530192 “Photonics in semiconductors”,
(5 op / 3 ov),
period III and IV – Spring 2017

Lecturer: Docent Ivan Kassamakov,
Assistant: Risto Montonen and Anton Nolvi, Doctoral students

Course webpage:
<table>
<thead>
<tr>
<th>Lecture #</th>
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<th>Ending time</th>
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Solide State Lightening

- For now, between 25 & 50% efficiency - traditional light bulb which has 5%!
- Still expensive, they could come in the market for residential lighting in the next 5 or 10 years
"20 percent of the world's electricity that's generated is used for lighting. Three quarters of that can be saved by using LEDs; 15 percent of today's electricity consumption (more electricity than solar will produce) can be saved," said Roland Haitz, LED pioneer, former chief technology officer, semiconductor products group, Hewlett-Packard (later Agilent) at the Economist's Innovation Summit.

Haitz invented the LED equivalent of Moore's Law named after him.

Haitz's Law states that every decade, the cost per lumen falls by a factor of 10, the amount of light generated per LED package increases by a factor of 20 for a given wavelength of light.

- In 2010 the LED efficacy cross 100 lm/W.
- In May 2011, Cree announced a LED prototype with 231 lm/W efficacy at 350 mA.
- In March 2014, Cree announced another prototype with a record breaking 303 lm/W efficacy at 350 mA.
## Comparison Between Light Sources

<table>
<thead>
<tr>
<th>Light Output</th>
<th>Light Emitting Diodes (LEDs)</th>
<th>Incandescent Light Bulbs</th>
<th>Compact Fluorescents (CFLs)</th>
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<tbody>
<tr>
<td>Lumens</td>
<td>Watts</td>
<td>Watts</td>
<td>Watts</td>
</tr>
<tr>
<td>450</td>
<td>4-5</td>
<td>40</td>
<td>9-13</td>
</tr>
<tr>
<td>800</td>
<td>6-8</td>
<td>60</td>
<td>13-15</td>
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<tr>
<td>1,100</td>
<td>9-13</td>
<td>75</td>
<td>18-25</td>
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<tr>
<td>1,600</td>
<td>16-20</td>
<td>100</td>
<td>23-30</td>
</tr>
<tr>
<td>2,600</td>
<td>25-28</td>
<td>150</td>
<td>30-55</td>
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# Comparison Between Light Sources

<table>
<thead>
<tr>
<th>FEATURES</th>
<th>LEDs</th>
<th>INCANDESCENT</th>
<th>CFLs</th>
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<tbody>
<tr>
<td>Lifespan (avg)</td>
<td>50,000 hrs</td>
<td>1200hrs</td>
<td>8000hrs</td>
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<tr>
<td>Watts used</td>
<td>6-8 watts</td>
<td>60 watts</td>
<td>13-15 watts</td>
</tr>
<tr>
<td>Toxic mercury</td>
<td>No toxic Hg</td>
<td>No toxic Hg</td>
<td>Yes, causes harm</td>
</tr>
<tr>
<td>Sensitivity to low temp</td>
<td>None</td>
<td>Some</td>
<td>Yes (-10&lt;T&lt;50) °C</td>
</tr>
<tr>
<td>On/Off Cycling</td>
<td>No Effect</td>
<td>Some Effect</td>
<td>Decrease life span</td>
</tr>
<tr>
<td>Turns On instantly</td>
<td>Yes</td>
<td>Yes</td>
<td>No (take time to warm up)</td>
</tr>
<tr>
<td>Durability</td>
<td>Very durable</td>
<td>Not durable (glass can break)</td>
<td>Not durable (glass can break)</td>
</tr>
<tr>
<td>Light output for 450 lumens</td>
<td>Requires 4-5 watts</td>
<td>Require 40 watts</td>
<td>Requires 9-13 watts</td>
</tr>
<tr>
<td>Annual operating costs (30 incandescent bulbs per year equivalent)</td>
<td>$32.85</td>
<td>$328.59</td>
<td>$76.65</td>
</tr>
</tbody>
</table>
Led Bulbs
Led Bulbs

- Remote Phosphor
- Type of Remote Phosphor
- Diffuser
- LED array
- Heat sink
- Drive electronics
- Screw-in base
Blue LED to white light: color mixing

