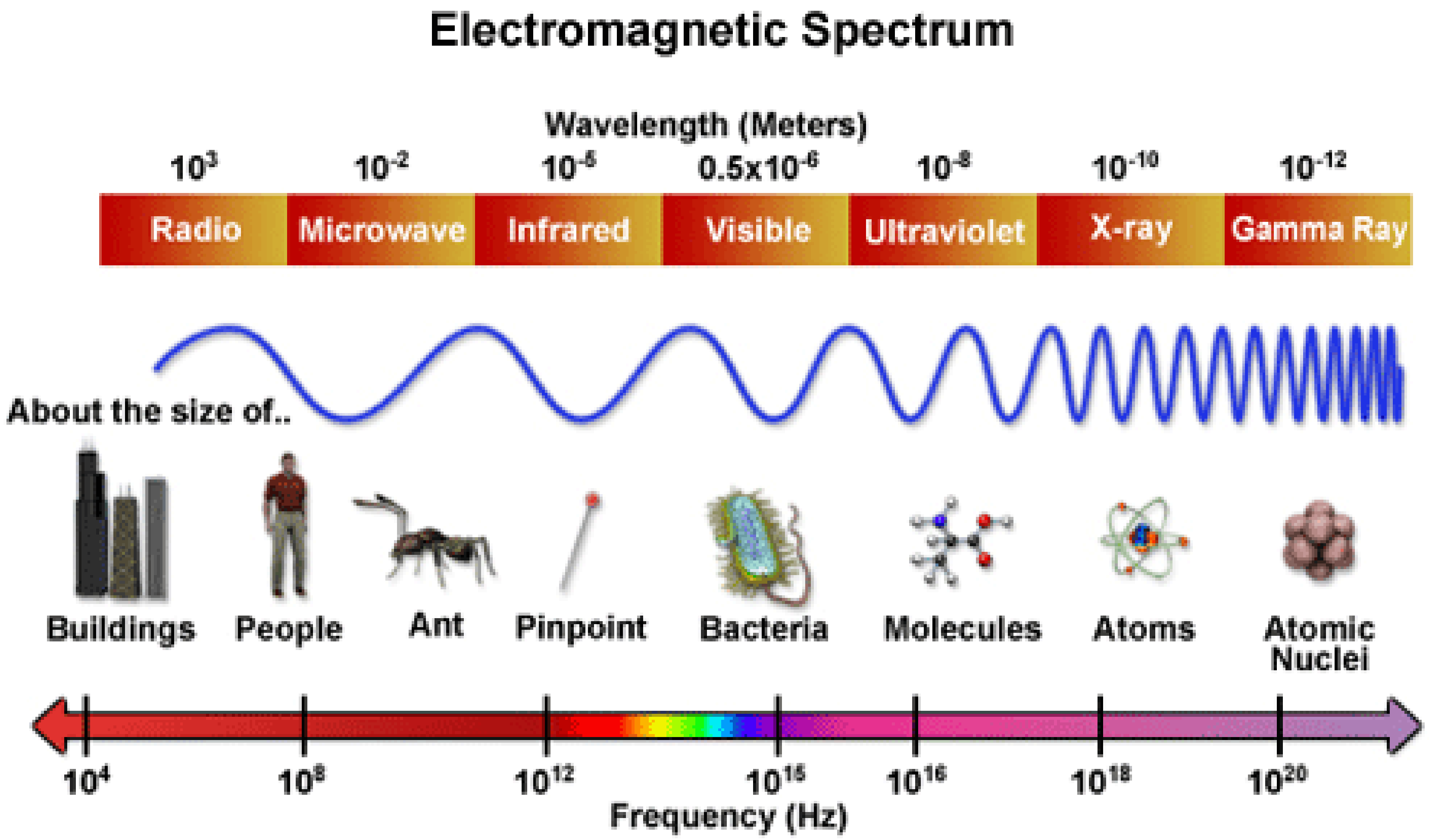
Class 17 Electromagnetic Waves (3/21/24)



UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

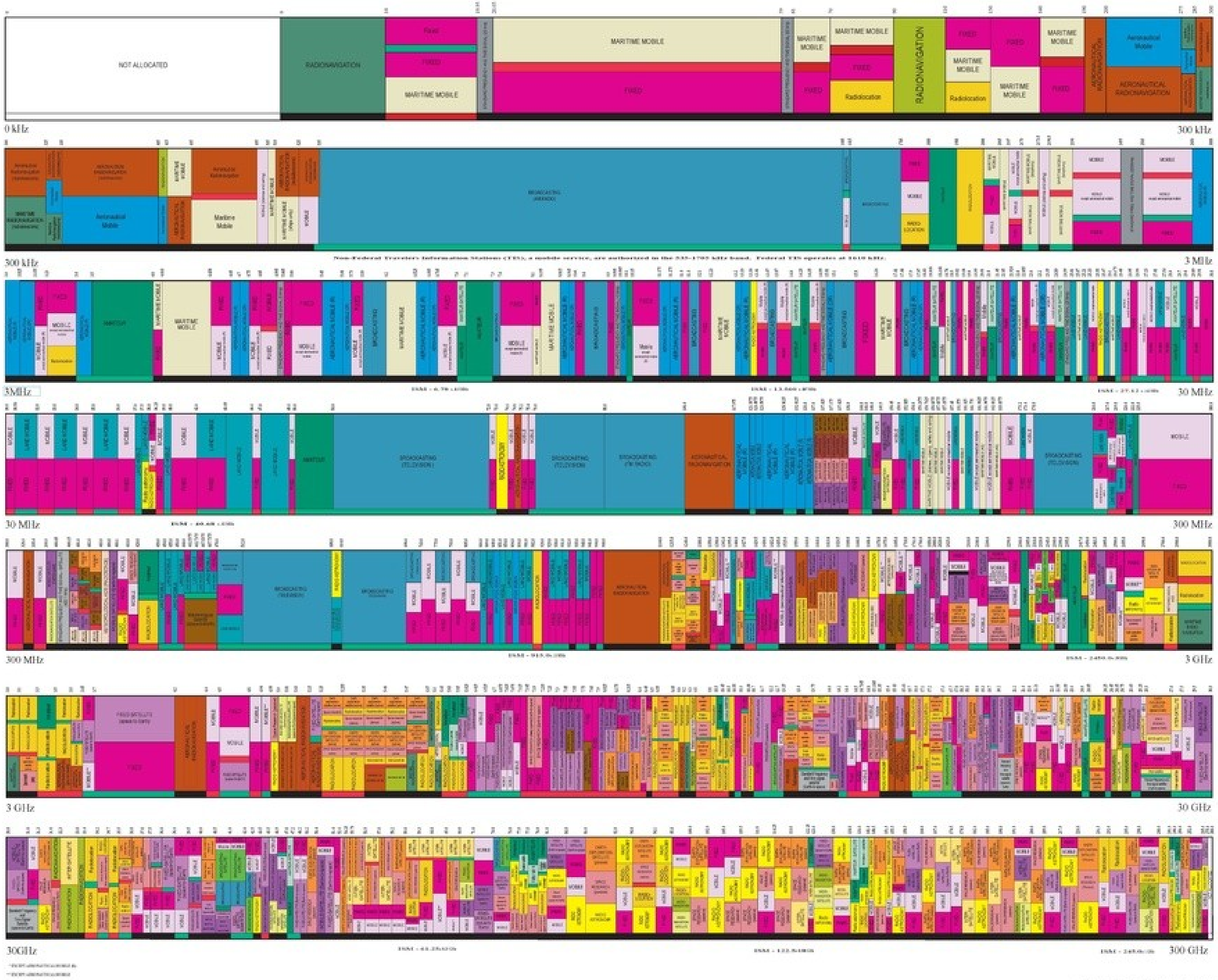
- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED
- NON-FEDERAL EXCLUSIVE

