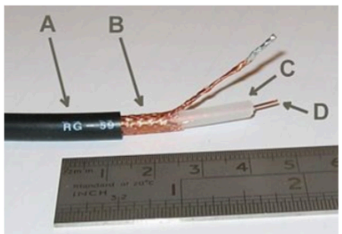


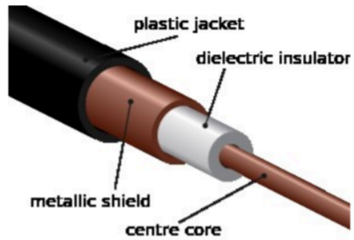
Source:
https://physics.stacke
96/how-do-electroma

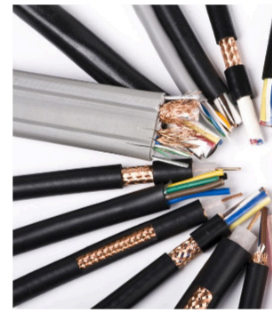
Microwave Transmission Lines

Coaxial lines

- A coaxial line is made up of two conductors: one cylindrical conductor at the outer shell and c
- There is an insulating dielectric layer between the conductors
  - Insulates the two lines from each other
  - Provides the propagation medium for the electromagnetic waves
- <u>Examples</u>: TV cables, leads of an oscilloscope, SMA cables







Source:
https://en.wikipedia.org/wiki/Coaxial_cable
https://www.clooms.com/types-of-coaxial-cable/

Microwave Transmission Lines

Waveguides

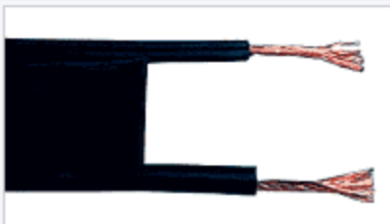
- Waveguides are among the earliest transmission lines used to transfer electromagnetic energ
- Waveguides are hollow metallic tubes through which EM waves can propagate.
  - Rectangular waveguides
  - Cylindrical waveguides
- Waveguides offer lower loss and better power handling capabilities but they are bulky, and la

Source:
https://www.fairviewmicrowave.com/n-fairview-microwave-releases-new-lines-of-flexible-waveguides-operating-to-40-ghz-over-nine-bands.aspx
https://www.everythingrf.com/Blogs/details/The-Largest-Online-Database-of-Waveguide-Components-Manufacturers
https://microwaveeng.com/product/circular-waveguide/

Microwave Transmission Lines

Parallel lines

- Parallel lines have two conductors spaced at a critical distance apart with insulation between
- Example: Flat 300Ω twin lead, usually found on TV antennas.



300 ohm twin-lead

A 300-to-75-ohm balun, showing twin-lead on the right hand side

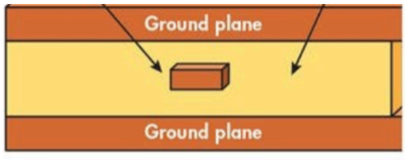
450 ohm "Ladd

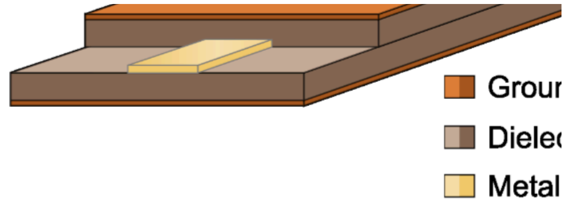
Source:
https://en.wikipedia.org/wiki/Twin-lead

Microwave Transmission Lines

Striplines

- Stripline is a planar type of transmission line commonly used in RF Integrated Circuits (ICs) an boards (PCBs).
- A thin conducting strip is centered between two wide conducting ground planes.
- In practice, stripline is usually constructed by etching the center conductor on a grounded die and then covering with another grounded substrate.



