Physics: Waves and Optics & Quantum Mechanics Subject code: BSC-PHY-102G

EEE

Ist Year

Introduction of subject

- **Optics** is the branch of physics which deals with the study of optical phenomena**.** Optics can be divided into two categories, which is **Ray optics** and Wave optics. **Wave optics** deals with the connection of waves and rays of light. It is used when the wave characteristics of light are taken in account. Wave Optics deals with the study of various phenomenal behaviors of light like reflection, refraction, interference, diffraction, polarization etc. It is otherwise known as Physical Optics.
- Quantum mechanics is a physical science dealing with the behaviour of matter and energy on the scale of atoms and subatomic particles / waves.
- It also forms the basis for the contemporary understanding of how very large objects such as stars and galaxies, and cosmological events such as the Big Bang, can be analyzed and explained.
- Quantum mechanics is the foundation of several related disciplines including nanotechnology, condensed matter physics, quantum chemistry, structural biology, particle physics, and electronics.

Syllabus

UNIT – I: Wave and Light Motion

Waves: Mechanical and electrical simple harmonic oscillators, damped harmonic oscillator, forced mechanical and electrical oscillators, impedance, steady state motion of forced damped harmonic oscillator Non-dispersive transverse and longitudinal waves: Transverse Wave on a string, the wave equation on a string, Harmonic waves, reflection and transmission of waves at a boundary, impedance matching, standing waves and their Eigen frequencies, longitudinal waves and the wave equation for them, acoustics waves. Light and Optics: Light as an electromagnetic wave and Fresnel equations, reflectance and transmittance, Brewster's angle, total internal reflection, and evanescent wave.

UNIT – II: Wave Optics and Lasers

Wave Optics: Huygens' principle, superposition of waves and interference of light by wave-front splitting and amplitude splitting; Young's double slit experiment, Newton's rings, Michelson interferometer. Fraunhofer diffraction from a single slit and a circular aperture, the Rayleigh criterion for limit of resolution and its application to vision; Diffraction gratings and their resolving power. Lasers: Einstein's theory of matter radiation interaction and A and B coefficients; amplification of light by population inversion, different types of lasers: gas lasers (He-Ne, CO), solid-state lasers (ruby, Neodymium), dye lasers; Properties of laser beams: mono-chromaticity.

UNIT – III: Introduction to Quantum Mechanics

Wave nature of Particles, Time-dependent and time-independent Schrodinger equation for wave function, Born interpretation, probability current, Expectation values, Free-particle wave function and wave-packets, Uncertainty principle. Solution of stationary- state Schrodinger equation for one dimensional problems–particle in a box, particle in attractive delta-function potential, square-well potential, linear harmonic oscillator. Scattering from a potential barrier and tunneling; related examples like alpha-decay, field-ionization and scanning tunneling microscope, tunneling in semiconductor structures.

UNIT – IV: Introduction to Solids and Semiconductors

Free electron theory of metals, Fermi level, density of statesin1, 2 and 3 dimensions, Bloch's theorem for particles in a periodic potential, Kronig-Penney model and origin of energy bands. Types of electronic materials: metals, semiconductors, and insulators. Intrinsic and extrinsic semiconductors, Dependence of Fermi level on carrier-concentration and temperature (equilibrium carrier statistics), Carrier generation and recombination, Carrier transport: diffusion and drift, p -n junction.

Future scope

The future of this subject in electrical engineering has broad spectrum analysis on nanotechnology, image processing, renewable energy sources, embedded systems, imaging, optoelectronics, optical fibers etc., Each and every new idea of electronics is making the life to move ahead. The future electrical engineering has major medical applications.

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Unit I : Wave and Light Motion

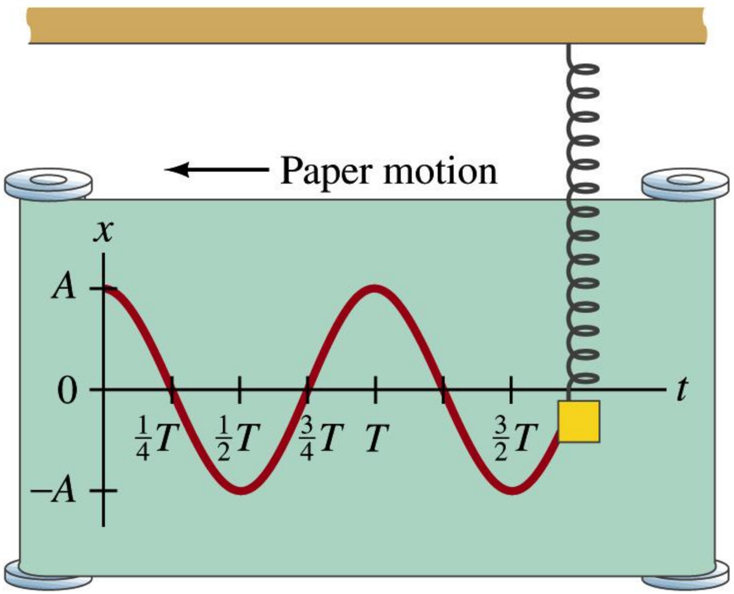
Simple Harmonic Motion

Phase Constant

Amplitude

$$x(t) = x_m \cos(\omega t + \phi)$$

Angular Frequency

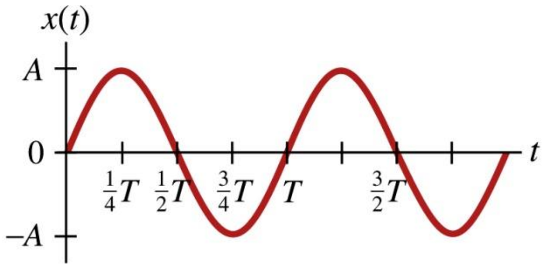


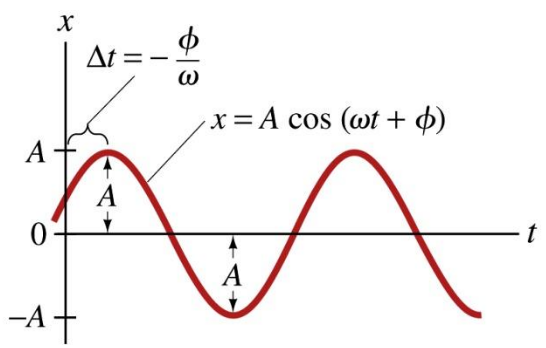
Simple Harmonic Motion

- Other variables frequently used to describe simple harmonic motion:
  - The period T: the time required to complete one oscillation. The period T is equal to $2\pi/\omega$.
  - The frequency of the oscillation is the number of oscillations carried out per second:

    $\nu = 1/T$

    The unit of frequency is the Hertz (Hz). Per definition, 1 Hz = 1 s^{-1}.