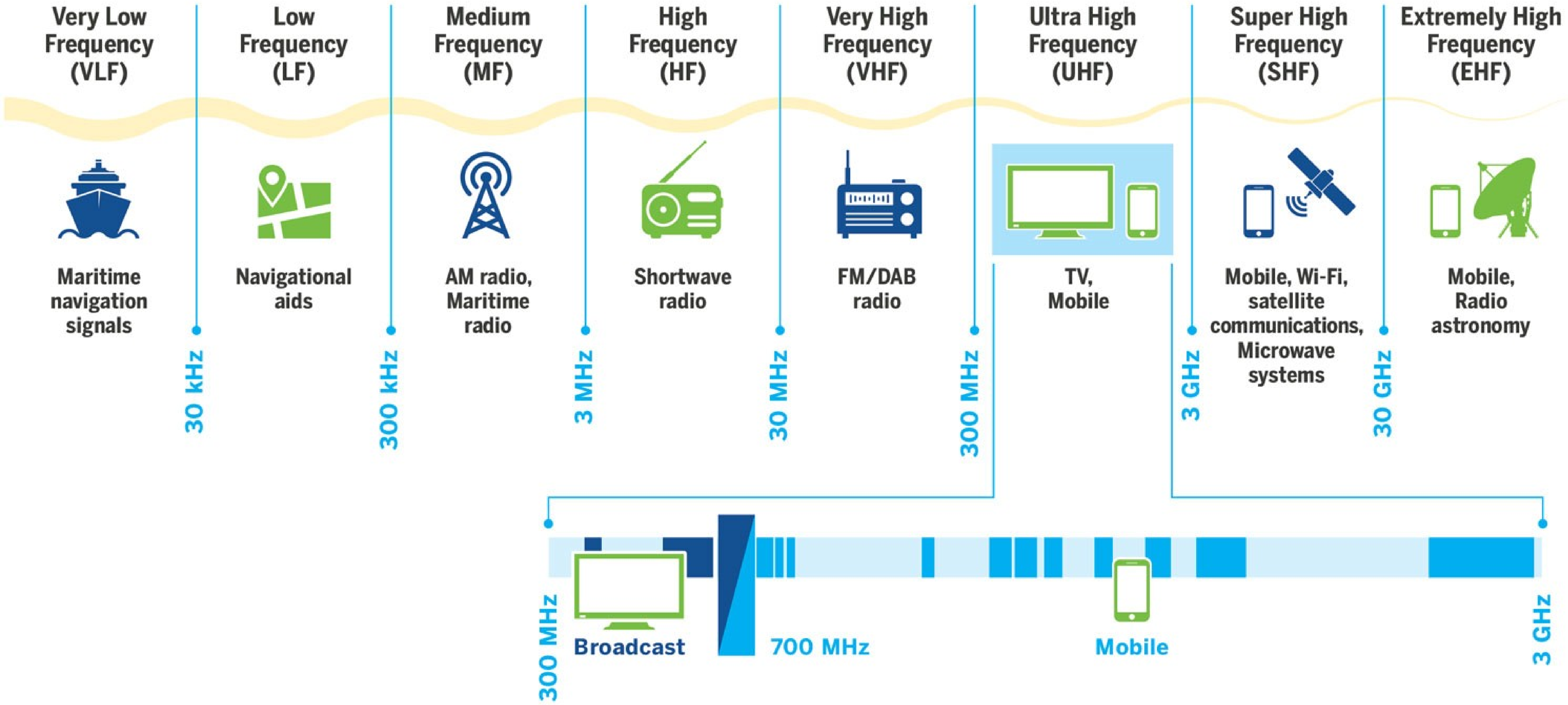
ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