- Efficiency lower than for phosphors – 300 lm/W
- Highest CRI
- Possibility of color changing

Color Rendering Index (CRI) is the measurement of how colors look under a light source when compared with sunlight. The index is measured from 0-100, with a perfect 100 indicating that colors under the light source appear the same as they would under natural sunlight.
Blue LED to white light: phosphors

- Ce$^{3+}$:YAG
- Excited by LED radiation
- Blue + Yellow = White
- Highest efficiency – 425 lm/W
- Reasonable Color Rendering Index (CRI)
White LED

- Commercial high intensity white LEDs
- LED of one color (mostly blue LED made of InGaN or GaN) are coated with layer of phosphor of distinct color
- Blue light goes Stokes shift and the spectrum is broadened
- Cerium-doped Yttrium Aluminium Garnet (Ce$^{3+}$:YAG) is a commonly used phosphor
- UV LEDs can be coated with europium-based red and blue emitting phosphors plus green emitting copper and Aluminium doped zinc sulfide (ZnS:Cu, Al)
- Simpler and cheaper than RGB system
White LED

Eg. Coumarin 6

Absorption

Emission

Relative Intensity

Typical Spectrum

Wavelength (nm)

300 400 500 600 800
RGB Color Space Model

The x and y coordinates are determined using the International Commission on Illumination (CIE) 1931 color space.

- The x and y coordinates are determined using the International Commission on Illumination (CIE) 1931 color space.
- Any color enclosed in the triangle formed by the coordinate points representing the three color can be obtained.
- Ratio of luminance (brightness) of three colors determines the resultant color.
Current LED Market $15 B - 2014

- Mobile phone
- Streetlights
- Traffic signals
- TVs (LED)
- Large Displays (NASDAQ)
- Automotive

LED industry grew 6% from 2013 to 2014

- Lighting: 15%
- Automotive lighting: 10%
- Signage: 10%
- Mobile devices: -8.7%
- Backlight in displays & monitors: -0.4%
- Others: 8%

Packaged LED revenues ($B)

2013: $14.6B → 2014: $15.4B
LEDs in Architectural Lighting

Installation Benjamin Franklin Bridge, PA, USA (Color Kinetics Inc.)

Lighting Systems by Color Kinetics Inc.
Takarazuka University of Art and Design
LEDs in Air/Water Purification

Fruit and Vegetable Storage Life Extended 1 week
Water Purification: UV LED to kill bacteria

Refrigerator with UV LED 375 nm, 590 nm

(Credit: Hydro-Photon Inc.)
LED Plant Growth

- Blue and Green LEDs used to grow Wasabi at night.
- It is known that chlorophyll has the second distinct absorption peak in the vicinity of 450nm (blue light region) other than the first peak in the vicinity of 660nm (red light region) in its light absorption spectrum.
- The blue light is also indispensable to the morphologically healthy growth plant.
- On the other hand, the red light contributes to the plant photosynthesis.

![Absorption spectra of chlorophyll and carotenoids. The primary light harvesting chlorophylls absorb light in the blue and red regions. Carotenoids absorb in the blue and green regions.](image-url)
Impacts of Light Pollution on Human Populations

Reason for artificial light:
- Improved night time safety and reduced fear of darkness
- Night time businesses
- Safe navigation during low light periods

Culture of Safety – High Quality White Light
What is Light Pollution?

- Light pollution, also known as photopollution or luminous pollution, is excessive or obtrusive artificial light.

- Light pollution first made news in 1964, when an observatory was specially placed just to avoid light pollution
What is Light Pollution?

