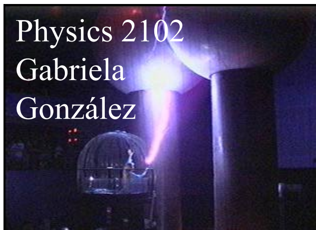
Physics 2102
Gabriela González



Electromagnetic waves

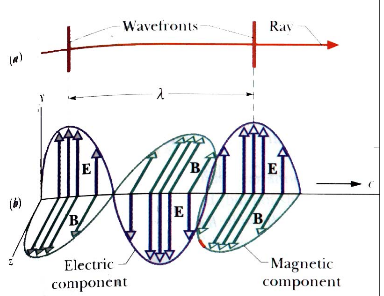
Electromagnetic waves

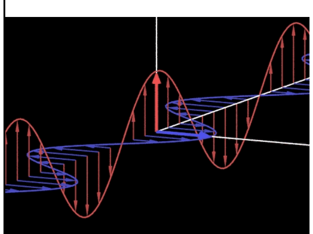
A solution to Maxwell's ec

$$E = E_m \sin(kx - \omega t)$$

$$B = B_m \sin(kx - \omega t)$$

$\frac{\omega}{k} = c,$
speed of propagation.





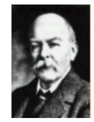
$$c = \frac{E_m}{B_m} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$
$$= 299{,}462{,}954 \frac{m}{s} = 187{,}163 mph$$

Visible light, infrared, ultraviolet, radio waves, X rays, Gamma rays are all electromagnetic waves.

http://phys23p.sl.psu.edu/CWIS/

The Poynting vector

Electromagnetic waves are able to transport energy from transmitter to receiver (example: from the Sun to our skin).



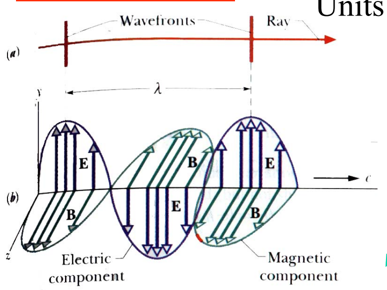
John Henry Poynting (1852-1914)

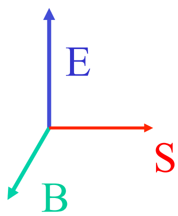
The power transported by the wave and its direction is quantified by the Poynting vector.

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

Units: Watt/m^2

For a wave, since E is perpendicular to B: $|S| = \frac{1}{\mu_0} EB = \frac{1}{c\mu_0} E^2$





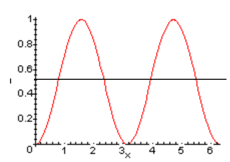
In a wave, the fields change with time. Therefore the Poynting vector changes too!!The direction is constant, but the magnitude changes from 0 to a maximum value.

EM wave intensity, energy density

A better measure of the amount of energy in an EM wave is obtained by averaging the Poynting vector over one wave cycle. The resulting quantity is called **intensity**.

$$I = \overline{S} = \frac{1}{c\mu_0} \overline{E^2} = \frac{1}{c\mu_0} E_m^2 \overline{\sin^2(kx - \omega t)}$$

The average of sin^2 over one cycle is ½:



$$I = \frac{1}{2c\mu_0} E_m^2 \quad \text{or,} \quad I = \frac{1}{c\mu_0} E_{rms}^2$$

Both fields have the same energy density.

$$u_E = \frac{1}{2}\varepsilon_0 E^2 = \frac{1}{2}\varepsilon_0 (cB)^2 = \frac{1}{2}\varepsilon_0 \frac{B^2}{\varepsilon_0 \mu_0} = u_B$$

The total EM energy density is then $u = \varepsilon_0 E^2 = B^2 / \mu_0$

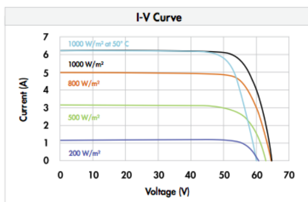
Solar Energy

The light from the sun has an intensity of about $1kW/m^2$. What would be the total power incident on a roof of dimensions 8x20m?

