Semiconductor Lasers for High Bit Rate Optical Communication Networks

R. Paoletti, R&D manager
TTC- Avago Technologies Italy, Via Schiaparelli 12, 10148 Torino, ITALY

Pavia, 22/06/2009
Semiconductor Lasers for High Bit Rate Optical Communication Networks

Abstract

- Internet and intranet data traffic constantly increased during last years, and the consequent band demand is pushing research and development of high speed optical modules operating at 17 Gb/s (Fiber Channel applications, FC) and 40 / 100Gb/s (Gigabit Ethernet, GbE). Main requirements of such a transmitters are high performances, reliability, power consumption and manufacturability. Talk will reports semiconductor laser sources suitable for such demanding applications, underlying the key technologies, and benchmarking the results proposed by the world’s most important research centers.

Roberto Paoletti (M’97) Roberto Paoletti was born in Vado Ligure (Savona), Italy, in 1966. He received the laurea degree in Electronic Engineer from the University of Genova in 1991, and the Ph. D. degree in Electronic at the Electronic Department of Politecnico of Turin, Italy, in 1995, studying high frequency characterization, modeling and equivalent circuits of high speed semiconductor lasers and packages. In 1995 he joined the former CSELT, Torino, Italy, then TTC Agilent technologies and now Avago technologies, Italy. In the last years he has been responsible of research projects on new laser devices, and mainly involved in design, characterization and reliability of high speed optoelectronic devices. He is author and co-author of more than 50 papers, 5 patents and a book on high frequency modeling and characterization of semiconductor laser sources, as well as reviewer for technical journals. Mr. Paoletti is a member of the IEEE Lasers and Electro-Optics Society.
Outline

• Avago: company overview

• Laser sources for “pluggable transceiver world”
Avago History

1939
Hewlett Packard Foundation (T&M)

- Test & Measurement
- Life science
- Semiconductor components
- Computers/imaging...

November 1, 1999
Agilent spin-off

~40000 employees
T&M, Life science, semiconductor components

December 1, 2005
Avago spin off
~ 6500 employees
Semiconductor components

~80000 employees
Computers, printers, imaging, ...

Acquisition of TTC
former optoelectronic technology division of CSELT
R&D Corporate Center of STET (now Telecom)
Product leadership in target markets

**Market Position**

<table>
<thead>
<tr>
<th>Optoelectronics and RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Optical Navigation</td>
</tr>
<tr>
<td>• #1 in optical mouse sensors</td>
</tr>
<tr>
<td>- Isolation</td>
</tr>
<tr>
<td>• #1 in photo-IC optocouplers</td>
</tr>
<tr>
<td>- Motion Control</td>
</tr>
<tr>
<td>• #1 in office automation encoders</td>
</tr>
<tr>
<td>- Infrared</td>
</tr>
<tr>
<td>• #1 in infrared transceivers</td>
</tr>
<tr>
<td>- LEDs and Displays</td>
</tr>
<tr>
<td>• #3 in LEDs</td>
</tr>
<tr>
<td>- Wireless</td>
</tr>
<tr>
<td>• #1 in semiconductor-based filters</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Enterprise Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Fiber Optics</td>
</tr>
<tr>
<td>• #2 in Fiber Optic Components</td>
</tr>
<tr>
<td>- Imaging</td>
</tr>
<tr>
<td>• #2 in printer ASICS</td>
</tr>
<tr>
<td>- Enterprise ASICs</td>
</tr>
<tr>
<td>• Leading supplier to Cisco and HP</td>
</tr>
</tbody>
</table>

**Solutions for Mobile Handsets**

- CMOS Image Sensors
- Improved picture quality
- Position Sensors
- Lens focus control
- Front-end Modules
- Size advantage and higher integration
- E-Phirent Power Modules
- Extended Battery life
- FISAR Filters
- Size & performance advantage
- Color Chip LEDs
- Improved aesthetics
- LED Flash
- Higher quality pictures
- IrDA + Remote Control, IRF
- Size advantage plus increased functionality
- Proximity Sensor
- Automates speech control phones
- Ambient Light
- Photo Sensors
- Extended battery life
- Navigation
- Improved user interface