- Light pollution can be divided into two main types:
  - (1) annoying light that intrudes on an otherwise natural or low-light setting
  - (2) excessive light (generally indoors) that leads to discomfort and adverse health effects
- It is most severe in highly industrialized, densely populated areas of North America, Europe, and Japan and in major cities in the Middle East and North Africa.
NASA’s New View of Earth at Night

Composite map of the world assembled from data acquired by the Suomi NPP satellite in April and October 2012. Credit: NASA Earth Observatory/NOAA NGDC

## Types of Light Pollution

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td><strong>Glare</strong></td>
<td>Too much background light that reduces visibility</td>
</tr>
<tr>
<td><strong>Sky Glow</strong></td>
<td>Upward directed light reflects on particles in the sky reducing visibility of stars</td>
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<tr>
<td><strong>Light Trespass</strong></td>
<td>Light spills into an area where it is unneeded</td>
</tr>
<tr>
<td><strong>Overlighting</strong></td>
<td>The excessive use of light</td>
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The American Medical Association gave a report in June 2016 regarding the hazardous impacts of LEDs to human health and the environment. The report titled "Human and Environmental Effects of Light Emitting Diode Community Lighting," detailed findings from scientific evidence that explains exposure to blue-rich white light at night is liable to increase risks for cancer, diabetes and cardiovascular disease and was approved by the entire membership of AMA.

It corroborated with concerns presented by the International Dark-Sky Association, called "Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting," which was released back in 2010 and discussed the threats associated with exposure LEDs.

Not only is blue-rich white LED street lighting five times more disruptive to our sleep cycle than conventional street lighting, according to the report, but recent large surveys have documented that brighter residential night-time lighting is associated with reduced sleep, impaired daytime functioning and a greater incidence of obesity.

As a result of a potential risk to public health from excess blue light exposure, the AMA report encourages attention to optimal design and engineering features when converting from existing lighting technologies to LED. These include:

- requiring properly shielded outdoor lighting,
- considering adaptive controls that can dim or extinguish light at night,
- and limiting the correlated color temperature (CCT) of outdoor lighting to 3000 Kelvin (K) or lower.
This photo shows the divide between East and West Berlin that is still visible at night from space. On the left are the gas lamps of the West and on the right, the orange high-pressure sodium lamps of the East, with a stark contrast between them. The image is a powerful reminder that lighting choices made by city planners are long lasting.
Impacts of Light Pollution on Human Populations

- Negative effects on human health by suppression of Melatonin Hormone
  - Strong antioxidant
  - Protective hormone
  - Oncostatic (inhibits the growth of cancer cells)  
- Disruption of circadian rhythms leading to sleep disorders, depression, reproductive disorders and increase in metabolic conditions such as obesity and diabetes (Pauly, 2004; Boyce, 2010; Wysea, et al, 2011; Falchia, et al, 2011; Stevens, et al, 2013).
- Human health particularly affected by blue wavelength, high intensity light, utilised in high intensity outdoor lighting such as high pressure sodium lighting and mercury vapour lighting (Pauly, 2004; Stevens, et al, 2013; Gaston, et al, 2014).
- The international Agency for Cancer Research suggests that shift work and circadian rhythm disruptions can result in higher cancer rates; with increased risk of breast cancer in women based on the “Light-at-Night Theory” (Stevens, 2009; Stevens, 2013).
- Research: insertion of cancer cells into the groins of lab rats with measurements taken of cancer cell growth: results constant light exposure group showed increased growth rate of cancer cells (Pauly, 2004).
Light Pollution - Solution

Reduce intensity
Choose luminaires that produce low-keyed and constant lighting, with not too excessive light intensity. This will let the eye better adapt to ambient brightness while ensuring necessary visibility and site security.

Adjust orientation
Choose luminaires whose luminous flux is oriented towards the area to be lighted. Don’t forget that light emitted towards the sky does not help to see better and that light emitted towards the horizon contributes to glare.

Control time
Time and length of use of light fixtures must also be considered. Install a timer, a motion detector, or simply always turn off the lights before going to bed... the idea is to use only the lighting you need.

Limit blue light
Give preference to amber light sources over white ones, which are more harmful to sky glow and health, due to their large proportion of blue light.
It is sometimes easy to see the difference.

Limiting the correlated color temperature of outdoor lighting to 3000 (K) or lower.
For short haul applications like local area networks (LANs), LEDs are:
1. Simpler to “drive.”
2. Cheaper
3. Longer life (~150,000 hours) than for laser diode
4. Provide the necessary output power.

The type of light source suitable for optical communications depends not only on the communication distance but also on the bandwidth requirement. But even with the LED virtues listed above, the output spectrum is much wider than that of a laser diode. The situation will dictate which compromises can be made.

