Semiconductor Lasers for Optical Communication

Claudio Coriasso
Manager
claudio.coriasso@avagotech.com

Turin Technology Centre

10Gb/s DFB Laser

MQW
Outline

1) Background and Motivation
   • Communication Traffic Growth
   • Why Photonics?
   • Photonics evolution

2) Semiconductor Laser Basics
   • Active material
   • Optical Feedback
Communication has always been one of the main driving force for the development of new technologies: Telegraph, Telephone, Fiber Optic, Laser, ...

Worldwide communication traffic is doubling every 18 months (2dB/year)
Traffic structure and Energy Consumption

- Data Centers and the Internet consume about 4% of electricity (8.7 \times 10^{11} \text{kWhr/year including PCs})
- By 2018 the energy utilized by IP traffic will exceed 10% of the total electrical power generation in developed countries \(^{(1)}\)
- Most of the traffic is between machines and much of the information created today cannot even be stored \(^{(2)}\)
  - 100 MW power
  - Tens of thousands of fibers

1 Server = 1 SUV

FACEBOOK \(^{(3)}\):
- 1.01 billion active users worldwide (23M in Italy, 39.5% population)
- 584 million active users every day
- 10.5 billion minute/day

\(^{(1)}\) L.Kimerling, MIT
\(^{(2)}\) R.Tkatch, Alcatel Lucent
\(^{(3)}\) D. Lee, Facebook
Why Photonics?

• Short monochromatic optical pulses are easily produced with semiconductor lasers (ps range ⇒ Gb/s to Tb/s)

• Photons do not interact each other

• Photons can be propagated in optical fiber with very low loss (0.2dB/km)

• Several data streams at different wavelength can be combined, propagated together in optical fibers and then split (high channel capacity)
Photonics in Optical Communication

Today Photonic Network:

- **SAN**: Storage Area Network
- **LAN**: Local Area Network
- **MAN**: Metro Area Network
- **Metro Access Network**
- **Metro Interoffice Network**
- **WAN**: Wide Area Network
- **Submarine**

Traffic volume:

- 10m
- 100m
- 1km
- 10km
- 100km
- 1000km
Photonics:
Science and technology of light

Emission, Transmission, Processing (modulation, switching, amplification, …)
Detection

Began with Laser (1960) and Fiber Optic (1966) inventions. These inventions formed the basis for the telecommunications revolution of the late 20th century and provided the infrastructure for the internet.

1st Laser demonstration: T. Maiman 1960
1st Low-Loss Fiber Optic Proposal: C. Kao 1966
Fiber Optics

1966: First proposal of fiber optic for telecom. Basic design [Kao STC, Nobel Prize 2009]
1970: Production of first fiber optic [Corning]
1976-77: First fiber optic networks
1988: First transoceanic fiber-optic cable (3148 miles, 40000 simultaneous telephone calls)

C. K. Kao receiving his Nobel Prize Stockholm 2009
Semiconductor Laser Basics
1962: First Realization of Semiconductor Laser (GaAs @ T = -200 °C) [GEC, IBM, MIT]
1970: First Realization of Heterostructure Semiconductor Laser (Z. Alferov)
1972: Proposal of Distributed Feedback Laser (DFB)
1970: Room Temperature CW operation of 1.5μm Laser
1977: Proposal of Vertical Cavity Surface Emitting Laser (VCSEL)
1984: First Realization of Strained MQW in semiconductor laser
1988: First Realization of VCSEL
2000: First Uncooled Telecom Lasers
Laser requirements for optical communication

- High bandwidth (≥ 10Gb/s)
- Single mode operation
- Low consumption
- Uncooled operation (up to 80°C)

DFB MQW Laser

State of Art of uncooled high-speed lasers

Electrodes (current injection)
Grating (optical feedback)
Waveguide (optical confinement)
Quantum wells (optical gain)
High-speed laser key factors

1. **Electrical confinement** (p-n heterostructure)
2. **Optical confinement** (single-mode waveguide)
3. **Gain** (quantum-confined material)
4. **Feedback** (distributed Bragg grating)

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High carrier density and high photon density in an active material within a small-volume optical resonator

\[
\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_n} - G(N) \cdot (1 - \varepsilon \cdot S) \cdot S
\]

\[
\frac{dS}{dt} = \Gamma_a \cdot G(N) \cdot (1 - \varepsilon \cdot S) \cdot S - \frac{S}{\tau_p} - \frac{\Gamma_a \beta_p N}{\tau_n}
\]

\[
\frac{d}{dt} = 0
\]

\[
I_{th} = \frac{qVN_{th}}{\tau_n}
\]
Semiconductor material basic requirements for photonic devices

• Optical gain, light emission (direct band gap) ...

