AC Circuits and Electromagnetic Waves

Physics 102
Lecture 5
7 March 2002

MIDTERM
Wednesday, March 13, 7:30-9:00 pm, this room
Material: through next week—AC circuits
Next week: no lecture, no labs, no quiz
Any Cyclists Here?

- How about Bike New York?
- 43 Miles through all five boroughs.
- Sunday, May 5, 2002
- Leave from U-store parking lot, 4 am!!!
- See http://www.bikenewyork.org/
- Email me if interested - groth@physics.princeton.edu
Capacitive Reactance

- A resistor has a value that is independent of frequency. Ohm’s law: $V = IR$

- For a capacitor, $V = IX_C$, where $X_C = \frac{1}{2\pi fC}$ is the capacitive reactance where $V$ and $I$ are $\text{rms}$ values:

$$\sqrt{\frac{1}{V_0^2}}$$

- A capacitor thus acts as a small resistance to a high frequency AC signal, and a large resistance to a low frequency signal (and completely blocks DC signals, for which $f=0$).
A light bulb, resistor, and capacitor are powered by a 10 V AC generator that can run at different frequencies.

A. The lightbulb is brightest at low frequencies.
B. The lightbulb never lights up.
C. The lightbulb is brightest at high frequencies.
D. The intensity is the same at both high and low frequencies.
Capacitors vs Resistors

In a resistor, the current and voltage are in phase with each other.

In a capacitor, the current **leads** the voltage by 90 degrees.

Instantaneous

\[ Q = CV \]

(not rms)

\[ I = \frac{\Delta Q}{\Delta t} = C \frac{\Delta V}{\Delta t} \]

The dissipated power is VI. In a capacitor, the average of VI is ZERO so there is no power dissipation.
Inductive Reactance

For an inductor, $V = IX_L$, where the inductive reactance

$$X_L = 2\pi f L$$

An inductor thus presents a large resistance to a high frequency AC voltage and a small resistance to a low frequency AC voltage.

In an inductor, the current lags the voltage by 90 degrees.

There is also no power dissipated in an inductor because the current and voltage are 90 degrees out of phase.
In the circuit below, the switch is closed at time $t=0$...

...after which:

A. First light B comes on followed by light A.

B. Lights A and B come on at the same time.

C. Light A never comes on because the inductor impedes the current.

D. Light B goes out because the inductor acts just like a wire if one waits a long enough time.
OLD FASHIONED MNEMONIC

ELI       the      ICE     man
INDUCTOR   CAPACITOR
EMF        CURRENT   CURRENT   EMF
leads      leads
RLC Circuits and Resonance

In simple circuits containing R, L, and C, energy can be “sloshed” back and forth between the L and C (while the R dissipates it).

This occurs because of the phase relations between V and I in L and C.

When \( f = \frac{1}{2\pi \sqrt{LC}} \) the “sloshing” is maximum and we say we are at resonance. \( X_L = X_C \)

\[
V_{rms} = I_{rms} Z
= I_{rms} \sqrt{R^2 + (X_L - X_C)^2}
\]
The circuit below is run at resonance. Lights A and B are on but light C is not because:

A. The bulb is dead.

B. The net impedance of the parallel resonance circuit is small so no current flows.

C. Only a little current flows through this path because we are at resonance.

If we now unplug bulb B

A. Light C remains unchanged

B. Light C lights up.
Maxwell’s Equations

Don’t panic: for culture only!

Gauss’ law \[ \sum E \cos \phi \Delta A = \frac{Q}{\varepsilon_0} \Rightarrow \int \int_A E \cdot dA = \frac{Q}{\varepsilon_0} \]

Magnetic poles come in pairs

Faraday’s law \[ EMF = -\frac{\Delta (BA \cos \phi)}{\Delta t} \Rightarrow \oint_l E \cdot dl = -\frac{d\Phi_B}{dt} \]

Ampere’s law \[ \sum B_l \Delta l = \mu_0 I \Rightarrow \oint_l B \cdot dl = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 I \]
Electromagnetic waves

- By examining the behavior of fields, Maxwell deduced that to Ampere’s law must be added a new term, the “displacement current.”
- He then predicted that light was made of electric and magnetic fields.
- He also predicted that electromagnetic waves of all frequencies travel with the same speed.

\[ v = c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 299792458 \text{ m/s} \]
Standing waves and the speed of light

Source is 200 MHz oscillator (based on a resonant circuit!)

$\nu = f\lambda = (2 \times 10^8 \text{Hz})(1.5 \text{ m}) = 3 \times 10^8 \text{ m/s}$
Properties of EM Radiation

\[ \lambda \text{ (m) } 10^3 \quad 10^{-2} \quad 10^{-4} \quad 10^{-7} \quad 10^{-9} \quad 10^{-11} \quad 10^{-14} \]

radio \quad infrared \quad ultraviolet \quad gamma-ray
microwave \quad visible \quad x-ray

\[ f \text{ (Hz) } 10^6 \quad 10^{11} \quad 10^{13} \quad 10^{15} \quad 10^{17} \quad 10^{19} \quad 10^{22} \]

- produced by oscillating charges
- transverse waves (perpendicular to direction of motion)
- \( \mathbf{B} \) is perpendicular to \( \mathbf{E} \)

If this is \( \mathbf{E} \) field, then \( \mathbf{B} \) oscillates into/out of page
The Doppler Effect for Light

A source and receiver of EM waves have relative speed \( u \). If the waves are emitted at frequency \( f_s \) with respect to the source, then

\[
fo \approx f_s \sqrt{1 \pm u/c} \approx f_s (1 \pm u/c)
\]

the observer sees with the top if the source and observer are approaching and bottom if they are receding from each other (and \( u \ll c \) for the last equation).

What happens if we receive both \( f_o \) and \( f_s \)?

NB. This is different from the Doppler effect for sound because E&M radiation does not need a medium in which to travel.
Polarization

Ordinary light is a mixture of light with two linear polarizations.

A polarizer, for example Polaroid, allows only one polarization to pass. Thus if the incident light is *unpolarized* with intensity $S_{\text{unpol}}$, the emerging light will have intensity $S_{\text{unpol}}/2$ and be *polarized*.

**Puzzler:**
Why, when two polarizers are “crossed” — so no light gets through—and a third is inserted between them, light gets through again?