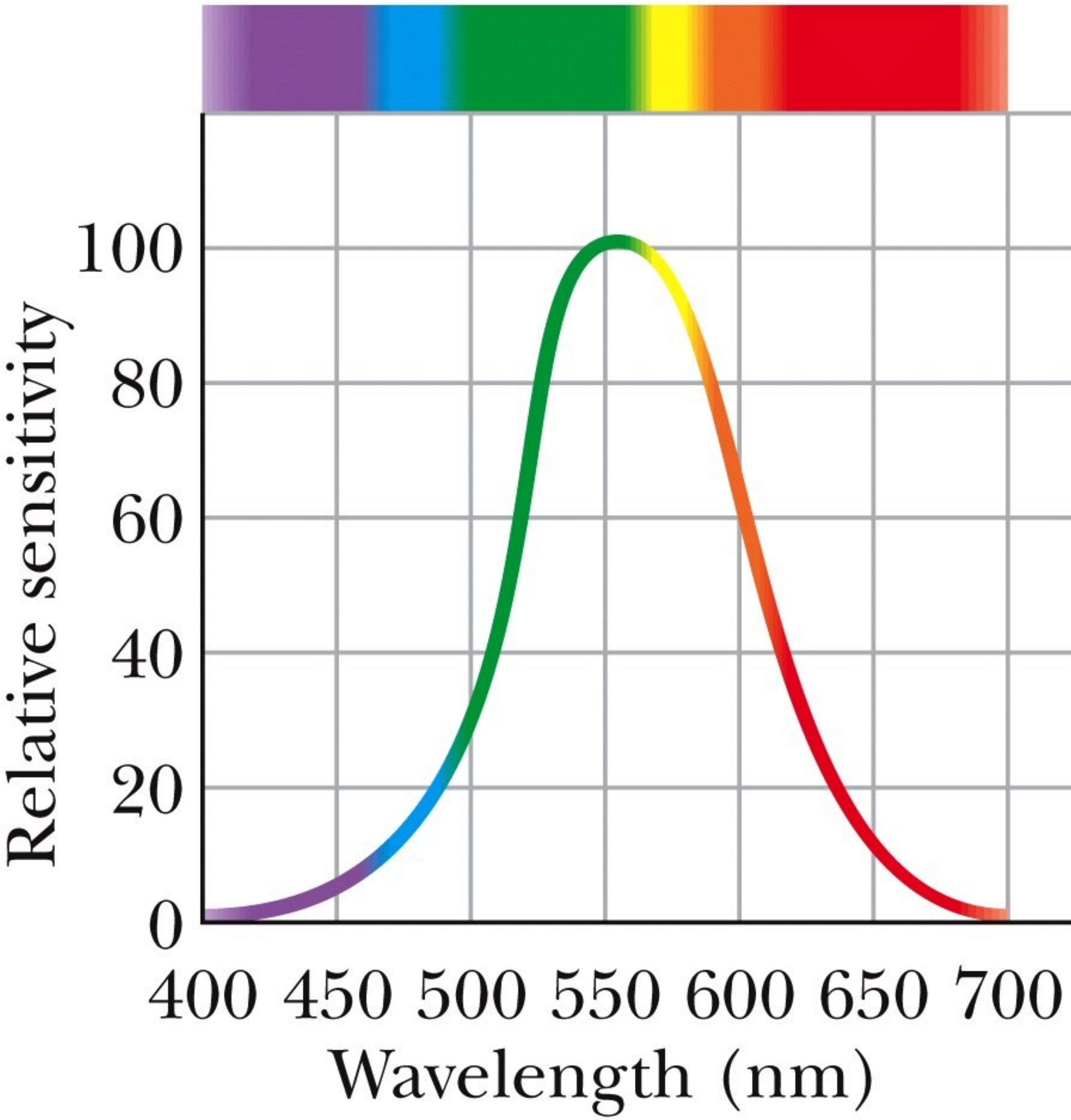
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

JANUARY 2016





Very Low Frequency (VLF)
Low Frequency (LF)
Medium Frequency (MF)
High Frequency (HF)
Very High Frequency (VHF)
Ultra High Frequency (UHF)
Super High Frequency (SHF)
Extremely High Frequency (EHF)
Maritime navigation signals
Navigational aids
AM radio, Maritime radio
Shortwave radio
FM/DAB radio
TV, Mobile
Mobile, Wi-Fi, satellite communications, Microwave systems
Mobile, Radio astronomy
30 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 MHz
Broadcast
700 MHz
Mobile
3 GHz



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As human beings we are outfitted with sensors (eyes) which detect electromagnetic waves between 400nm and 800nm. This the reason behind calling this spectral range the “Visible Light”.

9.2 Electromagnetic waves in vacuum

em waves travel through vacuum, corresponding set of Maxwell's eqs:

$$\vec{\nabla}\cdot\vec{E}=0\ ,\quad \vec{\nabla}\cdot\vec{B}=0\ ,\quad \vec{\nabla}\times\vec{E}=-\dot{\vec{B}}\ ,\quad \vec{\nabla}\times\vec{B}=\mu_0\varepsilon_0\frac{\partial\vec{E}}{\partial t}=\mu_0\varepsilon_0\dot{\vec{E}}$$

derivation of wave equation:

$$\vec{\nabla}\times\vec{\nabla}\times\vec{E}=-\vec{\nabla}\times\dot{\vec{B}}=-\mu_0\varepsilon_0\ddot{\vec{E}}$$

$$\vec{\nabla}\times\vec{\nabla}\times\vec{B}=\mu_0\varepsilon_0\vec{\nabla}\times\dot{\vec{E}}=-\mu_0\varepsilon_0\ddot{\vec{B}}$$

$$\vec{\nabla}(\vec{\nabla}\cdot\vec{E})-\vec{\nabla}^2\vec{E}=-\mu_0\varepsilon_0\ddot{\vec{E}}\quad\Rightarrow\quad\vec{\nabla}^2\vec{E}=\mu_0\varepsilon_0\ddot{\vec{E}}$$

$$\vec{\nabla}(\vec{\nabla}\cdot\vec{B})-\vec{\nabla}^2\vec{B}=-\mu_0\varepsilon_0\ddot{\vec{B}}\quad\Rightarrow\quad\vec{\nabla}^2\vec{B}=\mu_0\varepsilon_0\ddot{\vec{B}}$$

