Optical Sources & Detectors for Fiber Optic communication

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• The Nobel Prize in Physics 2009 Charles Kuen Kao "for groundbreaking achievements concerning the transmission of light in fibers for optical communication", the other half jointly to Willard S. Boyle and George E. Smith "for an imaging semiconductor circuit - the CCD sensor".
Charles Kao
OPTICAL FIBER Communication

Optical Fiber

Tx Light Source

Rx Photo detector
Optical fiber Attenuation
Types of Optical Fiber compatible Sources

- LED (Light Emitting Diodes)
- LASER (Light Amplification by Stimulated Emission of Radiation)
LEDs

Emits incoherent light through spontaneous emission.

Used for Multimode systems with 100-200 Mb/s rates.

Broad spectral width and wide output pattern.

850nm region: GaAs and AlGaAs

1300–1550nm region: InGaAsP and InP

Two commonly used types: ELEDs and SLEDs
Electron diffusion across a pn junction
Light-Emitting Semiconductors

- **Direct Band gap**
  - Semiconductors like Si

- **Indirect Band gap**
  - III V compounds like GaAlAs, GaAsP, InGaAsP

<table>
<thead>
<tr>
<th>Material</th>
<th>Wavelength Range (µm)</th>
<th>Bandgap Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlGaInP</td>
<td>0.61 - 0.68</td>
<td>1.82 - 1.94</td>
</tr>
<tr>
<td>GaAs</td>
<td>0.9</td>
<td>1.4</td>
</tr>
<tr>
<td>AlGaAs</td>
<td>0.8 - 0.9</td>
<td>1.4 - 1.55</td>
</tr>
<tr>
<td>InGaAs</td>
<td>1.0 - 1.3</td>
<td>0.95 - 1.24</td>
</tr>
<tr>
<td>InGaAsP</td>
<td>0.9 - 1.7</td>
<td>0.73 - 1.35</td>
</tr>
</tbody>
</table>
LED Output Characteristics

Typical Powers
• 1-10 mW

Typical beam divergence
• 120 degrees FWHM – Surface emitting LEDs
• 30 degrees FWHM – Edge emitting LEDs

Typical wavelength spread
• 50-60 nm

Figure 5.8 Output power vs. drive current for a typical LED source.
TYPES of LEDs

• Edge Emitting LED’s

• Surface Emitting LED’s
Coupling lens used to increase efficiency.
Short optical Links with Large NA fibers.
Data rates less than 20 Mbps.
Coupling lens used to increase efficiency.
Short optical Links with Large NA fibers.
Data rates less than 20 Mbps.
Edge Emitting LED’s

**Edge-emitting Diode**: An LED that emits light from its edge, producing more directional output than surface-emitting LED's that emit from their top surface.

**Effective Area**: Light is not distributed in the fiber core uniformly. Rather, it follows a distribution that typically peaks in the center of the core and then tails off near the core-cladding interface. It usually extends some short distance into the cladding as well.
LED : Specifications of importance

- Optical Output Power
- Output Spectrum
- Light coupling into Fiber
- Modulation Bandwidth
Packaging – Microlensed LED
Laser Diodes
Movie
Semiconductor
Diode Inventor

The Edison
Exploratorium
Presents
Commercial Laser for Optical Communications

An RCA Solid State Laser that fits through the eye of a needle can transmit 500 million bits of information per second through a thread of glass.

The entire contents of a 24-volume encyclopedia in 3 minutes, 3000 phone conversations or 20 TV programs at the same time. Suggesting this is possible is a thread of glass by a solid state laser that solution gets here an extremely small size of the period at the end of this sentence.

The laser, discovered by RCA scientists, emits a narrow, intense beam of light that can be efficiently coupled into the microscopic fibers that carry this information. Because of its incredible stability and small size, this laser represents a significant new approach toward laser science, using a fusion in fiber optic communications systems.

