5. LASER – Tissue Interactions I

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Literature

[Image of references]
Part I: Matter Acting On Light

- Reflection
- Refraction
- Transmission
- Absorption
- Scattering

Reflection

- smooth surface → specular reflection
  \[ \theta = \theta \]
- rough surface → diffuse reflection:
  several beams, not necessarily in plane of incident

Refraction not trivial to measure!
**Total Reflection**

Snell’s Law:

\[ n \cdot \sin(\theta) = n' \cdot \sin(\theta') \]

\[ \sin(\theta) \leq 1 \]

\[ \theta_c = \arcsin\left(\frac{n}{n'}\right) \]

**Brewster Angle - Linear Polarisation**

Brewster Angle:

Reflected ray polarized due to radiation characteristic of Hertzian dipole!
Reflectivity and Reflectance

Maxwell’s Equation

\[ \frac{E'}{E} = \frac{\sin(\theta - \theta')}{\sin(\theta + \theta')} \]

Boundary Condition: Charge- and Current-Free Surface

Fresnel Equation → Reflectivity: Measure of the amount of reflected radiation

\[ \frac{E'}{E} = \frac{\sin(\theta - \theta')}{\sin(\theta + \theta')} \]

(\text{polarized } \perp \text{ to plane of incident})

\[ \frac{E_{||}}{E_{||}} = \frac{\tan(\theta - \theta')}{\tan(\theta + \theta')} \]

(\text{polarized } \parallel \text{ to plane of incident})

Reflectance: Intensity Ratio = Reflectivity²

\[ R = \left( \frac{E'}{E} \right)^2 \]

→ Brewster Angle: \( R_{\parallel} = 0 \) (Water: 53°)

Angular Distribution

\[ \text{Reflectance of water} \]

\[ R_{\parallel} \approx R_{\perp} \approx 2\% \]

\text{normal incidence: } R_{\parallel} \approx R_{\perp} \approx 2\%
Wavelength Dependence

Literature values:
- Air: $n=1.0003$
- Tissue / Water: $n=1.33$

But $\eta = \eta(\lambda)$!

What causes minima?

Absorption bands of water:
- Vibration and rotation

Absorption:
...due to molecular vibration & rotation (heat)

Lambert-Beer Law:

$$I(z) = I_0 e^{-\alpha z}$$

Absorption coefficient $\alpha$

Absorption length $L = \frac{1}{\alpha}$

$$I(L) = \frac{I_0}{e}$$
Absorption Spectra

**Biological Tissue:** main absorption due to water molecules, proteins, pigments

- **IR**
- **visible, UV**

"Therapeutic Window" (near IR: 600 – 1200 nm)
- low absorption
- higher penetration depth of radiation
- enabling treatment of deeper tissue structures

Krypton Ion Laser:
- $\lambda = 531$ nm (green) and $\lambda = 568$ nm (yellow)
- good for coagulation of blood vessels!
Scattering

Electromagnetic waves → Elastically bound charged particle

Absorption
Resonance frequency of free vibrations/rotations of particle

Scattering
Non-resonance frequency of free vibrations of particle

Turbid Media

Most media such as biological tissue shows absorption and scattering (= turbid media)

Lambert-Beer Law:

\[ I(z) = I_0 e^{-\alpha_z z} \]

Total Attenuation:

\[ \alpha_t = \alpha + \alpha_s \]

Free Optical Path:

\[ L_t = \frac{1}{\alpha_t} = \frac{1}{\alpha + \alpha_s} \]

Optical Albedo:

\[ a = \frac{\alpha_s}{\alpha_t} = \frac{\alpha_s}{\alpha + \alpha_s} \]

\( a = 0 \) Absorption

\( a = 1 \) Scattering
Scattering

Electromagnetic waves \rightarrow \text{Elastically bound charged particle}

Absorption \rightarrow \text{Scattering}

\text{Elastic Scattering} \rightarrow \text{Inelastic Scattering}

\sigma_{\text{elastic}} >> \sigma_{\text{inelastic}}

Elastic Scattering

\text{Rayleigh Scattering:}
\text{Incident Photon Energy} = \text{Scattered Photon Energy}
\lambda_{\text{incident}} = \lambda_{\text{scattered}}

\begin{align*}
I &= I_0 \left( \frac{1 + \cos^2 \theta}{2R^2} \right) \frac{2\pi}{\lambda} \left( \frac{n^2 - 1}{n^2 + 2} \right)^\frac{2}{\lambda} \left( \frac{d}{2} \right)^6 \\
\text{angle dependence:} & \quad \text{wavelength dependence}
\end{align*}

\text{forward and backscattering same!}

\text{R: distance to the particle}
\text{D: particle diameter}

\text{UV, VIS, IR, wavelength (nm)}
Elastic Scattering

Rayleigh Scattering

\[ I = I_0 \left( 1 + \cos^2 \theta \right) \left( \frac{2\pi}{\lambda} \right)^4 \left( \frac{n^2 - 1}{n^2 + 2} \right)^2 \left( \frac{d}{2} \right)^6 \]

- long way through atmosphere
- blue light filtered out
- short way through atmosphere: sky predominantly blue

Mie Scattering

\[ I_s \sim \frac{1}{\lambda^x} \quad (0.4 \leq x \leq 0.5) \]

- weak wavelength dependence
- preferably only forward scattering

- red blood cells, 6-8 µm
- water droplets in clouds

Mie scattering in clouds.

