Photonics & Electronics
Photonics Detailed Study in VCE Physics

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Communications using Optics & Photonics

- Optics/photonics can transmit information very efficiently, and it is the major enabling technology for current and future generations of telecommunications and information systems.
Optical Fibres versus Copper Cables

- 600 twisted-pair copper cable carries 600 conversations
- 6 coaxial copper cable carries 2700 conversations
- One single optical fibre, with modern wavelength division multiplexing (WDM) technology, can carry over 1,000,000 conversations.
Optics/Photonics and other “High Tech” Industries

- Photonics technology also has important uses in...
- the **manufacturing** industry
- the **medical** industry
- the **civil engineering** industry
- the **entertainment** industry
- the **sustainability** industry
- the **transport** industry

- Miniature mirror array used in data projectors
- Laser Eye Surgery
- Tsing Ma Bridge, Hong Kong
- Blu-ray DVDs use new generation blue light laser diodes
- Australian manufactured solar energy collectors
- Fly-by-wire control systems use optical fibre
Optics/Photonics and “Low Tech” Industries

- Lighting solutions for isolated communities in developing countries
- **Light Up The World (LUTW)**
- Development of an inexpensive, ultra-efficient, self-sustaining, ultra-bright WLED* system

*WLED is... White LED

High power WLED torches now commonly available
Using Light for Communications

- **Early examples:**
  - smoke signals, signal flags, signal fires, etc

- **More recent and more organised examples:**
  - (a) Optical telegraph (1790’s Claude Chappe d’Auteroche)
    - Used semaphores (either flags or lanterns) to transmit info from one place to another.
    - France had a network of 556 stations stretching a total distance of 4,800 km.
    - Replaced in mid to late 1800s by the “electric” telegraph
Using Light for Communications

• More recent and more organised examples:
  
• (b) Aldis lamps (1867) for naval communications
  
  – Navy signal lamps show all the characteristic modules of modern fibre optic communication systems.
  
  (light source, modulation, transmission medium and detector)
• Optical Telegraph

Use a LED transmitter and a PT receiver to send coded digital messages.

Optical telegraph is an example of a DIGITAL optical communications system.
The photophone: A great idea *but* before its time

- In 1876, Alexander Graham Bell invented the telephone.
- In 1880, he invented the **photophone**.
- Photophone used sunlight modulated by a voice-driven diaphragm to transmit speech to a receiver over 200m away.
Intensity Modulation: Simple Photophone

Photophone is an example of an ANALOG optical communications system.
Build your own 21st Century Photophone Transmitter

external power supply ~3 V

R (1 Ω)

modulation voltage from audio source (~200 mV)

LD
Build your own 21st Century Photophone Receiver

Audio analog optical communications
**Photophone: Technical Issues**

- Fast modulation rate sufficient for good audio response.
- But idea lay dormant for a century due to problems with...
  - transmission medium stability
    - Moving obstructions (people, horses etc.) and fluctuations in atmospheric conditions (fog, rain dust, etc.) meant that the transmission medium was unpredictable over long distances
      - (1970: high purity optical fibres produced)
  - light sources intense but not bright
    - light energy could not be channelled into a small forward solid angle (ie large divergence, and its intensity decreased according to the inverse square law (ie no good over long distances))
      - (1960: Laser invented)
Internet Revolution & the Hunger for Bandwidth

- Internet started 1970 (5 hosts)
- 1977 (100 hosts)
- 1984 (1000 hosts)
- 1987 (10,000 hosts)
- 1989 (100,000 hosts)
- 2000 (100M hosts)
- 1992 (1M hosts)
- 2002 (200M hosts and 850M users)
- 2006 (1B users) nearly 17% of the world population
- 2009 (1.7B users) or 26% of the world population
- 2012 (2.5B users or 30% of the world population)
National Broadband Network

• National Broadband Network is a full “fibre to the home” network proposed for Australia.

• Will provide download speeds of around 100 megabits per second to 93% of Australian homes and businesses (ultra-fast wireless for other 7%)

• Will cost around $43 billion (over 8 years) to establish

• Major infrastructure investment in our “information future”

• Bigger than “Snowy Mountains Hydro-Electric Scheme
National Broadband Network

• A full “fibre to the home” NBN network makes a lot of sense, even though it may cost a lot of cents.
• Business & Commerce (access to national/international suppliers)
• Leisure and lifestyle (eg video on demand)
• Education (eg video conferencing)
• Medicine (eg on-line diagnosis)
Total Internal Reflection

If the incident angle is greater than the critical angle, then none of the beam is transmitted and all of the beam is reflected (this is called total internal reflection or TIR).

Perspex hemisphere
Without TIR, light is refracted at each reflection and intensity of channelled light quickly decreases (Many thousands of reflections per meter!!!)