$I=1kW/m^2$ is power per unit area.
$P=IA=(10^3\ W/m^2) \times 8m \times 20m=0.16$ MW!!

The solar panel shown (Sunpower E19) is 61in x 41in.
The actual solar panel delivers ~6A at 50V.
What is its efficiency?

The planet's most powerful solar panel.
The SunPower™ 320 Solar Panel provides today's highest efficiency and performance. Utilizing 96 back-contact solar cells, the SunPower 320 delivers a total panel conversion efficiency of 19.6%. The 320 panel's reduced voltage-temperature coefficient, anti-reflective glass and exceptional low-light performance attributes provide outstanding energy delivery per peak power watt.

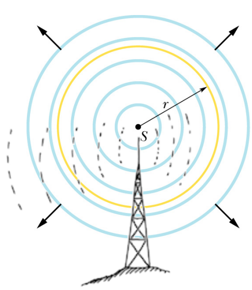


Current/voltage characteristics with dependence on irradiance and module temperature.

http://us.sunpowercorp.com/homes/products-services/solar-panels/

EM spherical waves

The intensity of a wave is power *per unit area*. If one has a source that emits isotropically (equally in all directions) the power emitted by the source pierces a larger and larger sphere as the wave travels outwards.



$$I = \frac{P_s}{4\pi r^2}$$

So the power per unit area decreases as the inverse of distance squared.

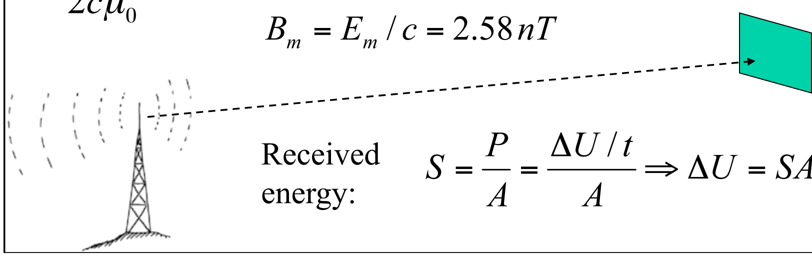
Example

A radio station transmits a 10 kW signal at a frequency of 100 MHz. (We will assume it radiates as a point source). At a distance of 1km from the antenna, find (a) the amplitude of the electric and magnetic field strengths, and (b) the energy incident normally on a square plate of side 10cm in 5min.

$$I = \frac{P_s}{4\pi r^2} = \frac{10kW}{4\pi(1km)^2} = 0.8mW/m^2$$

$$I = \frac{1}{2c\mu_0}E_m{}^2 \Rightarrow E_m = \sqrt{2c\mu_0 I} = 0.775V/m$$

$$B_m = E_m/c = 2.58\,nT$$

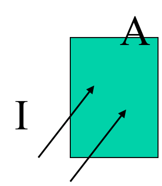


Received energy: $S = \frac{P}{A} = \frac{\Delta U/t}{A} \Rightarrow \Delta U = SAt = 2.4\,mJ$

Radiation Pressure

Waves not only carry energy but also momentum. The effect is very small (we don't ordinarily feel pressure from light). If light is completely absorbed during an interval Δt, the momentum transferred is given by $\Delta p = \frac{\Delta u}{c}$ and twice as much if reflected.

Newton's law: $F = \frac{\Delta p}{\Delta t}$



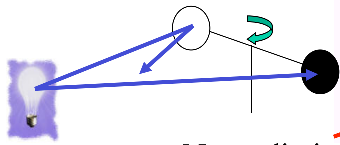
Now, supposing one has a wave that hits a surface of area A (perpendicularly), the amount of energy transferred to that surface in time Δt will be

$\Delta U = IA\Delta t$ therefore $\Delta p = \frac{IA\Delta t}{c}$ → $F = \frac{IA}{c}$

Radiation pressure: $p_r = \frac{I}{c}$ (total absorption), $p_r = \frac{2I}{c}$ (total reflection)

Radiation pressure: examples

Solar mills?



Not radiation pressure!!