Simple Harmonic Motion
What forces are required?

- Using Newton's second law we can determine the force responsible for the harmonic motion:

$$F = ma = -m\omega^2 x$$

- The total mechanical energy of a system carrying out simple harmonic motion is constant.

- A good example of a force that produces simple harmonic motion is the spring force: $F = -kx$. The angular frequency depends on both the spring constant k and the mass m:

$$\omega = \sqrt{(k/m)}$$

Simple Harmonic Motion (SHM). The equation of motion.

- All examples of SHM were derived from he following equation of motion:

$$\frac{d^2x}{dt^2} = -\omega^2 x$$

$$x(t) = A\cos(\omega t + \alpha) + B\sin(\omega t + \beta)$$

- The most general solution to the equation is

Simple Harmonic Motion (SHM). The equation of motion.

- If $A = B$

$$x(t) = A\cos(\omega t + \alpha) + B\sin(\omega t + \beta) =$$

$$= A\left(\sin\left(\frac{1}{2}\pi - \omega t - \alpha \right) + \sin(\omega t + \beta) \right) =$$

$$= 2A\sin\left(\frac{1}{4}\pi + \frac{\beta}{2} - \frac{\alpha}{2} \right)\cos\left(\frac{1}{4}\pi - \omega t - \frac{\beta}{2} - \frac{\alpha}{2} \right)$$

which is SHM.

Damped Harmonic Motion.

- Consider what happens when in addition to the restoring force a damping force (such as the drag force) is acting on the system:

$$F = -kx - b\frac{dx}{dt}$$

$$\frac{d^2x}{dt^2} + \frac{b}{m}\frac{dx}{dt} + \frac{k}{m}x = 0$$

- The equation of motion is now given by:

Damped Harmonic Motion.

- The general solution of this equation of motion is

$$x(t) = Ae^{i\omega t}$$

- If we substitute this solution in the equation of motion we find

$$-\omega^2 Ae^{i\omega t} + i\omega \frac{b}{m} Ae^{i\omega t} + \frac{k}{m} Ae^{i\omega t} = 0$$

- In order to satisfy the equation of motion, the angular frequency must satisfy the following condition:

$$\omega^2 - i\omega \frac{b}{m} - \frac{k}{m} = 0$$

Damped Harmonic Motion

- We can solve this equation and determine the two possible values of the angular velocity:

$$\omega = \frac{1}{2}\left(i\frac{b}{m} \pm \sqrt{4\frac{k}{m} - \frac{b^2}{m^2}} \right);\ \frac{1}{2}i\frac{b}{m} \pm \sqrt{\frac{k}{m}}$$

- The solution to the equation of motion is thus given by

$$x(t);\ x_m e^{-\frac{bt}{2m}} e^{it\sqrt{\frac{k}{m}}}$$

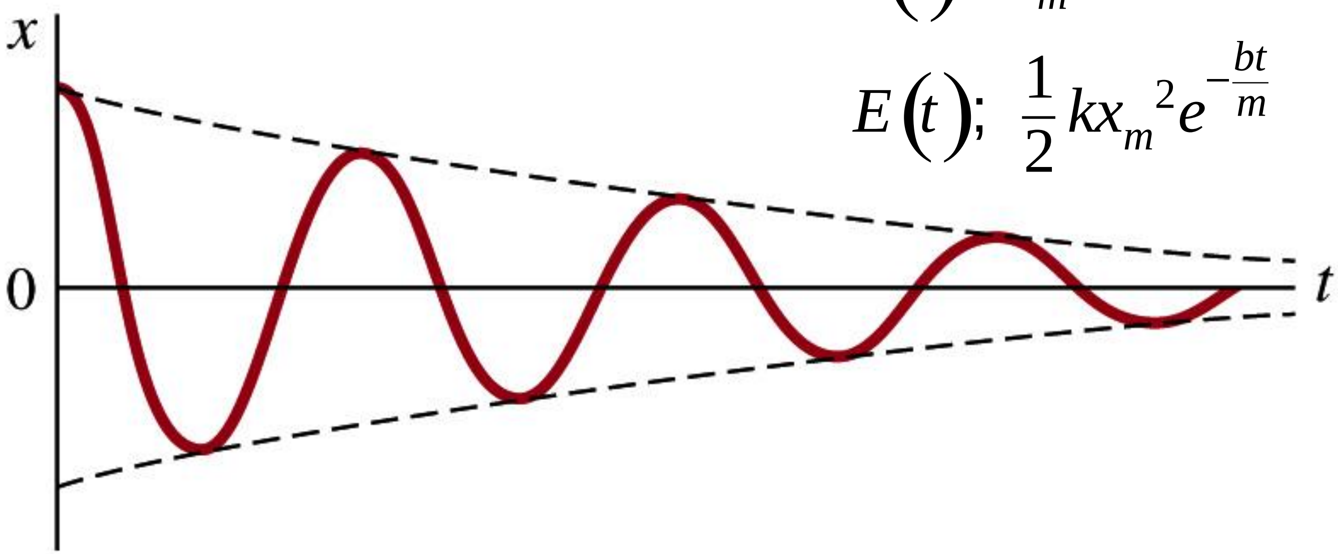
SHM Term

Damping Term

Damped Harmonic Motion.

$$x(t);\ x_m e^{-\frac{bt}{2m}} e^{it\sqrt{\frac{k}{m}}}$$

$$E(t);\ \frac{1}{2} k x_m{}^2 e^{-\frac{bt}{m}}$$



The general solution contains a SHM term,
with an amplitude that decreases as function of time

Driven Harmonic Motion.

- Consider what happens when we apply a time-dependent force $F(t)$ to a system that normally would carry out SHM with an angular frequency ω_0.

- Assume the external force $F(\mathrm{t}) = mF_0\sin(\omega t)$. The equation of motion can now be written as

$$\frac{d^2x}{dt^2} = -\omega_0{}^2 x + F_0 \sin(\omega t)$$

- The steady state motion of this system will be harmonic motion with an angular frequency equal to the angular frequency of the driving force.

Driven Harmonic Motion.

- Consider the general solution

$$x(t) = A\cos(\omega t + \phi)$$

- The parameters in this solution must be chosen such that the equation of motion is satisfied. This requires that

$$-\omega^2 A\cos(\omega t + \phi) + \omega_0{}^2 A\cos(\omega t + \phi) - F_0 \sin(\omega t) = 0$$

- This equation can be rewritten as

$$\left(\omega_0{}^2 - \omega^2\right) A\cos(\omega t)\cos(\phi) - \left(\omega_0{}^2 - \omega^2\right) A\sin(\omega t)\sin(\phi) - F_0 \sin(\omega t) = 0$$

Driven Harmonic Motion.

