NON-IONISING RADIATION IN MEDICINE

POZNAN UNIVERSITY OF MEDICAL SCIENCES
POLAND

- The Effects of Infrared, Visual and Ultraviolet Radiation on Matter
- Properties and Some Applications of Laser Light

Reference textbook:

Introduction to Physics in Modern Medicine,
Susan Amador Kane
Taylor & Francis, London, New York, 2003, ISBN 0-415-30171-8 (pbk), ISBN 0-415-29963-2 (hbk)

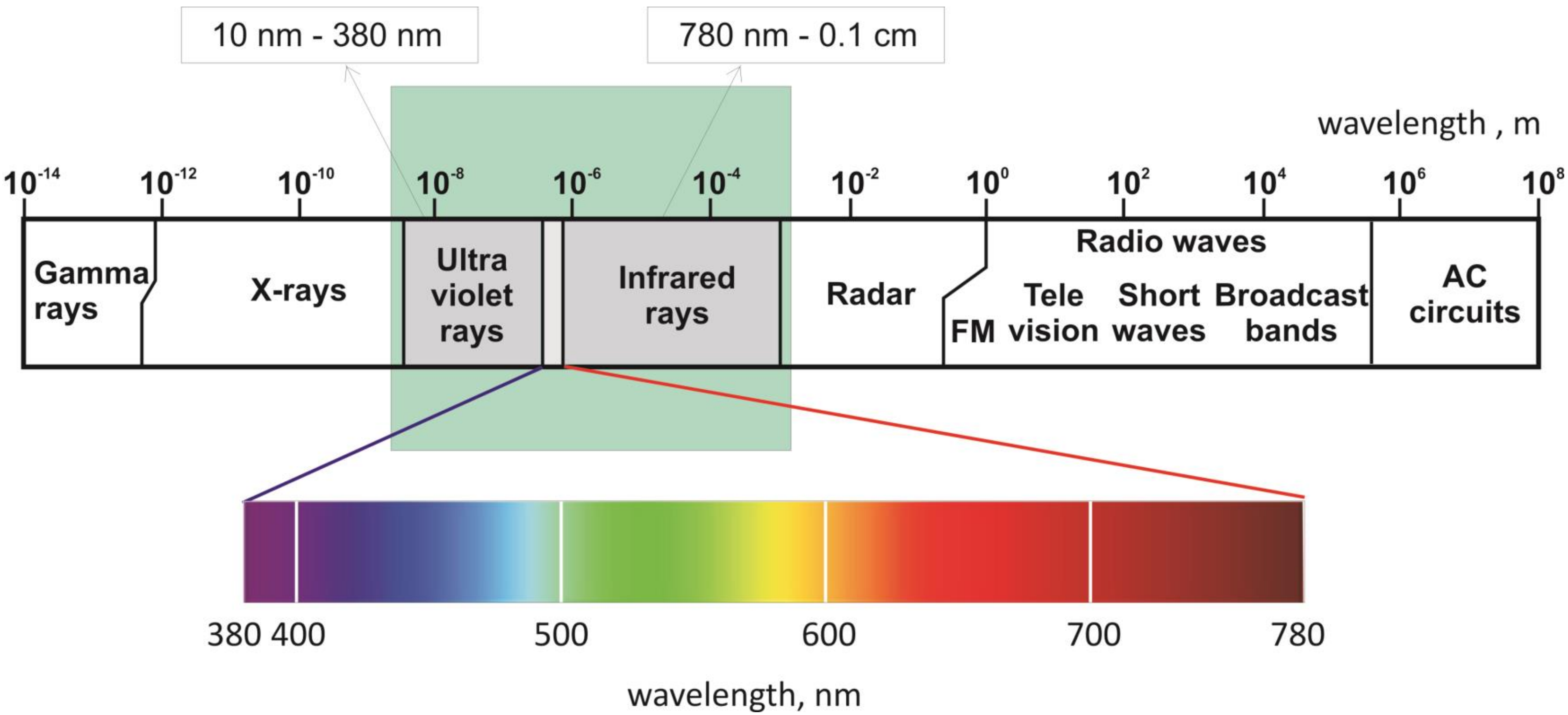
Chapter 3. **Lasers in Medicie**
Healing with light

OBJECTIVES

- ✓ To understand the difference between ultraviolet (uv), infrared (ir) and visual (vis) radiation
- ✓ To understand principles of interaction of light with matter
- ✓ To become acquainted with properties of laser light and its possible applications in dentistry

WHAT ARE WE INTERESTED IN?