Comet tails

Solar sails?

From the Planetary Society

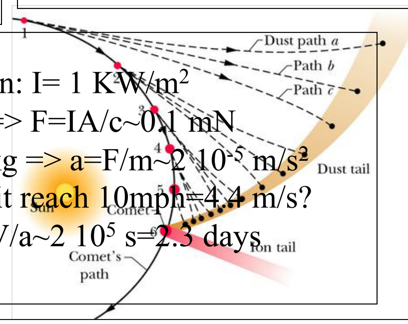
Sun radiation: I= 1 KW/m^2

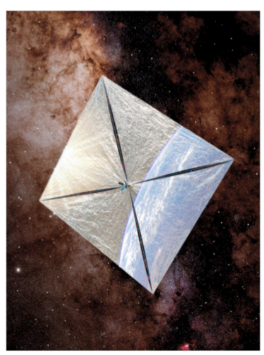
Area 30m^2 => F=IA/c~0.1 mN

Mass m=5 kg => a=F/m~2 10^{-5} m/s^2

When does it reach 10mph=4.4 m/s?

V=at => t=V/a~2 10^5 s=2.3 days





Setting Sail Into Space, Propelled by Sunshine

BY DENNIS OVERBYE

NOVEMBER 10, 2009

Peter Pan would be so happy.

About a year from now, if all goes well, a box about the size of a loaf of bread will pop out of a rocket some 500 miles above the Earth. There in the vacuum it will unfurl four triangular sails as shiny as moonlight and only barely more substantial. Then it will slowly rise on a sunbeam and move across the stars.

LightSail-1, as it is dubbed, will not make it to Neverland. At best the device will sail a few hours and gain a few miles in altitude. But those hours will mark a milestone for a dream that is almost as old as the rocket age itself, and as romantic: to navigate the cosmos on winds of starlight the way sailors for thousands of years have navigated the ocean on the winds of the Earth.

"Sailing on light is the only technology that can someday take us to the stars," said Louis Friedman, director of the Planetary Society, the worldwide organization of space enthusiasts.

Even as the National Aeronautics and Space Administration continues to flounder in a search for its future, Dr. Friedman announced Monday that the Planetary Society, with help from an anonymous donor, would be taking baby steps toward a future worthy of science fiction. Over the next three years, the society will build and fly a series of solar-sail spacecraft dubbed LightSails, first in orbit around the Earth and eventually into deeper space.

The voyages are an outgrowth of a long collaboration between the society and Cosmos Studios of Ithaca, N.Y., headed by Ann Druyan, a film producer and widow of the late astronomer and author Carl Sagan.

DEEP-SPACE TRAVEL If the launching of LightSail-1 goes off according to plan next year, humans may soon be solar-sailing, as shown in this illustration. (Rick Sternbach/Planetary Society)

symbol for the wise use of technology.

There is a long line of visionaries, stretching back to the Russian rocket pioneers Konstantin Tsiolkovsky and Fridrich Tsander and the author Arthur C. Clarke, who have supported this idea. "Sails are just a marvelous way

How thin are the reflective sails, and what material are they made of?

The sails are made of aluminized, reinforced Mylar™ 4.5 microns (.18 mil) thick, about ¼ the thickness of a trash bag. The sail must be as light as possible to maximize the acceleration.

How fast does a solar sail go?

The speed of an interplanetary solar sail spacecraft will depend on how long it has been propelled by sunlight. The acceleration from sunlight is very small and depends on the size and weight of the sail and spacecraft. For our ***LightSail-1***, the acceleration from the solar force will be approximately 0.06 mm per second per second.

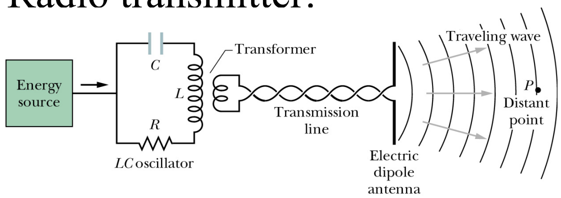
The real advantage of solar sailing is that, unlike a chemical rocket that applies a lot of thrust for a very short time, sunlight hitting the sail applies thrust continuously. In 100 days, a sail-propelled craft could reach 14,000 kilometers per hour. In just three years, a solar sail could reach over 150,000 miles per hour. At that speed, you could reach Pluto in less than five years.

