What is Photonics?

- New Macquarie Research Center

- New courses:

  "Doing stuff with lasers" ............. not that simple!
What is Photonics

**Photonics** is the science of generating, controlling, and detecting photons, particularly in the visible and near infra-red spectrum (Wikipedia)

**Photonics** is the use of light to obtain, convey or process information. "Light" here includes infrared and ultraviolet radiation, as well as the light that is visible to our eyes. (University College Cork)

- **Obtain:**
  - Detectors (photodiodes), Sources (lasers)
- **Convey:**
  - Optical fibre networks
- **Process:**
  - Switching, routing, signal conditioning, signal conversion etc
What is photonics (cont)

Or more simply….  

• “Photonics is the optical equivalent of electronics”
What is photonics (cont)

Or more simply….

• “Photonics is the optical equivalent of electronics”

Electronic Processing ➔ All-Optical Processing
Why is it called Photonics?

- The flow of electricity in a wire consists of the combined movement of tiny fundamental particles of charge, called "electrons". The devices and systems used to generate and manipulate electrical signals are widely known as "electronics". Albert Einstein and other scientists working at the beginning of the 20th century, showed that light consists of a different kind of tiny fundamental particles, called "photons". And so the word "photonics" has been coined to describe devices and systems used to generate and manipulate optical signals (University College Cork).

- Electricity and electronics uses electrons, photonics uses photons - the fundamental particles of light (University of Southampton).
Light Amplification by Stimulated Emission of Radiation

A LASER is a unique light source

What is light?

A wave AND a particle

1801

1905
Waves

- Waves show **Interference**
- When two wave crests reach the same point simultaneously, the wave height is the sum of the two individual waves.
- Conversely, a wave trough and a wave crest reaching a point simultaneously will cancel each other out.
- Water, sound, and **light waves** all exhibit interference
Young’s Double-Slit Experiment

- Young (1801) showed that light *interferes.*
Laser Light as an electromagnetic wave

Maxwell’s wave equations:

\[ \nabla \cdot E = 0 \]
\[ \nabla \cdot H = 0 \]

Maxwell’s equations for a vacuum:

\[ \nabla \times H = \varepsilon_0 \frac{\partial E}{\partial t} \]
\[ \nabla \times E = \mu_0 \frac{\partial H}{\partial t} \]

From this it follows that:

\[ \nabla^2 E = \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2} \]
\[ \text{and} \]
\[ \nabla^2 H = \mu_0 \varepsilon_0 \frac{\partial^2 H}{\partial t^2} \]
Laser light is a very simple kind of light and a suitable example for a completely simplified physical description of light as an electromagnetic wave.

The speed of (laser) light $v = c / n$

$c$... universal constant (299 792 500 ± 300 m.s$^{-1}$)

$n$... refractive index of the medium, for vacuum $n=1$

$\rightarrow v = c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 2.99792 \times 10^8 \text{m/s}$
The one-dimensional wave equation

The one-dimensional wave equation for scalar (i.e., non-vector) functions, $A$:

$$\frac{\partial^2 A(z, t)}{\partial z^2} - \frac{1}{v^2} \frac{\partial^2 A(z, t)}{\partial t^2} = 0$$

where $v$ will be the velocity of the wave. $v = c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 2.99792 \times 10^8 \text{ m/s}$

The wave equation has the simple solution:

$$A(z, t) = C e^{-i(k_z z - \omega t)}$$

with $k_z = \frac{2\pi}{\lambda} = \frac{\omega}{v}$

$k_z$……Propagation constant or Wave number

$\omega = 2\pi v$……Angular frequency; $v$……Oscillating frequency [Hz]

$T = 1 / v$ …..Period of oscillation [s]

For visible light:
$v \sim 10^{14} - 10^{15} \text{ Hz}$
$T \sim 10^{-14} - 10^{-15} \text{ s}$
Definitions

Spatial quantities:

Wavelength: $\lambda$

The k-vector: $k = \frac{2\pi}{\lambda}$

The wave number: $\kappa = \frac{1}{\lambda}$

Temporal quantities:

Period: $\tau$

The angular frequency: $\omega = \frac{2\pi}{\tau}$

The frequency: $\nu = \frac{1}{\tau}$
The expression \( E_0 \exp[-i(k_z z - \omega t)] \) is called a plane wave.