The solid state laser is a product of RCA research—the kind of dedicated research that has been a tradition at RCA ever since Nipper started listening to His Master's Voice. Today research and development are every bit as important in the communications field.
The U.S. Government was RCA’s First Customer

High Power GaAs Laser Diode

Performance Features
- 60 Watts Peak Power Output
- Emitting Width 55 Mils
- Room Temperature Operation

Applications
- Range Finder
- Secure Communications

Mil. Spec.
- EL-CP2000-002A

First used in air-to-air missiles and infantry weapon simulation.
LDs – Laser Diodes

- Emit coherent light through stimulated emission
- Mainly used in Single Mode Systems
- Light Emission range: 5 to 10 degrees
- Require Higher complex driver circuitry than LEDs
- Laser action occurs from three main processes: photon absorption, spontaneous emission, and stimulated emission.
Lasing Characteristics

- Lasing threshold is the minimum current that must occur for stimulated emission.
- Any current produced below threshold will result in spontaneous emission only.
- At currents below threshold, LDs operate as ELEDs.
- LDs need more current to operate and more current means more complex drive circuitry with higher heat dissipation.
- Laser diodes are much more temperature sensitive than LEDs.
Semiconductor Laser Diode

- GaAs Substrate
- n-AlGaAs, $W_g$ 1.8 eV Confinement
- n-AlGaAs, $W_g$ 1.55 eV, Active Layer
- p-AlGaAs, $W_g$ 1.83 eV, Confinement
- p-GaAs, Contact
- SiO$_2$, Insulation
- Metallization

Stripe Contact
Edge emitting lasers

- Active layers very thin
- Light emitting area $\sim 0.5 \mu m \times 5 \mu m$
- Diffraction causes rapid beam spread
VCSELs and VECSELs

- vertical-cavity surface-emitting laser (VCSEL)
  - gain material is sandwiched between DBRs (top right)
  - aperture defined in a layer on or in the VCSEL
  - no facet cleaving necessary; VCSELs can be easily mass-produced
  - can be made into high-power arrays

- vertical-external-cavity surface-emitting laser (VECSEL)
  - essentially a VCSEL with one DBR mirror replaced with an external-cavity mirror
  - can be made into high-power arrays
  - external cavity allows for internal frequency-doubling (bottom right)
VCSEL

- Vertical cavity surface emitting laser
- Mirrors above and below junction
- Top partly reflective
- Bottom totally reflecting
• Apple awards Finisar $390 million for VCSEL R&D, manufacturing
  • December 14, 2017

• Apple says. VCSELs will be used to support smartphone and other consumer product capabilities.
• For example, VCSELs currently enable Face ID, Animoji and Portrait mode selfies with the iPhone X True Depth camera, and other popular Apple features, as well as the proximity-sensing capabilities of AirPods
VCSEL LASER Movie
Fiber coupling

- Fiber butt coupled to light-emitting spot
- Light fits in core
External cavity laser-2

Facet coated to prevent reflection

Diode Laser (Size Exaggerated)

Reflective Grating

Selected λ

Other Wavelengths

Length of Laser Cavity

Output Beam

Output Facet

c. External Cavity Tunable Laser
Tunable Laser

• Tunable Laser
  – Employed in broad-band interconnections and broadcast networks where the need for high power, narrow line width, and a tunable single-frequency emission is a must.
  – Laser that is able to produce controllable multiple wavelengths within single cavity.
  – Able to switch transmission of different wavelengths without using multiplexer for transmission to many different channels at by tuning the output frequency to its designated channel.
Tunable Laser Operation

- Current is injected into the Active Region causing the entire optical cavity to oscillate in a single longitudinal mode.
- A current is then injected into the grating control region causing a refractive index decrease which induces a shift of the Bragg wavelength and variation in the mode.
- The phase region with the injected phase current allows for recovery in Bragg wavelength in order to keep the same mode in the center of the filter band.
- This results in an output with variable wavelength.
Edge emitter with mirrored facets

- Gain region is defined within semiconductor, is much wider than it is thick.
- Cavity is defined by cleaved facets that are coated to serve as laser mirrors.
- Can be single or multiple lateral mode.
- Due to rectangular cavity cross-section, single-mode output is elliptical; can be circularized externally by anamorphic optics.

External-cavity edge emitter

- one (or both) of the cavity mirrors is external to the LD itself
- more-complex optomechanical arrangement
- can achieve narrower linewidths
- a wavelength-selective element such as a grating can be incorporated for tunability
Edge-emitting LD with DBR or FBG

- A distributed Bragg reflector (DBR, above) can be used as a cavity mirror within an edge-emitting LD; adds wavelength stability.

- An optical fiber containing a short section of fiber Bragg grating (FBG, below) can be coupled to an edge-emitting LD for wavelength stability, relative insensitivity to temperature changes.