What can a solar sail be used for?

Solar sails can be used to boost or decrease the orbits of spacecraft, hold a spacecraft in position to monitor the Sun for solar storms, provide stable Earth observation platforms, travel between the planets within our solar system, and someday take us to worlds around other stars. However, once you get much beyond the orbit of Jupiter, energy from sunlight is too weak to keep you accelerating. Far away from the Sun, the highly focused beams of lasers can be directed at the sails to boost them onto interstellar trajectories.

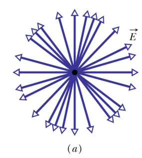
EM waves: polarization

Radio transmitter:

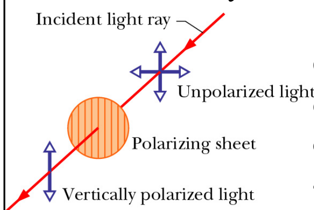


If the dipole antenna is vertical, so will be the electric fields. The magnetic field will be horizontal.

The radio wave generated is said to be "polarized".

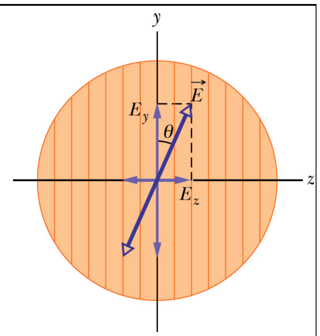


In general light sources produce "unpolarized waves" emitted by atomic motions in random directions.



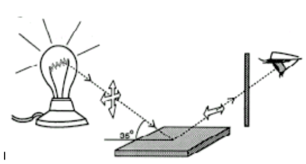
Completely unpolarized light will have equal components in horizontal and vertical directions. Therefore running the light through a polarizer will cut the intensity in half: $I=I_0/2$

When *polarized* light hits a polarizing sheet, only the component of the field aligned with the sheet will get through.



$$E_y = E\cos(\theta)$$

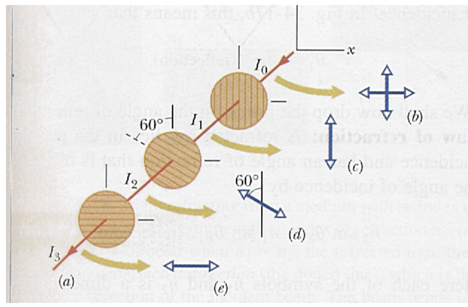
And therefore: $I = I_0 \cos^2\theta$



Light reflected from surfaces is usually polarized horizontally.
Polarized sunglasses take advantage of this: they are vertical polarizing sheets, so that they cut the horizontally polarized light from glare (reflections on roads, cars, etc).

Example

Initially unpolarized light of intensity I_0 is sent into a system of three polarizers as shown. What fraction of the initial intensity emerges from the system? What is the polarization of the exiting light?



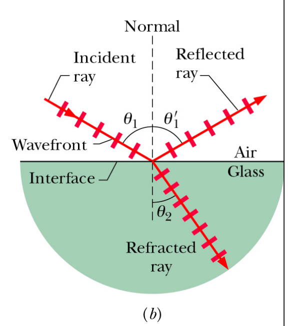
- Through the first polarizer: unpolarized to polarized, so $I_1=\frac{1}{2}I_0$.
- Into the second polarizer, the light is now vertically polarized. Then, $I_2=I_1\cos^2 60^o = 1/4\ I_1 =1/8\ I_0$.
- Now the light is again polarized, but at 60°. The last polarizer is horizontal, so $I_3=I_2\cos^2 30^o =3/4\ I_2=3/32\ I_0=0.094\ I_0$.
- The exiting light is horizontally polarized, and has 9% of the original amplitude.

Reflection and refraction

When light finds a surface separating two media (air and water, for example), a beam gets **reflected** and another gets **refracted** (transmitted).

