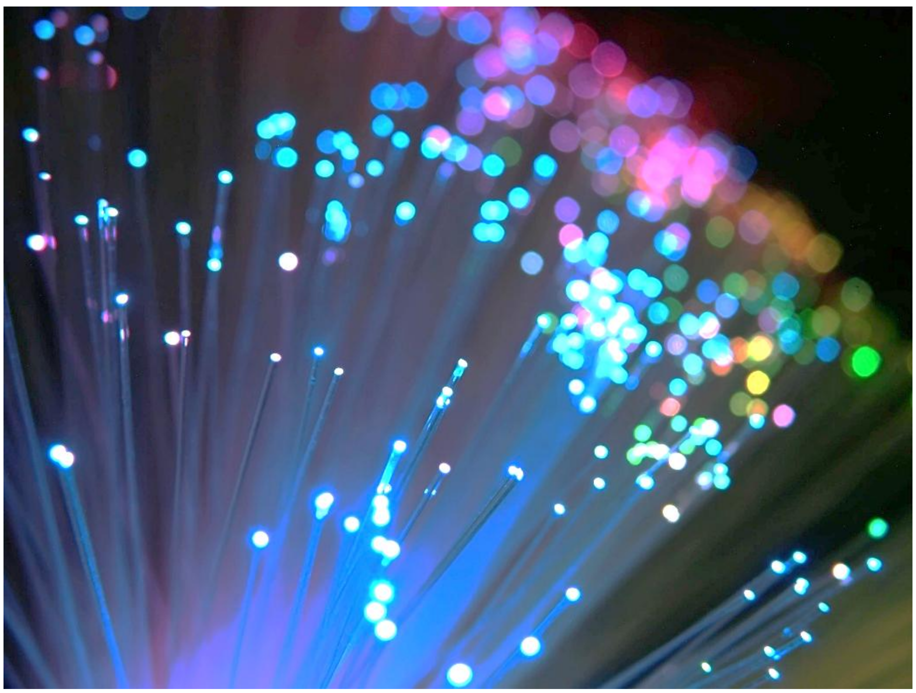
Al-Mustaqbal University / College of Engineering & Technology
Department of Medical Instrumentation Techniques Engineering
Class: 4th
Subject: Medical Laser Systems
Lecturer: MSc. Huda Wasfi Hassoon
2nd term – Lecture No. 10 & Lecture Name: Quantum Detectors

Lecture 10
Quantum Detectors



Lecturer:
MSc. Huda Wasfi Hassoon

Email: (huda.wasfi@uomus.edu.iq)

Quantum detectors play a fundamental role in modern medical laser systems, particularly when laser radiation is delivered and monitored through optical fibers. In medical laser engineering, the system does not only consist of a laser source; it also requires precise control, monitoring, and feedback mechanisms to ensure safe and effective interaction with biological tissues. Quantum detectors provide this essential measurement capability.

In medical laser systems, coherent radiation generated by laser sources such as the Nd:YAG laser or the CO2 laser is often transmitted through optical fibers to reach internal tissues. Optical fibers act as guided-wave structures that transport photons with minimal loss. However, during transmission and tissue interaction, part of the optical energy may be reflected, scattered, or attenuated. Accurate detection of this optical signal is crucial for power calibration, dosimetry, and safety control.

Quantum detectors, which operate based on the photoelectric effect, convert incident photons into measurable electrical signals. Their operation is wavelength-dependent, making them highly suitable for laser systems where monochromatic radiation is used. In fiber-coupled laser systems, quantum detectors are positioned either at the output port for power monitoring or in diagnostic subsystems to detect backscattered or fluorescent light from tissues.

Furthermore, many advanced diagnostic techniques integrated with medical laser platforms—such as Optical Coherence Tomography—depend entirely on highly sensitive quantum detectors to measure extremely weak optical signals. In such systems, parameters like responsivity, quantum efficiency, response time, noise-equivalent power (NEP), and detectivity directly determine imaging resolution and diagnostic accuracy.

Therefore, the relationship can be summarized as follows:

- The laser generates coherent photons.
- Optical fibers deliver photons to the target tissue.
- Quantum detectors measure photon intensity for monitoring, feedback, and imaging.

This integration ensures treatment precision, patient safety, and real-time system control in medical laser applications.

