WEL05 ELECTROMAGNETIC WAVES AND LIGHT

SPH4U

CH 10 (KEY IDEAS)

- describe polarized light in terms of its properties and behaviour and how it is applied in everyday applications
- explain single-slit diffraction and diffraction grating interference patterns, both qualitatively and quantitatively
- explain the operation of the spectroscope and the interferometer in terms of the wave properties of light
- describe how the wave properties of light are important in resolution of optical instruments and how these properties are applied in various applications of thin-film interference, for example: Newton’s rings, colours in thin films, coated surfaces, CDs, and DVDs
- explain the basic concepts holography
- describe electromagnetic waves in terms of their properties and where they belong in the electromagnetic spectrum

MAXWELL'S EQUATIONS

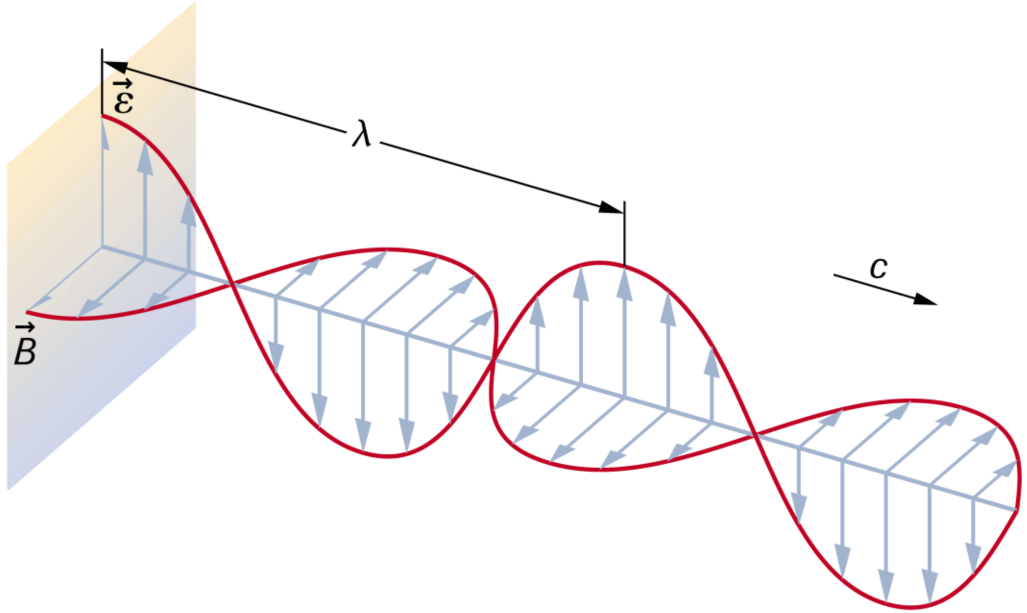
- Maxwell's equations of electromagnetism can be summarized as the following main ideas:
  1. **Gauss' Law** $\left(\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}\right)$**:** The distribution of electric charges in space (electric flux) produces an electric field.
  2. **Gauss' Law for Magnetism** $(\nabla \cdot \mathbf{B} = \mathbf{0})$**:** Magnetic field lines are continuous loops without beginning or end. Electric field lines, on the other hand, begin and end on electric charges.
  3. **Faraday's Law** $\left(\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}\right)$**:** A changing electric field produces a magnetic field.
  4. **Ampère's Law** $\left(\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}\right)$**:** A changing magnetic field produces an electric field.
- Note: the mathematical notation used in the equations is beyond the scope of this course and will <u>not</u> be tested. The differential form is shown.

EM WAVES AND LIGHT
WAVE CHARACTERISTICS

- Electromagnetic (EM) waves are produced whenever electric charges are accelerated
- The accelerated charge loses energy that is carried away in the electromagnetic wave
- If the electric charge is accelerated in <u>periodic motion</u>, the frequency of the electromagnetic waves produced is exactly equal to the frequency of oscillation of the charge.
- All electromagnetic waves
  - travel through a vacuum at a common speed ($c = 3.00 \times 10^{8}$ m/s)
  - obey the universal wave equation $c = f\lambda$

EM WAVES AND LIGHT
WAVE CHARACTERISTICS – CONT.

- Electromagnetic waves consist of electric and magnetic fields oscillating in phase, perpendicular to each other, and both at 90° to the direction of propagation of the wave, as depicted in the figure below.