Law of reflection: the angle of incidence θ_1 equals the angle of reflection θ'_1.

Law of refraction: $n_2 \sin\theta_2 = n_1 \sin\theta_1$ Snell's law.



n is the index of refraction of the medium.
In vacuum, n=1. In air, n~1. In all other media, n>1.

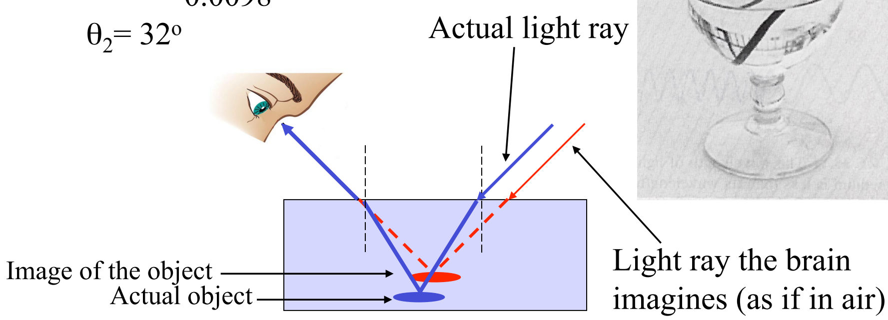
Example

Water has n=1.33. How much does a beam incident at 45º refracts?

$n_2 \sin \theta_2 = n_1 \sin \theta_1$

$\sin \theta_2 = (n_1 / n_2) \sin \theta_1$
$= (1/1.33) \sin 45^o$
$= 0.0098$

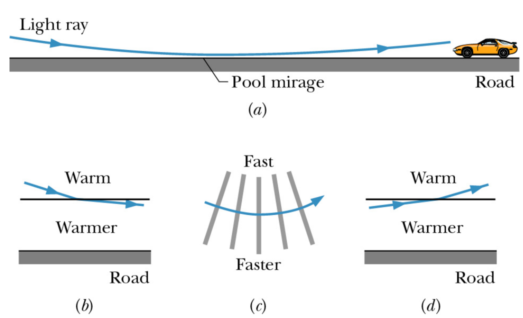
$\theta_2 = 32^o$



Example: an optical illusion

The index of refraction decreases with temperature: the light gets refracted and ends up bending upwards.

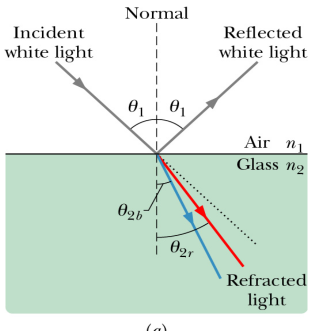
We seem to see water on the road, but in fact we are looking at the sky!

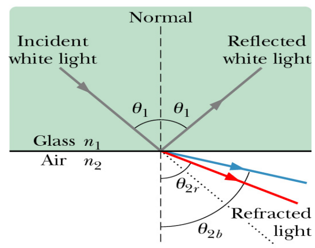


Chromatic dispersion

The index of refraction depends on the wavelength (color) of the light.

$$n_2 \sin\theta_2 = n_1 \sin\theta_1$$

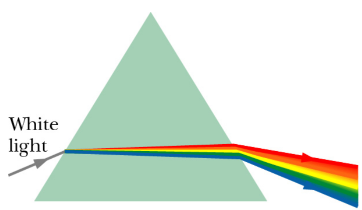




(*b*)

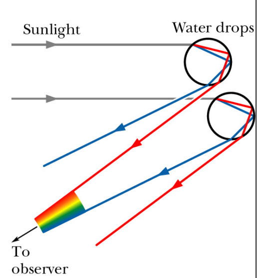
Examples

Prisms



(*b*)

Rainbows: water drops act as reflecting prisms.