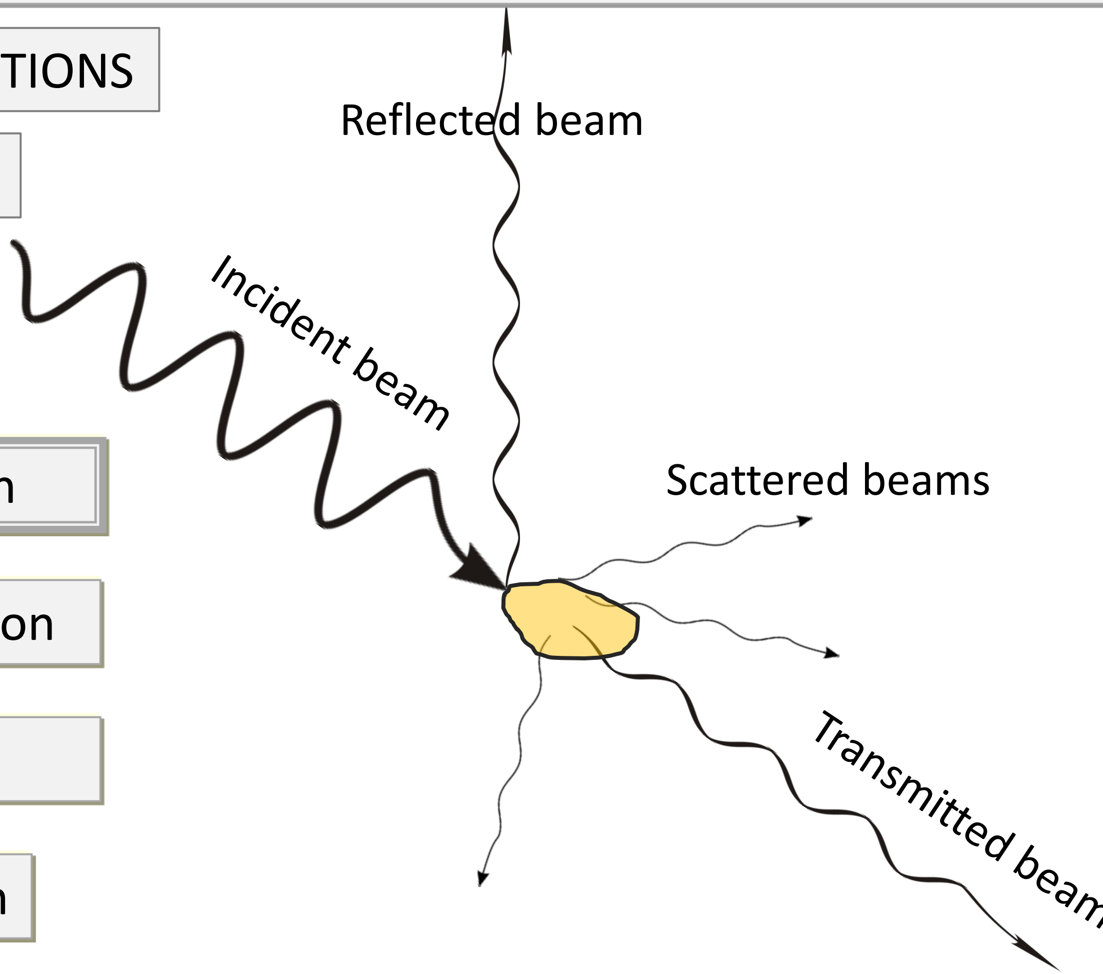
Spectrum of Electromagnetic Radiation



INTERACTION OF LIGHT WITH MATER, INCLUDING BODY TISSUES

Application of light in medicine involves transfer of energy from light to human tissue through several mechanisms to initiate:

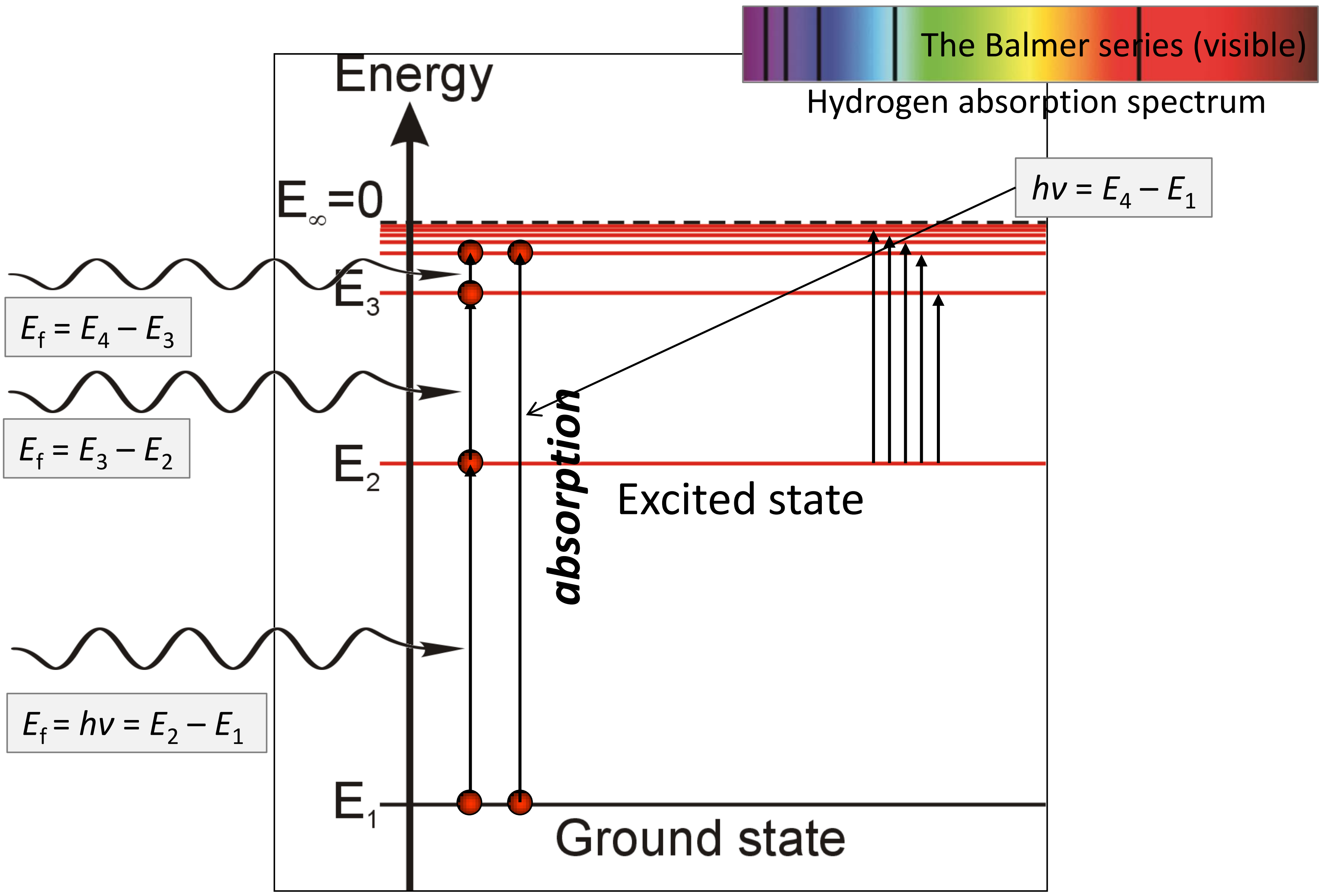
- CHEMICAL INTERACTIONS
- THERMAL DAMAGE



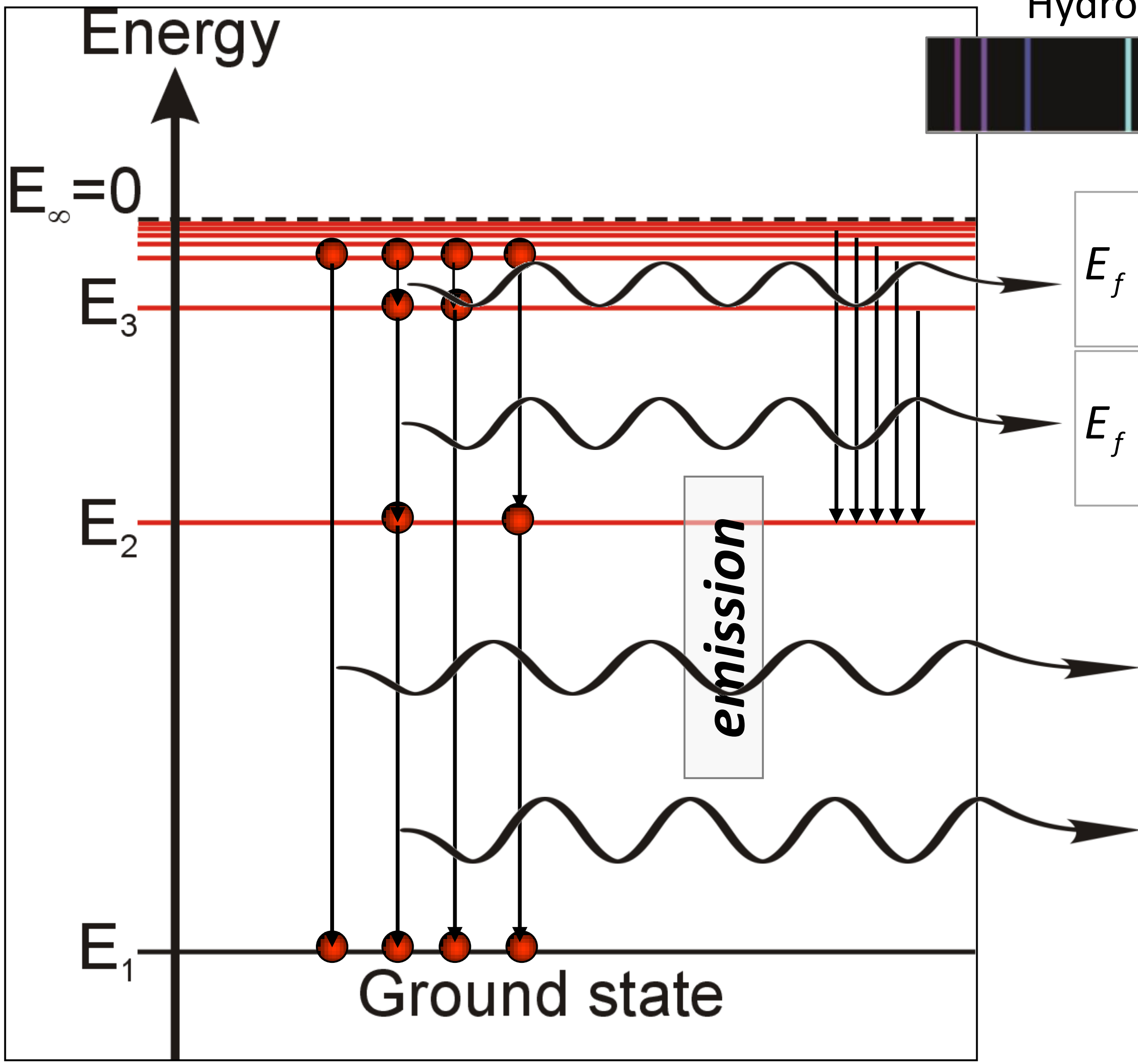
- Absorption
- Transmission
- Scattering
- Reflection

EMISSION AND ABSORPTION OF LIGHT

Energy level diagram of a simple atomic system: absorption



Energy level diagram of a simple atomic system: emission



Hydrogen emission spectrum

$$E_f = E_4 - E_3 = h\nu_{43} = h\frac{c}{\lambda_{43}}$$

$$E_f = E_3 - E_2 = h\nu_{32} = h\frac{c}{\lambda_{32}}$$

$$E_f = E_4 - E_1 = h\nu_{41} = h\frac{c}{\lambda_{41}}$$

$$E_f = E_2 - E_1 = h\nu_{21} = h\frac{c}{\lambda_{21}}$$

Energy of a photon determines the effect on matter

$E = h\nu = hc/\lambda$

$c = 3\times10^8$ m/s, h (Planck's constant) = 6.6×10^{-34} J·s, 1eV = 1.6×10^{-19} J

❖ ***Ultraviolet radiation***

wavelength: 10 – 380 nm

frequency: 3×10^{16} Hz – 7.9×10^{14} Hz

energy of photons: 1.98×10^{-17} J (124eV) – 5.2×10^{-19} J (3.3 eV)

❖ ***Visible radiation***

wavelength: 380 – 780 nm

frequency: 7.9×10^{14} Hz – 3.8×10^{14} Hz

energy of photons: 5.2×10^{-19}J (3.3 eV) – 2.5×10^{-19} (1.6 eV)