**Solutions for Storage, Computing and Networking**

- Networking ASICs
- Printer ASICs, SOCs
- Motion Control, Infrared, Optical Interconnect

**Solutions for Consumer, Industrial and Automotive**

- Automotive
- LEDs
- Fiber Optics
- Infrared
- Electronic Signs and Signals
- Consumer Appliances

**Avago Technologies**
Leading in Technology Innovation

- **40-years** heritage of innovation and technology leadership
- Over **2,000** patent and patent applications
- Over **1,000** design engineers
Fiber Optic Products Division
Technical Edge: Innovation History and Expertise
Strategic Partner of Choice

- Module design
- 30 years of first’s and standards leadership
- Leading green technologies – lowest power / extended temperature SFP+ designs
- IC development
- Enable next generation optics, time to market
- Lower cost, best power roadmaps, features
- Only POD supplier with DMI, pre-emphasis, etc.
- Packaging and sub-assembly
- Proven mastery of bulk optic technology
- Capability for highly dense optical footprints

World’s 1st production transceiver

1st to market with VCSEL transceivers
1st OC-48 part (2x9 SC Duplex)

Agilent is spun off from HP

1st 10G XENPAK
1st 12x2.5G parallel optic transceiver

Avago is spun off from Agilent

1st to market with 8G SFPs
1st to market with 12x6G parallel optic
1st to market with 10G SFP+
1st to demonstrate full 17G SFP
1st to demonstrate full 100G parallel optics

Roberto Paoletti, Pavia
22 June, 2009
Outline

• Avago: company overview

• Laser sources for “pluggable transceiver world”
Outline

- Introduction
  - Datacom – telecom networks history
  - Pluggable solutions
- 10 Gb devices and technologies for pluggable transceivers
  - Laser basic concepts
  - Key design elements for high performances laser sources
  - Advanced laser sources for pluggable transceivers
  - TTC III-V technology overview
(Optical) Telecom History

LASER History:

1960: First Laser (Ruby) [Hughes Labs]
1962: First Semiconductor Laser (GaAs @ T = -200 °C) [GEC, IBM, MIT]
1972: Invention of DFB Laser [Bell Labs]
1984: First Strained MQW in semiconductor laser
1990- Lasers for optical telecom
2000- Uncooled telecom lasers

FIBER OPTIC History:

1960: First proposal of fiber optic for telecom. Basic design [Kao STC]
1970: Production of first fiber optic [Corning]
1977: First fiber optic network (1.5 miles) in Chicago [ATT Bell Labs]
1988: First transoceanic fiber-optic cable (3148 miles, 40000 simultaneous telephone calls)
Today Optical Network

DATACOM                                 TELECOM

10 Gb/s LASER Sources

Storage       Enterprise

Metro Access Network   Metro Interoffice Network

Access  Core  Terrestrial

Submarine

Long Haul

10m  100m  1km  10km  100km

2-20 km  20-100 km  Metro
Pluggability: a keyword…
From transceiver cards to hot-pluggable transceiver modules

- Strong limits in space available and power budget
- Wide temperature operation (0÷85°C)

⇒ Requirement on lasers:
  - High temperature operation (preferably uncooled)
  - Low cost, high manufacturing yield, high reliability
  - No compromise on High performance
    (high bit rate, high optical power, high spectral purity, …)
  - Monolithic integration can provide:
    - Small and smart devices (High functionality)

Evolution (since 2000)
PLUGGABILITY: PAY AS YOU GO
From a Butterfly Laser Module....

