The National Broadband Network, Fibre Optics and VCE Physics

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.

Optics Technology & how it relates to our modern life

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.
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

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”

Existing Hybrid Network

- Currently optical fibre for main “information highways” only, with copper cables from neighbourhood nodes to homes.
- Reason: cost of interfaces and connectors etc very high at the moment
- BUT we are very quickly hitting the “copper technology” limit, if demand trend continues.

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)
Why Optical Fibres: (a) 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).

Total Internal Reflection

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

Simple Glass light Pipe

$n_{glass} > n_{air}$

TIR occurs and the light is channelled through the fibre...

BUT any grease or dust on the core-air interface will change the reflection-refraction conditions and light may not be TIR

Optical fibre with Cladding

Surround glass core with a glass cladding with a slightly lower refractive index ($n_{core} > n_{cladding}$ but by just a little)

This protects and stabilised the core-cladding interface

Light is always channelled regardless of what contaminates cladding-air interface
**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 in Glass Fibres**

- Attenuation of 0.2 dB/km (95.5% transmission over 1 km)
  - Lowest possible theoretical attenuation using silica glass fibres and long wavelength infrared light sources @ 1550 nm.
- If seawater has an optical attenuation of just 1 dB/km (i.e., about 80% transmission over 1 km)...
- We would be able to see to the bottom of the sea floor even in the deepest ocean trench (The Mariana Trench, which lies about 2000 km east of the Philippines in the western North Pacific Ocean is approx. 11,000 metres below sea level)
- An optical attenuation of 1 dB/km would be totally unacceptable in a modern communications grade optical fibre.
More Bandwidth… Please More Bandwidth!!

- In an information hungry world, photonics scientists and engineers always working on fibre optic communication systems with more bandwidth.
- Information is transmitted as coded pulses of light.
- How can we increase bandwidth… use shorter pulses that are closer together.
- This means more information transferred per unit time.
- But this process is limited by the spreading out of pulses.

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.

Single Mode Fibre

- Actually, **RAY model breaks down for analysis of single mode fibre** (since the core diameter is the same order of magnitude as the wavelength of light).
- Need to use wave model to correctly explain SM fibre behaviour.
**Typical Optical Fibres**

Laser light shining out from the cores of a multimode fibre (left) with a 50 micron core and a 125 micron cladding, and a single mode fibre with an 8 micron core and 125 micron cladding.

Typical refractive indices:
- Core: $n_c = 1.4512$
- Cladding: $n_{cl} = 1.4440$

Glass fibres also coated with a plastic jacket to protect against moisture penetration and mechanical damage.

~80 micron

**Low Order Propagating Modes in Optical Fibres**

A mode is a stable propagation state for an EM field traveling through a waveguide.

**How Much Bandwidth is Currently Possible**

- **Current World Record**
  - dispersion management (not just modal dispersion but other dispersions as well), wavelength-division multiplexing, optical amplifiers, modern-day optical fibres, ultra-fast light sources & detectors...
  - means that light can now carry information at a few Terabits per second over 160 kilometres of fibre

- A Terabit = $1 \times 10^{12}$ bits or 1,000,000,000,000 bits

**Generating Light – Fibre Optic 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

Need to faithfully convert electrical energy to optical energy.
Electronics:

**P-N Semiconductor Junction Diodes**

- **External reverse bias:** increased $E$ field kills off any majority diffusion, only minority drift can occur (means only have extremely small reverse current).

- **External forward bias:** reduced $E$ field kills off minority drift, but enhances amount of majority diffusion (means have large forward current whose magnitude is strongly dependent upon level of forward bias).

Light-emitting Diodes - LEDs

- Follows directly from electronics discussion of pn semiconductor junction diode.
- Materials chosen (like Gallium Arsenide etc) so that electron-hole recombination energy is released as a photon, rather than as thermal energy.

Light-emitting Diodes - LEDs

- Previous slides show the "physical description" of what happens with energy conversion in a PN semiconductor junction.
- Can also describe the energy conversion process via an "energy level description".

Discrete nature of band-gap energy gives "monochromatic" light ($\Delta \lambda \approx 20$ nm).