❖ ***Infrared radiaition***

wavelength: 780 – 1000,000 nm (1mm)

frequency: 3.8×10^{14} Hz - 3×10^{11} Hz

energy of photons: 2.5×10^{-19} (1.6 eV) - 1.98×10^{-22} Hz (0.0012 eV)

Chemical bond energy:
O-H: 4.8eV,
C=C: 6.2eV

Energy of ionization:
Li: 5.4 eV
H: 14 eV
O: 11 eV

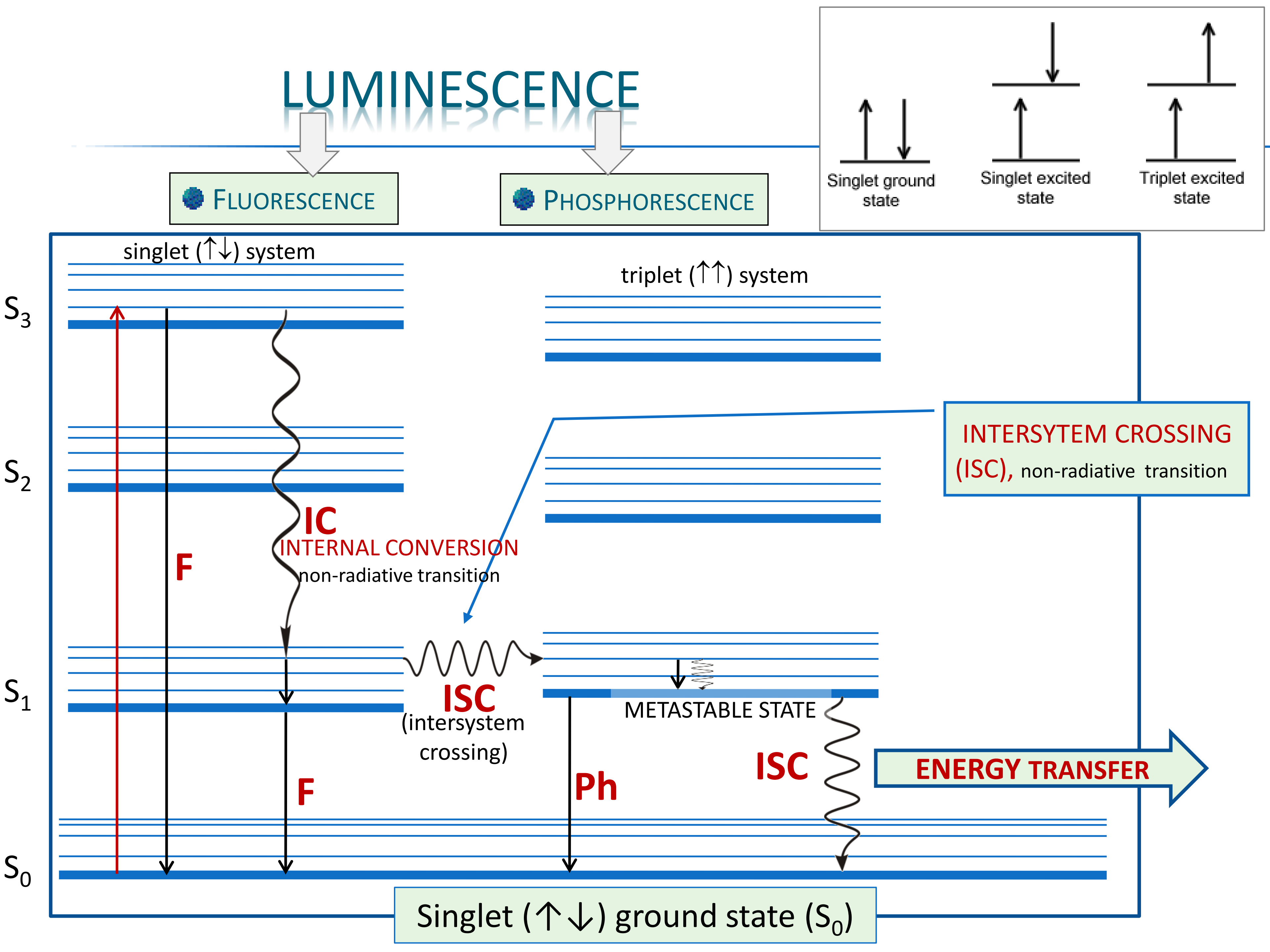
Energy of excitation:
H: 10 eV (Lyman-α) – ultraviolet
2.6 eV (Balmer m=3) – red

Energy of random thermal motion
(k – Boltzman constant, 25°C = 298K):
$E \approx kT = 0.03$ eV

LUMINESCENCE:

FLUORESCENCE

PHOSPHORESCENCE



LUMINESCENCE
FLUORESCENCE
PHOSPHORESCENCE
Singlet ground state
Singlet excited state
Triplet excited state
singlet (↑↓) system
triplet (↑↑) system
S3
S2
S1
S0
F
IC
INTERNAL CONVERSION
non-radiative transition
F
ISC
(intersystem crossing)
INTERSYTEM CROSSING (ISC), non-radiative transition
METASTABLE STATE
Ph
ISC
ENERGY TRANSFER
Singlet (↑↓) ground state (S0)

