UNIVERSITÀ DEGLI STUDI DI PADOVA

# Optics and Laser Physics

Tiziana Cesca

Master degree in Materials Science
AA. 2020-2021

**Video course online (Moodle DiSC)**
**asynchronous mode**

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Dipartimento di Fisica e Astronomia Galileo Galilei

UNIVERSITÀ DEGLI STUDI DI PADOVA

1222-2022 800 ANNI

# Time schedule

*Optics and Laser Physics*
T. Cesca

**L.M. SCIENZA DEI MATERIALI – 2° ANNO 1° SEMESTRE - A.A. 2020/21**
**Tutto il semestre, a partire dal 21 settembre 2020**
**MODALITÀ TELEMATICA**

| ORE | LUNEDì | MARTEDì | MERCOLEDì | GIOVEDì | VENERDì |
|---|---|---|---|---|---|
| 8.30 – 9.15 | Optics of Materials<br>**MENEGHETTI** | Optics of Materials<br>**MENEGHETTI** | Tecnologia dei Materiali<br>**MARTUCCI** | | |
| 9.30 – 10.15 | | | | Elettrochimica dei Materiali<br>**DURANTE** | |
| 10.30 – 11.15 | Elettroch. Materiali<br>**DURANTE** | Nanofabbricazione<br>**ROMANATO** | | | |
| 11.30 – 12.15 | | | Ott. Fisica Laser<br>**CESCA** | Tecnologia dei Materiali<br>**MARTUCCI** | |
| 12.30 – 13.15 | Ott. Fisica Laser<br>**CESCA** | | | | |
| 12.30 – 13.15 | | | | | |
| 14.30-15.15 | Brevettazione e Sviluppo di Prodotti<br>**MARETTO,FACHINI, STOCCO** | Brevettazione e Sviluppo di Prodotti<br>**MARETTO,FACHINI, STOCCO** | Nanofabbricazione<br>**ROMANATO** | Nanofabbricazione<br>**ROMANATO** | |
| 15.30-16.15 | | | | | |
| 16.30-17.15 | | | Brevettazione e Sviluppo di Prodotti<br>**MARETTO, FACHINI, STOCCO** | | |
| 17.30-18.15 | | | | | |

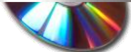
Zoom Meeting
Moodle DiSC
17:00-19:00












# Nobel Prize in Physics 2018

The Nobel Prize in Physics 2018 was awarded

"**for groundbreaking inventions in the field of laser physics**"

**Arthur Ashkin**, born in 1922 in New York, USA

"**for the optical tweezers and their application to biological systems**"

**Gérard Mourou**, born in 1944 in Albertville, France.

**Donna Strickland**, born in 1959 in Guelph, Canada.

"**for their method of generating high-intensity, ultra-short optical pulses**"

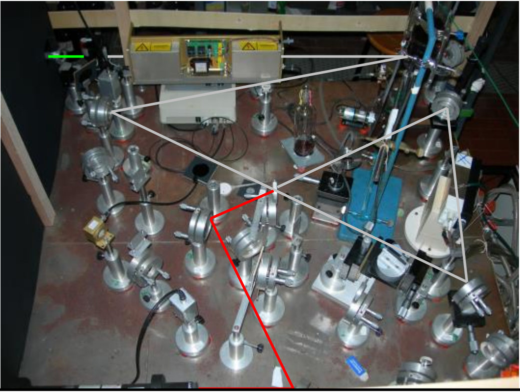
The Nobel Prize in Physics 2018. NobelPrize.org. Nobel Media AB 2018. Tue. 2 Oct 2018. <https://www.nobelprize.org/prizes/physics/2018/summary/>

# Mode-locked Nd:YAG (15 ps)



# Mode-locked Nd:glass (6 ps)
# Ring cavity

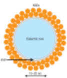




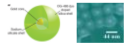
# Plasmonic nanolasers

## Spaser

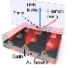
D.J. Bergman & M.I. Stockman, PRL 90 027302 (2003)



## Experimental spaser-based nanolaser

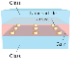


M.A. Noginov et al., Nature 460 1110 (2009)