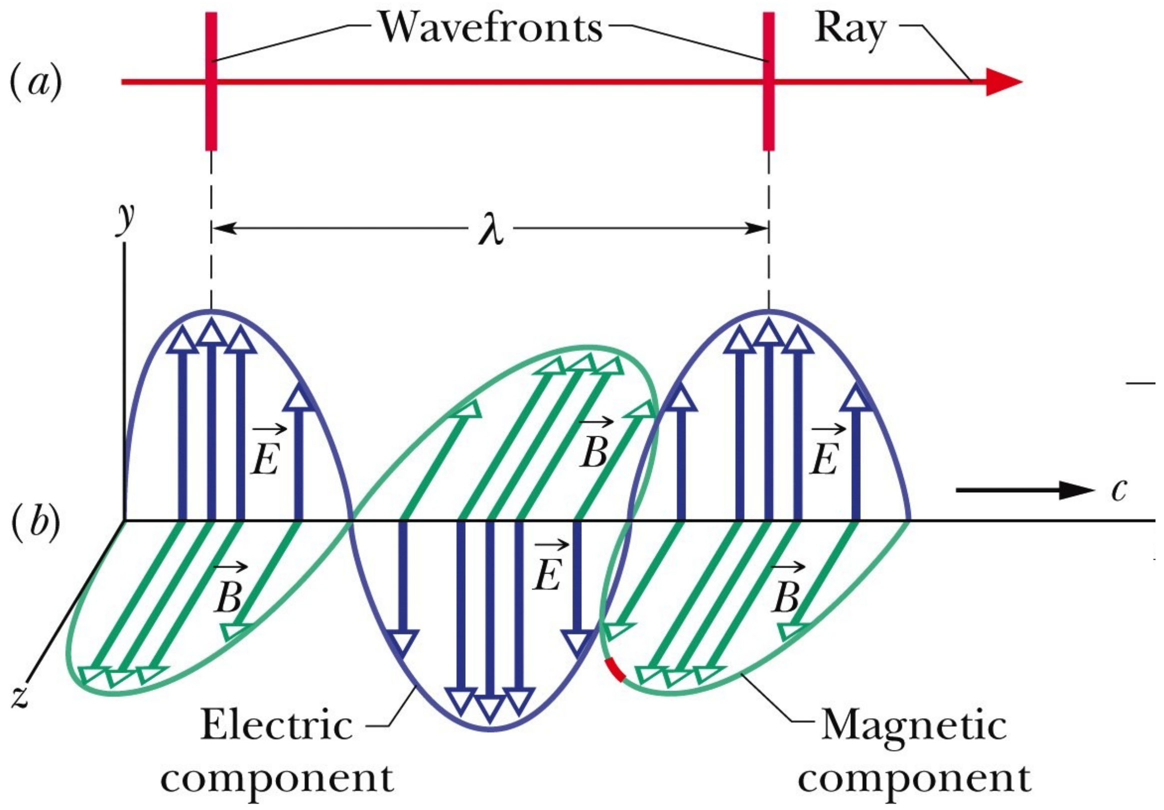
with $\mu_0\varepsilon_0=\frac{1}{c^2}$

general solutions $\vec{E}(z,t) = \vec{E}_0 e^{i(kz-\omega t)}$

$$\vec{B}(z,t) = \vec{B}_0 e^{i(kz-\omega t)}$$

monochromatic (oscillates at a single frequency)

plane wave



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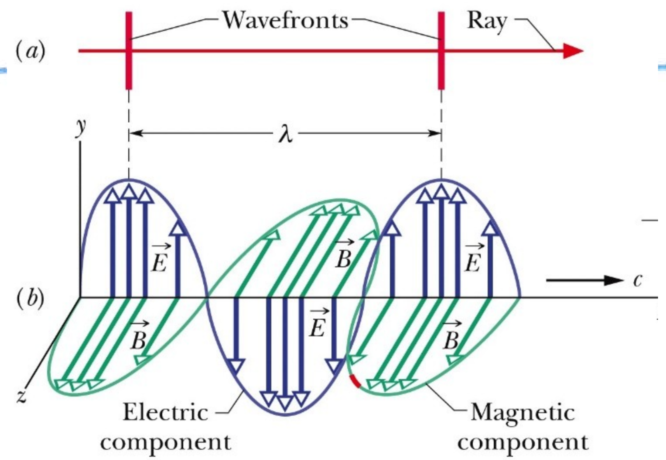
em waves are transverse waves follows from