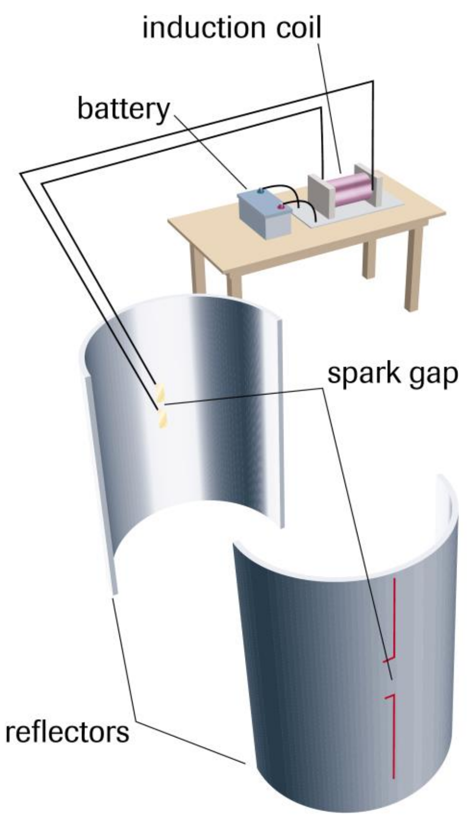


EM WAVES AND LIGHT
WAVE CHARACTERISTICS – CONT.

- Electromagnetic waves have the following properties:
  - Diffraction
  - Polarization
  - Refraction
- EM waves can also carry linear and angular momentum
- Recall: EM waves are called <u>plane-polarized</u> when the electric field vector is in only one plane
  - the plane of polarization is the plane containing all of the changing electric field vectors

ELECTROMAGNETIC WAVES

- **Hertz (Hz) [1/s]:** the SI unit for frequency, equivalent to "one cycle per second".
- **Radio Waves:** electromagnetic waves in the frequency range 10^4 to 10^{10} Hz; used in radio and TV transmission
- German physicist Heinrich Hertz generated electromagnetic waves using a spark gap, which causes electric charges to move quickly back and forth
- He called the waves radio waves, and concluded that they travel at the speed of light
- This led to the conclusion that visible light is a type of electromagnetic wave



THE ELECTROMAGNETIC SPECTRUM

Type of Radiation	Frequency Range	Origin of Radiation	Applications or Effects of Radiation
low frequency AC	60 Hz	weak radiation emitted from conductors of AC power	causes interference in radio reception when passing near high-voltage transmission lines
radio, radar, TV	$10^4 - 10^{10}$ Hz	oscillations in electric circuits containing inductive and capacitive components	transmission of radio and TV communication signals; ship and aircraft navigation by radar; reception of radio waves from space by radio telescopes; control of satellites, space probes, and guided missiles
microwaves	$10^9 - 10^{12}$ Hz	oscillating currents in special tubes and solid-state devices	long-range transmission of TV and other telecommunication information; cooking in microwave ovens
infrared	$10^{11} - 4 \times 10^{14}$ Hz	transitions of outer electrons in atoms and molecules	causes the direct heating effect of the Sun and other radiant heat sources; is used for remote sensing and thermography

THE ELECTROMAGNETIC SPECTRUM – CONT.

Type of Radiation	Frequency Range	Origin of Radiation	Applications or Effects of Radiation
ultraviolet	$8 \times 10^{14} - 10^{17}$ Hz	even higher energy transitions of outer electrons in atoms	causes fluorescence in some materials; causes "tanning" of human skin; kills bacteria; aids in the synthesis of vitamin D by the human body
X rays	$10^{15} - 10^{20}$ Hz	transitions of inner electrons of atoms or the rapid deceleration of high-energy free electrons	penetrate soft tissue easily but are absorbed by denser tissue, like bones and teeth, to produce X-ray images of internal body structures; used for radiation therapy and nondestructive testing in industry
gamma rays	$10^{19} - 10^{24}$ Hz	nuclei of atoms, both spontaneous and from the sudden deceleration of very high-energy particles from accelerators	treatment for localized cancerous tumours
cosmic rays	$> 10^{24}$ Hz	bombardment of Earth's atmosphere by very high-energy particles from space	responsible for auroras

PROBLEM 1

Microwaves with a wavelength of 1.5 cm are used to transmit television signals coast to coast, through a network of relay towers.

(a) What is the frequency of these microwaves?

(b) How long does it take a microwave signal to cross the continent from St. John's, Newfoundland, to Victoria, British Columbia, a distance of approximately 5.0×10^3 km?

PROBLEM 1 – SOLUTIONS

(a) $\lambda = 1.5 \text{ cm}$

$v = c = 3.00 \times 10^8 \text{ m/s}$

$f = ?$

$$f = \frac{c}{\lambda}$$

$$= \frac{3.00 \times 10^8 \text{ m/s}}{1.5 \times 10^{-2} \text{ m}}$$

$$f = 2.0 \times 10^{10} \text{ Hz}$$

The frequency is 2.0×10^{10} Hz.