THE OPTICAL WINDOW FOR BODY TISSUES

THE LAMBERT LAW OB. ABSORPTION

ABSORPTION SPECTRUM OF WATER

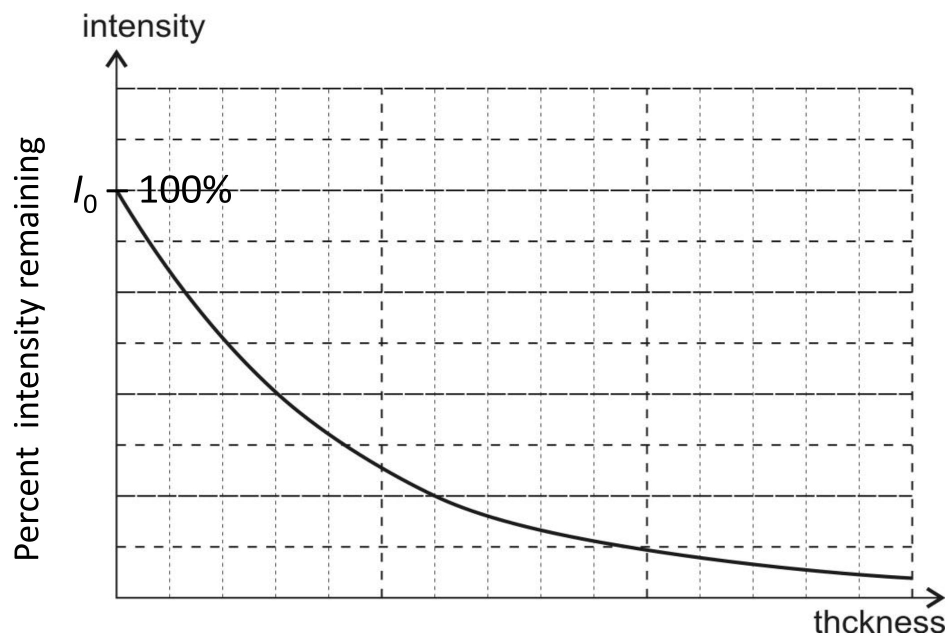
ABSORPTION SPECTRA OF SOME NATURAL BODY DYES

Penetration of Light – depth of penetration

The Lambert law:

$I = I_0 e^{-kx}$

k – absorption coefficient



EXAMPLE

$k = 0.001\ \mathrm{cm}^{-1}$

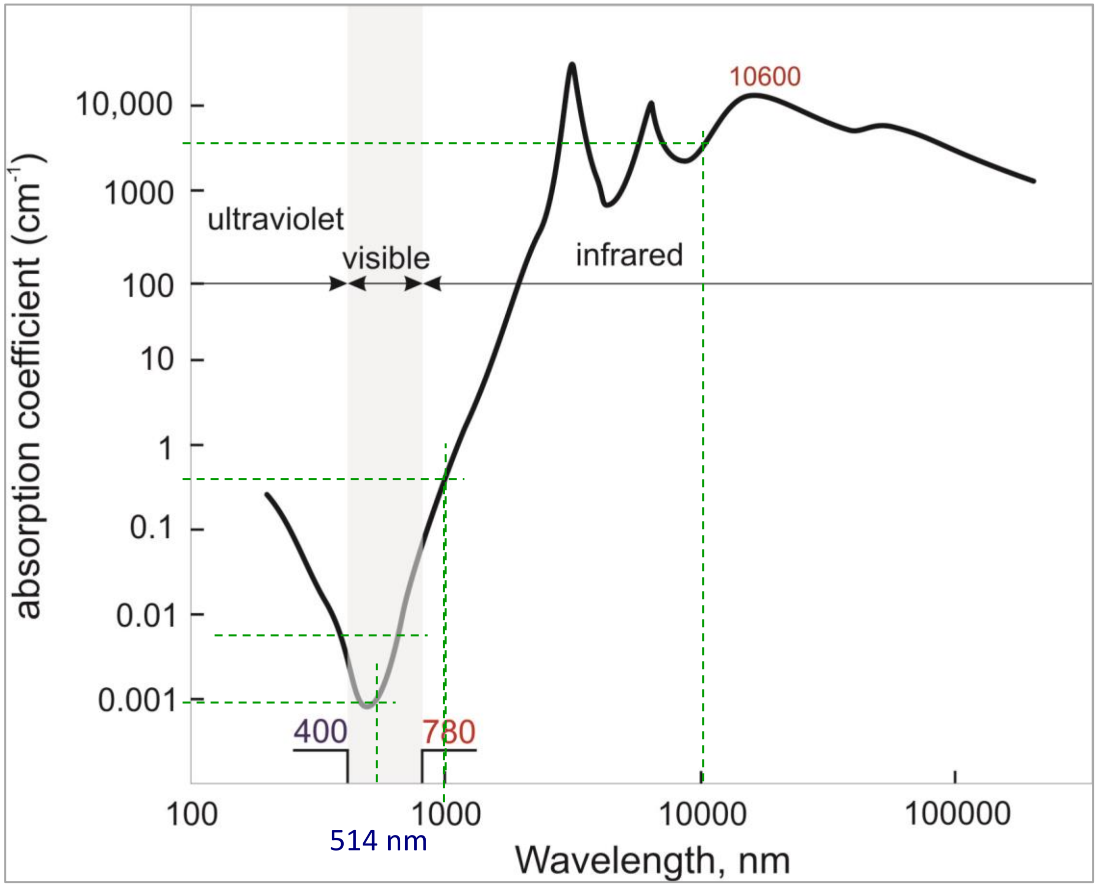
$I = I_0 e^{-0.1x}$

$x = ?\quad I = I_0 e^{-1} = 0.37 \times I_0$

$x = 1/k = 1000\ \mathrm{cm}$

$k = 0.001\ \mathrm{cm}^{-1}$ means that the radiation intensity drops to 1/e (0.37) of incident value after 1000 cm travel in tissue.