- Our general solution must thus satisfy the following condition:

$$\left(\omega_0{}^2 - \omega^2\right)A\cos\left(\omega t\right)\cos\left(\phi\right) - \left\{\left(\omega_0{}^2 - \omega^2\right)A\sin\left(\phi\right) - F_0\right\}\sin\left(\omega t\right) = 0$$

- Since this equation must be satisfied at all time, we must require that the coefficients of cos(ωt) and sin(ωt) are 0. This requires that

$$\left(\omega_0{}^2 - \omega^2\right)A\cos\left(\phi\right) = 0$$

and

$$\left(\omega_0{}^2 - \omega^2\right)A\sin\left(\phi\right) - F_0 = 0$$

Driven Harmonic Motion.

- The interesting solutions are solutions where $A \neq 0$ and $\omega \neq \omega_0$. In this case, our general solution can only satisfy the equation of motion if

$$\cos(\phi) = 0$$

and

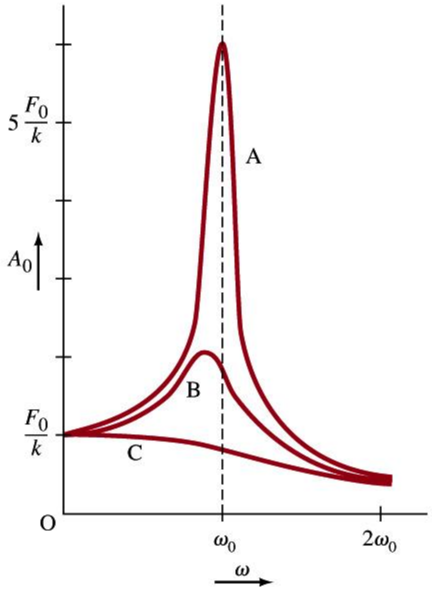
$$\left(\omega_0{}^2 - \omega^2\right) A \sin(\phi) - F_0 = \left(\omega_0{}^2 - \omega^2\right) A - F_0 = 0$$

- The amplitude of the motion is thus equal to

$$A = \frac{F_0}{\left(\omega_0{}^2 - \omega^2\right)}$$

Driven Harmonic Motion.

- If the driving force has a frequency close to the natural frequency of the system, the resulting amplitudes can be very large even for small driving amplitudes. The system is said to be in resonance.
- In realistic systems, there will also be a damping force. Whether or not resonance behavior will be observed will depend on the strength of the damping term.



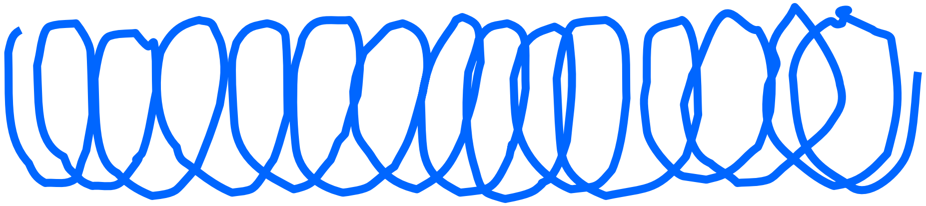
Waves

- https://www.youtube.com/watch?v=7cDAYFTXq3E

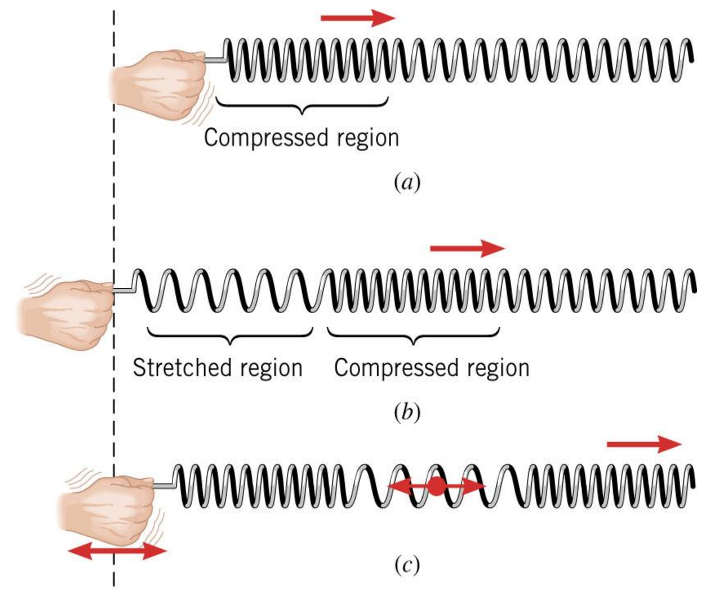
transverse wave on a string

- jiggle the end of the string to create a disturbance
- the disturbance moves down the string
- as it passes, the string moves up and then down
- the string motion in vertical but the wave moves in the horizontal (perpendicular) direction➔ transverse wave
- this is a single pulse wave (non-repetitive)
- the "wave" in the football stadium is a **transverse wave**

Slinky waves



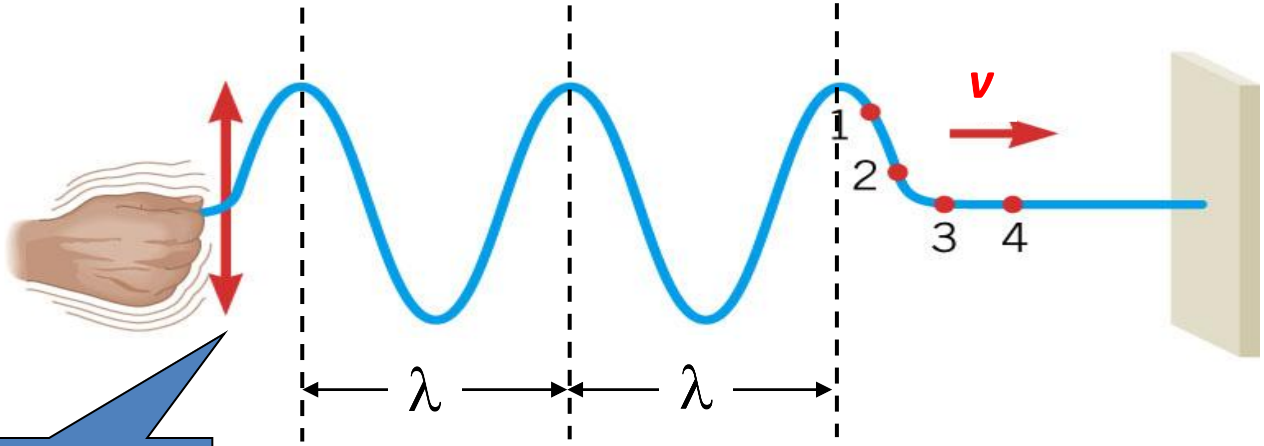
- you can create a **longitudinal** wave on a slinky
- instead of jiggling the slinky up and down, you jiggle it in and out
- the coils of the slinky move along the same direction (horizontal) as the wave