(b) $\Delta d = 5.0 \times 10^3 \text{ km} = 5.0 \times 10^6 \text{ m}$

$\Delta t = ?$

$$\Delta d = v\Delta t$$

$$= c\Delta t$$

$$\Delta t = \frac{\Delta d}{c}$$

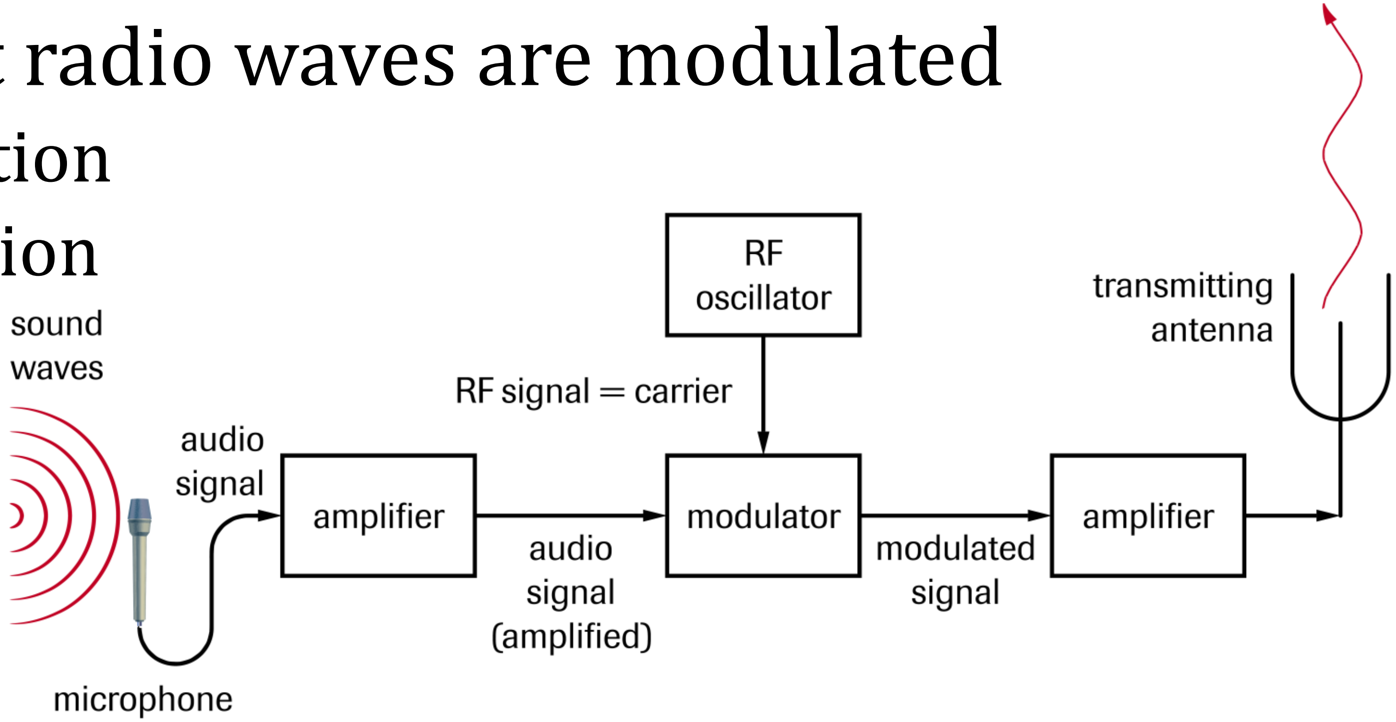
$$= \frac{5.0 \times 10^6 \text{ m}}{3.0 \times 10^8 \text{ m/s}}$$

$$\Delta t = 1.6 \times 10^{-2} \text{ s}$$

The time required is 1.6×10^{-2} s.