• ... at wavelength of interest: \( \lambda = 1.3 \, \mu m \) \& 1.55 \( \mu m \)

• compatibility with semiconductor substrates: Si, GaAs, InP
There are no single elements or binary compounds compatible with commercial substrates and emitting light at 1.3 μm e 1.55 μm. Semiconductor alloys of III-V elements are the best materials for photonic devices.
Quaternary alloy InGaAsP

In $1-x$Ga$_x$As$_y$P$_{1-y}$ alloy cover all the spectral range required for optical telecom

- High quality material
- Established growth techniques and material processing
- Suited for active devices (lasers, amplifiers, modulators, ...) and passive structures (waveguides, couplers, ...)

InP $(\lambda_g=0.92\,\mu m)$

InGaAs $(\lambda_g=1.65\,\mu m)$

In $1-x$Ga$_x$As$_y$P$_{1-y}$ lattice matched to InP $(\lambda_g=0.92\, -\, 1.65\,\mu m)$

Variation of the bandgap as a function of lattice constant for III–V binary and alloy semiconductors

T. P. Pearsall, GaInAsP Alloy Semiconductors, Wiley (1982)
Further alloy systems

1. $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ on InP
2. $\text{Al}_{1-x-y}\text{Ga}_x\text{In}_y\text{As}$ on InP
3. $\text{Al}_{1-x}\text{Ga}_x\text{As}$ on GaAs

![Graph showing bandgap energy (Eg) at 300 K vs. lattice constant (a) for various alloy systems.](image-url)
Three bands are involved in optical transitions:
- Electrons
- Heavy holes
- Light holes

Joint density of states (available for optical transitions) is a square root function of the energy in excess of the energy gap

\[ JDOS \propto \sqrt{\hbar \omega - E_g} \]

\[ m_{hh}^* > 9 m_e^* \]

\[ m_{lh}^* \approx m_e^* \]
**Semiconductor Heterostructures**

Double Heterostructure (DH)  \[ \lambda_{ph} > \lambda_e \]

- Combination of layers of different crystalline semiconductors.
- H. Kroemer, Varian associates 1963 (Nobel Prize in Physics, 2000)
- The idea was experimentally demonstrated using the Liquid Phase Epitaxy (LPE)

Separate Confinement Heterostructure (SCH)

- Photon confinement
- \[ E_g(A) > E_g(C) > E_g(B) \]  \[ n(A) < n(C) < n(B) \]
Quantum Wells

Quantum-Size Double Heterostructure (Quantum Well) is a planar waveguide for electrons

C. H. Henry, Bell Labs 1972

The idea was experimentally demonstrated in 1974 using the newly developed Molecular Beam Epitaxy (MBE).

![Quantum Well Diagram]

Quantum Well (QW) is now a widely spread quantum product based on atomic-scale technology.
Photon wave eqn. vs. Electron wave eqn.

Helmholtz equation (photon)

\[
\left[ \frac{d^2}{dz^2} + k_0^2 n^2(z) \right] \psi(z) = n_{\text{eff}}^2 \psi(z)
\]

Schroedinger equation (electron)

\[
\left[ -\frac{\hbar^2}{2m} \frac{d^2}{dz^2} + V(z) \right] \psi(z) = E \psi(z)
\]

refractive index ridges confine photons (optical waveguides)

potential wells confine electrons (quantum wells)

\[ n^2(z) \Rightarrow -V(z) \]

cladding \(\Rightarrow\) barrier

core \(\Rightarrow\) well
Eigenfunction/Eigenvalues Calculation

Optical Waveguide

Quantum Well

\[ \Psi_{TE0}(z^-) = \Psi_{TE0}(z^+) \]

\[ \frac{\partial}{\partial z} \Psi_{TE}(z^-) = \frac{\partial}{\partial z} \Psi_{TE}(z^+) \]

\[ \frac{1}{m(z^-)} \frac{\partial}{\partial z} \Psi(z^-) = \frac{1}{m(z^+)} \frac{\partial}{\partial z} \Psi(z^+) \]
Reduced dimensionality structures