A plane wave’s contours of maximum field, called **wave-fronts** or **phase-fronts**, are planes. They extend over all space.

A wave's wave-fronts sweep along at the speed of light.

Wave-fronts are helpful for drawing pictures of interfering waves.

A plane wave's wave-fronts are equally spaced, a wavelength apart. They're perpendicular to the propagation direction.
Laser beams vs. Plane waves

A plane wave has flat wave-fronts throughout all space. It also has infinite energy. It doesn’t exist in reality.

A laser beam is more localized. We can approximate a laser beam as a plane wave vs. $z$ times a Gaussian in $x$ and $y$:

$$E(x, y, z, t) = E_0 \exp\left[-\frac{x^2 + y^2}{w^2}\right] \exp[i(kz - \omega t)]$$

Localized wave-fronts

Laser beam spot on wall
E and H are vector fields

- $\vec{k}$ is the propagation wave vector
  - points per our definition in z-direction, magnitude $k_z$
- $\vec{E}$ and $\vec{H}$ are perpendicular to each other and perpendicular to $\vec{k}$
  - transverse waves

$$\vec{E} = E_0 \ e^{-i(k_z z - \omega t)}$$
$$\Rightarrow \vec{E} = E_{0x} \ e^{-i(k_z z - \omega t)} \vec{e}_x +$$
$$+ E_{0y} \ e^{-i(k_z z - \omega t + \Phi)} \vec{e}_y$$

- $\Phi = 0$....linearly polarised light
- $\Phi = \pi$....circular polarisation
- General: Elliptical polarisation
Energy flow

• The time rate flow of electromagnetic energy is described by the Poynting vector $\mathbf{S}$
  – Unit: $W/m^2$

$$\mathbf{S} = \mathbf{E} \times \mathbf{H}$$

$$\langle \mathbf{S} \rangle = \frac{1}{2} \mathbf{E}_0 \times \mathbf{H}_0 \quad \text{.....average value}$$

Spatial distribution of the field-
Vectors for circular polarised light
Clasification of electromagnetic waves

The radiations from different regions are interact in different ways with the matter

General dividing:

- **X-rays** – from 0.01 nm to ~10 nm
- **Ultraviolet radiation** – from ~10 nm to 400 nm
- **Visible light** – from 400 nm to 700 nm
- **Infrared radiation** – from 0.7 μm to 1000 μm
Visible region depending on the color sensation of human eye

<table>
<thead>
<tr>
<th>Color Light</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Violet light</td>
<td>from 400 nm to 450 nm</td>
</tr>
<tr>
<td>Blue light</td>
<td>from 450 nm to 500 nm</td>
</tr>
<tr>
<td>Green light</td>
<td>from 500 nm to 560 nm</td>
</tr>
<tr>
<td>Yellow light</td>
<td>from 560 nm to 590 nm</td>
</tr>
<tr>
<td>Orange light</td>
<td>from 590 nm to 620 nm</td>
</tr>
<tr>
<td>Red light</td>
<td>from 620 nm to 760 nm</td>
</tr>
</tbody>
</table>

The infrared region

<table>
<thead>
<tr>
<th>Region</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near infrared</td>
<td>from 0.7 μm to 1 μm</td>
</tr>
<tr>
<td>Intermediate</td>
<td>from 1 μm to 10 μm</td>
</tr>
<tr>
<td>Far infrared</td>
<td>from 10 μm to 1000 μm</td>
</tr>
</tbody>
</table>

The ultraviolet region (mainly used)

<table>
<thead>
<tr>
<th>Region</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum ultraviolet (VUV)</td>
<td>from 100 nm to 200nm is absorbed much faster in the air</td>
</tr>
<tr>
<td>Extreme ultraviolet (EUV)</td>
<td>from 10 nm to 100 nm</td>
</tr>
</tbody>
</table>
A common wavelength unit → not included the angstrom

(1 Angstrom = $10^{-10}$ m)

