EM Waves

From Faraday's law (Lenz) we saw that an EMF is generated in a conducting loop of fixed size and orientation, if the strength of the magnetic field varies with time

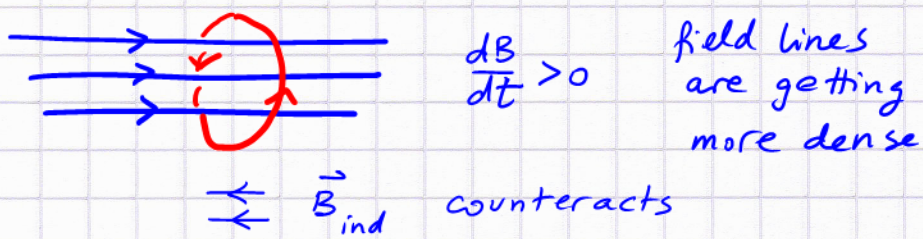
$$\Phi_M = B\,A\cos\vartheta \; : \quad \frac{dB}{dt} \rightarrow \frac{d\Phi_M}{dt} \rightarrow \mathcal{E}$$

Lenz: There is an induced current in the loop to generate an induced $\vec{B}$ field to counteract $\frac{d\Phi_M}{dt}$.

The EMF $\mathcal{E}$ responsible for the induced current is associated with an $\vec{E}$ field (otherwise no induced current) which is very different from previously discussed $\vec{E}$ fields:

Previously: $\vec{E}$ starts at $q>0$ charge and ends at $q<0$ charge

Here: $\vec{E}$ goes around in a loop without beginning and end.

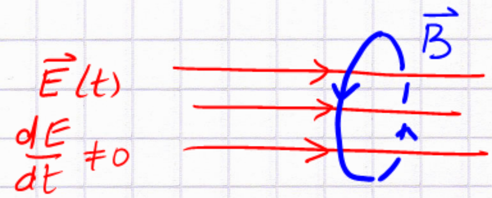


When the time variation is very rapid (high frequency begins at ~ 100 kHz = 10^5 Hz) it was found ~1900 by Hertz that this form of induction can happen over distances.

LC oscillator / receiver circuits can communicate at such and higher frequencies → the induced $\vec{E}$ field can exist in air (vacuum) without a conducting metal loop.

To fully understand the propagation of electric/magnetic fields one also had to figure out the following symmetry:

A time-varying $\vec{E}$ field surrounds itself with a circular $\vec{B}$ field.



Note: $\vec{E}$ generated from ϕ_M:
$\vec{E} \perp B$
and $\vec{B}$ generated from ϕ_E:
$\vec{B} \perp \vec{E}$

time varying ϕ_E through virtual loop $\rightarrow$ $\vec{B}$ is generated

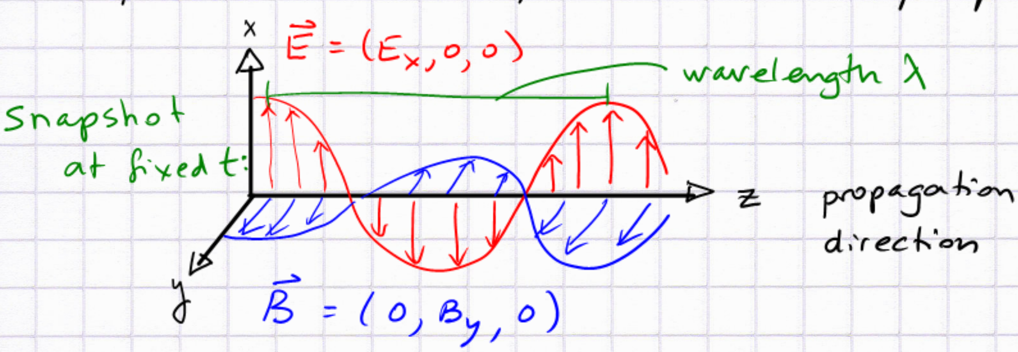
The symmetry:

$\frac{d}{dt}\phi_M \rightarrow \vec{E}$ Faraday law

$\frac{d}{dt}\phi_E \rightarrow \vec{B}$ (generalized Ampère law)

forms the basis for EM wave propagation through free space

see Fig. 23.3



$\vec{E}$ and $\vec{B}$ are in phase

$\vec{E} \times \vec{B} \sim \hat{k}$ propagation direction

$\boxed{\vec{E} \perp \hat{k} \text{ and } \vec{B} \perp \hat{k} \Rightarrow \text{transverse wave}}$

when such a wave encounters charges (e.g., bound electrons in glass)

$\longrightarrow$ $\vec{E}$ sets them in oscillatory motion

When a charge oscillates rapidly

$\rightarrow$ it gives off EM radiation with the oscillation frequency

antenna $\rightarrow$ radiowaves, microwaves

Characterization of an EM wave

1) shown above is a special form:

$\vec{E}, \vec{B}$ oscillate in fixed, perpendicular directions

→ linearly polarized EM wave

(lasers can produce such waves)

2) the wave is a very long train of regular oscillations

practical durations: nsec – laser
psec – laser
fsec → "short" pulse
atto second → ultra-short pulse
(Paul Corkum in Ottawa: world leader!)

