Semiconductor lasers for optical communication

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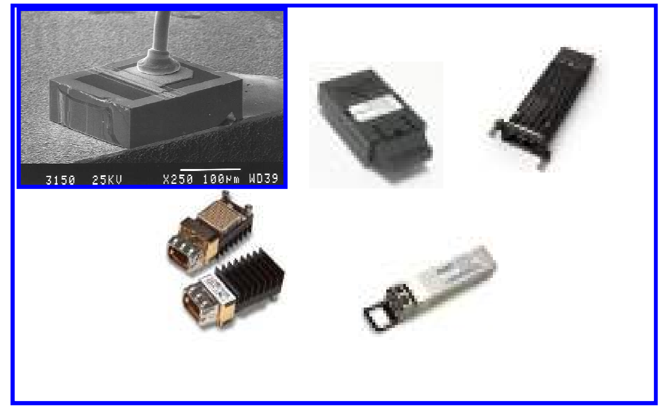
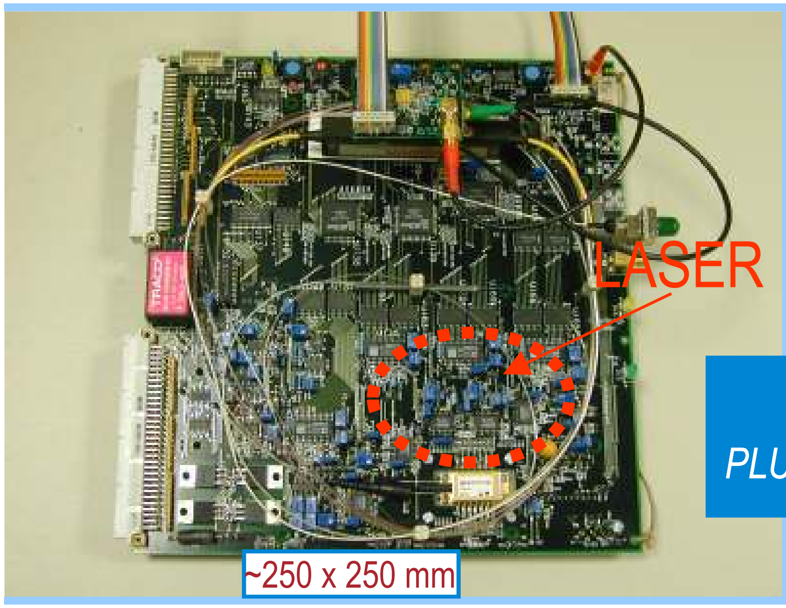


- **Laser sources for *"pluggable transceiver world"***
  - *Design for performances*
  - *Fast lasers*

- **Transceiver for next generation networks**
- ***Torino Technology Center - Avago Technologies Italy***

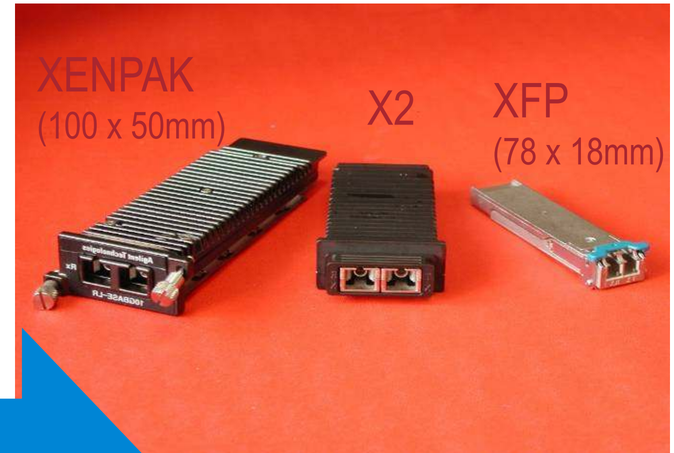
Pluggability: a keyword…

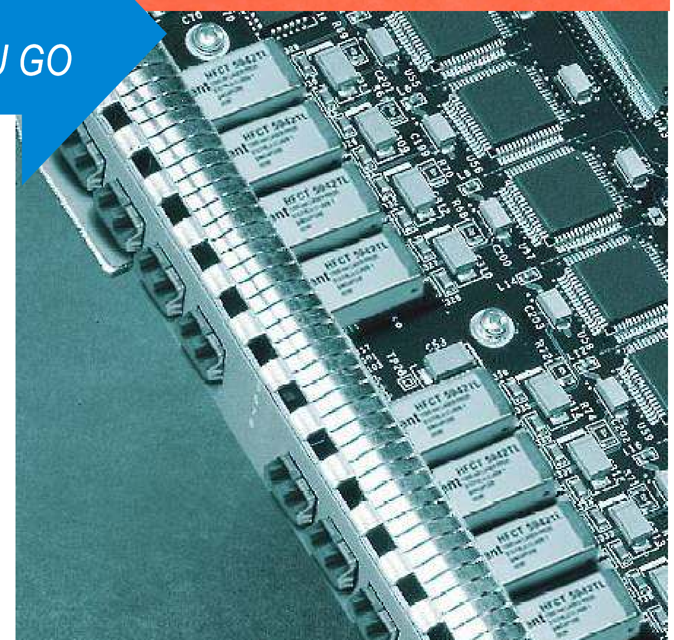
From transceiver cards to hot-pluggable transceiver modules



Evolution (since 2000)

PLUGGABILITY: PAY AS YOU GO





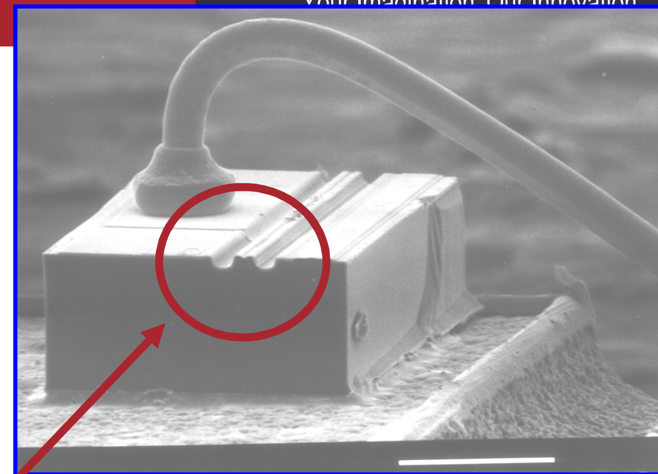
- Strong limits in space available and power budget
- Wide temperature operation (0÷85°C)

$\Rightarrow$ *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, …)

AVAGO TECHNOLOGIES

Semiconductor Laser is:



Active material → ***Semiconductor layer with optical gain***

Carrier population generation → ***Electrical injection***

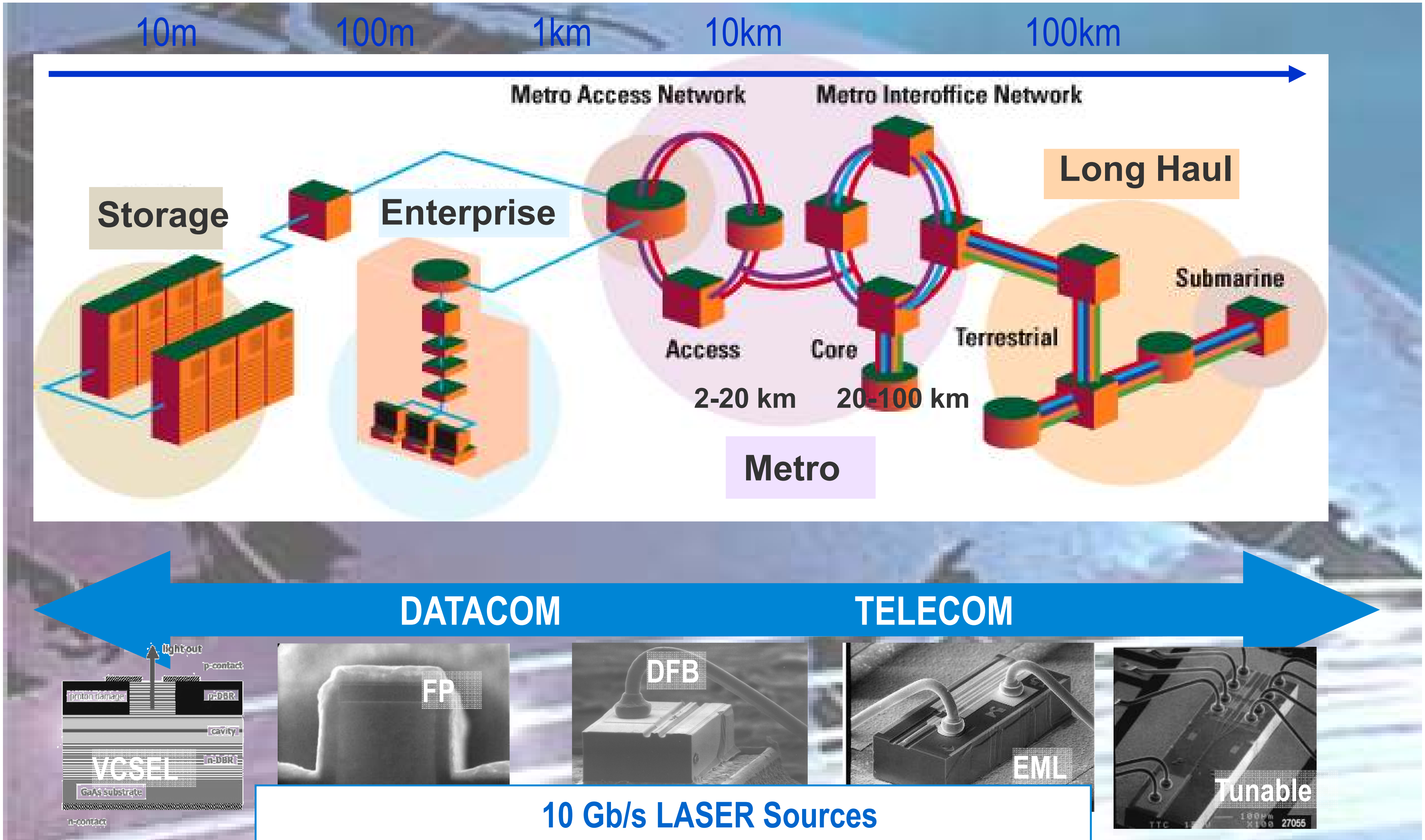
Cavity → ***Crystal Mirrors* (FP)**
or *Grating* (DFB – DBR)

Confinements:

electrical → **Heterojunction**

optical → **Optical waveguide**

Lasers for Optical Networks



Design for performance (ridge)

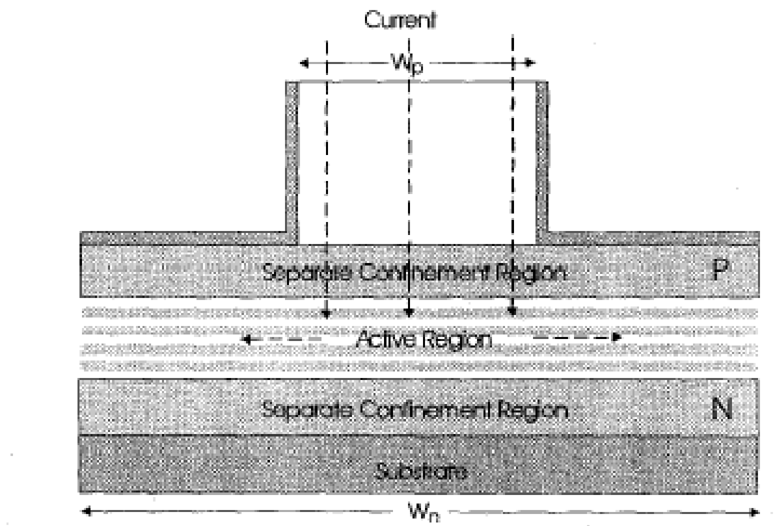
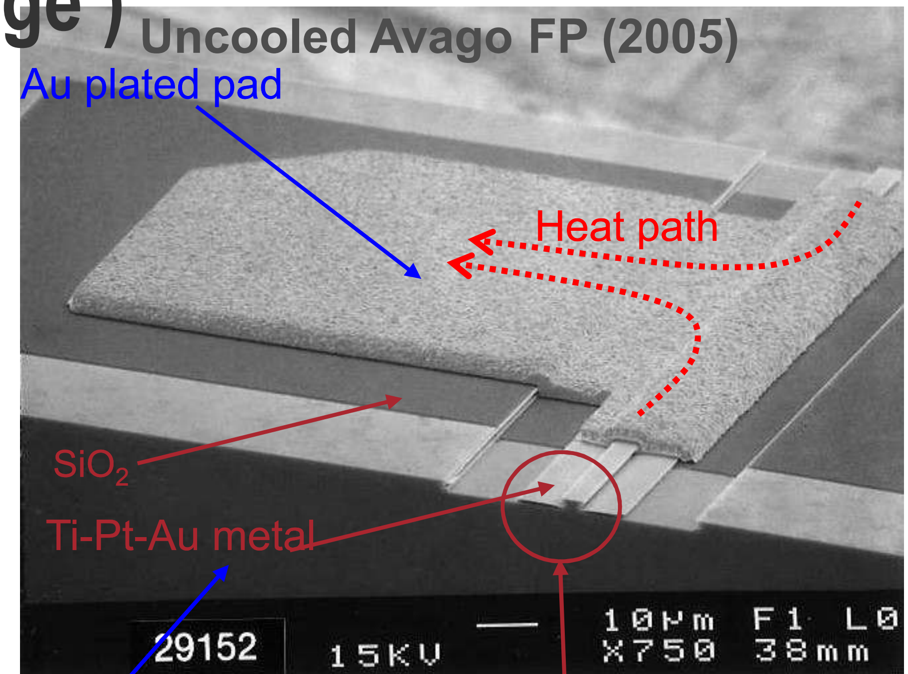


Fig. 1. Transverse profile of the ridge waveguide structure.