- Or the LD itself can contain a longer, weaker grating that produces distributed feedback (DFB) for linewidth narrowing.
## Source Comparison

<table>
<thead>
<tr>
<th></th>
<th>LDs.</th>
<th>LED</th>
<th>SLED</th>
<th>LD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principle of Light Generation</strong></td>
<td>Spontaneous Emission</td>
<td>Amplified Spontaneous Emission</td>
<td>Stimulated Emission</td>
<td></td>
</tr>
<tr>
<td><strong>Optical Spectrum</strong></td>
<td>Broadband</td>
<td>Broadband</td>
<td></td>
<td>Narrowband or multiple Fabry-Perot modes</td>
</tr>
<tr>
<td><strong>Total optical output power</strong></td>
<td>Medium</td>
<td>Medium</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td><strong>Optical power density</strong></td>
<td>Low</td>
<td>Medium</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td><strong>Optical waveguide</strong></td>
<td>No</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Light Emittance</strong></td>
<td>All directions</td>
<td>Divergence-limited</td>
<td>Divergence-limited</td>
<td></td>
</tr>
<tr>
<td><strong>Spatial coherence</strong></td>
<td>Low</td>
<td>High</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td><strong>Coupling into single-mode fibers</strong></td>
<td>Poor</td>
<td>Efficient</td>
<td></td>
<td>Efficient</td>
</tr>
<tr>
<td><strong>Temporal coherence</strong></td>
<td>Low</td>
<td>Low</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td><strong>Generation of speckle noise</strong></td>
<td>Low</td>
<td>Low</td>
<td></td>
<td>High</td>
</tr>
</tbody>
</table>
Figure 10.18  Functional block diagram of a transmitter. (Adapted from Opto Electronic Products with permission of Ericsson Microelectronics AB, Stockholm, Sweden.)
CHAIN LASER DIODE DRIVER CIRCUIT

VR Voltage Reference

LDC Laser Diode Cathode
PDA Photo Diode Anode
COM+ Common Positive

Is = 51 mA

VR = 1.66 V
(Vs): @4.0 VDC

Figure 4
Example Commercial Transmitter Module
Transmitter Packages

- There are a variety of transmitter packages for different applications.
- One popular transmitter configuration is the **butterfly package**.
- This device has an **attached fiber fly lead and components such as the diode laser, a monitoring photodiode, and a**
Optical light sources convert electrical signals into optical signals and launch them. Commonly used light sources include LEDs, ELEDs, SLEDs, and LDs. LEDs produce nonlinear incoherent light whereas a Laser Diode produces linear coherent light. Incoherent light sources used in multimode systems as where Laser Diodes/Tunable Lasers in single mode systems. Laser diodes must operate above their threshold region to produce coherent light, otherwise operating as ELED. Laser diodes are much faster in switching response than LEDs. Tunable laser is able to produce coherent light output with controlled variable wavelength. Tunable laser is used in multi wavelength systems by replacing a system where many sources are coupled into a multiplexing device system.
Optical Detectors
Requirements of Optical detector

- High sensitivity at the operating wavelength
- High Fidelity
- Large electrical response to the optical signal
- Short response time to obtain a suitable bandwidth
- A minimum noise introduced by the detector
- Stability of performance characteristics
- Small Size
- Low bias voltage
- High reliability
- Low cost
Reverse bias condition

- Minority carrier flow
- Widened depletion region
- External battery
Input Output Characteristics of Photodiode

- Input to a photodiode is light power $P$
- Output is current $I_p$  $I_p \propto P$  So $I_p = RP$
- Responsivity $R$ ranges from .5A/W and this characteristics shows how effectively a photodiode convert light into an electrical signal
Disadvantages of PN photodiode

• Narrow depletion Region

• There is need to increase the width of the depletion region without manipulating unnecessarily the value of the reverse bias voltage.
Basic PIN Photodiode Structure

Front Illuminated Photodiode

Rear Illuminated Photodiode

Front Illuminated Photodiode
PIN diode Optical Detectors

- The most common optical detector used with fiber-optic systems is the PIN diode.
- The PIN diode is also operated in the reverse-bias mode.
- As a photodetector, the PIN diode takes advantage of its wide depletion region, in which electrons can create electron-hole pairs.
- The low junction capacitance of the PIN diode allows for very fast switching.
Advantages of P-I-N photodiode

• Intrinsic layer is thick, so more number of incident photons enter into this layer and generate electron hole pair, so results in the high quantum efficiency of the device.