With TIR, all light is fully reflected (none refracted) at each reflection and intensity of channelled light remains constant

Perspex Pretzel
Why Optical Fibres: (b) Bandwidth

- Bandwidth of twisted-pair solid copper cable limited by skin effect
  - (Bandwidth decreases rapidly with increasing frequency)
  - Unworkable transmission losses above 30 MHz
Optical Fibre Bandwidth

- **Bandwidth:** Optical fibres do not have skin effect
  - Theoretical maximum carrier frequency is very high!
  - Practical bandwidth limited by light source and detector characteristics. Currently ~ 500 GHz.
  - But still orders of magnitude higher than coax cable (next best option).
  - Theoretical max. bandwidth, for 1500 nm light...
    \[ f_c = \frac{c}{\lambda} = \frac{3 \times 10^8}{1.5 \times 10^{-6}} = 200,000 \text{ GHz}. \]
Why Optical Fibres: (c) Attenuation

- Rayleigh Scattering by inhomogeneities frozen into the glass structure itself
- Absorption by impurity ions and atoms of the pure glass (e.g., OH- ion)
- Absorption by vibrating molecular bonds (e.g., Si - O)

Attenuation minimum is around 0.2 dB/km
Stepped-Index Multimode Fibre

- Lowest order mode transits the fibre in the shortest time.
- Highest order mode transits the fibre in the longest time (travel at the same velocity over a longer distance)
- So a narrow input pulse spreads out (in time) at the exit end of the fibre.
- Limits rate at which you can send info down the fibre (pulse overlap).
- Process called MODAL DISPERSION (typically around 100 ns per km)
Graded-Index Multimode Fibre

- ALL modes transit the fibre in approximately the same time.
- **Lowest order mode** travels the shortest distance but at the slowest velocity.
- **Highest order mode** travels the longest distance but at the fastest velocity.
- Modal dispersion only about 1 ns per km

Core has varying index of refraction (higher $n$ and $v$ near centre, lower $n$ and $v$ near periphery)

Reduced pulse spread means we can have pulses closer together and hence more bandwidth
Single Mode Fibre

- No more MODAL dispersion but still some (2\textsuperscript{nd} order) dispersions that cause pulse spreading

Core has small diameter so only lowest order mode can propagate (only 1 ray path possible)

No modal dispersion

Only one path so minimal pulse spread, means we can have pulses very close together and hence much more bandwidth
How Much Bandwidth is Currently Possible

- dispersion management (not just modal dispersion but other dispersions as well), wavelength-division multiplexing, optical amplifiers, modern-day optical fibres, light sources and detectors can now carry information at a few Terabits per second over 160 kilometres of fibre (2010 data)
- A Terabit = $1 \times 10^{12}$ bits or 1,000,000,000,000,000 bits
Generating light - *Photonic sources*

• Require a highly controllable and efficient form of light production (*beyond thermal sources such as sunlight, incandescent lamp, etc*)
  – light-emitting diodes (LEDs)
  – semiconductor lasers (“laser diodes” or LDs)

  • *important for telecoms*
  • *close tie-in to electronics & LEDs*
  • *many other types of laser used in photonics*
Light-emitting Diodes - LEDs

- Follows directly from electronics discussion of semiconductor *pn* junction
- Materials chosen so that electron-hole recombination energy is released as a photon, rather than as thermal energy.

- Discrete nature of band-gap energy gives “monochromatic” light \((\Delta \lambda = 20 \text{ nm})\)
**Light-emitting Diodes - LEDs**

Different materials lead to different band-gap energy, which results in different photon energy (wavelength).

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda$(nm)</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAsP</td>
<td>1000-1550</td>
<td>IR (telecoms)</td>
</tr>
<tr>
<td>GaAs</td>
<td>900</td>
<td>IR</td>
</tr>
<tr>
<td>GaAsP</td>
<td>665</td>
<td>red</td>
</tr>
<tr>
<td>GaPN</td>
<td>550, 590</td>
<td>green, yellow</td>
</tr>
<tr>
<td>GaN</td>
<td>430</td>
<td>blue</td>
</tr>
<tr>
<td>InGaN</td>
<td>405</td>
<td>Purple/UV</td>
</tr>
</tbody>
</table>

Bandgap energy of material related to colour of light produced.

$$E_g \sim E_{\text{photon}} = hf = hc/\lambda$$
Laser Diodes - LDs

- Generation of light follows same principle as for LED
- Geometry and high dopant levels of diode provides **optical cavity** (ie. reflection from “end mirrors”) and **population inversion** (high density of electrons in conduction band compared to valence)
- **Coherent** or LASER light. ($\Delta \lambda = 1$ nm or less, and *perfectly* in phase)
Simple LED circuit: exam examples

What is the current measured by the ammeter?

If there is sufficient voltage to turn on the LED, $V_{\text{LED}} = 1$ Volt, $I_{\text{LED}}$ will be the same as the current that will flow through the resistor $R$

Voltage across resistor $V_{500} = 6-1 = 5$ V, therefore current thru resistor = $V_{500}/R = 5/500 = 0.01$ A = 10mA

hence current thru LED and also thru the ammeter is also 10 mA and the LED is on

Interestingly the forward biased resistance of the LED in this situation is $R_{\text{LED}} = V/I \sim 1/0.01 \sim 100 \Omega$
Describe what happens to the current thru the LED as the resistance of the variable resistor (X) is decreased from 50 KΩ to 5 Ω? Look at 50 KΩ!