Quantum detectors

Quantum detectors are optical detectors that convert incident photons into electrical signals using quantum mechanical interactions between radiation and matter. Their operation depends on the **photoelectric effect**, where photon energy is transferred to electrons.

Quantum detectors are classified into four main types:

1. **Photoemissive detectors**
   - Vacuum photodiode
   - Photomultiplier tube
2. **Photoconductive detectors**
   - Semiconductor photodiode
   - Avalanche photodiode (APD)
3. **Photovoltaic detectors**
   - Silicon solar cell
4. **Photoionization detectors**

Email: (huda.wasfi@uomus.edu.iq)

General Characteristics of Quantum Detectors

1- Responsivity (S)

Responsivity measures how effectively a detector converts incident optical power into electrical current.

$$S = \frac{I_{out}}{P_{in}}$$

Where:

- S= Responsivity (A/W)
- I_{out}= Output photocurrent (A)
- P_{in}= Incident optical power (W)

Spectral Responsivity

Responsivity depends on wavelength:

$$S = S(\lambda)$$

This is called **spectral responsivity**, and it indicates detector sensitivity at each wavelength.

In medical lasers, since wavelength is fixed (e.g., 1064 nm for Nd:YAG), detector selection must match the laser wavelength.

2- Quantum Efficiency (QE)

Quantum efficiency is the ratio of the number of charge carriers generated to the number of incident photons:

$$QE = \frac{Number\ of\ emitted\ electrons}{Number\ of\ incident\ photons}$$

Email: (huda.wasfi@uomus.edu.iq)

Expressed as a percentage:

$$QE(\%) = QE \times 100$$

For photoemissive detectors, QE can be related to responsivity by:

$$QE = \frac{S(\lambda)\, hc}{q\lambda}$$

Where:

- h= Planck's constant
- c= speed of light
- q= electron charge
- λ= wavelength

Higher QE means better photon-to-electron conversion efficiency.

3- Response Time (τ)

Response time is the time required for detector output to reach 63% of its final value after sudden illumination.

If light is removed:

$$Output = 37\% \text{ of initial value after time } \tau$$

Fast response is required in pulsed laser systems (nanosecond range).

Email: (huda.wasfi@uomus.edu.iq)

4- Noise Equivalent Power (NEP)

NEP represents the minimum detectable optical power when:

$$S/N = 1$$

It is expressed as:

$$NEP(W/Hz^{1/2})$$

Mathematically:

$$NEP = NEI \times A$$

Where:

- NEI = Noise equivalent irradiance
- A = Detector area

Lower NEP → higher sensitivity.

5- Detectivity (D)

Detectivity is the reciprocal of NEP:

$$D = \frac{1}{NEP}$$

Higher detectivity means better performance.

Email: (huda.wasfi@uomus.edu.iq)

6- Normalized Detectivity (D*)

Since noise depends on area and bandwidth:

$$D^* = D\sqrt{A\Delta f}$$

Or:

$$D^* = \frac{\sqrt{A\Delta f}}{NEP}$$

Where:

- A= detector area
- Δf= bandwidth

Units:

$$cm \cdot Hz^{1/2}/W$$

D* allows fair comparison between detectors.

Photoemissive Detectors

Photoemissive detectors operate according to the **photoelectric effect**.

When a photon of energy $h\nu$strikes a metal surface:

$$K.E_{max} = h\nu - \phi$$

Where:

- ϕ= work function
- ν= frequency
- $h\nu_c = \phi$(threshold condition)

Emission occurs only if:

Email: (huda.wasfi@uomus.edu.iq)

$$\nu \geq \nu_c$$

Or:

$$\lambda \leq \lambda_c$$

Typically:

$$\lambda_c \leq 1.2\ \mu m$$

Properties of Photoemissive Detectors

1. Photocurrent ∝ light intensity
2. Electron energy depends on frequency
3. Fast response (<10 ns)
4. Wavelength dependent
5. Limited spectral range

Alkali materials (Cs, Sb, Na, K) are used due to low work function.

Dark Current

Dark current is thermionic emission in absence of light.

It increases with temperature:

$$I_d \propto e^{-\frac{\phi}{kT}}$$

Where:

- k= Boltzmann constant
- T= temperature

Dark current increases NEP and reduces sensitivity.

Cooling reduces dark current significantly.