ABSORPTION SPECTRUM OF WATER



Penetration depth in water:
- argon laser (λ = 514 nm)

$k < 0.001$ cm^{-1}

$x = 1/k = 1000$ cm

> 1000 cm (argon laser)

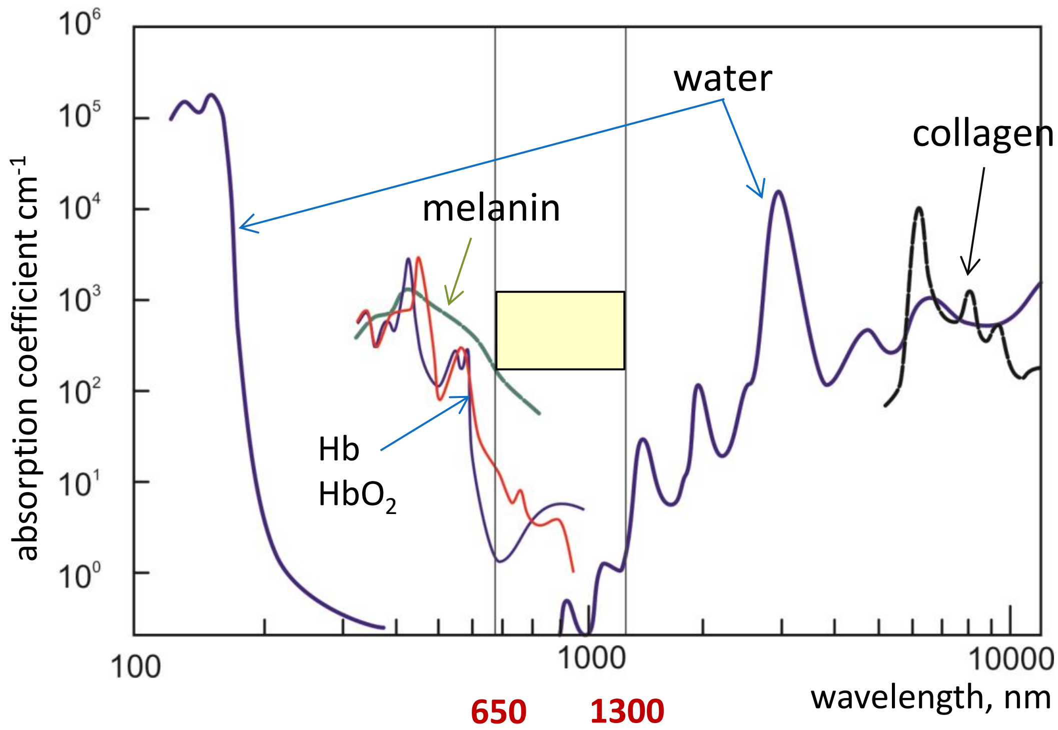
λ = 1064 nm, < 6 cm (Nd:YAG)

λ = 10600 nm, 0.004 cm (CO_2)

OPTICAL WINDOW

MAIN BODY DYES

- MELANIN
- HEMOGLOBIN (Hb)
- OXYHEMOGLOBIN (HbO_2)



TISSUE HAS MINIMUM ABSORPTION IN THE RED AND NEAR INFRA-RED RANGE FROM 650 nm – 1300 nm. THIS RANGE IS CALLED THE *OPTICAL ABSORPTION WINDOW.*

ABSORPTION IN TISSUES DETERMINES DEPTH OF PENETRATION

- *ULTRAVIOLET RADIATION* - LESS THAN 1 mm.
- *FAR INFRARED RADIATION* - FRACTIONS OF MILLIMETERS
- *VISIBLE AND NEAR-INFRARED RADIATION* – UP TO 10 MILLIMETERS

LASER LIGHT

PROPERTIES OF LASER LIGHT

- spatial and time coherence (!?)

emitted photons have a definite and constant phase relation to each other.

- narrow (!) beam of parallel rays

- high power density (intensity) (!!!!)

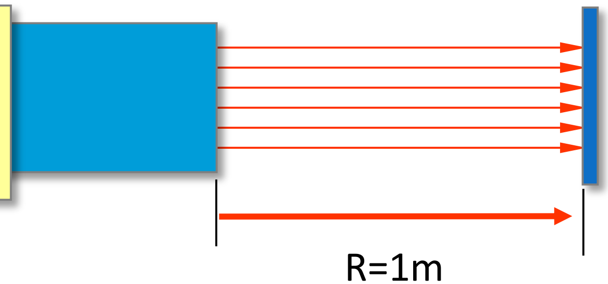
$$\text{Intensity} = \frac{\text{Energy}}{\text{time} \times \text{surface}} \quad \left[\frac{W}{m^2}\right]$$

- possible to focus down to extremely small spot (diameter of spot smaller than 0.1 mm)