There are essentially two types of LED devices.
If the emitted radiation emerges from an area in the plane of the recombination layer as in (a) then the device is a surface emitting LED.

If the emitted radiation emerges from an area on an edge of the crystal as in (b) then the LED is an edge emitting LED (ELED).
Coupling Methods

- Index matching
- Epoxy
- Heterostructure
- Multimode optical fiber
- Metal contact
- SiO₂
- Contact
- Gold contact
- p⁺-GaAs
- n⁻-GaAs
- n⁺-GaAs
- p- GaAs
- p⁺- AlGaAs
- N- AlGaAs
- P- AlGaAs
Coupling Methods
A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.
LEDs for Optical Fiber Communications

The light is guided to the edge of the crystal by a dielectric waveguide formed by the wider bandgap semiconductors surrounding a double heterostructure.
Light from an edge emitting LED is coupled into a fiber typically by using a lens or a GRIN rod lens.
Lecture 09

Light Amplification by Stimulated Emission of Radiation: LASERs
An electron in an atom can be excited from an energy level $E_1$ to a higher energy level $E_2$ by the absorption of a photon of energy $h \nu = E_2 - E_1$.

This absorption process requires that the electron change energy such that it moves from an allowed state to another allowed state. If the change is from the valence band to the conduction band, then the minimum energy is equal to the bandgap energy.
Stimulated Emission and Photon Amplification: Spontaneous Emission

When an electron at a higher energy level transits down in energy to an unoccupied energy level, it may emit a photon.

The electron can undergo the downward transition by itself quite spontaneously.
In spontaneous emission, the electron falls down in energy from level $E_2$ to $E_1$ and emits a photon of energy $h \nu = E_2 - E_1$ in a random direction.

Thus a random photon is emitted.

This spontaneous process occurs at some rate which will be constant under thermal equilibrium.

It is important to note that these spontaneous energy level changes will always occur and the spontaneous emission of a photon may result.
Another possibility is the electron can be induced to undergo the downward transition.

This transition is called *stimulated emission*.
In stimulated emission, an incoming photon of energy $h\nu = E_2 - E_1$ stimulates the whole emission process by inducing the electron at $E_2$ to transit down to $E_1$.

Due to the coupling of the electric fields of the photon and the transitioning electron, the emitted photon is in phase with the incoming photon, it is the same direction, it has the same polarization and it has the same energy $h\nu = E_2 - E_1$.

Stimulated emission is the basis for obtaining photon amplification since one incoming photon results in two outgoing photons which are in phase.

In an avalanche device, the two outgoing photons interact again so that two more photons are emitted and so on.

In 1917 Einstein predicted that:
- under certain circumstances a photon incident upon a material can generate a second photon of
  - Exactly the same
  - Energy (frequency)
  - Phase
  - Polarization
  - Direction of propagation
- In other word, a coherent beam resulted.
Optical Pumping

(a) Atoms in the ground state are pumped up to the energy level $E_3$ by incoming photons of energy $h\nu_{13} = E_3 - E_1$.
(b) Atoms at $E_3$ rapidly decay to the metastable state at energy level $E_2$ by emitting photons or emitting lattice vibrations; $h\nu_{32} = E_3 - E_2$.
(c) As the states at $E_2$ are long-lived, they quickly become populated and there is a population inversion between $E_2$ and $E_1$.
(d) A random photon (from a spontaneous decay) of energy $h\nu_{21} = E_2 - E_1$ can initiate stimulated emission. Photons from this stimulated emission can themselves further stimulate emissions leading to an avalanche of stimulated emissions and coherent photons being emitted.
The emission from $E_2$ to $E_1$ is called the **lasing emission**. By trapping nearly all of these photons in an optical cavity, the intensity **builds up** in much the same way as we build up voltage oscillations in an electrical oscillator circuit.

What leaks out of the optical cavity is a **highly coherent radiation** at high intensity.

It is this **coherency** of a well defined wavelength (same energy), same polarization, and same direction that makes laser light distinctly different from random sources such as a filament light or LEDs.
Coherence

Coherent

Partially Coherent

\[ L_c = c \Delta t \]

\[ \Delta t = \frac{1}{\Delta \nu} \]

Incoherent
Temporal Coherence

Coherence is a measure of how well we can predict the phase of any portion of the wave from any other portion of the wave.