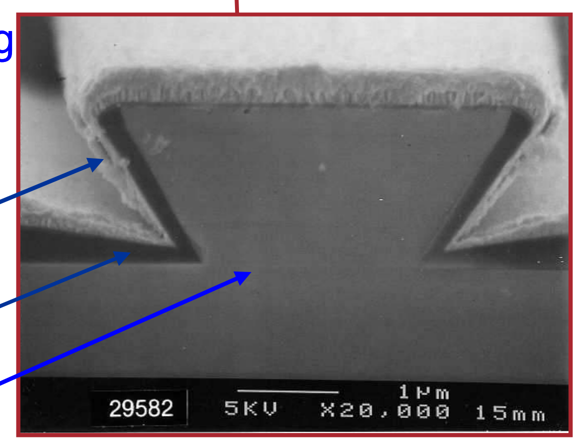


Ridge structure

Optimised facet cleavage / coating

No lateral blocking layers ⇨

- *Very simple technological process (one-step epi-growth)*
- *Suitable for Al-based lasers and low cost devices*



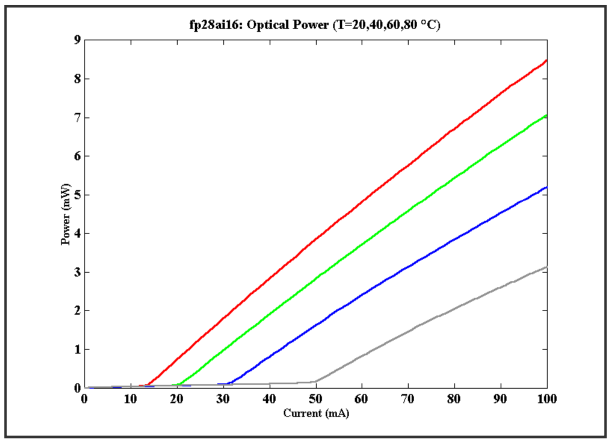
Metal

Dielectric

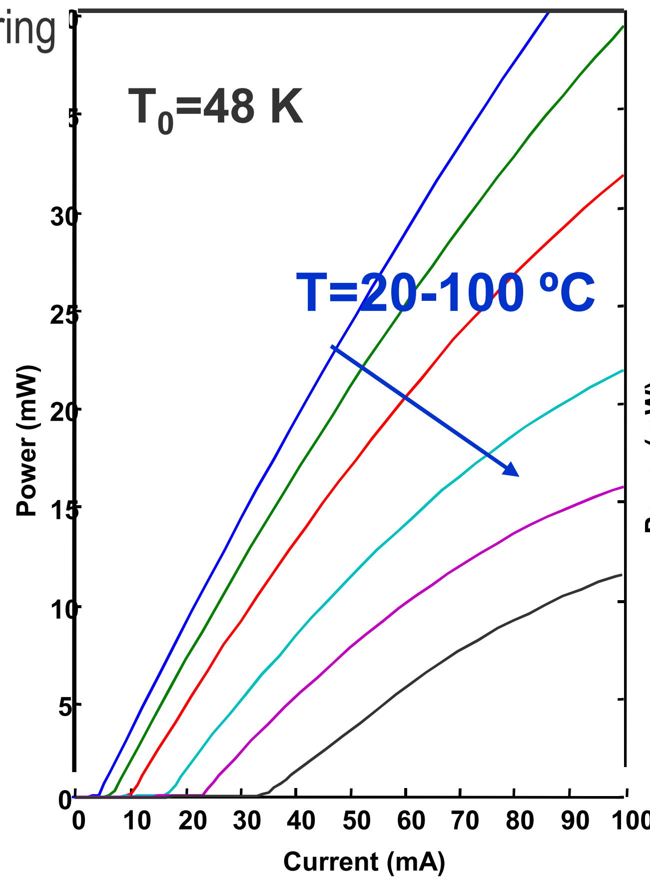
Narrow reverse mesa (Low Rs, small cavity, fast chips)

Active material: long path of performance improvement

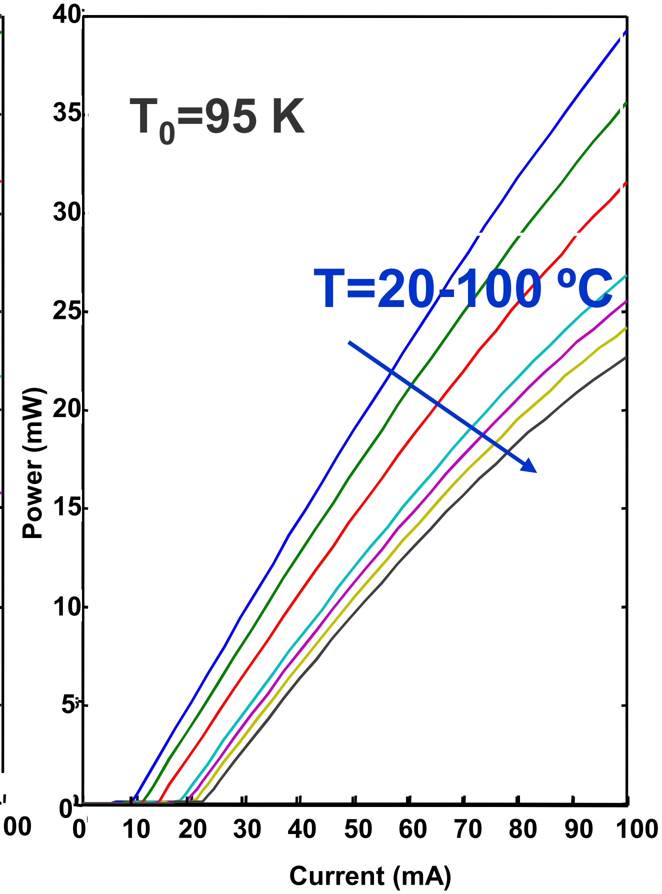
10 years of active material engineering leads to massive improvement of temperature performance



InGaAsP Bulk material (50 mA Threshold at 80C, CSELT, 1995)



InGaAsP-based MQW (Agilent, 2001)



InGaAsAl-based MQW (Avago, 2005)

Modulation schemes for datacom/transport NW

***Transmit information*:**

⇒ **Frequency/Phase Modulation of laser source: transport NW.**

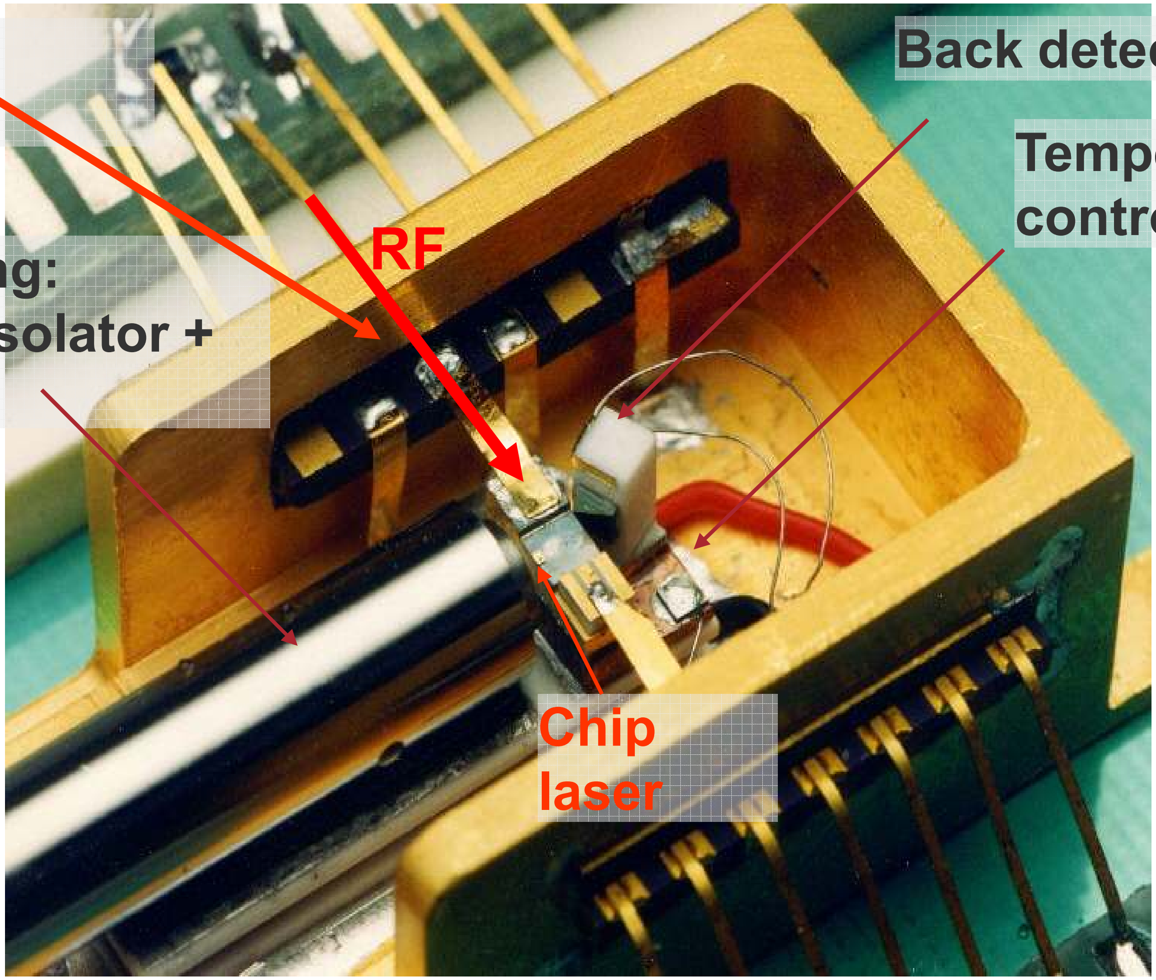
⇒ **Intensity modulation of laser source** ☺☺

- **Intensity modulation by:**
  - **External modulator:** ⇒ **expensive** ☹☹
    (long haul only)
  - **Direct modulation:** ⇒ **cheap/simple** ☺☺
    ⇒ **short haul** 😐
    (1.55um <200 km @ 2.5 Gb, 30 km @ 10Gb; <25 km 1300nm)
    ⇒ ***need high speed devices*** ☹

So we want uncooled, low cost laser … and fast!!!

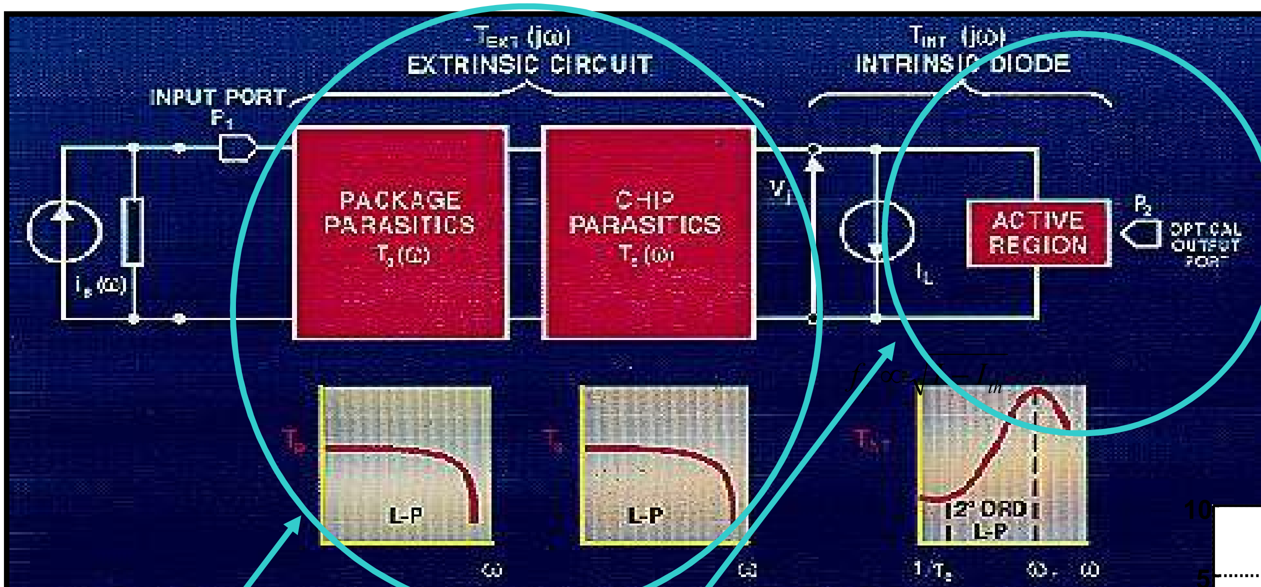
Direct Modulation of Laser Module

Butterfly Laser Module, (1990 – 2000)