Initially when $R_X$ is large (50 KΩ) compared to the previous forward biased resistance of the LED (100 Ω), we can ignore effect of $R_X$ in the parallel combination, hence $V_{LED} = 1$ Volt, and current through ammeter will be $I_A = (6-1)/500 = 0.01$ A or 10 mA.
Current through $R_X$ is $I_X = 1/50000 = 0.00002$ A or 0.02 mA
Current thru LED is $I_{LED} \sim 10$ mA and the LED is on
Describe what happens to the current thru the LED as the resistance of the variable resistor (X) is decreased from 50 KΩ to 5 Ω?

As $R_X$ decreases (say 200 Ω) it becomes comparable to the previous forward biased resistance of the LED (~100 Ω). We need to consider the effect of $R_X$ (parallel combination); the current through the LED will start to drop a little, and the LED resistance will rise.

Assuming the $V_{LED}$ is still around 1 V, then $I_A$ is still 10 mA and the current through $R_X = 1/200 = 5$ mA.
So $I_{LED} = 5$ mA, and the LED is on but not as brightly as before.
Now the forward biased resistance of the LED in this situation is $R_{LED} = V/I \sim 1/0.005 \sim 200$ Ω.
Describe what happens to the current thru the LED as the resistance of the variable resistor (X) is decreased from 50 KΩ to 5 Ω? Look at 5 Ω!

As $R_X$ decreases even further (say 5 Ω) it becomes much smaller than the forward biased resistance of the LED (now $>> 200$ Ω). We need to consider the effect of $R_X$ which now dominates the parallel combination; the current through the LED will drop a lot, and the LED resistance will rise a lot.

The voltage across $R_X$ is now $V_X = V_{cc} \times \frac{R_X}{(R_X+R_{500})} = \frac{6\times 5}{(5+500)} = 0.06$ V, then $I_A = \frac{V_{500}}{R_{500}} = \frac{(6-.06)}{500} = 5.94/500 = 11.9$ mA which is the same as the current thru $R_X$.

So $I_{LED} \sim 0$ mA and the LED is off.
Detecting Light: Fibre Optic Detectors

- Require devices to faithfully convert optical energy into electrical energy (which can be detected electronically)

- In photonics, usually use semiconductor materials
  - light-dependent resistors (LDRs)
  - photodiodes
  - phototransistors
Light-dependent resistor (LDR)

- Semiconductor material whose resistance changes when illuminated. (absorbed photons break bonds and create “free” electrons)
- Usually a zig-zag strip of cadmium sulphide (CdS)
- Quite sensitive, non-linear function of light intensity but slow time response ($\tau \geq 1$ ms)
Simple LDR circuit: exam examples

Characteristics for a particular LDR device: For 10 lux of illumination $R_{LDR} = 10 \, k\Omega$

As light level decreases $R_{LDR}$ increases

We want to design a simple LDR circuit that will trigger when the illumination falls below 10 lux
Simple LDR circuit: exam examples

Street lamp circuitry will switch on lamp when $V_{out} \geq 4V$

When Illumination $< 10$ lux, $V_{out} > 4V$

Look at the circuit: when the light level decreases, does $V_{out}$ increase or decrease and why?

If light $\downarrow$, $R_{LDR} \uparrow$, $V_{out} \uparrow$ because greater proportion of the battery voltage appears across $R_{LDR}$ (ie $V_{out}$)
Simple LDR circuit: exam examples

Street lamp circuitry will switch on lamp when $V_{out} \geq 4V$

When Illumination < 10 lux, $V_{out} > 4V$

What value of resistance for $R$ will give $V_{out} = 4V$
when Illumination = 10 lux

Voltage divider equation

$V_{out} = V_{batt} \cdot \frac{R_{LDR}}{R_{LDR} + R}$

$4 = 12 \cdot \frac{10K}{10K + R}$

$40K + 4R = 120K$

$4R = 80K$

$R = 20K \Omega$
Wavelength Division Multiplexing

- To get the high data transfer rates required to meet the ongoing demands of the internet revolution, we need to send many different data channels down a single optical fibre.

- Because light is an EM wave, several different light waves can travel down an optical fibre, and then be separated back into the original wave components.
Wavelength Division Multiplexing (WDM)

- WDM is cutting-edge optical research: several hundred slightly different wavelength (or colour) information channels travel on a single optical fibre.
- In our demonstration, we will simply use three colour channels to understand the basic principle of WDM.
- Three individual signal channels (Red, Green, Blue) are multiplexed (combined) into entrance end of one single optical fibre, and then de-multiplexed (separated) back into three individual signal channels at the exit end of the fibre.
Wavelength Division Multiplexing (WDM)