- Temporal coherence is a measure of the correlation of a light wave’s phase at different points along the direction of propagation – it tells us how monochromatic a light source is.

- Spatial coherence is a measure of the correlation of a light wave’s phase at different points transverse to the direction of propagation – it tells us how uniform the phase of the light front is.

How to make an incoherent light source COHERENT?

- Pinhole aperture
- Wavelength filter
- Essentially light from a single point source on the filament
Theodore Harold Maiman was born in 1927 in Los Angeles, son of an electrical engineer. He studied engineering physics at Colorado University, while repairing electrical appliances to pay for college, and then obtained a Ph.D from Stanford. On May 16, 1960, Theodore H. Maiman operated the first functioning laser, at Hughes Research Laboratories, Malibu, California.

There is a chromium ion doped ruby rod in the center of a helical xenon flash tube. The ruby rod has mirrored ends. The xenon flash provides optical pumping of the chromium ion. The output is a pulse of red laser light.
Maiman's original 1960 apparatus, containing his flashtube and ruby crystal inside a metal cylinder.

One of the ruby crystals that Maiman used in his groundbreaking 1960 experiments

"The Laser Odyssey"
By Theodore Maiman
(a) A more **realistic energy diagram** for the Cr$^{3+}$ ion in the ruby crystal (Al$_2$O$_3$), showing the optical pumping levels and the stimulated emission.

(b) The laser action needs an **optical cavity** to reflect the stimulated radiation back and forth to **build-up** the total radiation within the cavity, which encourages further stimulated emissions.

(c) A **typical construction** for a ruby laser, which uses an elliptical reflector, and has the **ruby crystal** at one focus and the **pump light** at the **other focus**.
1. High-voltage causes the quartz flash tube to emit an intense burst of light, exciting some of the atoms in the ruby crystal to higher energy levels.

2. At first the photons are emitted in all directions. Photons from one atom stimulate emission of photons from other atoms and the light intensity is rapidly amplified.

3. Mirrors at each end reflect the photons back and forth, continuing this process of stimulated emission and amplification.

4. The photons leave through the partially silvered mirror at one end.
Light Amplification by Stimulated Emission of Radiation: LASER

At a conference in 1959, Gordon Gould published the term LASER in the paper _The LASER, Light Amplification by Stimulated Emission of Radiation_. Gould’s linguistic intention was using the “-aser” word particle as a suffix - to accurately denote the spectrum of the light emitted by the LASER device; thus x-rays: _xaser_, ultraviolet: _uvaser_, etc.; none established itself as a discrete term, although “raser” was briefly popular for denoting radio-frequency-emitting devices.
The Nobel Prize in Physics 1964 was divided, one half awarded to C. Townes "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle", the other half jointly to N. Basov and A. Prokhorov "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle".
Charles Townes

Part of a September 1957 page from Townes’s notebook.
A useful LASER medium must have a higher efficiency of stimulated emission as compared to the efficiencies of the system in allowing spontaneous emission and absorption.

Consider a medium that has \( N_1 \) atoms per unit volume with energy \( E_1 \) and \( N_2 \) atoms per unit volume with energy \( E_2 \).

The rate of upward transitions from \( E_1 \) to \( E_2 \) by photon absorption will be proportional to the number of atoms \( N_1 \) and also to the number of photons per unit volume with energy \( h\nu = E_2 - E_1 \).

This number of photons per unit volume with energy \( h\nu \) is called the energy density in the radiation.
Consider a medium with $N_1$ atoms per unit volume with $E_1$; $N_2$ atoms per unit volume with $E_2$.

The rate of upward transitions from $E_1$ to $E_2$ is

$$R_{12} = B_{12}N_1 \rho(h\nu)$$  \hspace{1cm} (3 - 1)

Where $B_{12}$ is termed as Einstein coefficient;

$\rho(h\nu)$ is the photon energy density per unit frequency (the number of photons per unit volume with $h\nu$)
The rate of downward transitions from $E_2$ to $E_1$ is

$$R_{21} = A_{21} N_2 + B_{21} N_2 \rho(h\nu) \quad (3\text{ -- 2})$$

Where $A_{21}$ and $B_{21}$ are termed as Einstein coefficient for spontaneous and stimulated emissions respectively.