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Symbol</th>
<th>Value</th>
<th>Common Use</th>
<th>Wavelength $\lambda$ (m)</th>
<th>Time (sec)</th>
<th>Frequency $\nu$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tera</td>
<td>T</td>
<td>$10^{12}$</td>
<td></td>
<td></td>
<td></td>
<td>THz</td>
</tr>
<tr>
<td>Giga</td>
<td>G</td>
<td>$10^{9}$</td>
<td></td>
<td></td>
<td></td>
<td>GHz</td>
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<tr>
<td>Mega</td>
<td>M</td>
<td>$10^{6}$</td>
<td></td>
<td></td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Kilo</td>
<td>k</td>
<td>$10^{3}$</td>
<td></td>
<td></td>
<td></td>
<td>kHz</td>
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<tr>
<td>Milli</td>
<td>m</td>
<td>$10^{-3}$</td>
<td>km</td>
<td></td>
<td>ms</td>
<td></td>
</tr>
<tr>
<td>Micro</td>
<td>$\mu$</td>
<td>$10^{-6}$</td>
<td>mm</td>
<td></td>
<td>$\mu$s</td>
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</tr>
<tr>
<td>Nano</td>
<td>n</td>
<td>$10^{-9}$</td>
<td>$\mu$m</td>
<td></td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Pico</td>
<td>p</td>
<td>$10^{-12}$</td>
<td>nm</td>
<td></td>
<td>ps</td>
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</tr>
<tr>
<td>Femto</td>
<td>f</td>
<td>$10^{-15}$</td>
<td></td>
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<tr>
<td>Atto</td>
<td>a</td>
<td>$10^{-18}$</td>
<td></td>
<td></td>
<td></td>
<td>as</td>
</tr>
<tr>
<td>Peta</td>
<td>P</td>
<td>$10^{15}$</td>
<td></td>
<td></td>
<td></td>
<td>PHz</td>
</tr>
</tbody>
</table>
Photons

- Photoelectric effect

- Skin cancer caused only by UV light

→ Light consists of particles with

  - $m = 0$
  - $E = h\nu$ (h=6.626 068 96×10⁻³⁴ J s)
Unique properties of a laser

• Monochromaticity
  – “(Some) lasers emit only one frequency”
• Spatial coherence
• Temporal coherence
• Directionality
• Brightness
• Short pulse duration
Spatial coherence

Consider two points (A, B) on the same wave front:
- Phase difference at t=0 is zero (by definition)
- If the difference remains zero for any t > 0: perfect coherence between A and B
- If coherence occurs for any two points: **Perfect spatial coherence**
- In practice: Partial spatial coherence

- **diameter of coherence** – the maximum distance between the points of the cross-section for which spatial coherence is observed

For high quality lasers “**diameter of coherence**” ≡ D of laser beam
For light from ordinary sources – very small “**diameter of coherence**” (μm)
The oscillation at the point A is a continuous cosine oscillation only for a certain time interval.

- Consider the electric field of the EM wave at a given point A, at times $t$ and $t + \tau$. If, for a given time delay $\tau$, the phase difference between the two fields remains the same for any time $t$, we say that there is a temporal coherence over a time $\tau$.
- If this occurs for any value of $\tau$, the EM wave is said to have perfect temporal coherence.
- If this occurs for a time delay $\tau$ such that $0 < \tau < \tau_C$, the wave is said to have partial temporal coherence, with a coherence time equal to $\tau_C$. 
Temporal Coherence II

- Coherence length – $\tau_c \cdot c = l_c$
Temporal Coherence III

- Temporal coherence is connected to the spectral width of a light signal:

- Can not be applied for a repetitively reproducing beam (e.g., a repetitively Q-switched or a mode-locked laser beam)

\[ l_c = \frac{\lambda_0^2}{\Delta \lambda} \]
Temporal Coherence IV

- White (thermal) light source:

  \[
  \lambda = 400\text{nm} \ldots 700\text{nm} \rightarrow \\
  \Delta \nu \approx 10^{15}\text{Hz} \rightarrow \tau_C \approx 10^{-15}\text{s} \rightarrow l_c \approx 1\mu m
  \]

- (Cheap) HeNe laser (10mW power):

  \[
  \Delta \nu \approx 1\text{MHz} \rightarrow \tau_C \approx 1\mu s \rightarrow l_c \approx 300m
  \]

- To filter out a narrow spectrum from the white light:

  \[
  P_{WL,narrow} = P_{WL} \times \frac{10^6\text{Hz}}{10^{15}\text{Hz}} = 1\text{W} \times 10^{-9} = 1\text{nW}
  \]
Directionality

\[ \theta = \frac{\gamma \lambda}{D} \]