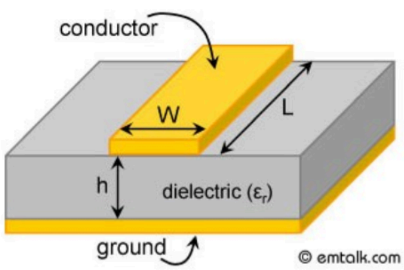


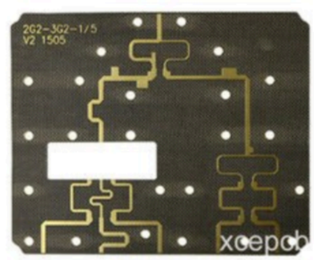
Source:
https://www.mwrf.com/technologies/active-components/article/21846859/whats-the-difference-between-microstrip-and-stripline
https://ca.wikipedia.org/wiki/Fitxer:Stripline_structure2.svg

Microwave Transmission Lines

Microstrip lines

- Microstrip line is one of the most popular types of planar transmission lines.
- Possibly the most practical, economical and easily miniaturized construction.
- A conductor strip is printed on a thin grounded dielectric substrate.
- Examples can be found in almost every RF/microwave printed circuit board (PCB)



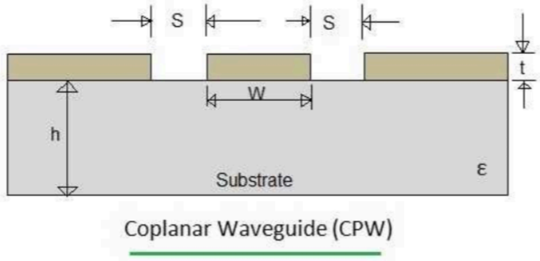


Source:
https://emtalk.com/mscalc.php
https://www.fr4-pcb.com/pcb-6260618-microstrip-patch-antenna-custom-pcb-board-with-taconic-rf-base-material-double-layer.html

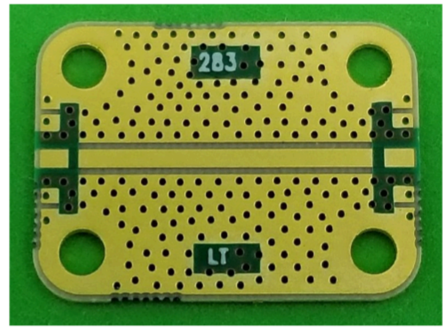
Microwave Transmission Lines

Co-planar waveguides

- Similar to microstrip lines.
- Practical and easy to fabricate on PCBs.



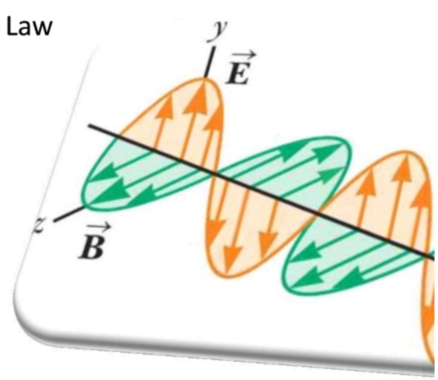
Coplanar Waveguide (CPW)



Source:
https://www.rfwireless-world.com/Terminology/CPW-Coplanar-Waveguide-basics.html
https://www.lotussys.com/products/pcbcpwg38mdc

Summary of Week 11, Class 9

- Reminder of the previous week
- Electromagnetic Waves (Ch. 33)
  - Displacement Current and General Form of Ampere's Law
  - Maxwell's Equations and Hertz's Discoveries
  - Plane Electromagnetic Waves
  - Energy Carried by Electromagnetic Waves
  - Momentum and Radiation Pressure
  - Production of Electromagnetic Waves by an Antenna
  - The Spectrum of Electromagnetic Waves
- Applied EM & Emerging Technologies
- Examples
- Next week's topic



Reading / Preparation for Next Week

Topics for next week:

- Nature of Light and Ray Optics (Ch. 34)
- Assignment-2 Due March 28th, 2023