$\vec{\nabla}\cdot\vec{E}=0$, $\vec{\nabla}\cdot\vec{B}=0$ (w/example)



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transverse em wave

$$\vec{E} = E_0\cos(kz-\omega t)\,\hat{x} + E_0\cos(kz-\omega t)\,\hat{y}$$

$$\vec{\nabla}\cdot\vec{E} = \frac{\partial E_x}{\partial x}+\frac{\partial E_y}{\partial y}+\frac{\partial E_z}{\partial z}=0$$

because E_x, E_y are independent of z, i.e. $\frac{\partial E_x}{\partial x}=0$, $\frac{\partial E_y}{\partial y}=0$,

and $E_z=0$, i.e. $\frac{\partial E_z}{\partial z}=0$.

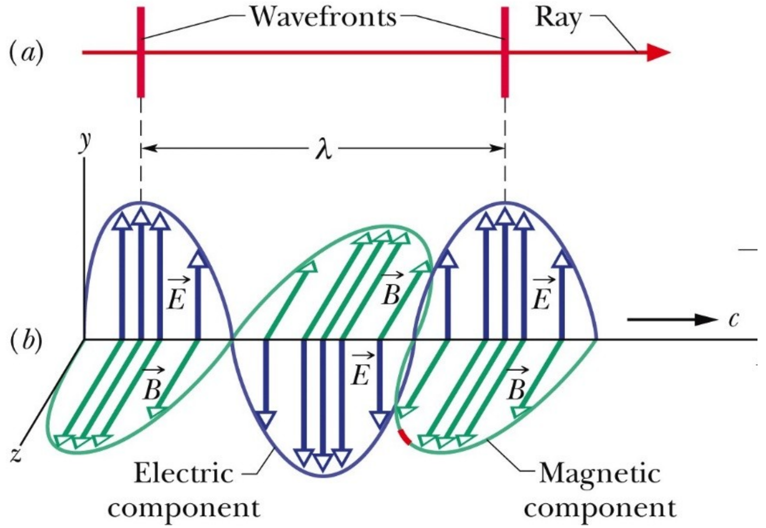
$\vec{E}, \vec{B}, \vec{k}$ are perpendicular to each other follows from Faraday's law $\vec{\nabla} \times \vec{E} = -\dot{\vec{B}}$ or $\vec{B}_0 = \frac{k}{\omega}(\hat{z} \times \vec{E}_0)$

for amplitudes $B_0 = \frac{k}{\omega} E_0 = \frac{1}{c} E_0$ (example)

$$\vec{E}(z,t) = E_0 \cos(kz - \omega t + \delta)\,\hat{x}$$

$$\vec{B}(z,t) = \frac{1}{c} E_0 \cos(kz - \omega t + \delta)\,\hat{y}$$

and $\vec{k} = k\,\hat{z}$



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$\vec{B}$ is $\perp$ to $\vec{E}$ follows from Faraday's law.

Consider $\vec{E} = E_0 \cos(kz - \omega t)\,\hat{x}$

Calculate:

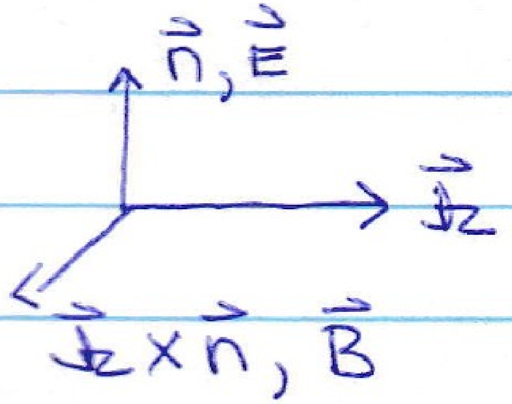
$$\vec{\nabla} \times \vec{E} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & 0 \end{vmatrix} = \Big(\underbrace{\frac{\partial}{\partial y} 0}_{=0} - \underbrace{\frac{\partial E_y}{\partial z}}_{=0}\Big)\hat{x} + \Big(\frac{\partial E_x}{\partial z} - \underbrace{\frac{\partial 0}{\partial x}}_{=0}\Big)\hat{y} + \Big(\underbrace{\frac{\partial E_y}{\partial x}}_{=0} - \underbrace{\frac{\partial E_x}{\partial y}}_{=0}\Big)\hat{z}$$

$$\vec{\nabla} \times \vec{E} = \frac{\partial E_x}{\partial z}\hat{y} = -\frac{\partial}{\partial t}\vec{B} \qquad \Leftrightarrow \vec{B} \text{ in } \hat{y} \text{ direction}$$