The ratio of stimulated to spontaneous emission is written as

$$\frac{R_{21}\text{ (stim)}}{R_{21}\text{ (spon)}} = \frac{c^3}{8\pi h\nu^3} \rho(h\nu) \quad (3\text{ -- 3})$$
Stimulated Emission Rate and Einstein Coefficients

The ratio of stimulated emission to absorption is written as

\[
\frac{R_{21} \text{ (stim)}}{R_{12} \text{ (absorp)}} = \frac{N_2}{N_1}
\]

(3 – 4)

Conclusions: For \( R_{21} \text{ (stim)} > R_{12} \text{ (absorp)} \), Population inversion \( N_2 > N_1 \) is needed; (non-thermal equilibrium)

For \( R_{21} \text{ (stim)} > R_{21} \text{ (spon)} \), large photon concentration is needed - building an optical cavity.
Three States System

Energy

Equilibrium

E0

E1

E2

Very fast

Metastable

Pump
Four States System

Equilibrium

Metastable

Very fast

Pump

Very fast
**Optical amplifier**: amplifying optical signals directly at certain intervals for **long haul** communications

**Erbium doped fiber amplifier (EDFA)**: The core region of an optical fiber is doped with $\text{Er}^{3+}$ ions (or other rare earth ion dopants, such as $\text{Nd}^{3+}$); The host fiber core material is a glass based on $\text{SiO}_2$-$\text{GeO}_2$ and so on

$E_1$ ---- the lowest energy possible for $\text{Er}^{3+}$ ion; $E_3$ & $E_3'$ ---- two convenient energy levels for optically pumping $\text{Er}^{3+}$ ion from a LD (980 nm).
The erbium (Er3+ ion) implanted fiber has the following energy levels.

Energy diagram for the Er$^{3+}$ ion in the glass fiber medium and light amplification by stimulated emission from $E_2$ to $E_1$. Dashed arrows indicate radiationless transitions (energy emission by lattice vibrations).
Optical Fiber Amplifier

The difference between stimulated emission ($E_2 \rightarrow E_1$) and absorption ($E_1 \rightarrow E_2$) rate controls the net optical gain:

$$G_{op} = K (N_2 - N_1) \quad (3-5)$$

Where $N_1$ & $N_2$ are the number of Er$^{3+}$ ions at $E_2$ & $E_1$;

$K$ is a constant depending on the pumping intensity.

The erbium doped fiber is inserted into the fiber communications line by splicing;

Optical isolators inserted at the entry and exit end of the amplifier allowing only the optical signals at 1550 nm to pass in one direction; preventing the 980 nm pump light from propagating back or forward into the communication system.
After optical pumping, the doped fiber has a long lived population inversion at $E_2 = 0.80\text{eV}$.

Incident photons at the 1550 nm wavelength will achieve stimulated emission as long as the pumping continues. If the optical pump fails, this system will see attenuation of the signal at the EDFA.

The gain efficiency of an EDFA is the maximum optical gain achievable per unit optical pumping power and are quoted in dB/mW. Typically gain efficiencies are around $8-10\ \text{dB/mW}$ at 980 nm pumping. A 30 dB or $10^3$ gain is easily attainable with a few milliwatts of pumping at 980 nm.
Optical Fiber Amplifier - EDFA Configurations

**Counterdirectional Pumping**

**Codirectional Pumping**
Erbium Doped Fiber Amplifier

EDFA (Strand Mounted Optical Amplifier, Prisma 1550) for optical amplification at 1550 nm. This model can be used underground to extend the reach of networks; and operates over -40 °C to +65 °C. The output can be as high as 24 dBm (Courtesy of Cisco).

EDFAs (LambdaDriver®-Optical Amplifier Modules) with low noise figure and flat gain (to within ±1 dB) for use in DWDM over 1528 - 1563 nm. These amplifiers can be used for booster, in-line and preamplifier applications. (Courtesy of MRV Communications, Inc)