<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>
Laser Diodes - LDs

- Generation of light follows same principle as for LED
- Geometry and high dopant levels of diode provides optical cavity (reflection from “end mirrors”) and population inversion (high density of electrons in conduction band compared to valence)
- Coherent or LASER light. (∆λ = 1 nm or less, and perfectly in phase)

NOTE
- Laser diodes chips are relatively cheap, but require driver circuits and can be easily damaged (static discharge, transient pick-up, heat)
- Often easier to use more robust diode modules or laser pointers

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 (τ ≥ 1 ms)
LDR Example Problem

- Circuit shown automatically turns on a street lamp when ambient light level is below a trigger value (LDR has characteristics shown on last slide; $I_b \sim$ zero)
- When $V_{be}$ is below 0.65, transistor is off, $V_{out}$ is ~6V and lamp is turned on
- When $V_{be}$ is above 0.65, transistor is on, $V_{out}$ is ~0V and lamp is turned off
- What is the value of $R_2$ if the trigger point is 100 mW/m²?

100 mW/m² $\rightarrow$ $RLDR \sim 25 \, k\Omega$
- If less light, $RLDR > 25 \, k\Omega$

Voltage divider equation
$$V_{be} = 6 \frac{R_2}{RLDR+R_2}$$

For a particular $R_2$, $V_{be} = 0.65V$
- If light ↓, $RLDR \uparrow$, $V_{be}$ ↓, lamp on
- Calculation: $R_2 = 3.04 \, k\Omega$

Photodiodes

- Uses a (silicon) pn junction, with a very thin $p$-region, allowing active area (depletion region) to be optically accessible.
- Usually reverse-biased, to give low “dark current”, linear and fast response (typically $\tau < 1 \, \mu s$, although this is dependant on circuit).
- Photon absorbed in the depletion region can break semiconductor lattice bond - creating electron-hole pair
- Reverse-bias field accelerates the charge carriers, creating a current (“photocurrent”)
- Si photodiodes sensitive in the visible and near-IR range

Photodiodes: Example Problem

- Light intensity falling on a PD (with characteristics shown) is 3 +/- 0.1 W/m²
- For the circuit shown, what is the value of $RL$ if the PD is to be reverse biased at 4 V?

3 W/m² $\rightarrow$ $i_{photocurrent} \sim 15 \, µA$
- 4 V across PD $\rightarrow$ 6V across $RL$
- Ohm’s Law $\rightarrow$ $RL = 400 \, k\Omega$
- 3 +/- 0.1 W/m² $\rightarrow$ 15 +/- 0.5 µA
- Ohm’s Law: $V_{out} = 6 +/- 0.2 V$
Phototransistors

- The photocurrent is the base current.
- Amplification gives large collector current, proportional to light intensity
- Much greater sensitivity (photocurrent gain from 10-100)
- Slower time response ($\tau > 1 \text{ ms}$)

Intensity Modulation

Practical Ideas: Analog Audio Modulation via a Laser Transmitter

- External power supply $\sim 3 \text{ V}$
- LD
- $R (1 \Omega)$
- Modulation voltage, from audio source ($\sim 200 \text{ mV}$)

Analog Audio Demodulation via a Phototransistor Receiver

- $V_{cc} 9 \text{ V}$
- $C (1 \mu F)$
- Audio Amp
- $R (1 \text{ k}\Omega)$
- $V_{out}$
- Speaker
Mobile Voice versus SMS

• What is the digital bandwidth required for voice messages?
  • Assume we digitize the volume level (i.e., voltage) into a code with 256 possible discrete possibilities (i.e., use an 8-bit code)
  • Assume we sample the voice signal 8000 times per second
  • How many bits do we require per second?
    • 8000 x 8 = 64,000 bits per second
  • Mobile voice messages cost ~1 cent per second
    so 64,000 bits costs 1 cent

Mobile Voice versus SMS

• Mobile voice messages:
  64,000 bits costs 1 cent

• SMS messages:
  64 bits cost 1 cent

• As there is no difference in transferring a “voice bit” or an “SMS bit”, why does an “SMS bit” cost 1000 times more than a “voice bit”,
  (ignoring overheads such as address headers etc.)

Mobile Voice versus SMS

• What is the digital bandwidth required for SMS messages?
  • Assume we use a unique code combination to represent each character.
  • Common ASCII uses 8-bit code to represent 256 different characters
    (letters, numbers, alphanumeric symbols etc)
  • Each character requires 8 bits
  • SMS messages cost ~20 cents for 160 characters
    • 160 x 8 = 1280 bits cost 20 cents

Mobile Voice versus SMS

• Mobile Voice messages:
  64,000 bits costs 1 cent

• SMS messages:
  64 bits cost 1 cent