Cutnell & Johnson
Wiley Publishing
Physics 5th Ed.
Figure 16.03 (W574)
C M Y K

Harmonic waves

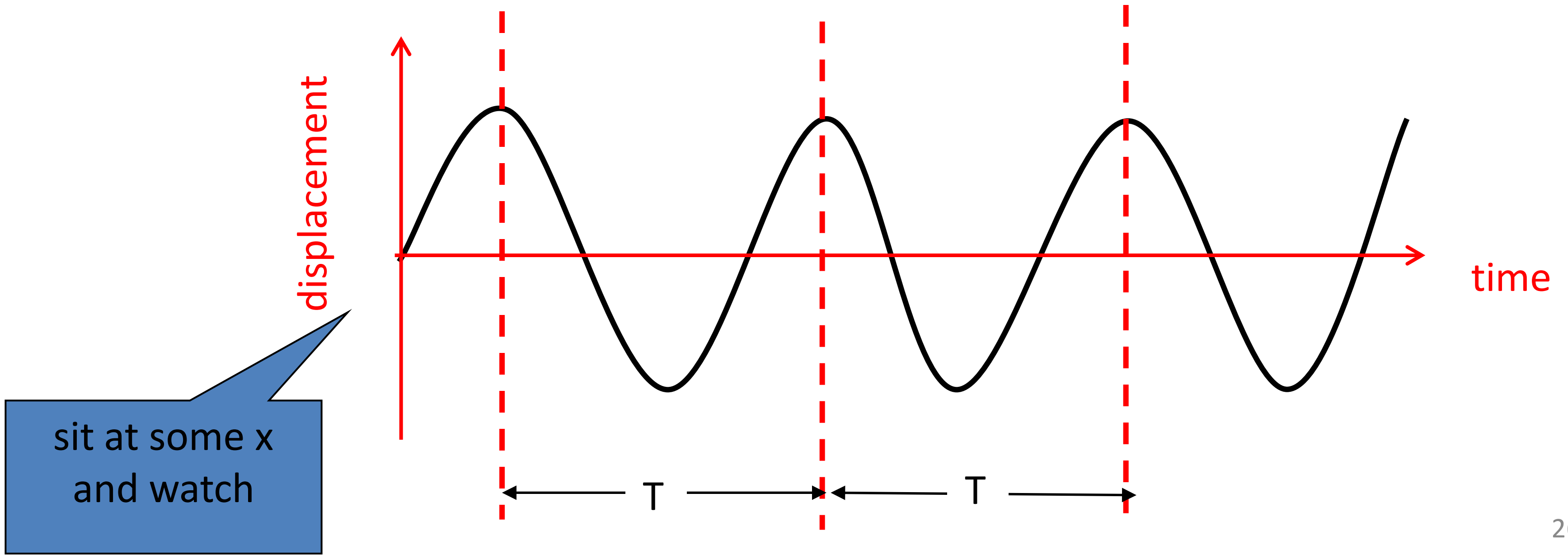
- continually jiggle the end of the string up and down
- each segment of the string undergoes simple harmonic motion and the disturbance (wave) moves with speed *v*
- the distance between successive peaks is called the WAVELENGTH, λ (lambda) measured in m or cm



snapshot of the string at some time

watching the waves go by

- suppose we keep watching one segment of the string as the wave goes by and then make a plot of its motion
- the time between the appearance of a new wave crest is the PERIOD of the wave, T
- the number of wave crests that pass by every second is the wave frequency, $f = 1/T$



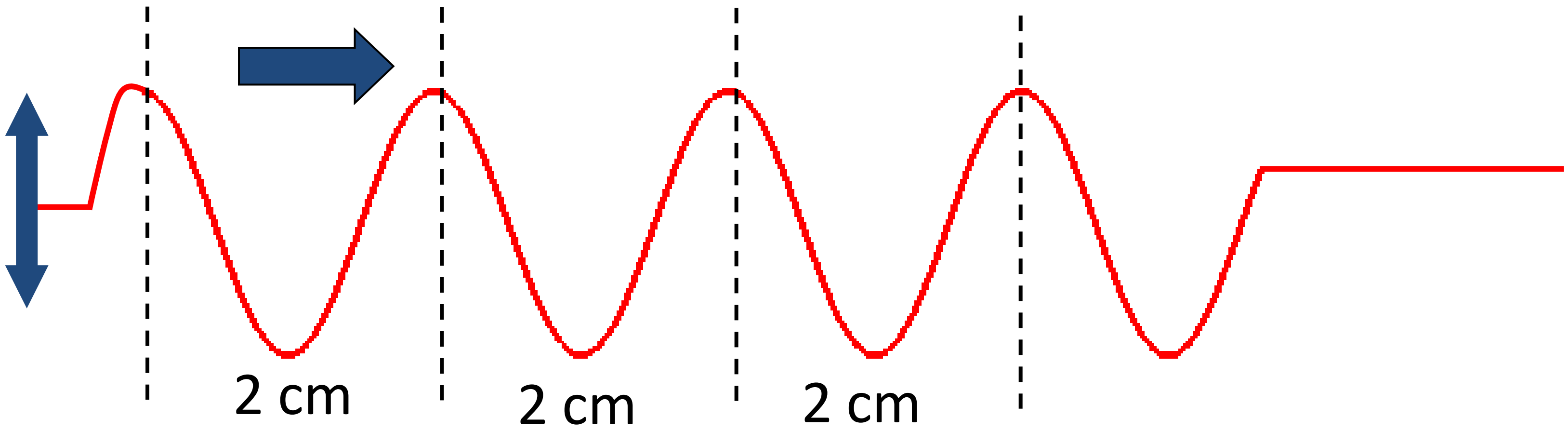
The golden rule for waves

- the speed of propagation of the wave (v), the wavelength (λ), and period (T) are related
- distance = speed x time → $\lambda = v\,T = v / f$
- The wavelength = wave speed / frequency

or → $v = \lambda \times f$ ← (golden rule)