$\vec{n}$: vector in direction of $\vec{E}$

$\vec{k}$: vector in direction of propagation

$\vec{k} \times \vec{n}$: vector perpendicular to $\vec{n}$ and $\vec{k}$



general description

$$\vec{E}(\vec{r},t) = E_0 e^{i(\vec{k}\cdot\vec{r}-\omega t)} \hat{n}$$

$$\vec{B}(\vec{r},t) = \frac{1}{c} E_0 e^{i(\vec{k}\cdot\vec{r}-\omega t)} (\hat{k} \times \hat{n}) = \frac{1}{c} \hat{k} \times \vec{E}$$

with $\hat{n} \cdot \hat{k} = 0$

Polarization of an em wave is defined with regard to the direction of the ~~em~~ electric field vector $\vec{E}$

in general $\vec{E} = \vec{E}_x + \vec{E}_y = E_0 \cos(kz - \omega t + \phi) \cdot \hat{x} +$

$E_0 \cos(kz - \omega t)\,\hat{y}$

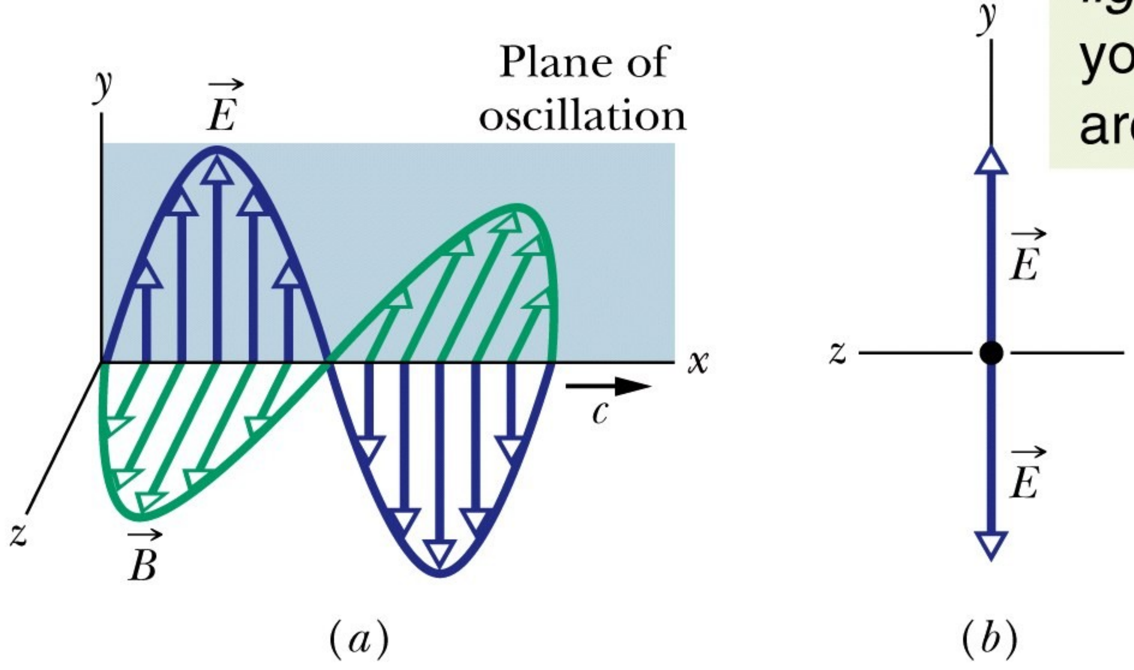
$\phi = 0$ linear polarization, $\phi = \frac{\pi}{4}$ circular polarization

and for ϕ other than $0, \frac{\pi}{4}$, elliptical polarization

derived from eliminating t from wave equation

for components E_x, E_y, i.e $E_x = E_{0x} \cos(\omega t + \phi)$ and

$E_y = E_{0y} \cos \omega t$



Vertically polarized light headed toward you—the electric fields are all vertical.