- monochromatic radiation

LASER LIGHT VS. ELECTRIC BULB LIGHT

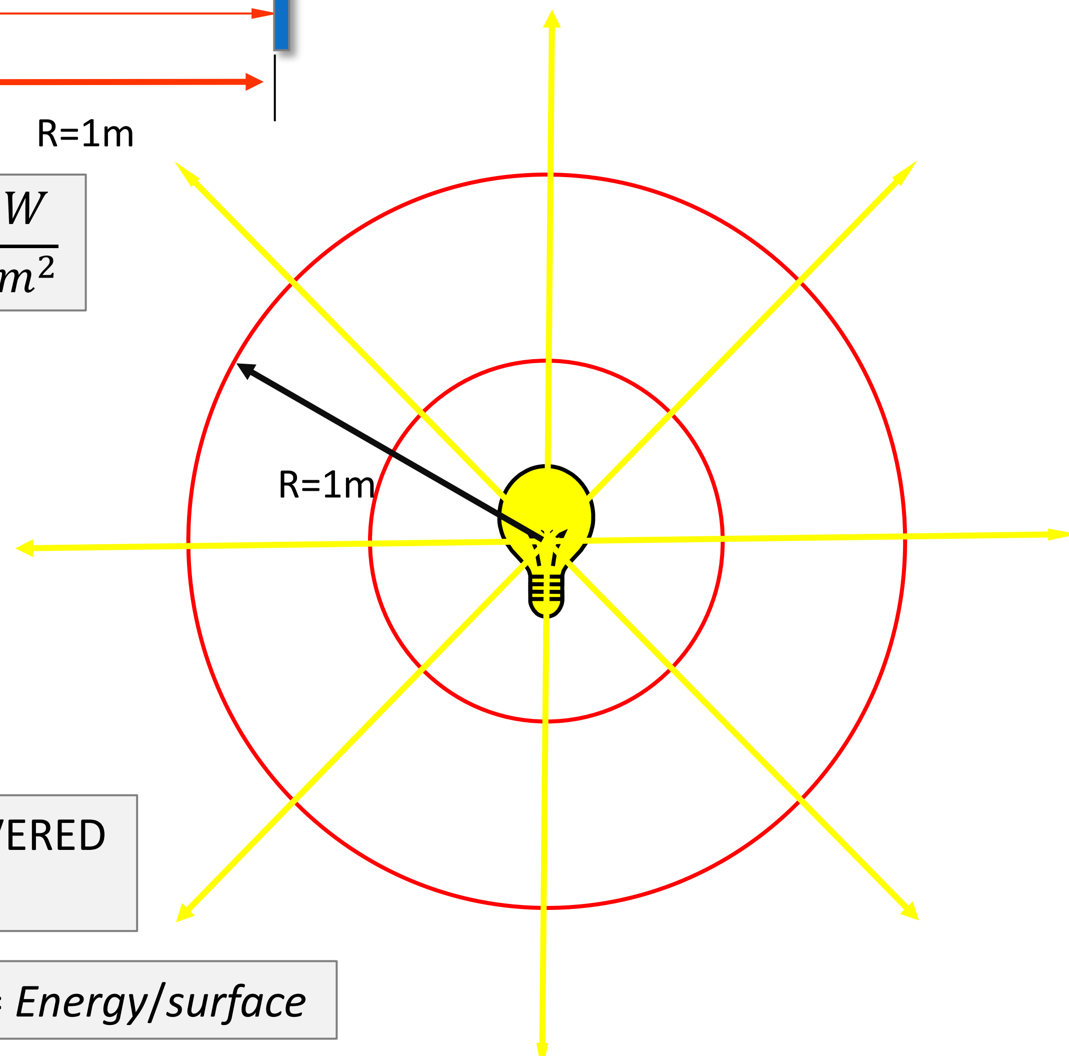
Surgical laser:
P=30W
Spot area 3 mm^2



$$I = \frac{30\ W}{3mm^2} = \frac{30\ W}{3 \times 10^{-6} m^2} = 10 \times 10^6 \frac{W}{m^2}$$

Light bulb P=30W - 1m away from it:

$$I = \frac{30\ \mathrm{W}}{4\pi r^2} = \frac{30\ \mathrm{W}}{4 \cdot 3.14 \cdot 1\mathrm{m}^2} \approx 2.4 \frac{\mathrm{W}}{\mathrm{m}^2}$$



FLUENCE (*F*)- THE TOTAL ENERGY DELVERED PER UNIT OF ILLUMINATED AREA:

F (J/m^2) = *Intensity* (W/m^2) × *time* (s) = *Energy/surface*

INTERACTION OF LASER LIGHT ....

- When the wavelength of the laser light beam matches the target's absorption band significant amount of the light energy is absorbed by the target.

- The light which is not absorbed is *scattered*, *reflected* or *transmitted*.

- Photons can pass through organs or cellular structures without damaging them if the photons' energies do not match the absorption bands of a tissue structure.

THE LASER LIGHT IS MOST COMMONLY USED TO HEAT THE TARGET AND DESTROY IT THERMALLY.

THERMAL EFFECTS

➢ Photo-vaporization

High absorption of IR radiation by tissue water raises temperature of the tissue dramatically leading to evaporation of it.

- surgical incisions or

- removal of thin layers of tissue

➢ Photo-coagulation:

Heat induced disordering (denaturation) of proteins, used for bloodless excision of tissue

NON-THERMAL EFFECTS

- Photoablation

Energy from photons can selectively break molecular bonds (*ultraviolet radiation!*) causing local damage.

- Photodisruption

Photodisruption: (resulting from extremely rapid photovaporisation) creation of ionised plasma causing shock-waves that breaks apart mineralised, hard deposits (*LASER LITHOTRIPSY*: breaking up gallstones and stones in the urinary tract),

When dye is concentrated in a target the laser light can cause the target to fluorescence for *diagnostic* purposes, or it can interact with the dye (*photosensitizer*) to destroy the target (PDT).

TECHNICAL CHARACTERISTICS OF LASERS

LASERS ARE CHARACTERIZED BY:

- ✓ chemical basis (active medium):
  CO_2, Nd:YAG (Yttrium Aluminum Garnet), argon, erbium laser
  holmium:YAG, diode laser and many other
- ✓ wavelength of emitted light

  Penetration depth in water:
  - argon laser: λ = 514 nm, >10 m
  - Nd:YAG: λ = 1064 nm, < 6 cm
  - CO_2: λ = 10600 nm, 0.04 mm
- ✓ power
- ✓ mode of operation: continuous mode or pulsed mode

LASERS IN DENTISTRY

CLASSIFICATION OF LASERS

ACTIVE MEDIUM

EMITTED WAVELENGTH

MAIN TISSUE CHROMOPHORE (TARGET)

TISSUE INTERACTION

✓ **ACTIVE MEDIUM** (CHEMICAL BASIS):

- CARBON DIOXIDE LASER (CO_2)

λ = 10600 nm - invisible far infrared

water

- surgery: removal of soft tissue by evaporation of intracelluar and extracellular fluids (*photo-vaporization*)
- coagulation – closing of blood vessels

<u>shalow depth of penetration !</u>

- ARGON LASER

- λ = 514 nm – blue-green, 488 nm blue

haemoglobin and oxyhaemoglobin

- acute inflammatory periodontal disease and highly vascularized lesions,
- light curing (hardening) by *photopolymerization*

- **NEODYMIUM LASER** (Nd:YAG – Neodimum-doper yttrium aluminum garnet)

