Overview

• Optics is a branch of physics focused on the study of lights’ nature and its’ use.

• **Geometric optics**
  • Formation of images due to reflection and refraction
  • Light treated as a ray

• **Physical optics**
  • Light treated as electromagnetic wave
  • Quantum Optics
  • Optical Engineering (mix between optics and electrical engineering)
Break Down

• Concepts learned this semester that apply here, with formulas
• Overview of UWOC (Underwater Wireless Optical Communications)
• Photodetectors (Receiver)
  • SPADs vs SNSPDs
Reflection, Refraction and Polarization

• Law of Reflection: $\theta_i = \theta_r$.

• Index of refraction: $N = \frac{c}{v}$
  • Speed of light in medium

• Snell’s Law: $n_1\sin\theta_1 = n_2\sin\theta_2$

• Polarization
  • By Reflection & By Scattering
  • Helps clarify transmitted videos, images
  • Brewers’ Law: $\tan\theta_b = \frac{n_2}{n_1}$ (by reflection)
    • Optical Bandpass Filter
  • US Navel Academy – Laser Polarization
Interference

Constructive

\[ dsin\theta = m\lambda \]

Destructive

\[ dsin\theta = \left( m + \frac{1}{2} \right)\lambda \]
Dispersion = Spreading of white light into full spectrum of wavelengths.

Rainbow

*Not just visible light

Diffraction – Bending of a light wave around the edges of an opening/obstacle.

Diffusion – Spreading of light from a light source
Lenses
Propagation, Light Intensity

Example 1:
When light is a distance $x$ away from its source it has an intensity of 40 Wm$^{-2}$. What will be its intensity when it is $2x$ away from its source?

Solution:
Original intensity

$$I_0 = \frac{\text{Power}}{\text{Area}} = \frac{\text{Power}}{4\pi x^2} = 40 \text{ Wm}^{-2}$$
Attenuation $k(\lambda)$

- Absorption Coefficient $a(\lambda)$

$$a(\lambda) = \left[ a_w(\lambda) + 0.06 a_c(\lambda) C^{0.65} \right] \{ 1 + 0.2 \exp \left[ -0.014 (\lambda - 440) \right] \}$$

- Scattering Coefficient $b(\lambda)$

$$b(\lambda) = 0.30 \frac{550}{\lambda} C^{0.62}$$
<table>
<thead>
<tr>
<th>Water Types</th>
<th>$C$ (mg/m$^3$)</th>
<th>$a$ ($\lambda$) (m$^{-1}$)</th>
<th>$b$ ($\lambda$) (m$^{-1}$)</th>
<th>$c$ ($\lambda$) (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure sea water</td>
<td>0.005</td>
<td>0.053</td>
<td>0.003</td>
<td>0.056</td>
</tr>
<tr>
<td>Clear ocean water</td>
<td>0.31</td>
<td>0.069</td>
<td>0.08</td>
<td>0.151</td>
</tr>
<tr>
<td>Costal ocean water</td>
<td>0.83</td>
<td>0.088</td>
<td>0.216</td>
<td>0.305</td>
</tr>
<tr>
<td>Turbid harbor water</td>
<td>5.9</td>
<td>0.295</td>
<td>1.875</td>
<td>2.170</td>
</tr>
</tbody>
</table>
UNDERWATER OPTICAL COMMUNICATIONS
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Acoustic</th>
<th>RF</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation</td>
<td>Distance and frequency dependent (0.1–4 dB/km)</td>
<td>Frequency and conductivity dependent (3.5–5 dB/m)</td>
<td>0.39 dB/m (ocean) 11 dB/m (turbid)</td>
</tr>
<tr>
<td>Speed</td>
<td>1500 m/s</td>
<td>$2.3 \times 10^8$ m/s</td>
<td>$2.3 \times 10^8$ m/s</td>
</tr>
<tr>
<td>Data Rate</td>
<td>kbps</td>
<td>Mbps</td>
<td>Gbps</td>
</tr>
<tr>
<td>Latency</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Distance</td>
<td>more than 100 km</td>
<td>≤10 m</td>
<td>10–150 m (500 m potential)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1 kHz–100 kHz</td>
<td>MHz</td>
<td>150 MHz</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>10–15 kHz</td>
<td>30–300 MHz</td>
<td>$5 \times 10^{14}$ Hz</td>
</tr>
<tr>
<td>Transmission Power</td>
<td>10 W</td>
<td>mW–W</td>
<td>mW–W</td>
</tr>
</tbody>
</table>
Figure 2

Absorption coefficient of pure seawater for different transmission wavelengths.
The Underwater Wireless Optical System

**TRANSMITTER**

- LDs
- LEDs

**Medium**
- Pure Sea Water
- Clear ocean water
- Coastal ocean water
- Turbid harbor water

**Photodetectors**

**RECEIVER**
Photodetectors: Convert light energy into electrical energy

Photodetector types

- Photomultiplier tubes
- Vacuum Photodiodes
- pn-PD
- P-i-N PD
- APD

SPADs
SNSPDs
SNSPD Device Concept

1. An SNSPD is simply a current-biased superconducting wire in parallel with a readout circuit.

2. When a photon hits the wire, it creates a hotspot, where a small region of the wire goes normal.

3. The current diverts around the hotspot.

4. The current density surrounding the hotspot exceeds the critical current, and the entire wire width goes normal. The current is redirected through the measurement circuit, creating a detectable voltage pulse.

5. With the current through the nanowire reduced, the hotspot cools off, returning the wire to its original state.

A Comparison: Advantages

• **SPADs:**
  • Less power to operate
  • Transmission distance extended
    • One experiment shown up to 112 m
  • Compared to APD which has 73 m

• **SNSPDs:**
  • High detection efficiency
  • Low dark count rate
  • Low timing jitter (<100 ps)
  • Fast recovery time (<10 ns)
  • Increases image scalability
A Comparison: Disadvantages

• SPAD:
  • Max counting rate: 100 MHz (not ideal for GHz links)
  • Efficiency, timing jitter and recovery time may not be as good as the SNSPD
  • Smaller range of wavelengths can be used

• SNSPDs:
  • Very cold temperatures required (more expensive)
  • Has mainly been tested in the infrared range
    • More experimenting needed in and visible spectrum
Which is better?

- As of now, the SPAD looks to be a better option for specifically UWOC Deep Space Optical Communications has the cold temperatures needed for SNSPDs. Underwater, this is more difficult to achieve
Remaining Questions:

• Using different types of materials with SNSPDs, SPADs
  • There are different versions of each

• Other ways to change the devices slightly to see how performance will change? – Array combinations

• More research needed using SNSPDs underwater = SPADs, APDs have been around longer, so more about them is known.
Thank you!

Questions?