Intensity modulation of laser sources

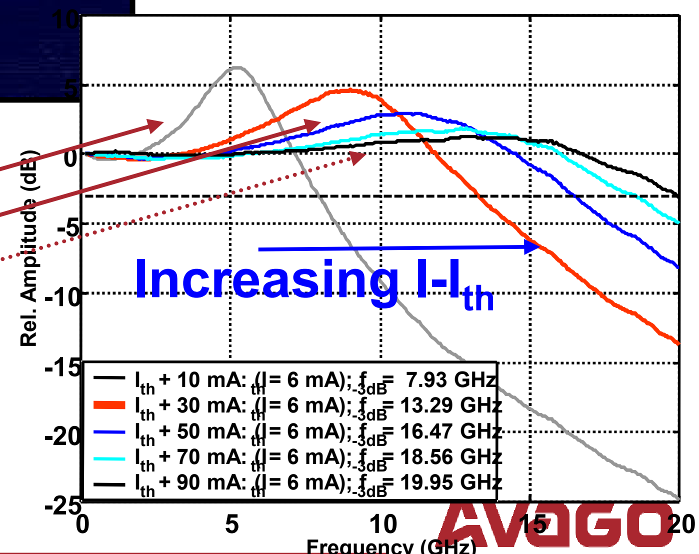
- Laser chip equivalent circuit



Parasitics

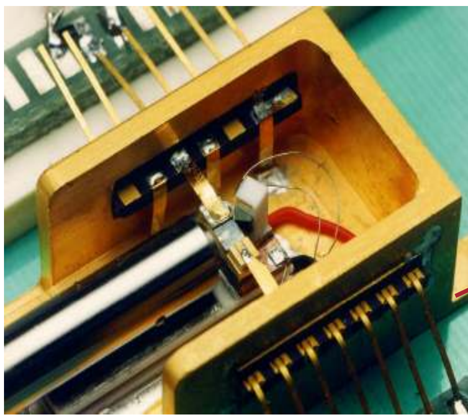
Active material

$$f_r \propto \sqrt{I - I_{th}}$$



Direct Modulation of Laser Module

Electro-optical measurement and simulation (1994) for bandwidth optimization



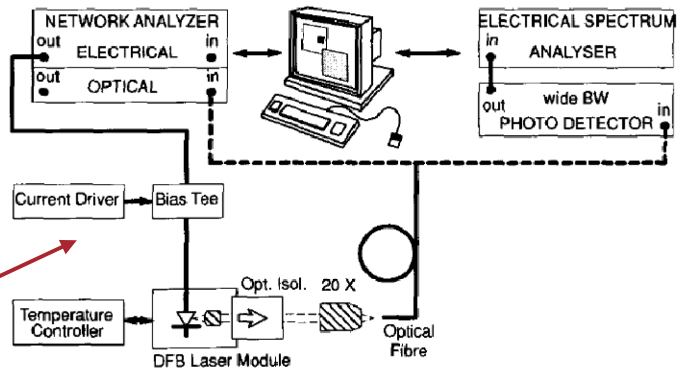
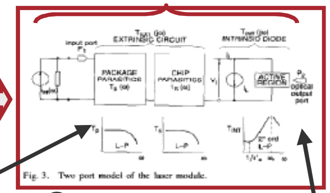


Fig. 5. Measurements setup.

E/O S_{21}



Elec. S_{11}

RIN, Optical S_{21}

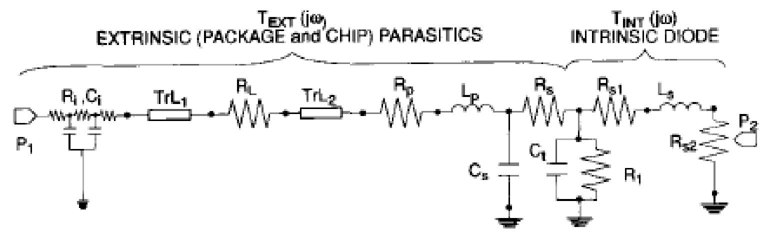


Fig. 10. Complete equivalent circuit of the laser module.

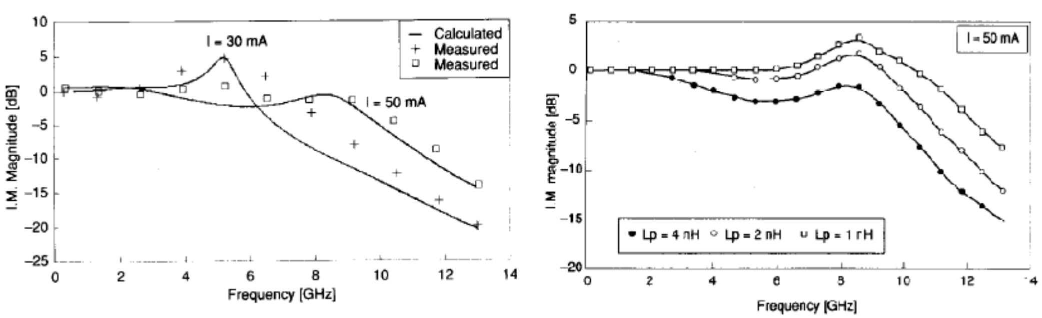
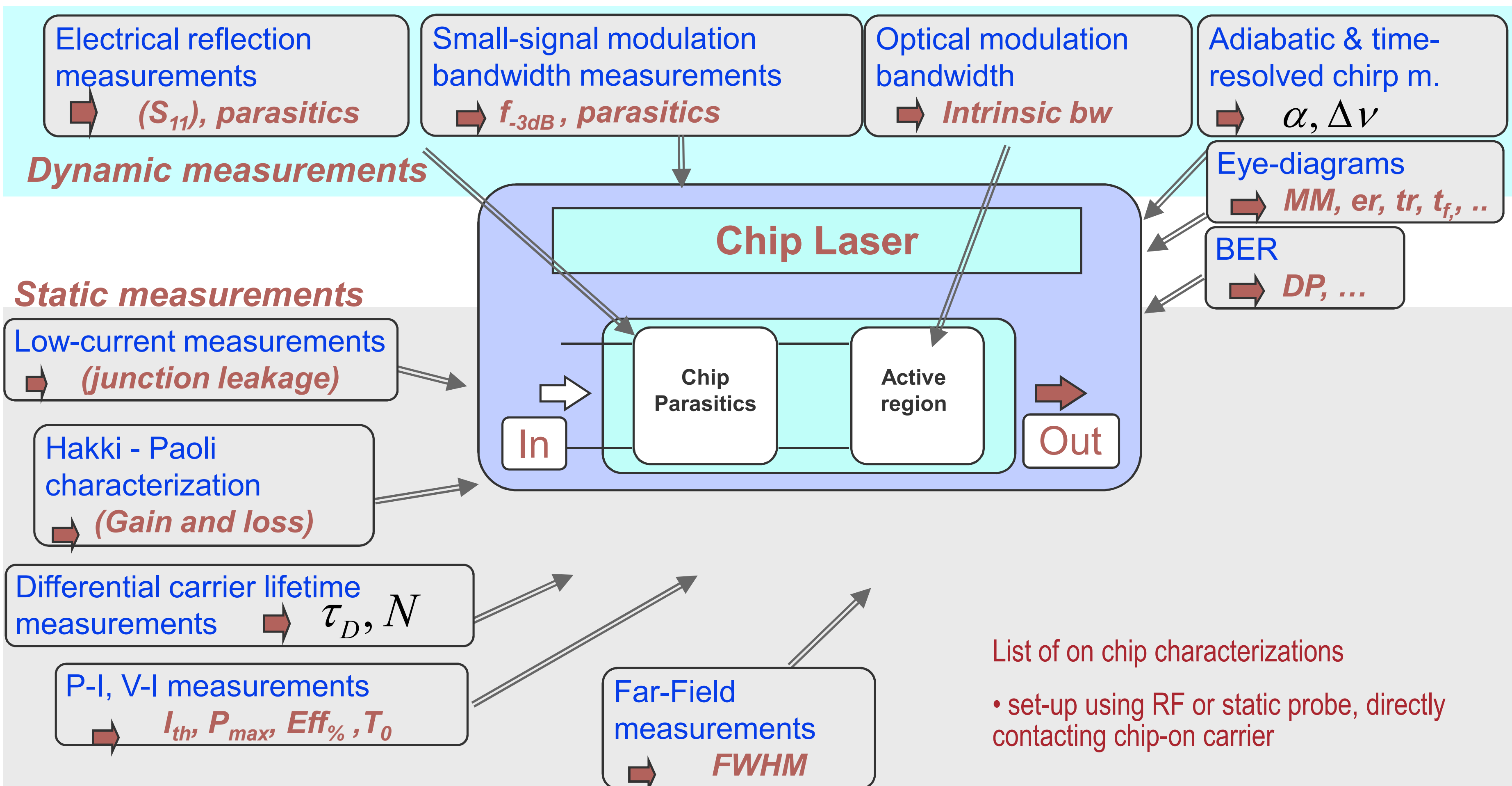


Fig. 14. Simulated IM response modification corresponding to the reduction of Lp.

F. Delpiano, R. Paoletti, P. Audagnotto and M. Puleo; High Frequency Modeling and Characterization of High Performance DFB Laser Modules; IEEE TRANS ON COMPONENTS, PACKAGING, AND MANUFACTURING TECHNOLOGY, VOL. 17, NO. 3, AUGUST 1994

Laser chip optimization

On-chip **static and dynamic characterizations, on dedicated optical benches.**



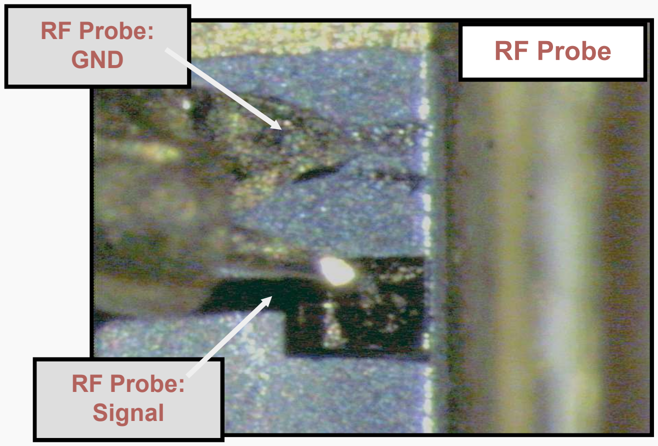
List of on chip characterizations

• set-up using RF or static probe, directly contacting chip-on carrier

Direct RF Probing of laser chip:

Chip parasitics analysis on SI-BH (1995)

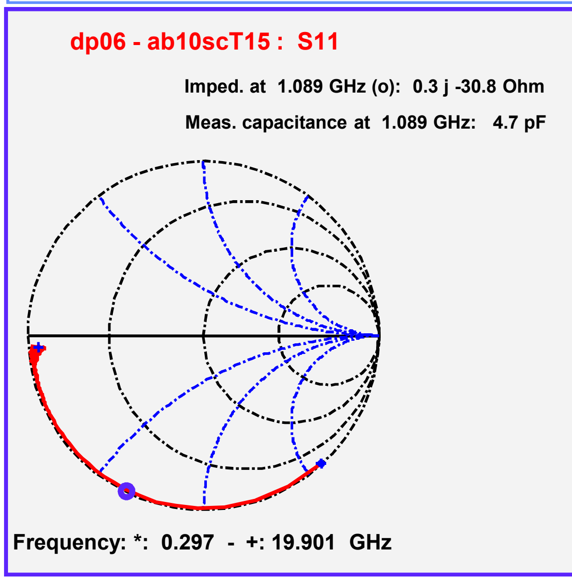
- Parasitics analysis by S_{11} measurement: a long story …



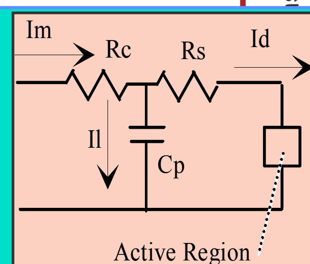
Key points:

- *RF Probes;*
- *Accurate calibration*

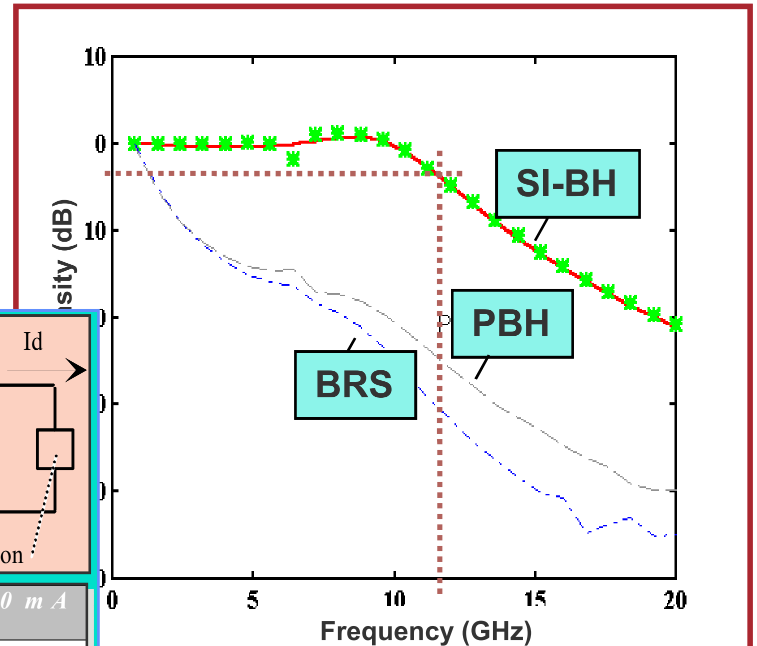
First 0-20GHz S_{11} – S_{21} measurements by custom designed RF probe (1995)



Equivalent Circuit
(Chip Parasitics)



I = 0 mA	
Rc	0.5 Ohm
Rs	∞
Cp	4.7 pF

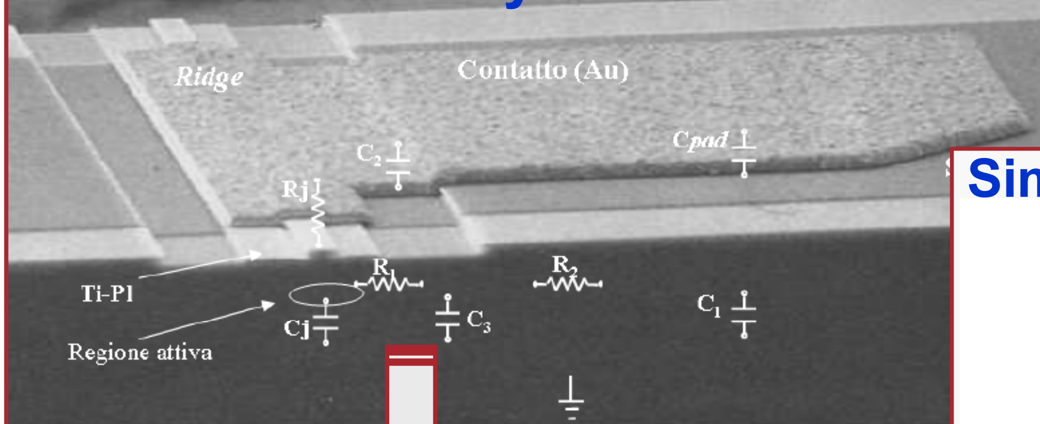


Paoletti et al, SPIE'S International Symposia - Photonics West '96

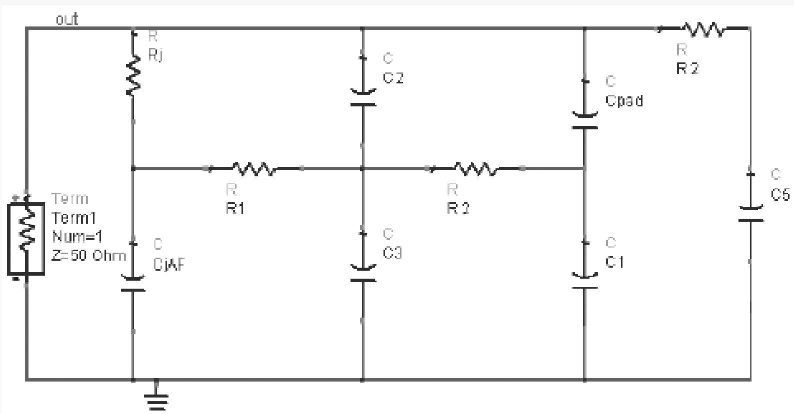
Laser chip RF optimization: direct RF probing of laser chip

Chip parasitics on Ridge Structure, ADS model, S_{11} measurements

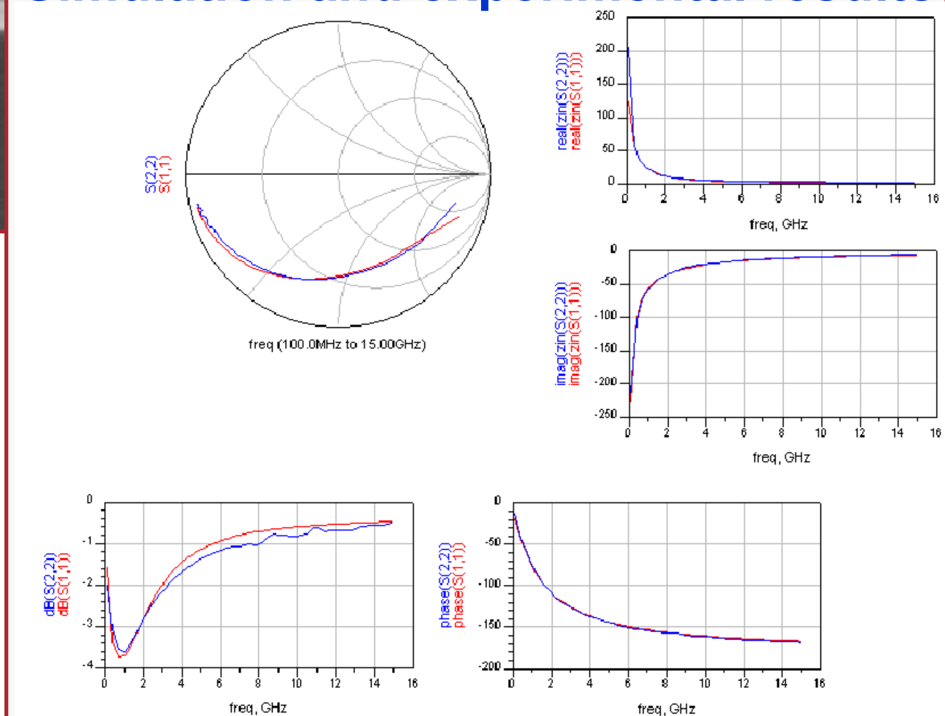
Geometrical analysis



Equivalent circuit

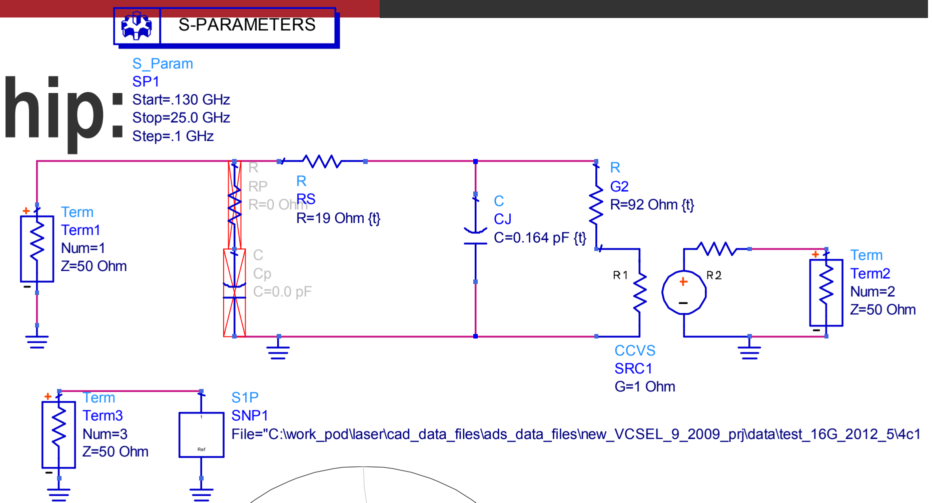


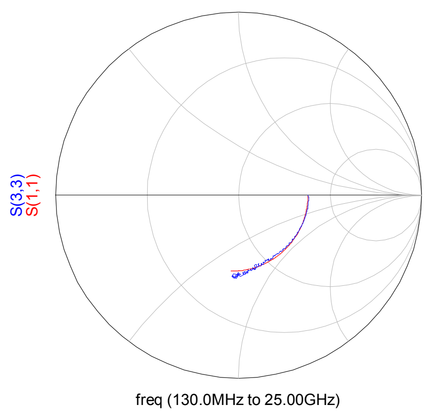
Simulation and experimental results



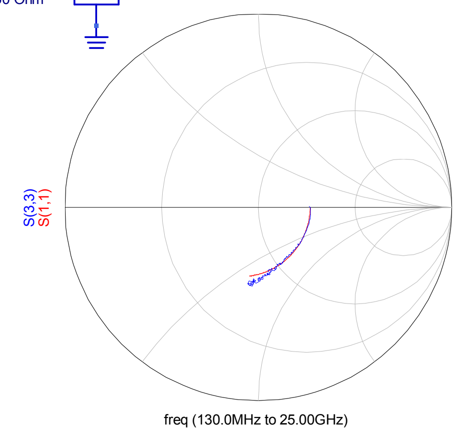
Direct RF Probing of laser chip:

VCSEL S_{11} modeling (ADS)

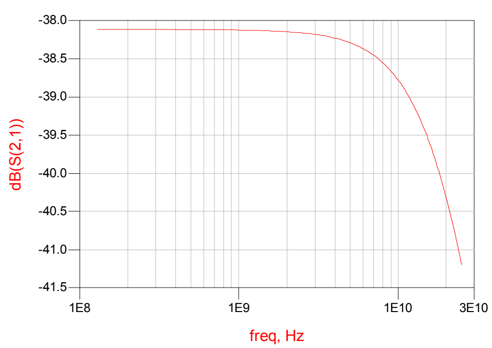




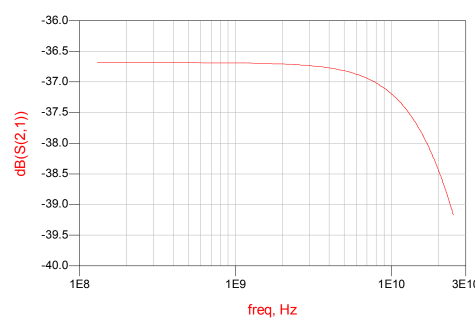
4 mA S11 parameter extraction



8 mA S11 parameter extraction



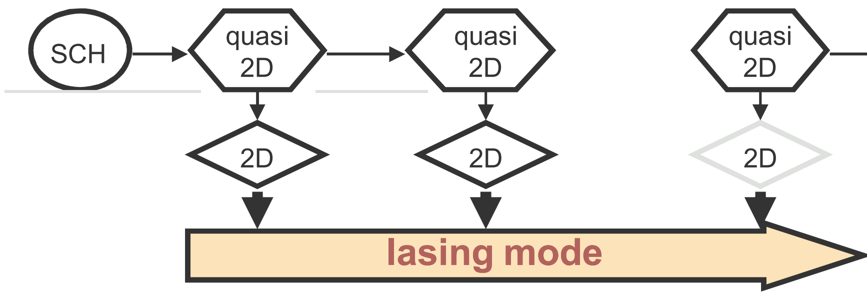
Expected parasitic S_{21} >25 GHz

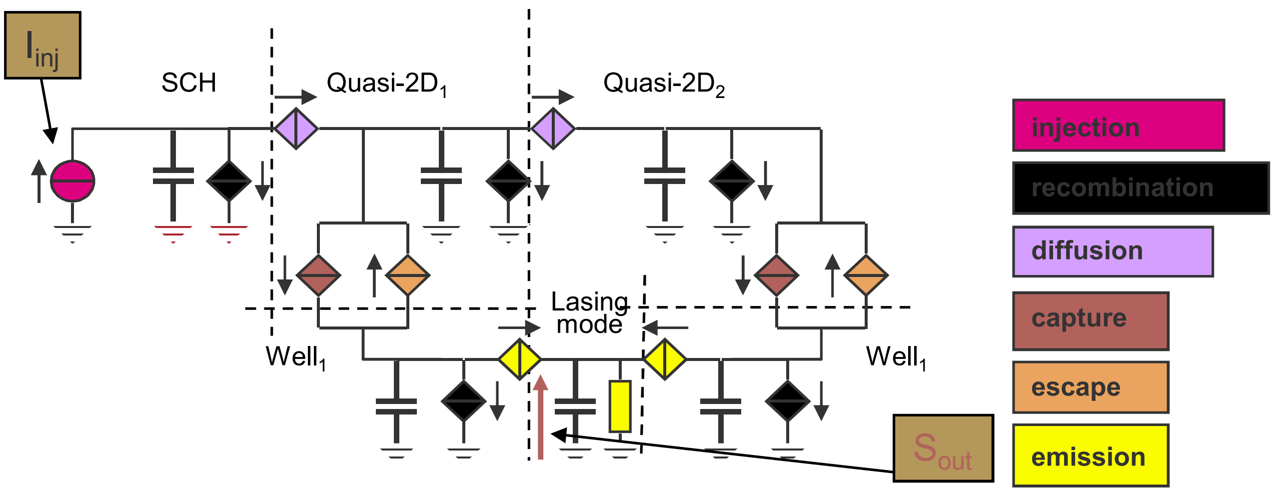


Set up: N4376B. Cascade probe + substrate calibration

Intensity modulation of laser sources

MQW active layer ADS model





G. Rossi, R. Paoletti, M. Meliga, "SPICE simulation for analysis and design of fast 1.55 μm MQW laser diodes", IEEE Journal of Lightwave Technology, Vol. 16, No. 7, July 1998

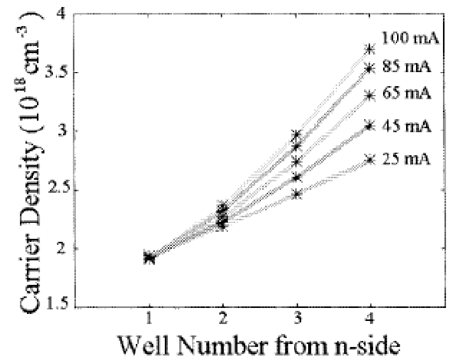


Fig. 8. Carrier injection nonuniformity in a four-QW laser at different bias points.