λ = 1064 nm - invisible near infrared

haemoglobin and melanin

less absorbed by water – deeper penetration

- removal soft tissue especially for lesions extending into tissue deeper than the 0.1 millimeter
- coagulation – closing of blood vessels

- **ERBIUM LASER** (Er:YAG)

λ = 2940 nm - invisible near infrared

water, hydroxyapatite

<u>the highest absorption in water</u> – soft tissue ablation

hard tissue surgery

- DIODE LASER

λ = 800 - 1000 nm - invisible near infrared

melanin (tissue pigment), haemoglobin

aesthetic purposes: cutting and coagulating gingiva (gingiva re-contouring) and mucosa

REPORTED BENEFITS:

- little or no sound associated with treatment
- reduced need for anesthesia
- treatment of hard-to-access places in the oral cavity by application of thin flexible quartz light guides
- *decreased bleeding*
- *no bacterial infections due to the tools used*

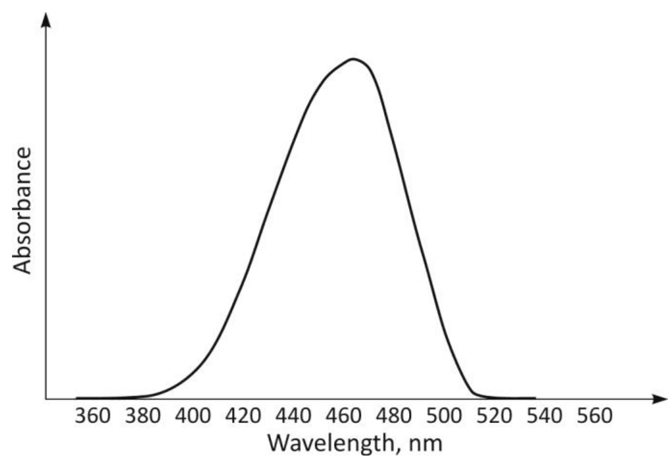
LIGHT HARDENING OF DENTAL RESTORATIONS

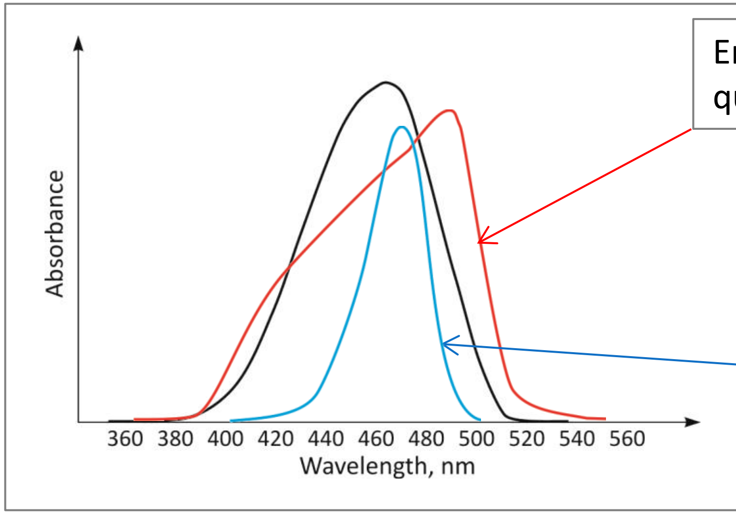
Light activated composite materials (usually supplied as a single paste) contain: monomers, comonomers, filler and an ***photo-****initiator.*

Photo-initiator – the light activated material - when exposed to light of proper wavelength range (for the *camphoroquinone* it is from 400 to 500 nm) becomes excited and reacts with the *amine* to produce free radicals.

The free radicals initiate polymerization process.

Absorption spectrum of *Camphoroquinone* (400-500 nm)





Emission spectrum of conventional quartz-tungsten halogen (QTH) source

Emission spectrum of LED (light emitting diode)

Halogen reflector bulb: 12V, 75 W
output wave length range:
380 - 540nm

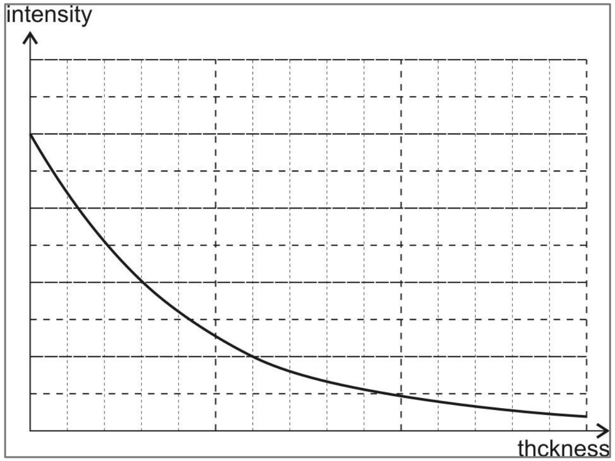
LED SOURCES

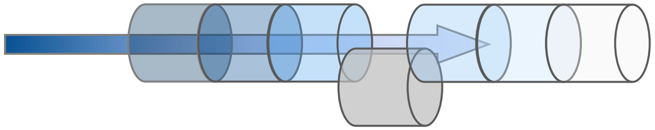
Argon laser - at 514,5 nm (green- useless) and 488 nm (blue - useful)
The advantage of the argon laser: deeper cure range.

PENETRATION OF LIGHT THROUGH DENTAL RESTORATIONS

The potential for activation declines exponentially as the intensity of light does, according to the Lambert law of absorption!

$$I = I_0 e^{-\mu x}$$





- Absorption of light limits the the depth of hardening!

- Increase of the exposure time has very little effect on the depth of cure.

- Shorter time that recommended may significantly reduce the depth of cure.

- As the distance from the light source and of the material increases the depth of cure decreases significantly! (THE INVERESE SQUARE LAW)