3) many conventional light sources

- discharge lamp tube* (atomic transitions from excited to lower levels)

↳ nsec bursts of single frequency/wavelength light

(*) Contains a gas, e.g., H_2

apply a high voltage (dangerous → LAB# ? !)

electron breakdown current → dissociates $H_2 \to H + H$
+ excites H atoms

H(2p → 1s) is strong ultraviolet → filtered by glass

H(3d → 2p)
H(4f → 3d, or 4p → 3s) } well-defined colors

...

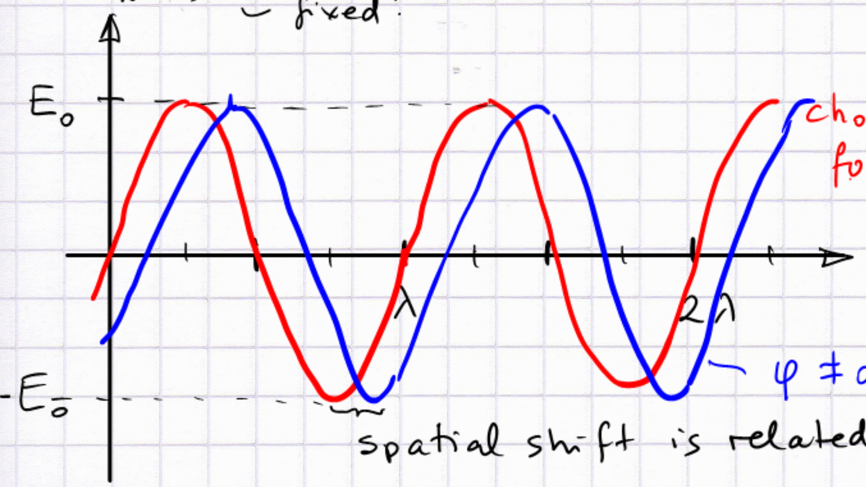
emission lines! → see Fig 29.7 p. 992!

Light from these sources → interference → wave model is needed!
(Michelson interferometer)

Two ways to look at the $\vec{E}_x$ field:

(1) spatial (fixed-time snapshot $t = t_0$) $E_x(t_0) = E_0 \sin\left(\frac{2\pi z}{\lambda} + \varphi\right)$

amplitude (E_0), wavelength (λ), phase (φ)



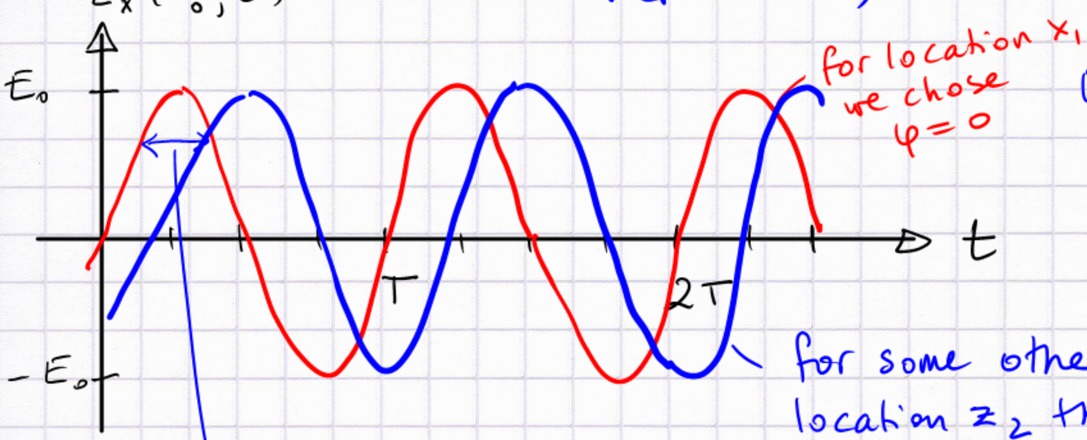
spatial shift is related to phase φ (which itself is dim. less) (radians)

For visible-light EM waves: $400\,nm < \lambda < 700\,nm$

short WL → UV (at 400 nm)

long WL → infrared (heat) (at 700 nm)

(2) temporal (fix location x_0, look how $E_x(z_0, t)$ changes over time)



$E_x(z_0, t) = E_0 \sin\left(2\pi \frac{t}{T} + \varphi\right)$

amplitude (E_0), period (T), phase (φ)

time delay is related to phase φ (φ is dimensionless)

Frequencies for visible light: hundreds of THz

Mega, Giga, Tera $= 10^{12}$

On dimensional grounds: the spatial (λ) and temporal (T, or $f = \frac{1}{T}$) properties are related by the propagation speed $c = 3.0 \times 10^8 \frac{m}{s}$

$$\boxed{\lambda \cdot f = c}$$