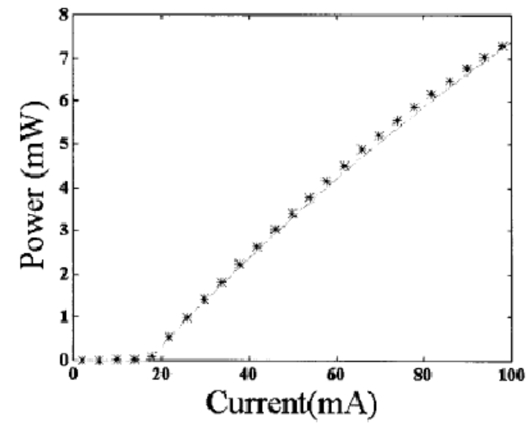
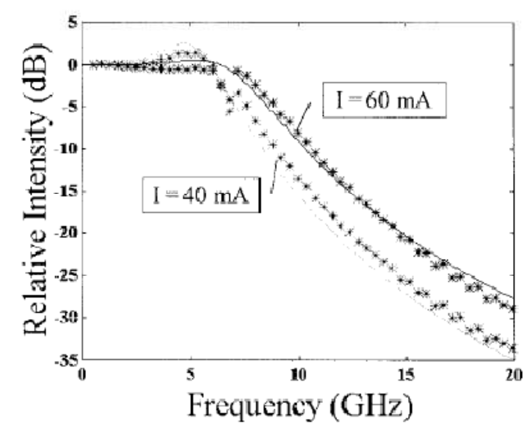
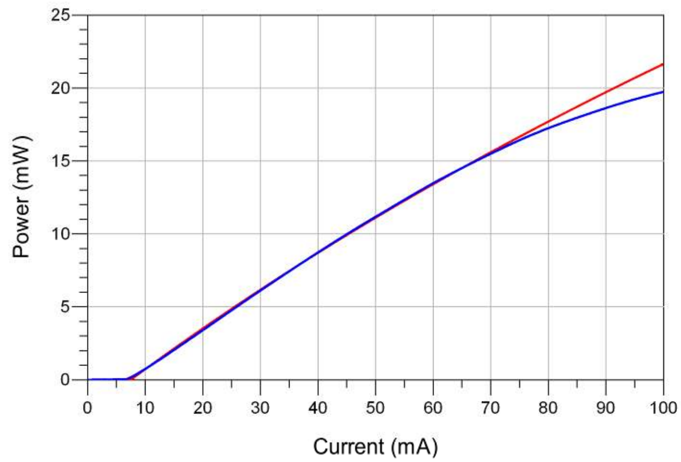


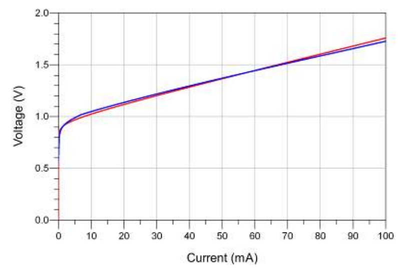
Fig. 11. Static characteristic for a 400-μm long device at 20 °C (Process A). Asterisks stands for data and continuous line for simulation.

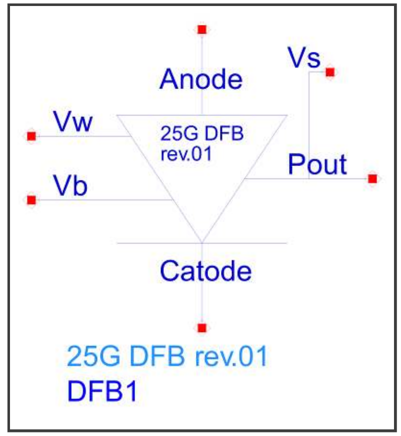


ADS model: simulation (red) vs. measurements (blue)

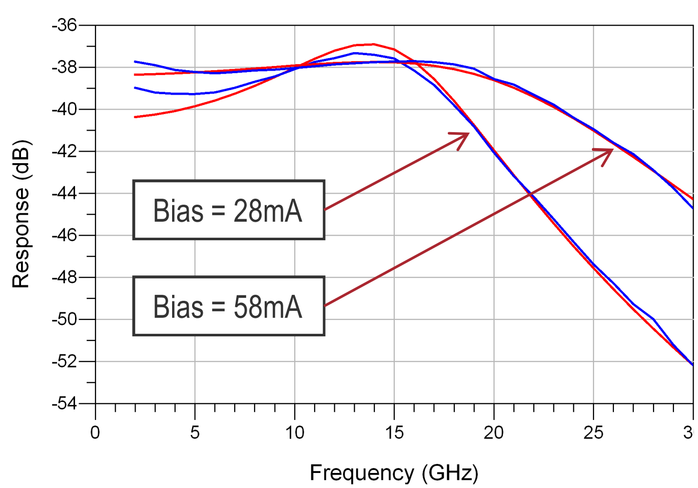


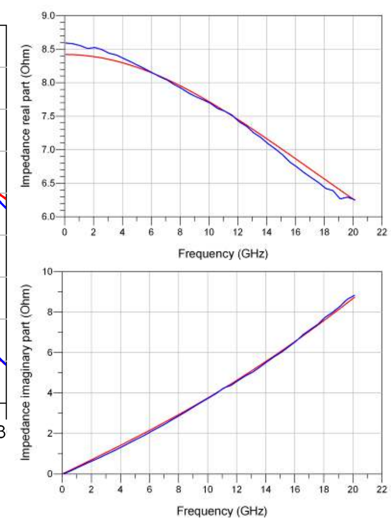
LIV curves



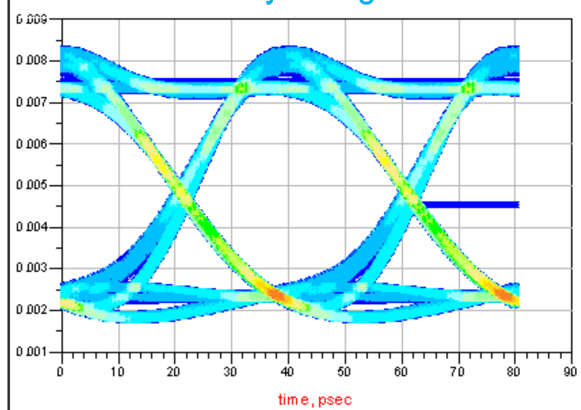


S parameters (bandwidth and dynamic impedance)





Simulated eye diagram



Direct Modulation of TOSA

Electro-optical measurement and simulation

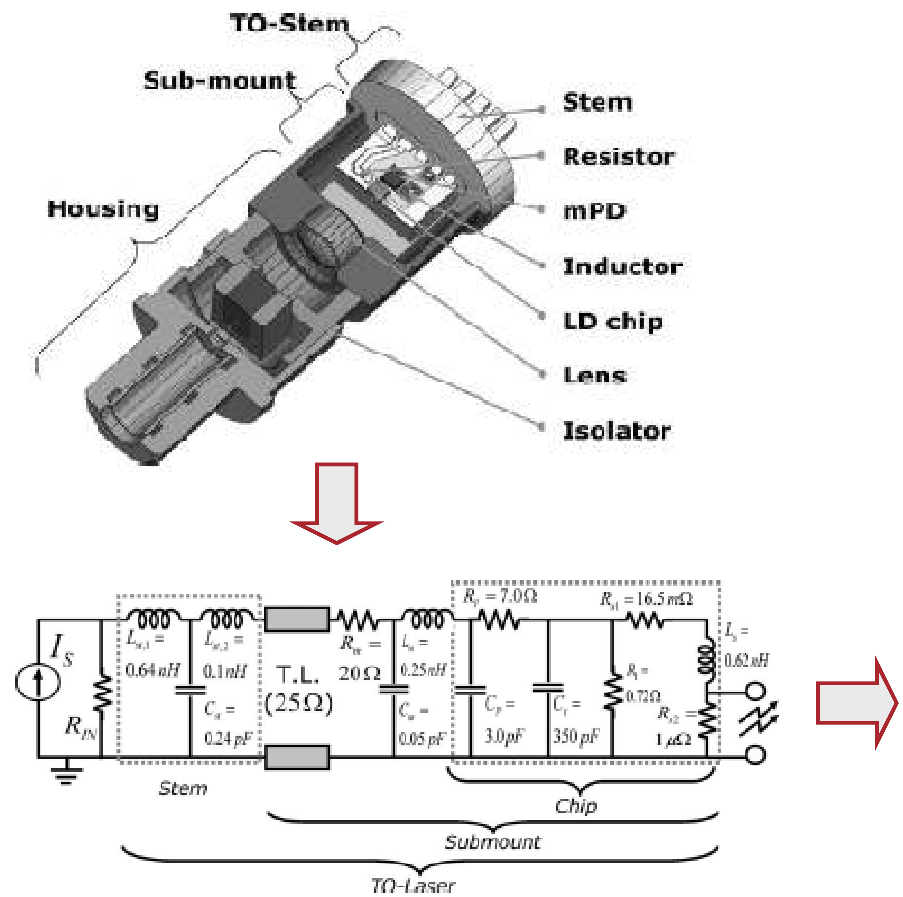


Fig. 10. Equivalent circuit model of the TOSA.

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 12, NO. 4, JULY/AUGUST 2006
KIM *et al.*: DESIGN AND FABRICATION OF A TOSA IN XFP TRANSCEIVER

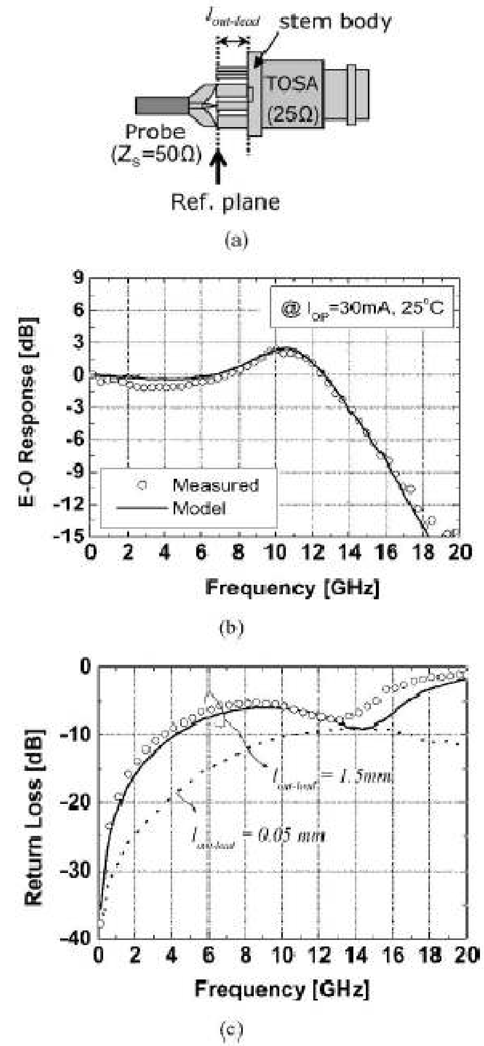
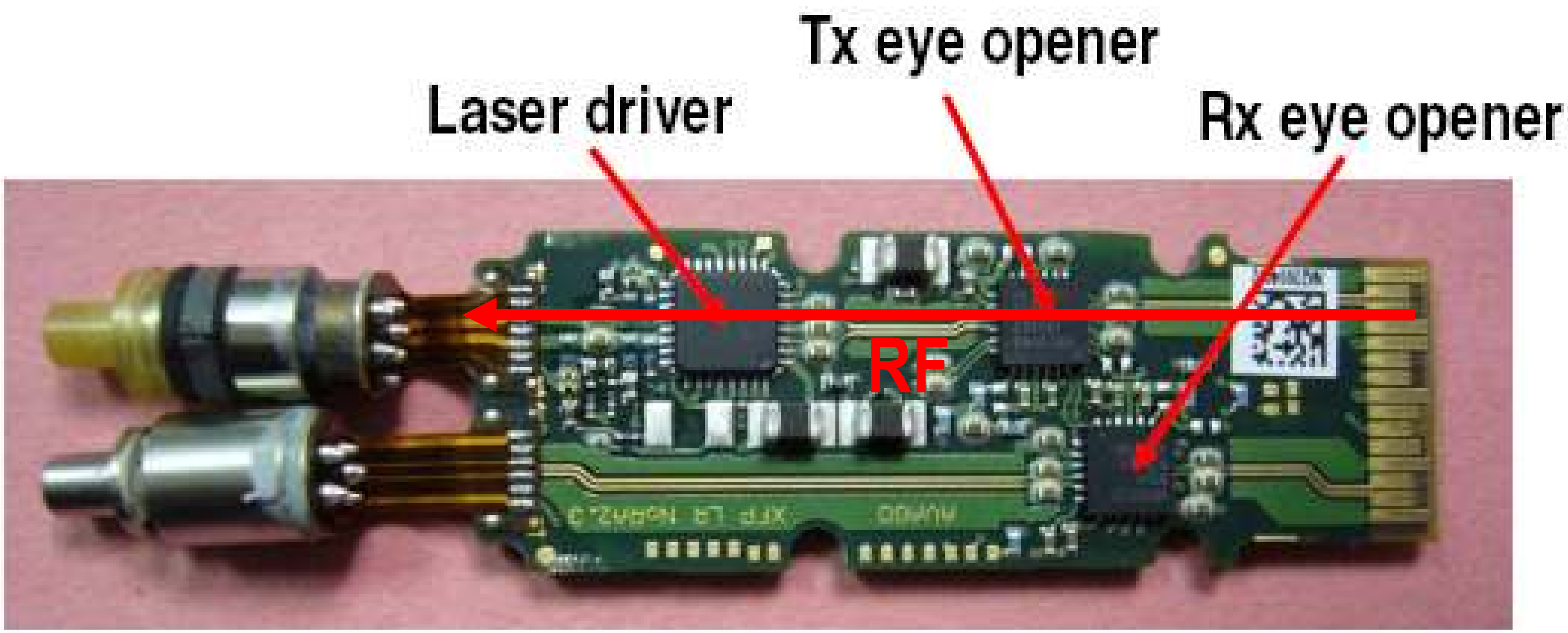