The 1990 Technology

Optical coupling: Lens+Optical Isolator + pigtailed fiber

Electrical / RF connections

Back detector

Temperature control

Chip laser
# Avago Fiber Optics Portfolio

<table>
<thead>
<tr>
<th>Enterprise</th>
<th>Storage</th>
<th>Parallel</th>
<th>Base Station</th>
<th>SONET</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10G leadership</strong>&lt;br&gt;• 1&lt;sup&gt;st&lt;/sup&gt; to market SFP+&lt;br&gt;• 1&lt;sup&gt;st&lt;/sup&gt; to market LRM&lt;br&gt;• Superior VCSELs&lt;br&gt;• Only extended temp range part&lt;br&gt;• Lower power&lt;br&gt;High reliability, low cost 1G SFP&lt;br&gt;Proven supply assurance</td>
<td><strong>#2 in market</strong>&lt;br&gt;• 8G leadership&lt;br&gt;• Industry’s most reliable 4G VCSEL&lt;br&gt;• Industry’s best defect PPM rate&lt;br&gt;• 1&lt;sup&gt;st&lt;/sup&gt; 17G SFP demo&lt;br&gt;• Only extended temp range 8G part&lt;br&gt;Strategic partner to key industry players&lt;br&gt;Innovative low cost design</td>
<td><strong>Enabling time-to-mkt</strong>&lt;br&gt;• 1&lt;sup&gt;st&lt;/sup&gt; 100G POD demo&lt;br&gt;• 1&lt;sup&gt;st&lt;/sup&gt; 12x6G POD&lt;br&gt;• World’s strategic parallel optics partner&lt;br&gt;Superior feature set – DMI, pre-emphasis&lt;br&gt;Unsurpassed delivery record&lt;br&gt;Proven quality</td>
<td><strong>Market leader</strong>&lt;br&gt;• 1&lt;sup&gt;st&lt;/sup&gt; and only OBSAI/CPRI specific portfolio&lt;br&gt;• High BER and industrial temp rates&lt;br&gt;Critical partner to leading players&lt;br&gt;• Nextgen partner&lt;br&gt;• Proven reliability</td>
<td><strong>Broad portfolio</strong>&lt;br&gt;• OC-3 to 192 in multiple form factors and distances&lt;br&gt;• Industrial temp available (including XFP-LR/SR1)&lt;br&gt;• Superior EMI performance</td>
</tr>
</tbody>
</table>

---

Roberto Paoletti, Pavia<br>22 June, 2009
Outline

• Introduction
  - Datacom – telecom networks history
  - Pluggable solutions

• 10 Gb devices and technologies for pluggable transceivers
  - Laser basic concepts
  - Key design elements for high performances laser sources
  - Advanced laser sources for pluggable transceivers
  - TTC III-V technology overview
Lasers for pluggable modules: key device elements for outstanding performances

- Active material: MQW Multi Quantum Well structure → dimensional control at nanometric scale
- Wavelength selection: grating structure → dimensional control at sub-μm scale
- Lateral confinement: ridge structure → dimensional control at μm range
Fabry-Perot Laser

N = integer
n = refractive index
\( \lambda \) = wavelength

Optical cavity = active material

Multimodal emission

Short haul – not necessarily true…
• Phase shifted grating allows to get 100% single mode yield, for ideal AR/AR coatings on both facets

\[
b + \Lambda = m \left( \frac{\lambda}{n} \right) \quad \text{Bragg wavelength} \quad \Lambda = m \left( \frac{\lambda}{2n} \right)
\]

\[
b = \Lambda \sin \theta \quad \Lambda (1+\sin \theta) = m \left( \frac{\lambda}{n} \right)
\]
To get performances: *design* (ridge)

Ridge structure

- No lateral blocking layers
- Very simple technological process (one-step epi-growth)
- Suitable for Al-based lasers and low cost devices
To get performances: *control* (MQW)

**MQW period control chart**

All production wafers are inspected before wafer fab processing MQW period control within 0.3 nm (3σ)

**Out of control:**

*NO Performances; NO reliability*
MQW active material optimization

InGaAsP-based MQW

\[ T_0 = 48 \, \text{K} \]

\[ T = 20 - 100 \, ^\circ\text{C} \]

Current (mA); - 09-Aug-2002

Power (mW)

InGaAsAl-based MQW

\[ T_0 = 95 \, \text{K} \]

\[ T = 20 - 100 \, ^\circ\text{C} \]

Current (mA); - 20-Aug 2004

Power (mW)
Direct Modulation of Laser Module

*Butterfly Laser Module*

- Optical coupling: Lens + Optical Isolator + pigtailed fiber
- Chip laser
- Back detector
- Temperature control
- Electrical / RF connections
- RF
Intensity modulation of laser sources

• Laser chip equivalent circuit

\[ f_r \propto \sqrt{I - I_{th}} \]