**BULK**
- $d = 3$

**Quantum Well**
- $d = 2$
- $L_z \sim \lambda_e$

**Planar Waveguide**

1975: R.Dingle and C.Henry
USA Patent Application

**Quantum Wire**
- $d = 1$
- $L_z, L_y \sim \lambda_e$

**Channel Waveguide**

**Quantum Dot**
- $d = 0$
- $L_z, L_y, L_x \sim \lambda_e$

**Optical Resonator**
Multi Quantum Wells are stacks of **decoupled** QWs (with sufficiently thick barriers): **enhancement of single QW effects**
**QW band structure**

### 2D JDOS related features:
- Sharp absorption edge (2D JDOS)
- High differential gain
- Wide gain bandwidth
- High electroabsorption efficiency (QCSE)
- Strong optical nonlinearities
- . . .

\[ JDOS = \sum_{ij} \frac{\mu_{ij}}{\pi \hbar^2} \Theta(\hbar \omega - E_{ij}) \]
Excitons

e - h semi-bound states ($\tau \sim 100$ fs) which produce sharp absorption peaks detuned from the transition energies (absorption steps) by their binding energy $E_b$ ($\sim 8$ meV per InGaAsP).
\( \alpha(\omega) \propto \text{JDOS} + \text{exciton state} \Rightarrow n(\omega) = 1 + \frac{c}{\pi} \int_0^\infty \frac{\alpha(\omega')d\omega'}{\omega'^2 - \omega^2} \Rightarrow \hat{n}(\omega) = n(\omega) + i \frac{\alpha(\omega)c}{2\omega} \)

**Polarisation selection rules:**
- TE: 3/4 hh, 1/4 lh
- TM: 0 hh, 1 lh

**Strong dichroism**

**Graphs:**
- \( \alpha_{TE} \) and \( \alpha_{TM} \) absorption coefficient (1/cm) vs. Energy (eV)
- \( n_{TE} \) and \( n_{TM} \) Refractive index vs. Energy (eV)
The epitaxial layer can be grown with a lattice parameter slightly different from the substrate lattice parameter (lattice mismatch).

\[ m = \frac{a_L - a_S}{a_S} \]

where:
- \( a_L = \text{lattice parameter of the epitaxial layer} \)
- \( a_S = \text{lattice parameter of the substrate} \)

\[ m > 0 \] for compressive strain

\[ m < 0 \] for tensile strain
Strain(2)


![Graph showing variation of bandgap as a function of lattice constant for III–V binary and alloy semiconductors.](image)

Variation of the bandgap as a function of lattice constant for III–V binary and alloy semiconductors.
Strain effect on band structure:

Compressive strain

Low escape time
High $T_0$ (low thermal dependence)
High-speed uncooled Lasers

Tensile strain

Low dichroism
Polarization-independent devices
Optical gain in MQW

- high differential gain \( \frac{dG}{dN} \)
- wider spectral bandwidth

\[ V_{-3dB} \propto \sqrt{\frac{dG}{dN} \left( I - I_{th} \right)} \]
Distributed Feedback

\[ \Delta \Phi = \pi \Rightarrow \lambda/4 \]

\[ \begin{align*}
\frac{da^+}{dz} &= -i \left( \beta - \frac{\pi}{\Lambda} \right) a^+ - ika^-
\frac{da^-}{dz} &= ika^+ + i \left( \beta - \frac{\pi}{\Lambda} \right) a^-
\end{align*} \]

Single-\(\lambda\) reflectivity:
Single mode laser

\[ \begin{align*}
\kappa &= 65 \text{ cm}^{-1} \\
\Lambda &= 0.24 \mu \text{m} \\
\beta &= \frac{2\pi}{\lambda} \left( 3.2 + 3.4 \times 10^{-4} i \right)
\end{align*} \]
Quantum Wells: Atomic-Controlled Artificial Structures

Control of Optical Properties through atomic-scale technology
Quantum Well requires sub-monolayer manufacturing control achievable with Molecular Beam Epitaxy or Metal Organic Chemical Vapor Deposition.
Thanks for your attention!

claudio.coriasso@avagotech.com