\( D \) – diameter of spatial coherence
\( \gamma \approx 1 \), depends on the definition of \( D \) and \( \theta \)

\( \theta \) is min when the light is completely spatially coherent

Laser beam:
\( \theta < 0.001^\circ \)
Pointed towards Vienna:
\( D_{\text{Vienna}} \approx 200 \text{ m} \)

Searchlight beam:
\( \theta \approx 5^\circ \)
Pointed towards Vienna:
\( D_{\text{Vienna}} \approx 2800 \text{ km} \)
Brightness B (Radiance)

- Defined as power emitted by unit surface area per unit solid angle

- Peak Intensity in the focal plane of a lens:

\[ I_p = \left( \frac{\pi}{4} \right) (N.A.)^2 B \]

- Brightest lamp (100W): \( B = 100 \text{ W/(cm}^2\text{sr)} \)

- 1mW laser pointer: \( B = 10^5 \text{ W/(cm}^2\text{sr)} \)
Short pulse duration

- Typical flashlight: 1 ms
- Ultrafast laser: 10 fs
A brief history…

• 1917 – A. Einstein, prediction of the phenomenon of induced radiation (A. Einstein, Zur quantentheorie der Strahlung, Phys. Z. 18,121-128 (1917)) …… gain

• 1954 – Charles H. Townes, Nikolai G. Basov and Alexander M. Prokhorov, independently suggested the most important element of the quantum oscillator, a cavity (feedback!). They conceived the Maser (microwave amplification by stimulated emission of radiation) idea

• 1960 – T. Maiman, the first demonstration of the ruby laser

• Nobel prize 1964: A. M. Prokhorov, N. G. Basov, C. H. Townes
Intensities...

\[ E_{\text{laser}} = \frac{zmc^2}{\varepsilon_\lambda_c} \]

Intensities above \(10^{29} \text{ W/cm}^2\) can make electron-positron pairs out of the vacuum.

Intensities greater than \(10^{24} \text{ W/cm}^2\) are beyond the capabilities of present-day solid state lasers.

\[ E_{\text{laser}} \approx \frac{mc^2}{e} \]

At \(10^{19} \text{ W/cm}^2\), optical laser fields drive electrons to relativistic speeds.

\[ E_{\text{laser}} \approx \frac{e}{a_0^2} \]

At \(10^{16} \text{ W/cm}^2\), intensity corresponds to atomic strength laser fields.

Chirped pulse amplification

Mode-locking

Q-switching
Pulse duration....
The wavelength of some of the laser sources

- Nd:YAG/Glass (Doubled): 0.53
- ALEXANDRITE: 0.72-0.8
- SAPPHIRE: 0.68-1.13
- RUBY: 0.69
- Ga:As: 0.85-0.9
- Nd:YAG & Nd:Glass: 1.06
- Ti: SAPHIRE: 1.54
- Nd:YAG Ramen Shifted
- HO: YAG: 2.06
- Dy:CaF: 2.35
- Nd:YAG: 1.64
- HF: 2.6-3.0
- CO2 (Doubled): 5.3
- DF: 3.4-4.0
- CO: 5.0-7.0
- CO2: 9.2-11

WAVELENGTH - Micrometers

0.4 0.6 0.8 1.0 μ 2 3 4 6 8 10 μ
The world’s smallest laser
National Ignition Facility
NIF

192 beams focused onto the target
Total pulse energy: 4 MJ
Pulse duration: ~1ns
Peak Power: 4 PW

https://lasers.llnl.gov/
(http://en.wikipedia.org/wiki/National_Ignition_Facility)
Laser market (USD)

Worldwide commercial laser revenues

- 2005: $5.46 billion (59% Diode, 41% Nondiode)
- 2006: $5.56 billion (56% Diode, 44% Nondiode)
- 2007: $6.87 billion (55% Diode, 45% Nondiode)
- 2008: $7.12 billion (58% Diode, 42% Nondiode)
- 2009: $6.32 billion (55% Diode, 45% Nondiode)
Laser market

Lasers by applications
- Materials Processing: 29%
- Communications: 27%
- Storage: 26%
- Medical therapy and diagnostics: 7%
- Basic research: 3%
- Pumps: 3%
- 1% Image recording
- 1% Instrumentation
- 3% All other