• Reverse biasing voltage is small (usually 50) because the thickness of the depletion region is controlled by the thickness of the intrinsic layer, not by reverse voltage.

• High bandwidth (Efforts to improve the bandwidth of 110 Ghz).
Wavelength Response

- Silicon 400-1100 nm
- Germanium 800-1600 nm
- GaAs 400-1000 nm
- InGaAs 400-1700 nm
- InGaAsP 1100-1600 nm
Absorption coefficient vs. Wavelength
for several materials
(Bowers 1987)

Photodiode Responsivity vs. Wavelength
for various materials
(Albrecht et al 1986)
Photomultiplier Tube
Avalanche Photodiode
APD

• Drawback of P-I-N photodiode is that it need of an amplifier to magnify the photocurrent produced by the photodiode.

• The quantum efficiency of the APD is $M$ times larger than that of a P-I-N photo diode.
  \[ R(\text{APD}) = M \times R(\text{PIN}) \]

$M$ depends upon

1. Accelerating voltage
2. Thickness of the gain region
3. Ratio of electrons to holes participating in the ionization process.

• $M$ ranges from 10 to 500.
Avalanche Photodiodes (APDs)

- High resistivity p-doped layer increases electric field across absorbing region

- High-energy electron-hole pairs ionize other sites to multiply the current - Leads to greater sensitivity
• Noise Sources in photodiode

• Shot Noise:
  Deviation of the actual number of electrons from the average numbers is known as shot noise.

• Thermal Noise
  The deviation of an instantaneous number of electrons from their average value because of temperature change is called Thermal Noise.

  Thermal Noise is often called Johnson noise.
Johnson (thermal) Noise

Noise in a resistor can be modeled as due to a noiseless resistor in parallel with a noise current source.

The variance of the noise current source is given by:

\[ s_i^2 = \langle i^2 \rangle = \frac{4k_BT}{R} \]

Where \( k_B \) is Boltzmann's constant
\( T \) is the Temperature in Kelvins
\( B \) is the bandwidth in Hz (not bits/sec)
• **Dark current Noise**

The dark current noise arises due to dark current which flows in the circuit when the photodiode is in unilluminated environment under bias condition.

The magnitude of this current depends on the

- Operating temperature.
- Biased voltage
- Type of detectors

• **Excess Noise:**

  Cause- Avalanche Multiplication Process
Receivers

• Convert optical signals to electronic signals

• Stages
  – Wavelength-division demultiplexing
  – Detection: optical-to-electronic signals
  – Thresholding, retiming (electronic regeneration)
  – Time-division demultiplexing

• WDM: must be done before detectors
  – Detectors can't discriminate close wavelengths
RECEIVERS
**Receiver Types**

**Low Impedance**
- Requires Equalizer for high BW
- High Sensitivity
- Low Dynamic Range
- Careful Equalizer Placement Required

**High Impedance**
- **Low Impedance**
- Requires Equalizer for high BW
- High Sensitivity
- Low Dynamic Range
- Careful Equalizer Placement Required

**Transimpedance**
- High Dynamic Range
- High Sensitivity
- Stability Problems
- Difficult to equalize
Bit Error Rate

BER is equal to number of errors divided by total number of pulses (ones and zeros). Total number of pulses is bit rate B times time interval. BER is thus not really a rate, but a unitless probability.
Eye Diagrams

- **Eye pattern measurements** are made in the time domain and immediately show the effects of waveform distortion on the display screen of standard BER test equipment.
  - The **eye opening width** defines the time interval over which signals can be sampled without interference from adjacent pulses (ISI).
  - The best sampling time is at the height of the *largest eye opening*.
  - The **eye opening height** shows the noise margin or immunity to noise.
  - The **rate at which the eye closes** gives the sensitivity to timing errors.
  - The **rise time** is the interval between the 10 and 90% rising-edge points.
Thank you

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91 9888410066
Bibliography:

The excerpts of this lecture are based on the information drawn from following reference.

3. www.google.co.in
4. www.youtube/OFC videos
5. www.FO4sale.com