- **Wave speed** = **wavelength** × **frequency**
- This applies to all waves → water waves, waves on strings, sound, radio, light . .
- This rule is important for understanding how musical instruments work

Example: wave on a string



- A wave moves on a string at a speed of 4 cm/s
- A snapshot of the motion reveals that the wavelength(λ) is 2 cm, what is the frequency (f)?
- v = $\lambda \times f$, so f = v / λ = (4 cm/s) / (2 cm) = 2 Hz

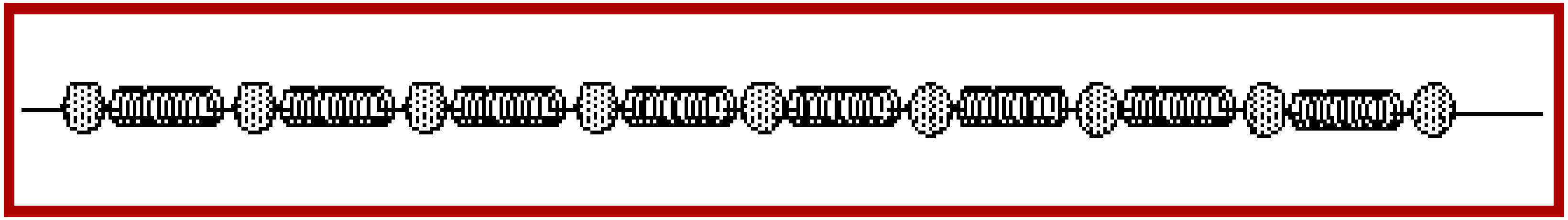
Standing waves

- At the NODE positions, the string does not move
- At the ANTINODES the string moves up and down harmonically
- Only certain wavelengths can fit into the distance L
- The frequency is determined by the velocity and mode number (wavelength)

Vibration frequencies

- In general, $f = v / \lambda$, where v is the propagation speed of the string
- The propagation speed depends on the diameter and tension
- Modes
  - Fundamental: $f_o = v / 2L$
  - First harmonic: $f_1 = v / L = 2 f_o$

Longitudinal waves



- **Longitudinal waves have vibrations moving in the same direction that the wave is travelling in**
- **Examples of longitudinal waves are:**

  Sound waves (in solids, liquids and gases)

  Shock waves (e.g. seismic waves)

  A slinky (when plucked)

Acoustic Waves

Acoustic wave: A longitudinal wave that (a) consists of a sequence of pressure pulses or elastic displacements of the material, whether gas, liquid, or solid, in which the wave propagates. In solids, the wave consists of a sequence of elastic compression and expansion waves that travel though the solid.

In acoustic wave devices acoustic waves are transmitted on a miniature solid substrate.

In a crystalline solid a sound wave is transmitted as a result of the displacement of the lattice points about their mean position. The wave is transmitted as an elastic wave. (Elastic substance is able to return to its original shape or size after being pulled or pressed out).

The term *sound wave* is sometimes confined to waves with the frequency falling within the audible range of the human ear, i. e. from about 20 Hz to 20 kHz. Waves of frequency greater than 20 kHz are *ultrasonic waves*. Waves of frequency 10^9–10^{13} Hz are called *hypersonic waves*.

Acoustic Waves

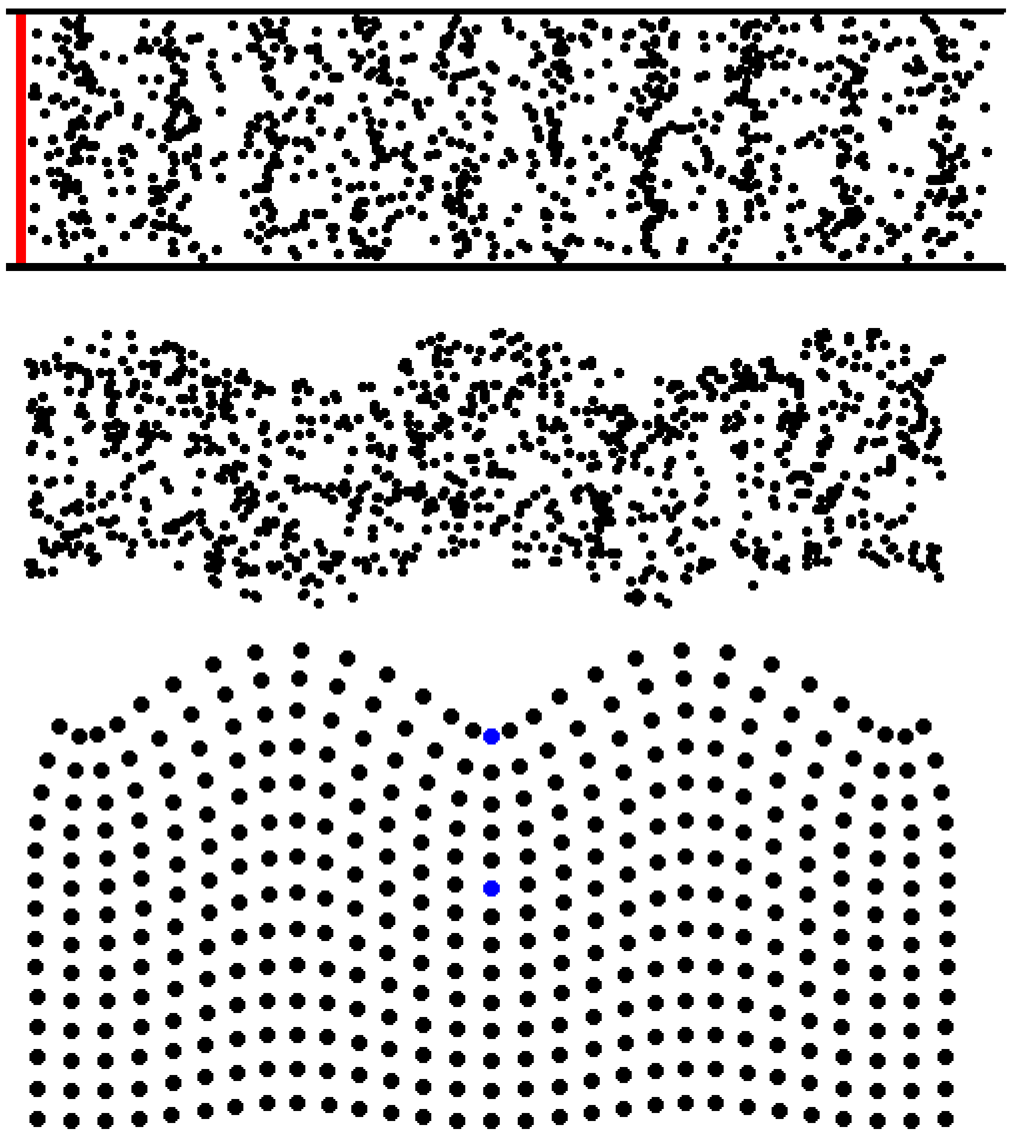
There are various kinds of acoustic waves. *Bulk acoustic waves* are acoustic waves propagated through the bulk substrate material.