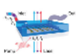


J.Y. Suh et al., Nano Lett. 12 5749 (2012)

W. Zhou et al., Nat. Nanotech. 8 506 (2013)



## Liquid gain nanolaser

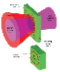


A. Yang et al., Nature Comm. 6 6386 (2015)

2003 2004-2007 2008 2009 2010 2011 2012 2013 2014 2015 2018 …

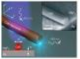
Progress in plasmonic cavity designs and gain media

N.I. Zheludev et al., Nat. Photon. 2 351 (2008)

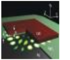


## Lasing spaser

X. Zhang et al., Nature 461 629 (2009)

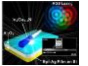


R.-M. Ma et al., Nature 10 110 (2011)

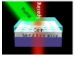


## Hybrid plasmonic nanolasers

X. Meng et al., Nano Lett. 13 4106 (2013)



Y.-J. Lu et al., Nano Lett. 14 4381 (2014)



X. Meng et al., Laser Photon. Rev. 8 896 (2014)

# Contents

- **Classical optics:**
  - **geometrical optics:** reflection, rifraction, optical systems, aberrations, …
  - **wave optics:** propagation, polarization, interference, diffraction, …

- **Lasers:**
  - **conventional lasers:**
    - Properties, working principle, laser systems and applications...
  - **nanolasers**

- **Quantum optics:**
  - Photons, radiation-matter interaction, atoms in a cavity, strong and weak coupling...

# Textbooks



- **"Principles of Physical Optics" C. A. Bennett, Wiley (2008).**
- "The light fantastic. A Modern Introduction to Classical and Quantum Optics" I. R. Kenyon, Oxford Press (2008).
- " Introduction to Modern Optics" G. R. Fowels, Dover Pubblications 2° ed. (1989).
- "Optics" E. Hecth, Addison Wesley, 4° ed. (2002) .
- **"Principles of Lasers" O. Svelto, Plenum Press, 5° ed. (2010).**
- "Principles of Optics" M. Born and E. Wolf, Cambridge University Press, 7° ed. (1999).
- "Fundamentals of Photonics" B. E. Saleh and M. C. Teich, Wailey Inc., 2° ed. (2007).
- **"Quantum Optics: an introduction" M. Fox, Oxford University Press (2006).**
- "Quantum Optics" G. S. Agarwal, Cambridge University Press, (2012).

# Maxwell's equations in vacuum

**James Clerk Maxwell**
(1831-1879)

$$\begin{cases} \vec{\nabla} \cdot \vec{E} = 0 & \text{(I) Gauss' law for field } \vec{E} \\ \vec{\nabla} \cdot \vec{B} = 0 & \text{(II) Gauss' law for field } \vec{B} \\ \vec{\nabla} \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} & \text{(III) Faraday's induction law} \\ \vec{\nabla} \times \vec{B} = \mu_0 \varepsilon_0 \dfrac{\partial \vec{E}}{\partial t} & \text{(IV) Ampére's circuitation law} \end{cases}$$

$$\varepsilon_0 = 8.854 \times 10^{-12} \ \text{F/m} \qquad \mu_0 = 4\pi \times 10^{-7} \ \text{H/m}$$

# Maxwell's equations in a medium



$$\vec{\nabla} \cdot \vec{D} = \rho$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

Electric displacement vector

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P}$$

Polarization

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M}$$

Magnetization

$$\vec{D} = \varepsilon \vec{E} \qquad \vec{J} = \sigma \vec{E}$$

linear media

conductivity

$$\vec{P} = (\varepsilon - \varepsilon_0)\vec{E} = \chi \varepsilon_0 \vec{E}$$

$$\chi = \frac{\varepsilon}{\varepsilon_0} - 1$$

Electric susceptibility

$\varepsilon(\omega) =$ **Dielectric function**

# Equation of the em waves (in vacuum)

$$\nabla \times \left(\nabla \times \vec{A}\right) = \nabla\left(\nabla \cdot \vec{A}\right) - \nabla^2 \vec{A}$$

$$\boxed{\nabla^2 \vec{E} - \mu_0 \varepsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} = 0}$$

$$\boxed{\nabla^2 \vec{B} - \mu_0 \varepsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2} = 0}$$