Fig. 11. Characteristics of TOSA directly probed at the end of outer leads: (a) measurement scheme, (b) E–O response, and (c) S_{11} return loss.

Intensity modulation of laser sources:

Package parasitics (Module + TOSA)

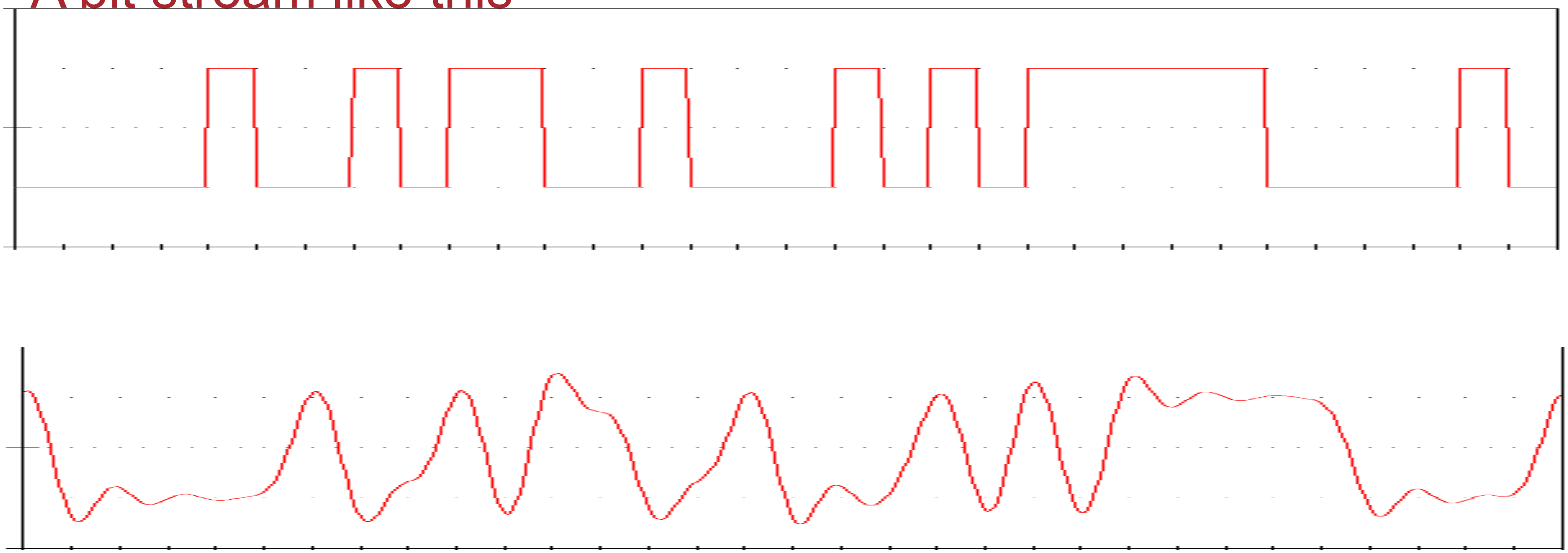


XFP Transceiver, 2005

Large Signal modulation

Recalls of digital communications

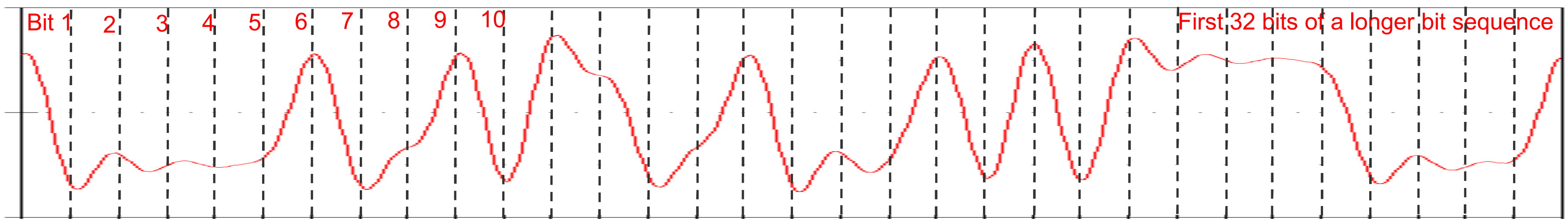
A bit stream like this

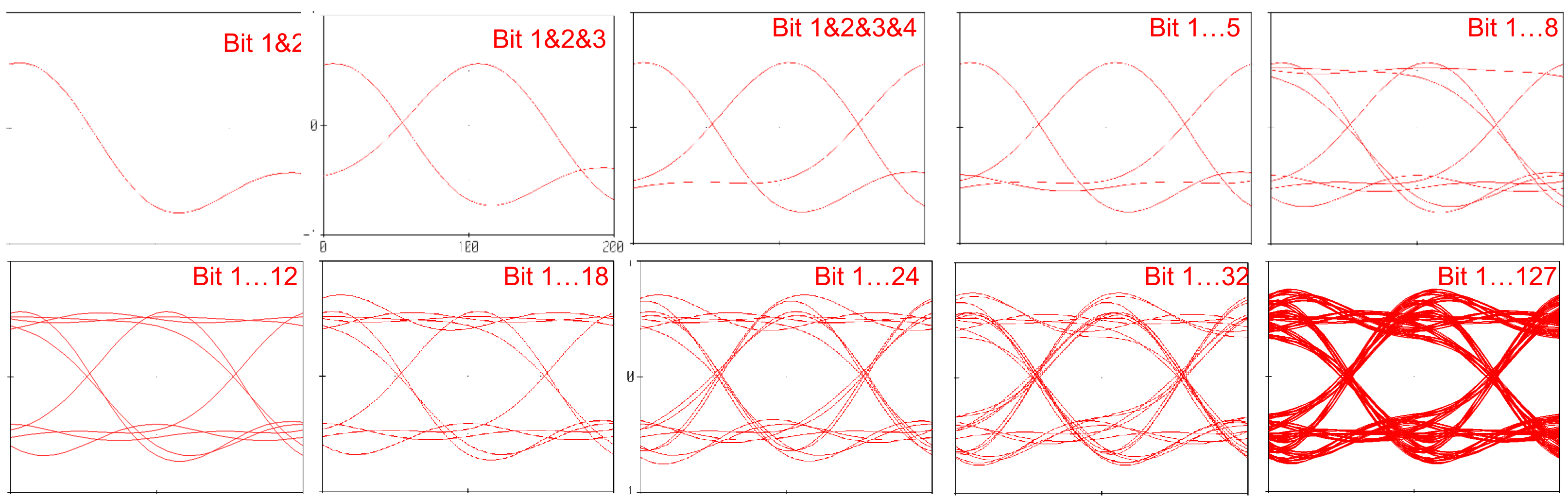


can be heavily distorted passing through a non ideal channel;
bit shape can be broadened and spread out of its time slot, overlapping
on its neighbours : this is called "InterSymbol Interference (ISI)"

Recalls of digital communications (2)

A picture like this gives little information on signal distortion



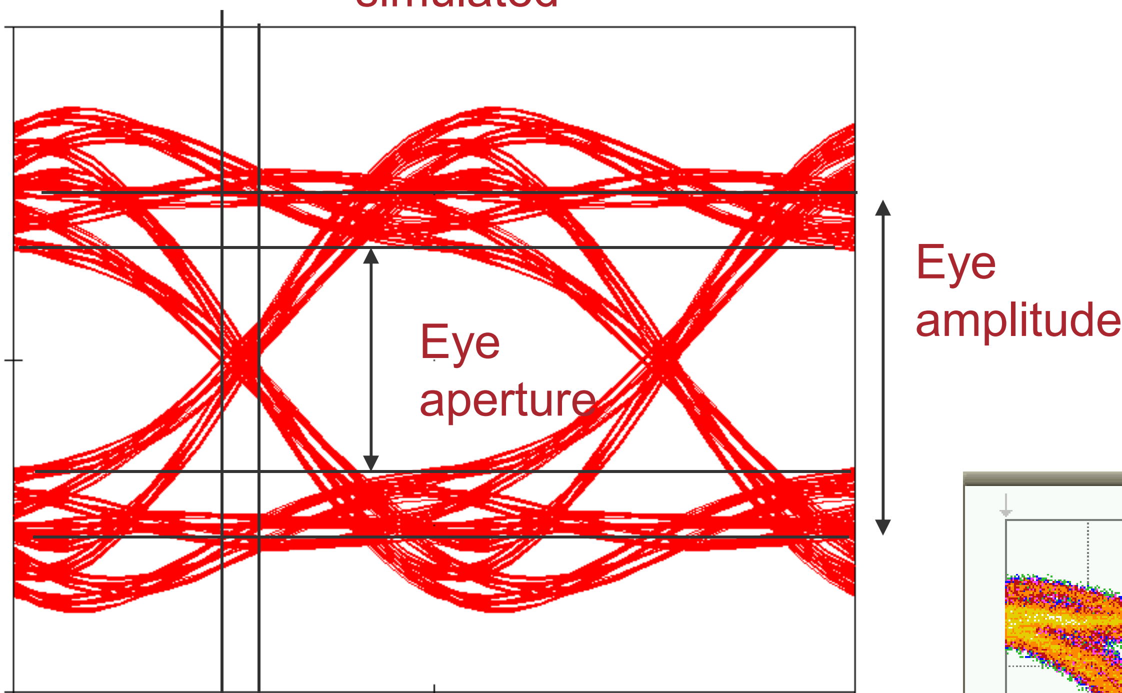


To better evaluate signal distortion an "Eye Diagram" is built

The eye diagram is obtained by slicing the bit sequence in one (or more) bit time slots and overlapping them.