If the motions of the matter particles conveying the wave are perpendicular to the direction of propagation of the wave itself, we have a *transverse* wave.

If the motion of particles is back and forth along the direction of propagation, we have a *longitudinal* wave.

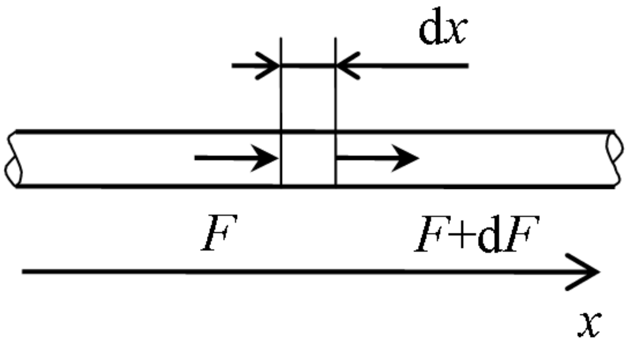
Surface acoustic waves propagate along the surface of a substrate. There are some types of the surface acoustic waves. In the case of the Rayleigh waves particles in the surface layer move both up and down and back and forth tracing out elliptical paths.

Acoustic waves



Acoustic Waves

Let us consider that longitudinal vibrations are excited in a rod.



$$\mathrm{d}m = \rho S\,\mathrm{d}x \qquad \mathrm{d}F = \frac{\partial F}{\partial x}\mathrm{d}x$$

$$a = \frac{\mathrm{d}^2 s}{\mathrm{d}t^2} = \frac{\mathrm{d}F}{\mathrm{d}m} = \frac{1}{\rho S}\frac{\partial F}{\partial x}$$

Hooke's law: $\dfrac{\mathrm{d}s}{\mathrm{d}x} = \dfrac{F}{ES}$ $\qquad \dfrac{\partial F}{\partial x} = ES\dfrac{\partial^2 s}{\partial x^2}$

$$\frac{\partial^2 s}{\partial t^2} = \frac{E}{\rho}\frac{\partial^2 s}{\partial x^2}$$

$$\underline{s}(x,t) = A\exp[\mathrm{j}\omega(t - x/v_1)] + B\exp[\mathrm{j}\omega(t + x/v_1)]$$

$$v_1 = \sqrt{E/\rho} \qquad \underline{\sigma} = E\frac{\partial \underline{s}}{\partial x}.$$

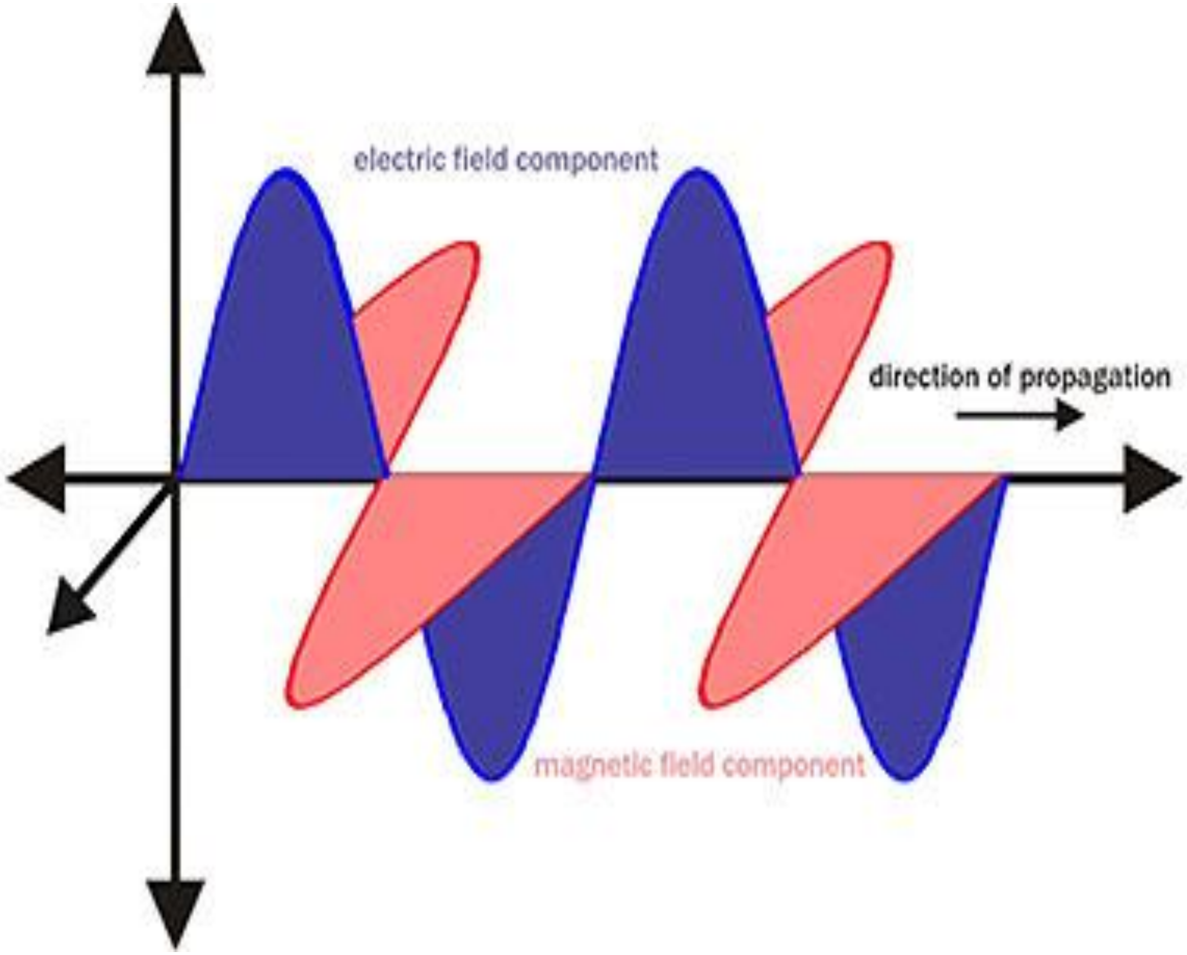
Here s is displacement; σ is stress.