Parasitics

Active material

Increasing \( I-I_{th} \)
Intensity modulation of laser sources: chip parasitics

Geometrical analysis

Equivalent circuit

Simulation and experimental results
Outline

• Introduction
  - Datacom – telecom networks history
  - Pluggable solutions

• 10 Gb devices and technologies for pluggable transceivers
  - Laser basic concepts
  - Key design elements for high performances laser sources
  - Advanced laser sources for pluggable transceivers
  - TTC III-V technology overview
Agilent uncooled InGaAlAs ridge FP laser for 10GBASE-LRM product (300 m MMF)

Device design:

- **Active layer: Al based material**
  - Designed to enhance $T_0$
  - 9 InGaAlAs 55Å wells; strain +0.8%
  - 8 InGaAlAs100Å barriers; strain −0.4%
  - 2xSCH$_1$: InGaAlAs 350Å
  - 2xSCH$_2$: InAlAs 500Å

- **Device technology:**
  - High yield/low cost/Al compatible
    - Reversed mesa ridge
    - Auto-aligned mesa

- **Optical cavity:**
  - Very fast chip at high $T$ operation
    - Narrow cavity volume
    - Hr coating optimised versus both Temperature and speed

200 µm long x
250 µm wide device

Avago/TTC Post
Deadline Paper at OFC 2005
Device results - static

20 °C base chip temperature:
- Threshold 7.6 mA
- High power 23 mW

85 °C base chip temperature:
- Threshold 15.6 mA
- Power 16.8 mW

95 °C base chip temperature:
- Threshold as low as 18 mA
- Still more than 15 mW

Key points:
- High optical power enable high coupling loss
- Small threshold increasing up to 95 °C since high T₀
- Small bias variation over T
- Small efficiency degradation over T

⇒ Constant eye quality with constant modulation current!
Technologies for LRM application: EDC (Electronic Dispersion Compensation)

EDC technology

Electronic Dispersion Compensation algorithm

• EDC uses adaptive electrical filtering techniques to compensate for limitations incurred during fiber propagation:
  - modal dispersion
  - chromatic dispersion
  - polarization modal dispersion
• EDC can be realized in an integrated circuit.
• EDC can enhance the performance of existing transceivers and enabling new applications.

10 Gbps to 300m over legacy multimode fiber

Why?
Modal dispersion in MM fibers

input pulse

multi-mode step index (POF)

output pulse

multi-mode graded index (LAN)

single-mode step index
Agilent uncooled InGaAsP BH 10 Gb DFB for 10GBASE-LR product: 2001 results

Eye diagram in the XFP module

Agilent uncooled InGaAsP BH 10 Gb DFB for 10GBASE-LR product: 2001 results
Spectral broadening of a direct modulated DFB laser
Dispersion penalty

Pulse broadening causes intersymbol interference (ISI) and then eye closure: less signal for the same received power.
Noise depends on receiver, not on link: same noise.
To get the same S/N more input power is needed: this is dispersion penalty.

<table>
<thead>
<tr>
<th>TX output</th>
<th>RX optical input</th>
<th>Decision input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-to-back</td>
<td>After a fibre link</td>
<td>Back-to-back</td>
</tr>
</tbody>
</table>
Dispersion penalty at 2.5 Gb, 80 km, for a directly modulated DFB laser
Integrated EAM-DFB (EML)

- Device based on the monolithic integration between a DFB laser and an Electro-Absorption Modulator (EAM).

- The DFB is biased at a constant current (CW).

- The EAM switch from transparency to opacity by applying modulated voltage (HF signal).

Key advantage of EML: The high frequency response is directly related to the fast dynamics of the modulator and not to the dynamic of the DFB laser: better eye quality, lower dispersion penalty.
50°C operation of 1550 nm 10Gb/s EML
And what next?