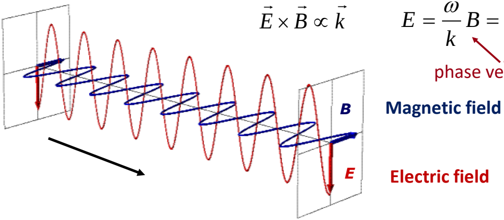
# em waves

Light is a transverse electromagnetic wave.

$$\vec{E} \times \vec{B} \propto \vec{k}$$

$$E = \frac{\omega}{k} B = c \ B$$

phase velocity




$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = (299792458 \quad \pm 1) \ \text{m/s} \approx 3 \times 10^8 \ \text{m/s}$$ in vacuum

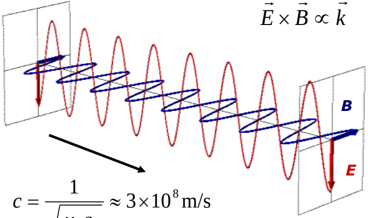
# em waves

Light is a <u>transverse</u> electromagnetic wave.

$$\vec{E} \times \vec{B} \propto \vec{k}$$

$$E = \frac{\omega}{k} B = v\, B$$

phase velocity




**Magnetic field**

**Electric field**

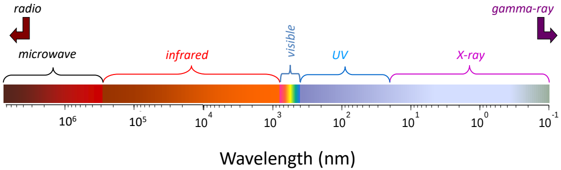
$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 3 \times 10^8 \,\mathrm{m/s}$$

$$n = \sqrt{\varepsilon_r \mu_r} \cong \sqrt{\varepsilon_r}$$

$\mathrm{v} = \dfrac{c}{n}$ in a medium

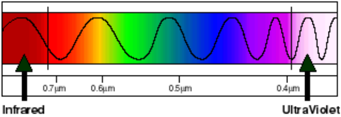
**refractive index**

# The spectrum of the electromagnetic radiation




Transition wavelengths are a bit arbitrary …

# The visible light

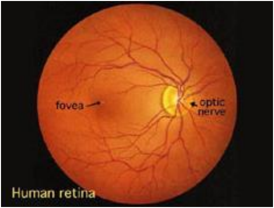


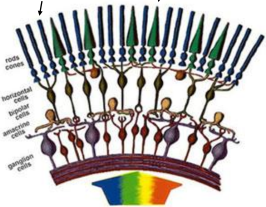

**Approximate Frequency and Vacuum Wavelength Ranges for the Various Colors**

| Color | $\lambda_0$ (nm) | $\nu$ (THz)* |
|---|---|---|
| Red | 780–622 | 384–482 |
| Orange | 622–597 | 482–503 |
| Yellow | 597–577 | 503–520 |
| Green | 577–492 | 520–610 |
| Blue | 492–455 | 610–659 |
| Violet | 455–390 | 659–769 |

*1 terahertz (THz) = $10^{12}$ Hz, 1 nanometer (nm) = $10^{-9}$ m.

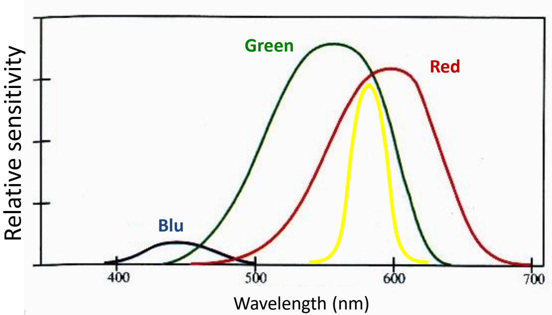
# The human retina



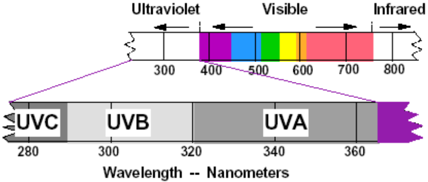



# The color perception





# The ultraviolet (UV)

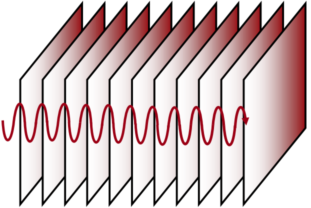



UVC (220-290 nm) UVB (290-320 nm) UVA (320-400 nm)