Scattering In Biological Tissues

Micrographs

- Spinal Cord
- Connective Tissue with Tumor
- Tissue with Nerves.

Rayleigh or Mie Scattering?

→ Both!
Scattering In Biological Tissue

Rayleigh Scattering

\[ I_s \sim \frac{1 + \cos^2(\theta)}{\lambda^4} \]

Mie Scattering

\[ I_s \sim \frac{1}{\lambda^x} \quad (0.4 \leq x \leq 0.5) \]

In Biological Tissue:

- preferably forward scattering → Mie scattering (weak \(\lambda\)-dependence)
- strong \(\lambda\)-dependence → Rayleigh scattering (forward & backward scattering)

How is the scattering in tissue best described?

\[ \text{probability function: } p(\theta) \]

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Henyey-Greenstein Function

Henyey-Greenstein Function (1941)

\[ p(\theta) = \sum_{n=0}^{\infty} (2n+1) g^n P_n(\cos \theta) \]

Probability Function

Associated Legendre Polynomials

\[ P_n(x) = \frac{1}{2^n n!} \frac{d^n}{dx^n} (x^2 - 1)^n \]

Orthogonal System

\( P_n(x) \): Cartesian coordinates

\( P_n(\theta) \): polar coordinates

\[ \Psi \]

\[ \alpha \]
Henyey-Greenstein Function - 1941

\[ p(\theta) = \sum_{n=0}^{\infty} (2n+1) g^n P_n(\cos \theta) = \frac{1-g^2}{(1+g^2-2g \cos \theta)^{3/2}} \]

coefficient of anisotropy

\[ g \in [-1...1] \]

back-scattering \hspace{1cm} forward-scattering

isotropic scattering

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Modified Henyey-Greenstein Function (Yoon et al., 1987)

\[ p(\theta) = \frac{1}{4\pi} \frac{u+1-u)(1-g^2)}{[1+g^2-2g \cos \theta]^{3/2}} \]  

\( \Rightarrow \) Fits experimental data better!

![Graph showing probability function of aortic wall.](image)

fit: \( g = 0.945; u=0.071 \)

**Biological Tissue:**

\( g = 0.7 - 0.99 \)

\( \theta = 8^\circ - 45^\circ \)
Total Attenuation Measurement

Angular Dependence of Scattering

Aortic wall (g = 0.945)
Absorption Measurement

Two separate measurements: with and without out sample

Δ-Intensity due to absorption!

Simultaneous Absorption & Scattering Measurement

Total Attenuation:

$$\alpha_t = \alpha + \alpha_s$$

Absorption / Scattering

E.g. thermal effects during LASER exposure

Low accuracy, if conditions change during the separate measurements!

Kubelka-Munk Theory (1931): Absorption and Scattering Model

$$\alpha_s = \frac{1}{yD} \cdot \ln \left[ \frac{1 - R_d(x - y)}{T_d} \right]$$

With

$$x = \frac{1 + R_d^2 - T_d^2}{2R_d}$$

And

$$y = \sqrt{x^2 - 1}$$

$$\alpha = (x - 1) \cdot \alpha_s$$

Transmitted diffuse intensity

Reflected diffuse intensity
Kubelka-Munk Theorie: Absorption & Scattering Measurement

Optical properties of white matter of human brain in its native and coagulated state simulated by Roggan et al. 1995a using the Kubelka-Munk theory.

Experimental Data

Table 2.3. Optical properties of human tissues in vitro

<table>
<thead>
<tr>
<th>Tissue</th>
<th>( \lambda ) (nm)</th>
<th>( \alpha ) (cm(^{-1}))</th>
<th>( \alpha_s ) (cm(^{-1}))</th>
<th>( \alpha_t ) (cm(^{-1}))</th>
<th>( g )</th>
<th>Reference</th>
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<tr>
<td>Aorta advent.</td>
<td>476</td>
<td>18.1</td>
<td>267</td>
<td>285</td>
<td>0.74</td>
<td>Keijzer et al. (1989)(^a)</td>
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<td>580</td>
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<td>633</td>
<td>5.8</td>
<td>195</td>
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<td>1.4</td>
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<td>89.4</td>
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<td>Blood</td>
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<td>1247</td>
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<td>Blood</td>
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<td>505</td>
<td>508</td>
<td>0.99</td>
<td>Reynolds et al. (1976)(^a)</td>
</tr>
</tbody>
</table>

Problems:
- optical properties often measured in-vitro! \( \rightarrow \) not the same characteristics as in-vivo
- comparability due to different models
Repetition

- Fresnel Equation: Reflectivity → Reflectance
- Absorption in Tissue: Therapeutic window in near IR
- Turbid media: Absorption + Scattering
- Elastic Scattering: Rayleigh + Mie (particle size ~ \( \lambda \))
- Tissue
  - Rayleigh + Mie → Henyey Greenstein Function
  - Scattering and Absorption measurement → Kubelka Munk Theory

Next Lecture

6. LASER – Tissue Interactions II