Main parameters of an eye diagram

simulated

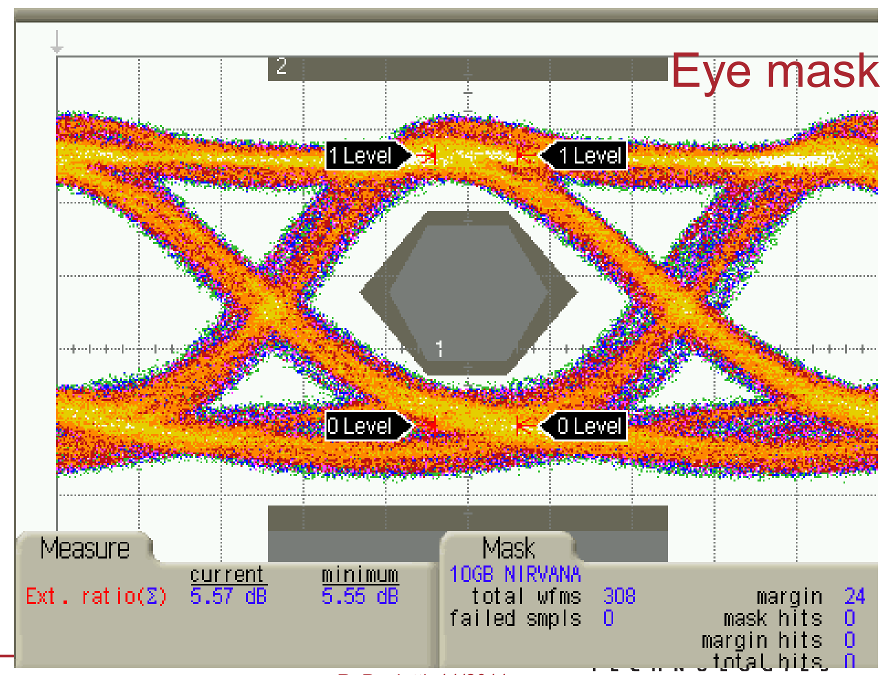


Jitter :

DJ deterministic or pattern dependent jitter

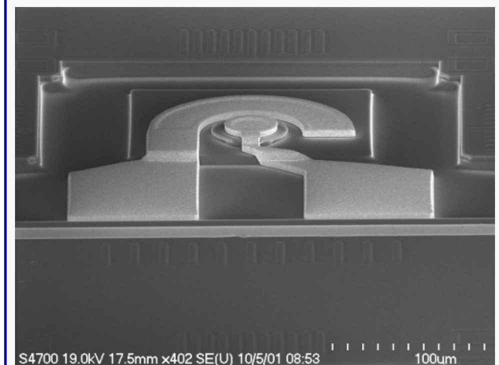
RJ random jitter

experimental

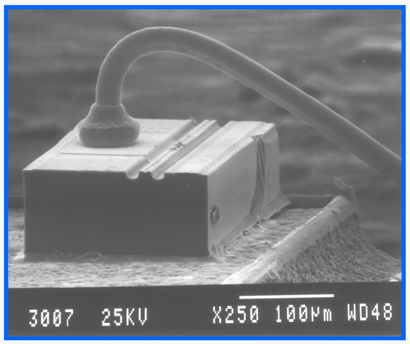


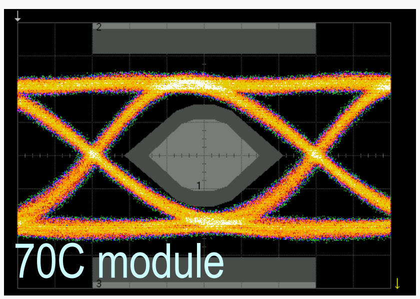
Agilent uncooled InGaAsP BH 10Gb DFB/PIN for 10GBASE-LR product

- Torino R&D team for Ipswich MFG. First product release: **first 10G DFB** and first **10G PIN** for Xenpak – ***first 10G uncooled hot pluggable transceiver in the market***
- DFB uncooled PNiP buried lasers, InGaAsP based

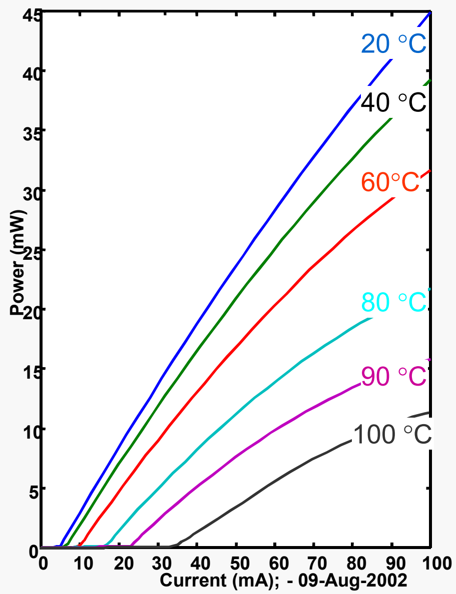


10G PIN





70C module



Uncooled 10G DFB laser

Post deadline at ECOC 2001

10 Gb/s uncooled InGaAlAs ridge FP laser

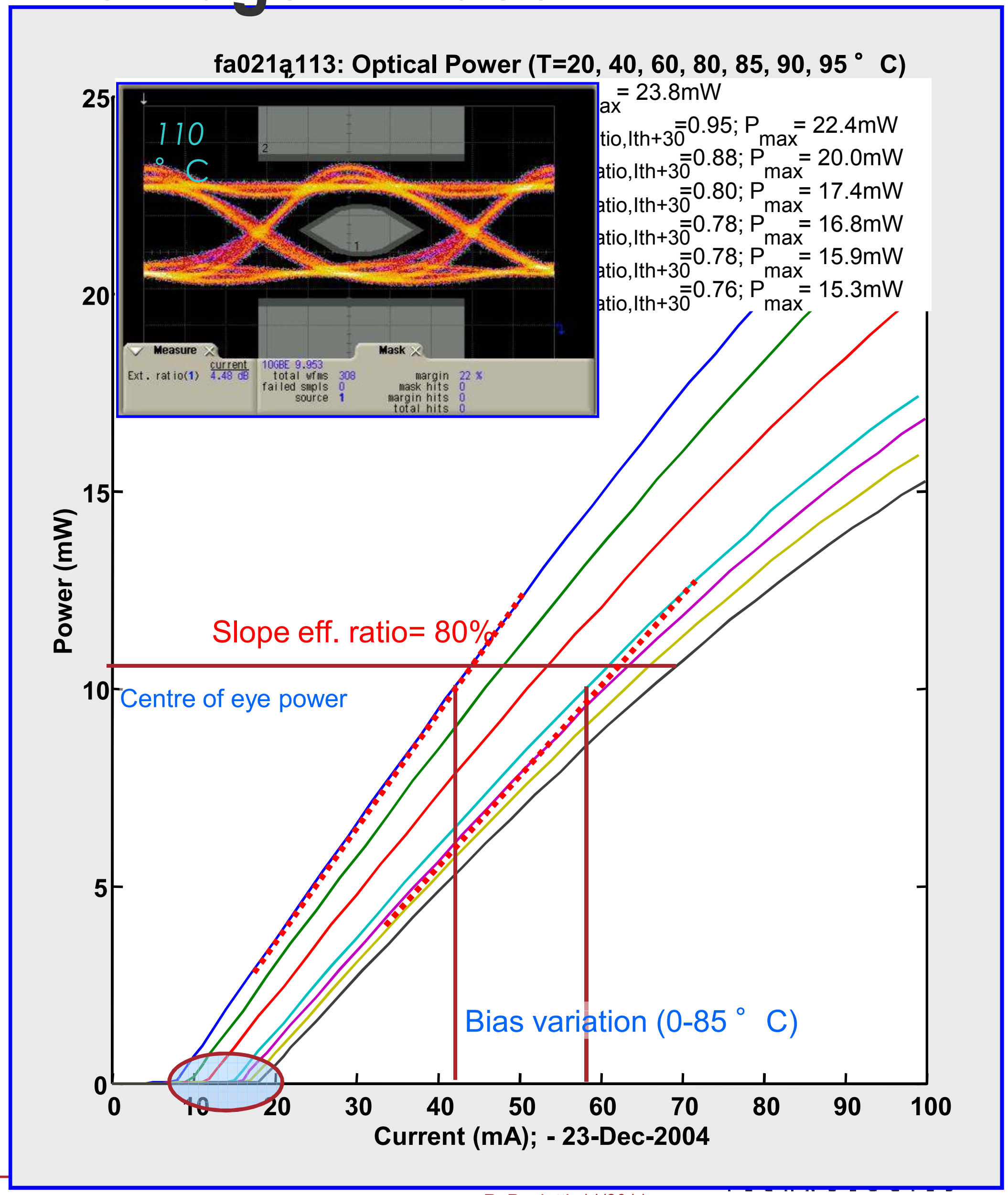
20 ° C base chip temperature:
- Threshold 7.6 mA
- High power 23 mW

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 T_0
- Small bias variation over T
- *Small efficiency degradation over T*

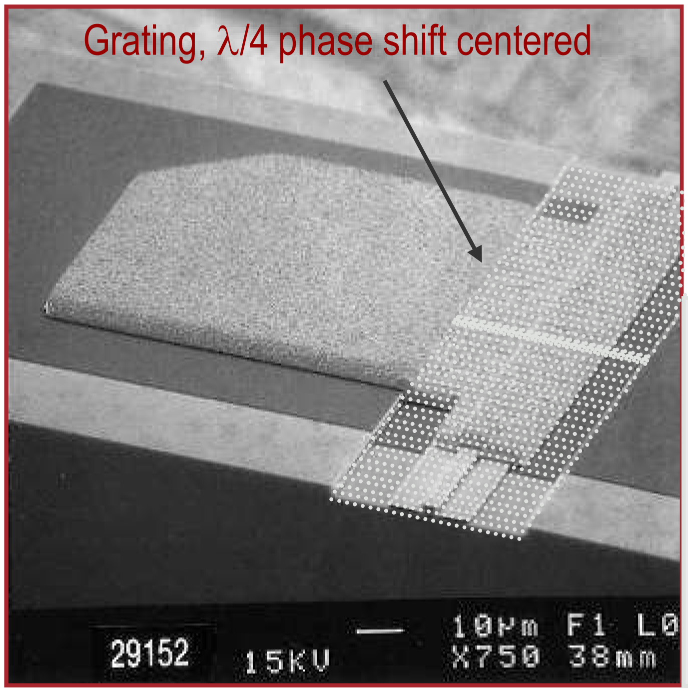
⇒ ***Constant eye quality with constant modulation current!***

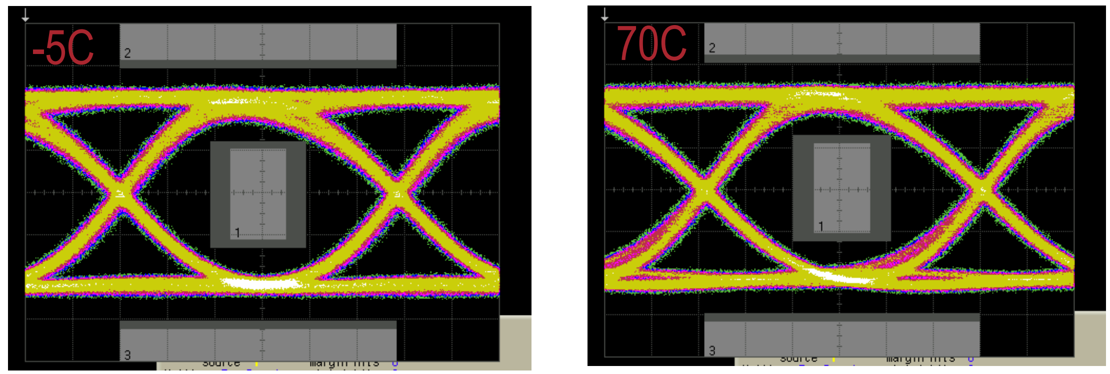


Paoletti et al, Post deadline at OFC 2005

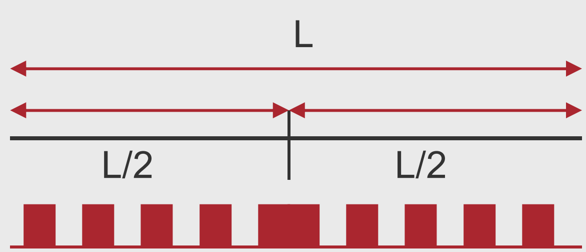
OC48 (4CG4), 10GbE (4CG5), 10Gb Sonet (4CG3)

Uncooled DFB Laser for XFP, SFP and SFP+ platform (2005 – 2006)

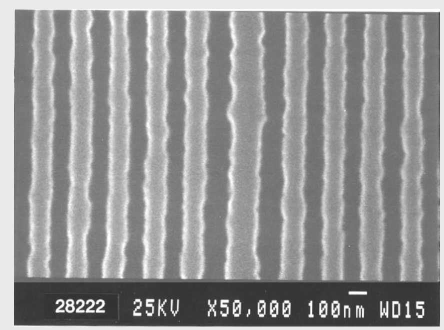




10 G Sonet on XFP module



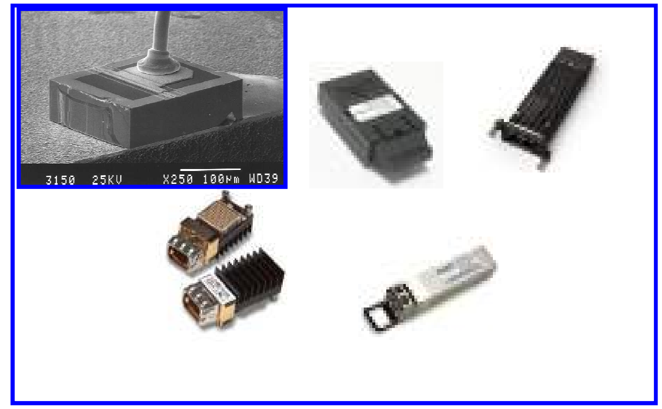
Phase shifted grating



AVAGO TECHNOLOGIES

Semiconductor lasers for optical communication

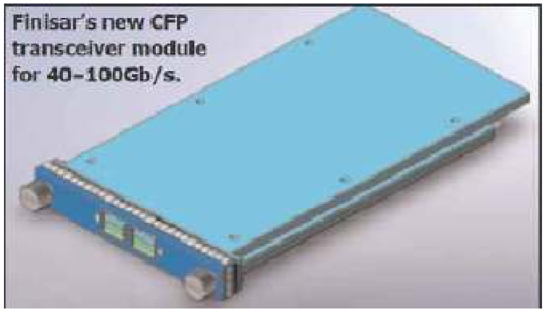
- Laser sources for *"pluggable transceiver world"*
    - *Design for performances*
    - *Fast lasers*
- **Transceiver for next generation networks**
- *Torino Technology Center - Avago Technologies Italy*