# Harmonic plane wave



Vectorial complex exponential representation



**Euler's formulas**

$$e^{i\vartheta} = cos\vartheta + i\ sin\vartheta$$

$$cos\vartheta = \frac{e^{i\vartheta} + e^{-i\vartheta}}{2}$$

$$sin\vartheta = \frac{e^{i\vartheta} - e^{-i\vartheta}}{2i}$$

**em plane wave**

$$f(\vec{r},t) = \vec{A}e^{i\left(\vec{k}\cdot\vec{r}-\omega t\right)}$$

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

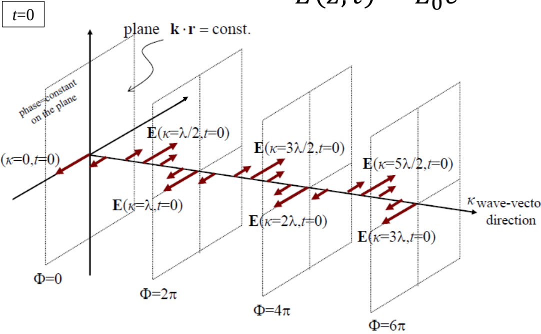
$$\vec{B}(z,t) = \vec{B}_0 e^{i(kz-\omega t)}$$

$$E = v\ B$$

**Polarization** vector

# em plane waves

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

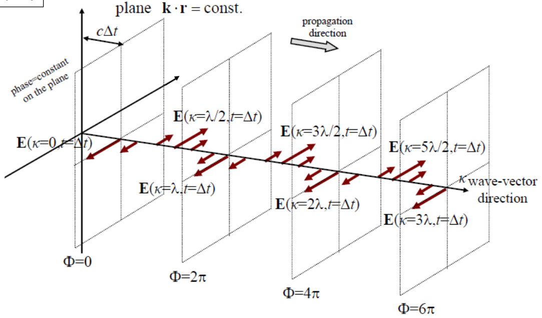


# em plane waves



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

$t=\Delta t$

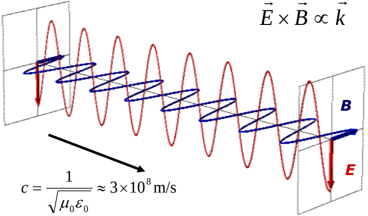


# Poynting vector and intensity



Light is a <u>transverse</u> electromagnetic wave.

$$\vec{E} \times \vec{B} \propto \vec{k} \qquad E = \frac{\omega}{k} B = v\, B$$




$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 3\times 10^8 \,\mathrm{m/s}$$

**Poynting vector**

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

**Intensity (Irradiance)**

$$\boxed{\langle |\vec{S}| \rangle = \frac{1}{2} n\, \varepsilon_0 c E_0^2 = I} \quad (\mathrm{W/m^2})$$

# Photons



The term *photon* was coined in 1926 by the American chemist Gilbert N. Lewis

$E = h\nu$ **Photon energy** $h = 6.63 \times 10^{-34}\, Js$ Planck's constant

$p = \dfrac{E}{c} = \dfrac{h}{\lambda} = \hbar k$ **Photon momentum** $\vec{p} = \hbar\vec{k}$ $\hbar = \dfrac{h}{2\pi}$

$F = \dfrac{I}{h\nu}$ **Photon flux** (number of photons per unit of area and unit of time)

**Radiation pressure**

The momentum transfer per photon is:

$\Delta p = 2p$ for complete reflection $\Rightarrow$ $P = F\Delta p = \dfrac{2I}{c}$

$\Delta p = p$ for complete absorption $\Rightarrow$ $P = F\Delta p = \dfrac{I}{c}$