- Economic crisis ⇒ profitability of Optics low since 2001;

- BUT
  - need for more speed and ability of transport more data remains unsatisfied
    - 100Gb/s Ethernet standardized and planned
    - 1Tb/s Ethernet is starting to be discussed

- So Low cost, low volumes (right now, especially in telecom) applications
  - Many believe that photonic integration is the only solution of the problem, like “discrete transistor versus ICs”
    - Particularly true for telecom (data formats…)
    - R&D still in good shape? Surely hit by the downturn…

Sources: Optical Fiber Conference 2009 and related overviews;
40 and 100 Gb/s standard

- (IEEE P802.3ba)
  - for 40Gb/s (40GBASE – SR4, 850nm, 4 x 10GbE; 40GBASE – LR4, 1300nm, 4 x 10GbE CWDM)
  - for 100 Gb/s (100GBASE – SR10, 850 nm, 10 x 10GbE; 100GBASE – LR4, 1300 nm, 4 x 25GbE, DWDM)

- 16G FC standard for Fiber channel
- Standard and MSA have focused the technology development:
  - 16G FC transceiver SFP+ (Avago 980, Optnext 1300)
  - First 40Gb/s and 100Gb/s CFP MSA (Multi-Source Agreement) Optnext, Finisar

- Pushing the DFB technology up to 25Gb/s uncooled!
DFB technology: beyond the limits….

- OFC session: Uncooled and semicooled DFB laser sources at 25 and 40 Gb/s
  - Key players: Avago, Finisar, Optnext/Hitachi, Fujitsu, NTT
- Avago: best eye quality up to 70C, 25Gb/s
... but manufacturability is key!

BoxPlot of Threshold / Max. Power / SMSR for 4 wafers
- Several hundredths chip/wafer automatically tested
- Tight statistics
- Good reproducibility wafer to wafer

Uniform / high yield technological process

Accelerated Life test
- ALT conditions: 95 °C, 80 mA ACC
- Burn In conditions: 100 °C, 90 mA, 24 h
- Devices stable over > 5000

Reliable technological process
Photonic integration trends

• On telecom network:
  - Low cost, 100Gb/s, modulation format…

• ⇒ Photonics on InP
  - *Infinera, (OFC2009, OThN2)* Transmitter PIC for 10-Channel x 40Gb/s per Channel Polarization-Multiplexed RZ-DQPSK Modulation
  - High complexity; system on a chip….

![Transmitter Architecture](image)
Wide tunable laser: DBR Array

InP Monolithically integrated DBR Array + PIC

Passive and tuning waveguides

DBR and SOA active waveguide

Paoletti et al. ECOC 2003

Roberto Paoletti, Pavia
22 June, 2009
Device results: emitted spectrum

chip4-M35-2 @ 20°C: $I_{act}=50\text{mA}$

41 nm tuning range

Paoletti et al. ECOC 2003
Revolution on active material: Is Quantum Dot ready to go?

OFC2009, OWJ1, “High-Speed and Temperature-Insensitive Operation in 1.3-μm InAs/GaAs High-Density Quantum Dot Lasers”, Fujitsu

![Graph showing light-current characteristics of the fabricated laser.]

![Diagram of quantum dot laser structure.]

200 um long 1.3um ridge FP laser, with amazing performances... on GaAs. Announced to be “ready for production”....
The Turin Technology Centre (TTC)

Acquisition by Agilent Technologies 19 April 2000

Activity: R&D and Production (laser chip)
• Short term Development projects (transceivers @ 2.5 Gbit/s and @10 Gbit/s)
• Medium term Research projects for active and passive devices
• Development and Production of 10G FP/DFB/EML laser source

Facilities
• EPI (2 MOCVD), material characterization, processing (including EBL), die fab (singulation, coating, testing, assembly and reliability tests)

Expertise: optoelectronic and photonic technologies
• New devices and components conception and design
• Semiconductors
• Device design, prototyping and characterisation
Key Strength

Developing a reliable technology….

- Reliability has always been the key strength in a III-V world
- Customer reliability expectation is almost compared to the ‘telecom’ field, but for low cost – consumer products

⇒ Reliability is the key investment in the III-V area

Example: DFB (SFP+, XFP) qualified for Cisco:
  - 7 M device* hours
  - Long endurance test

Enormous investments…
Key Strength

*Testing a production volume....*

- Testing is one of the most expensive part in the III-V production
- Typical application require 100% testing of the laser chip!
- Only key team have testing capability suitable for mass-production
  - Investment not scalable for start-up

⇒ (low cost) testing developing is a key strength.. Also from R&D design perspective

---

**Example: DFB qualification**
- Statistic of 9 qual wafers:
- Based on 15K chip tested across 8 wafers
Chip development requires team work across the globe: not an easy task!
The end!

- **Books**

- **Related published paper**