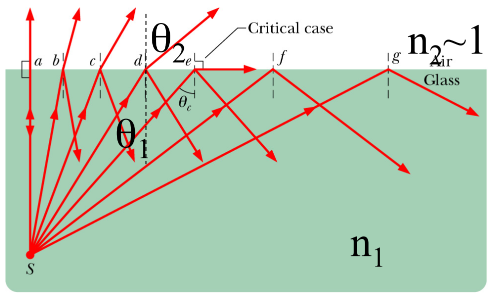


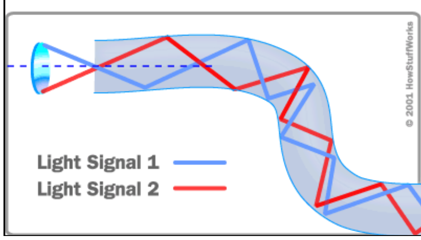
(*b*)

Total internal reflection

From glass to air, the law of refraction uses $n_2<n_1$, so $\theta_2>\theta_1$: it may reach 90º or more: the ray is "reflected" instead of "refracted".

$n_2 \sin \theta_2 = n_1 \sin \theta_1$





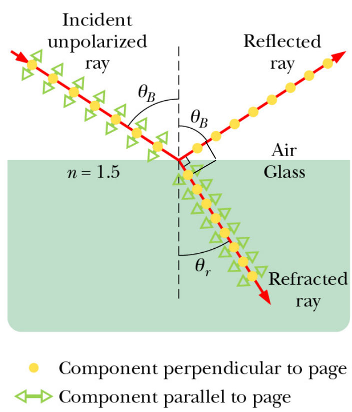
For glass (fused quartz) n=1.46, and the critical angle is 43º: optical fibers!

Polarization by reflection

Different polarization of light get reflected and refracted with different amplitudes ("birefringence").

At one particular angle, the parallel polarization is NOT reflected at all!

This is the "Brewster angle" θ_B, and $\theta_B + \theta_r = 90^o$.



$$n_1 \sin\theta_B = n_2 \sin(90^o - \theta_B) = n_2 \cos\theta_B$$

$$\tan\theta_B = \frac{n_2}{n_1}$$

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Glan Laser Prisms

- High power capacity: up to 500MW/cm^2 pulsed
- Made from high optical quality natural calcite
- Conveniently mounted in a metal cell
- Available with two, one or no escape ports for extra power capacity
- Excellent extinction ratio of 5x10^{-5}

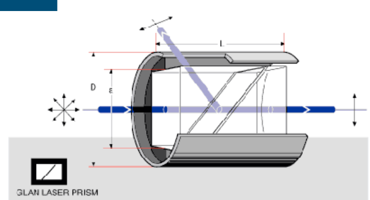
Glan laser prisms are a form of calcite prism which has been adapted for high power laser use. The two prism sections are polished at an angle between the critical angles of the e and o rays for the incoming light and are air-spaced and mounted within absorbing black glass in a cell. As light enters the polarizer one polarization orientation of the beam is refracted at a different angle from the other. Thus the e-ray hits the air-spaced interface at an angle below Brewster's angle and is transmitted. The o-ray is totally reflected out of the prism into either the black glass or the escape port. Normally they are supplied in a cylindrical cell but the cell can be cut away on one or both sides to provide an exit path for the unwanted beam. The escape port type has a greater power handling capacity than the plain metal mounts because the unwanted energy can be dumped outside the cell rather than being absorbed within it. The advantage of 2 ports is that light can enter the prism from either direction.

Specifications & Tolerances

Dimensions: $\pm$0.2mm
Angular field: $\pm$1.5°
Cell: Black finished aluminum
Surface quality: 40-20
Maximum beam deviation: $\leq$2.5arcmin

Extinction ratio: 5x10^{-5}
Length/Aperture ratio: 1.5:1
Material: Optical quality natural calcite
Wavelength range: 400-2300nm

www.optosigma.com



Glan Laser Prisms	CELL			
Prism Side, a (mm)	Diameter, D (mm)	Length, L (mm)	Price	PART NUMBER
8	18.9	16	$440.00	**066-2220**
10	22	21	$520.00	**066-2230**
12	25.3	23	$760.00	**066-2240**
15	28.5	26	$1,025.00	**066-2250**
17	31.75	28	$1,340.00	**066-2260**
20	34.8	32	$1,760.00	**066-2270**