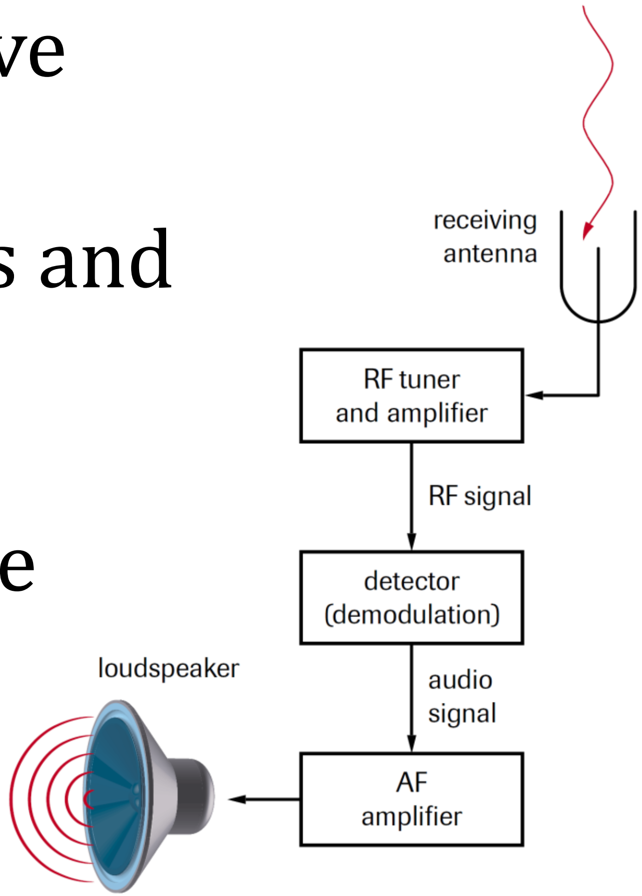
SOME APPLICATIONS OF EM WAVES: RADIO AND TV COMMUNICATIONS

- Sound waves are converted to radio waves using a modulator and are transmitted by antenna
- There are two ways that radio waves are modulated
  - AM – amplitude modulation
  - FM – frequency modulation
    - Uses radio frequency oscillator



SOME APPLICATIONS OF EM WAVES: RADIO AND TV COMMUNICATIONS

- A receiving antenna transfers the radio wave signals to the detector
- The detector "reads" the radio wave signals and sends out the corresponding sound waves (audio frequencies)
- The audio frequencies are finally sent to the loudspeaker



SOME APPLICATIONS OF EM WAVES: INFRARED

- Infrared waves are between microwaves and visible light (1.0×10^{11} to 4×10^{14} Hz)
- We feel infrared radiation as heat, even when we can't see it
  - For example, a stove element after it's no longer glowing red can still be hot
- Infrared detectors can produce full-colour pictures of the temperatures of an area
  - This is used in anything from military reconnaissance to charting areas of crop growth

SOME APPLICATIONS OF EM WAVES: LASER RADIATION

- **Recall:**
  - **Incoherent Light:** light of one or more wavelengths, out of phase (e.g., white light)
  - **Coherent Light:** light of one wavelength, in phase (e.g., laser light)
- Lasers are used in:
  - Surveying
  - Measuring distances
    - including extremely large ones – Earth to the Moon!
  - Measuring very small movements in the continents
  - Measuring very fast speeds
  - Modulated laser light is used in fibre optic cables
- Lasers can be made at a high enough intensity to cut through materials

SOME APPLICATIONS OF EM WAVES: ULTRAVIOLET RADIATION

- Ultraviolet (UV) light is at frequencies between visible light and X-rays, with frequencies ranging from 8.0×10^{14} to 1×10^{17} Hz
  - Also called “blacklight”, because it causes fluorescence in certain paints and minerals
- UV radiation is emitted by objects that are extremely hot
  - 7% of the Sun’s radiation is UV
- UV radiation is necessary for vitamin D production in humans, but too much can cause sunburn, potentially leading to cancer

SOME APPLICATIONS OF EM WAVES: IONIZING RADIATION

- **Ionizing Radiation:** radiation at the limit at which ionization can occur, at frequencies higher than ultraviolet
  - X-rays and gamma rays are ionizing
  - They cause atoms to release electrons, becoming ions
- Ionizing radiation can break up molecules, cause DNA mutations, or even cell death
- **Nonionizing Radiation:** radiation at or below the limit at which ionization can occur, at frequencies lower than ultraviolet
  - Any EM radiation at frequencies of UV or lower are nonionizing

SUMMARY – ELECTROMAGNETIC WAVES AND LIGHT

- Maxwell postulated and Hertz proved that light and all radiations travel as electromagnetic waves through space at the speed of light (3.00 108 m/s).
- Electromagnetic waves consist of electric and magnetic fields that oscillate in phase and perpendicular to each other and to the direction of wave propagation.
- Electromagnetic waves exhibit the properties of interference, diffraction, polarization, reflection, and refraction.
- The electromagnetic spectrum makes up all the radiations that originate from a source with a changing electric or magnetic field.
- The electromagnetic spectrum consists of radio waves (including microwaves), infrared waves, visible light, ultraviolet light, X rays, gamma rays, and cosmic rays.

SUMMARY – SOME APPLICATIONS OF ELECTROMAGNETIC WAVES

- Radio waves originate from an oscillating electric field in an antenna and involve a carrier wave modulated by an audio and/or a video wave.
- Infrared radiation originates from a hot object that radiates progressively higher frequency light as its temperature rises.
- Infrared radiation can be detected photographically and with infrared-sensitive cameras.
- Ultraviolet light has a high enough frequency that the rays can damage human tissue.
- The electromagnetic spectrum is further divided into two parts: ionizing and nonionizing radiation.
- By 1890, it was firmly established that light is an electromagnetic wave that travels at 3.00×10^8 m/s in a vacuum.

PRACTICE

Readings

- Section 10.8 (pg 530)
- Section 10.9 (pg 535)

Questions

- pg 534 #1-4
- pg 539 #1-3