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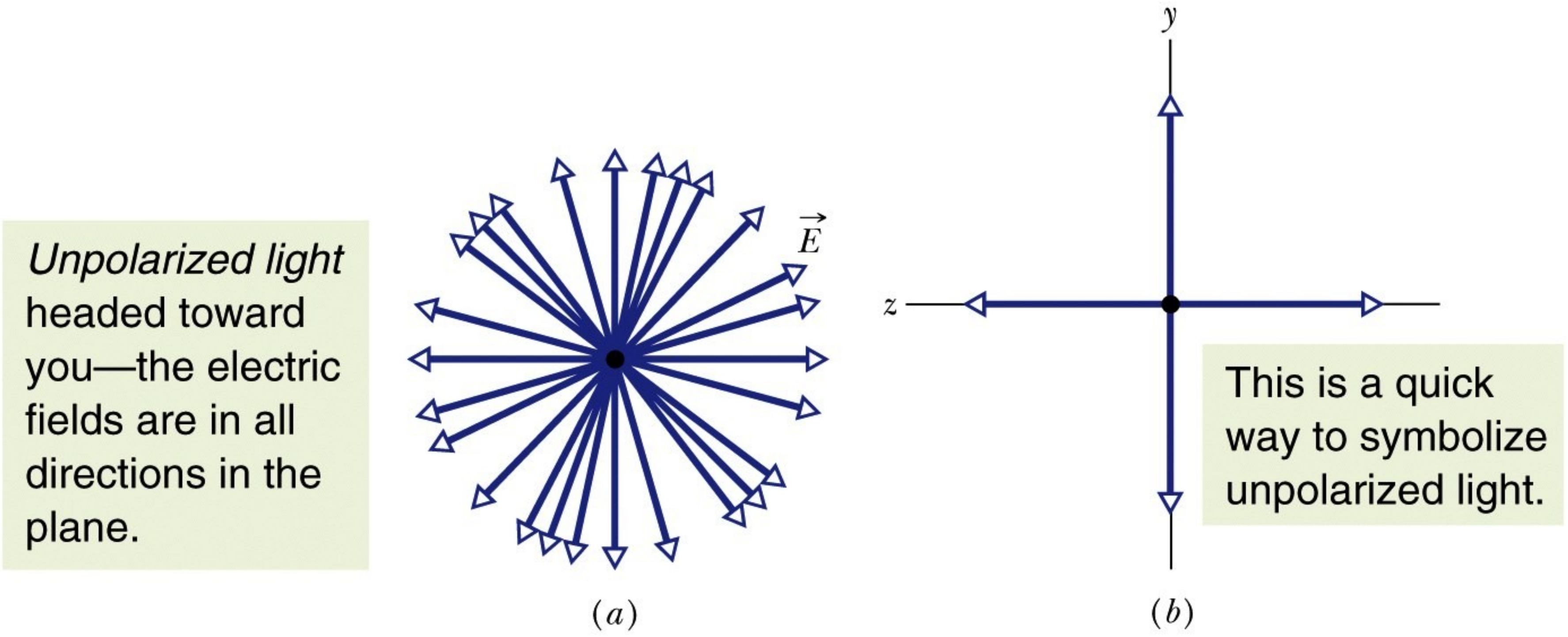

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Energy & momentum in electro magnetic waves

em energy density $u = \frac{1}{2}\left(\varepsilon_0 E^2 + \frac{1}{\mu_0} B^2\right)$

for monochromatic plane wave $B^2 = \frac{1}{c^2} E^2 = \mu_0 \varepsilon_0 E^2$

$\Leftrightarrow \quad u = \varepsilon_0 E^2 = \varepsilon_0 E_0^2 \cos^2(kz - \omega t + \delta)$

energy flux density $\vec{S} = \frac{1}{\mu_0}(\vec{E} \times \vec{B})$

$\vec{S} = c\,\varepsilon_0 E^2 \cos^2(kz - \omega t + \delta)\,\hat{z} = c\,u\,\hat{z}$

momentum density $\vec{g} = \frac{1}{c^2}\vec{S} = \frac{1}{c}\,u\,\hat{z}$ momentum density

$\langle u \rangle = \frac{1}{2}\varepsilon_0 E_0^2 \qquad \langle \vec{S} \rangle = \frac{1}{2} c\,\varepsilon_0 E_0^2\,\hat{z} \qquad \langle \vec{g} \rangle = \frac{1}{2c}\varepsilon_0 E_0^2\,\hat{z}$

classical em light is a wave, em energy density, Poynting vector, momentum, $\vec{l} = \vec{r} \times \vec{g}$

quantum light. particle, energy $E = h \cdot f$, momentum is $\vec{p} = \frac{h}{2\pi} \vec{k} = \hbar \vec{k}$, angular momentum $\vec{l} = \vec{r} \times \vec{p}$