Electromagnetic Radiation

- Light is electromagnetic radiation

- **Electromagnetic radiation** is a fundamental phenomenon of electromagnetism, behaving as waves propagating through space, and also as photon particles traveling through space, carrying radiant energy.

Electromagnetic Waves



Fresnel equations

TE waves	***TM waves***

Get all in terms of E and apply law of reflection ($\theta_i = \theta_r$):

TE waves:

$$E_i + E_r = E_t$$

$$n_i E_i \cos\theta_i - n_i E_r \cos\theta_i = n_t E_t \cos\theta_t$$

TM waves:

$$n_i E_i + n_i E_r = n_t E_t$$

$$-E_i \cos\theta_i + E_r \cos\theta_i = -E_t \cos\theta_t$$

<u>For reflection:</u> eliminate E_t, separate E_i and E_r, and take ratio:

$$r_{TE} = \frac{E_r}{E_i} = \frac{\cos\theta_i - \frac{n_t}{n_i}\cos\theta_t}{\cos\theta_i + \frac{n_t}{n_i}\cos\theta_t}$$

$$r_{TM} = \frac{E_r}{E_i} = \frac{\frac{n_t}{n_i}\cos\theta_i - \cos\theta_t}{\frac{n_t}{n_i}\cos\theta_i + \cos\theta_t}$$

Apply law of refraction $n_i \sin\theta_i = n_t \sin\theta_t$ **and let** $n = \dfrac{n_t}{n_i}$**:**

$$r_{TE} = \frac{\cos\theta_i - \sqrt{n^2 - \sin^2\theta_i}}{\cos\theta_i + \sqrt{n^2 - \sin^2\theta_i}}$$

$$r_{TM} = \frac{n^2\cos\theta_i - \sqrt{n^2 - \sin^2\theta_i}}{n^2\cos\theta_i + \sqrt{n^2 - \sin^2\theta_i}}$$

Fresnel equations

TE waves	*TM waves*

For transmission: eliminate E_r, separate E_i and E_t, take ratio…

$$t_{TE} = \frac{E_t}{E_i} = \frac{2\cos\theta_i}{\cos\theta_i + \sqrt{n^2 - \sin^2\theta_i}}$$

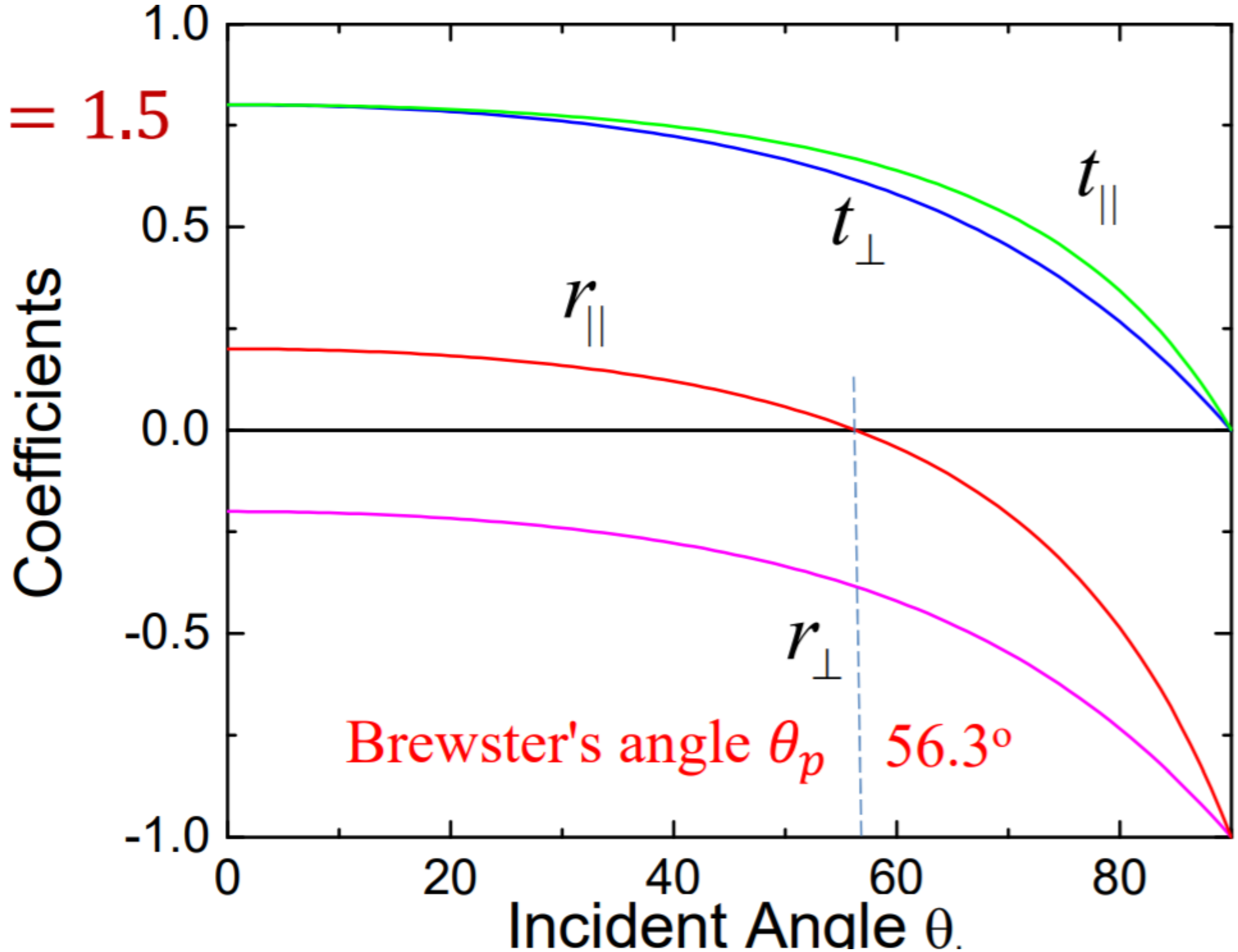
$$t_{TM} = \frac{E_t}{E_i} = \frac{2n\cos\theta_i}{n^2\cos\theta_i + \sqrt{n^2 - \sin^2\theta_i}}$$

And together:

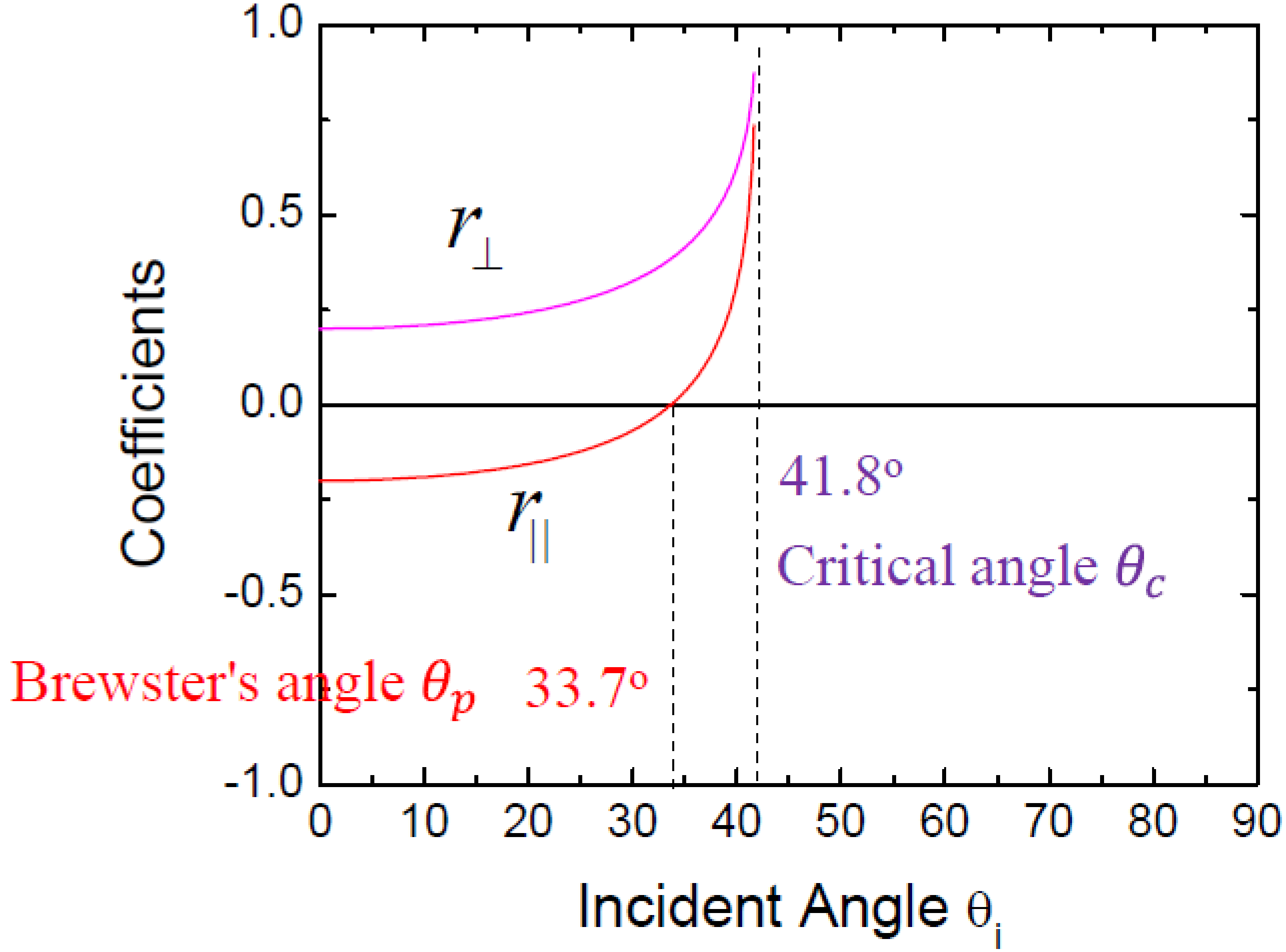
$$t_{TE} = 1 + r_{TE}$$

$$nt_{TM} = 1 - r_{TM}$$

$n_i = 1, n_t = 1.5$


1.0
0.5
0.0
-0.5
-1.0
Coefficients
0
20
40
60
80
Incident Angle θ
$t_{||}$
$t_{\perp}$
$r_{||}$
$r_{\perp}$
Brewster's angle θ_p 56.3°

$n_i = 1.5, n_t = 1$



1.0
0.5
0.0
-0.5
-1.0
Coefficients
$r_\perp$
$r_{||}$
41.8°
Critical angle θ_c
Brewster's angle θ_p 33.7°
0
10
20
30
40
50
60
70
80
90
Incident Angle θ_i

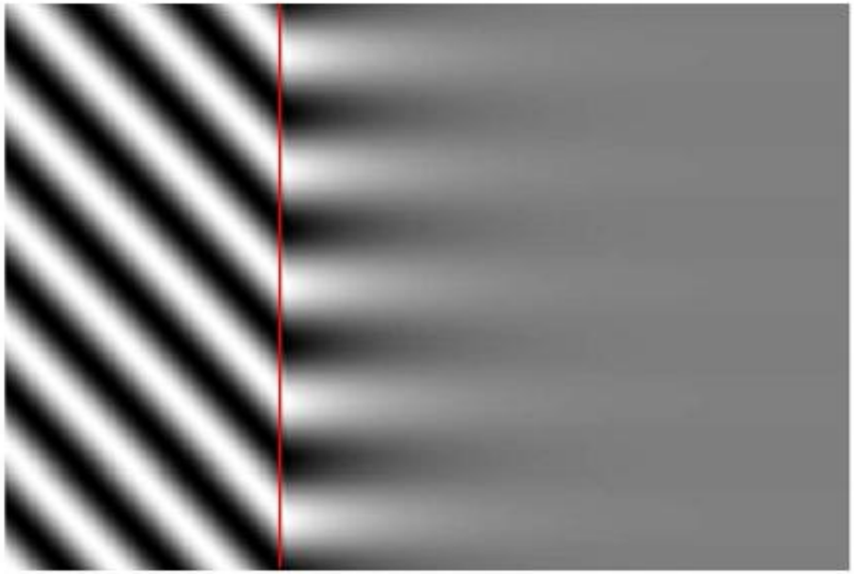
Brewster's angle

or the *polarizing* angle

is the angle θ_p, at which R_{TM} = 0: $\theta_p = \tan^{-1}(n) = \tan^{-1}\frac{n_2}{n_1}$

The Evanescent Wave

The evanescent wave decays exponentially in the transverse direction.



Future Scope and relevance to industry

Research based on:

- https://www.scirp.org/journal/articles.aspx?searchCode=+Simple+Harmonic+Motion&searchField=keyword&page=1
- https://www.researchgate.net/publication/320124852_A_Case_Study_on_Simple_Harmonic_Motion_and_Its_Application
- http://iopscience.iop.org/article/10.1088/1742-6596/901/1/012123/pdf