What next?
40 and 100 Gb/s Ethernet, 16-32Gb FC standards

- **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, LAN WDM 4.5 nm spaced or PSM4 (4 single mode fiber for short reach driven by datacenter)**
- **16G FC – *32G FC* standard for Fiber channel**
- ***Standard* and MSA have focused the technology development:**
- **16G FC transceiver SFP+ commercially available**
- **First 40Gb/s and 100Gb/s CFP MSA …*but form factor is the key development***

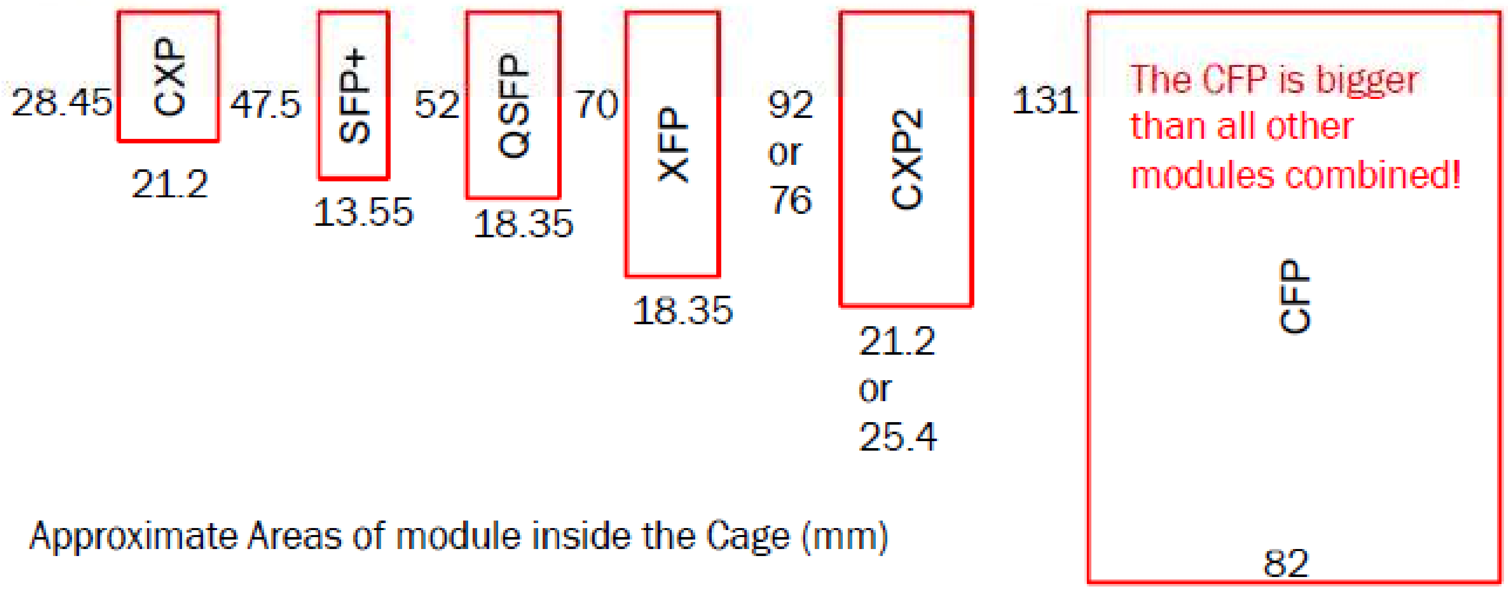

Opnext's 16G Fiber Channel SFP+ module.



OFC 2009-2010

Area and Power Dissipation: the competition on optical modules

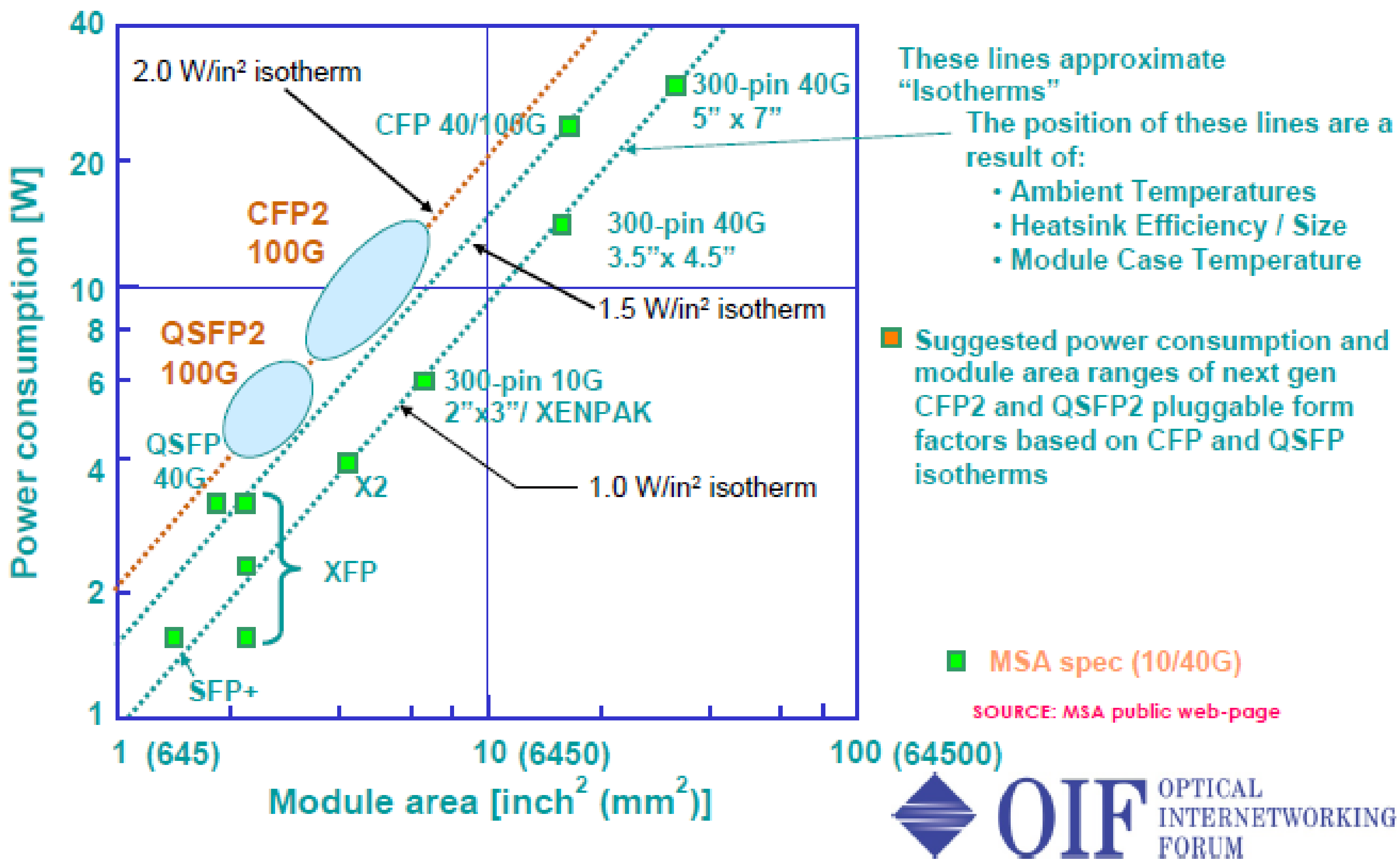
Module	CXP	SFP+	QSFP	XFP	CXP2	CFP
Area (sq in)	0.9	1.0	1.45	2.0	3.0	16.45
Max Power (Watts)	1	1.5	3.5	3.5	6	24/32



Approximate Areas of module inside the Cage (mm)

Next Gen 100G SMF Optical Module

Power Dissipation: data center driving force toward low power dissipation



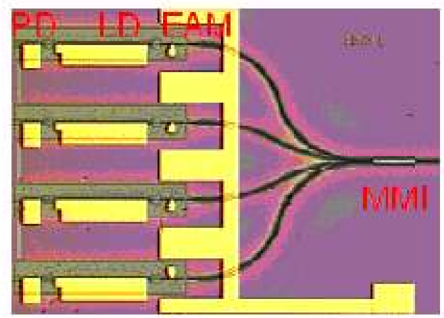
Sources for 100Gb:

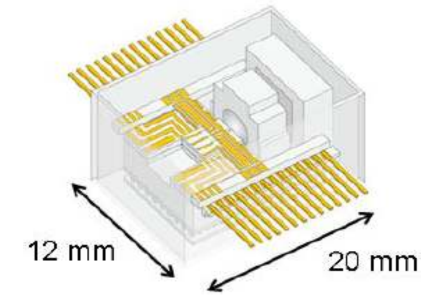
4 × 25-Gbit/s, 1.3-um, Monolithically Integrated Light source

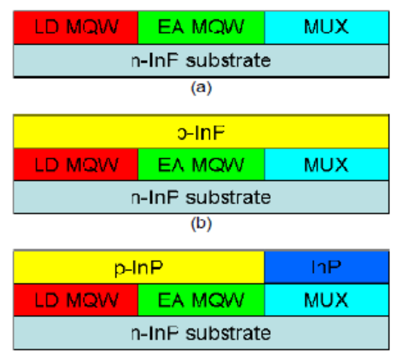
Takeshi Fujisawa (NTT Corporation, Japan)

- **Application: 100GbaseLR4 and ER4 (10 and 40 km) 1300nm**
- **Now CFP with 4 TOSAs, WDM filter**
- **To move from CFP to smaller size (CFP2/?):**
  - integration
  - Low power consumption
- **Then NTT approach**
  - Monolithic integration of EADFB and MUX (MMI)
  - 2 × 2.6 mm2
  - Quarter wavelength shift DFB
  - Ridge, buried in BCB
  - Shallow ridge EADFB, deep ridge MUX
  - InGaAlAs
  - Double " butt join" (one also fro the low doping cladding in the MMI…)

Complicated/high cost/high power dissipation







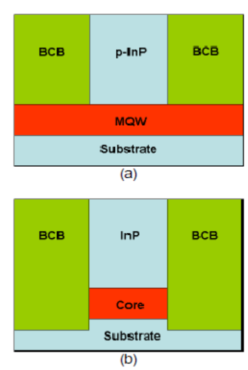


Fig. 4: Cross sections of (a) shallow- and (b) deep-ridge waveguides.

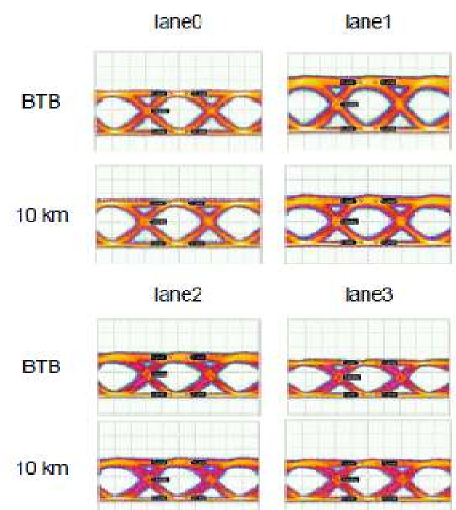


Fig. 14: 25-Gbit/s eye diagrams (simultaneous operation).

Sources for 100Gb:

DFB technology: best as cost and power dissipation….

OFC 2007 session: Uncooled and semicooled DFB laser sources at 25 and 40 Gb/s

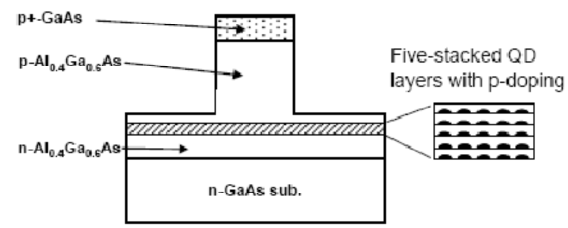
- *Avago: best eye quality up to 70C, 25Gb/s*

Paoletti et al, OFC 2007

Next steps: 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



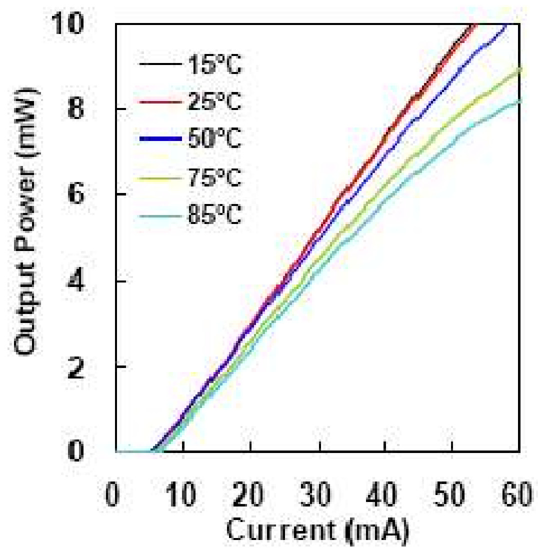


Fig. 3 Light-current characteristics of the fabricated laser

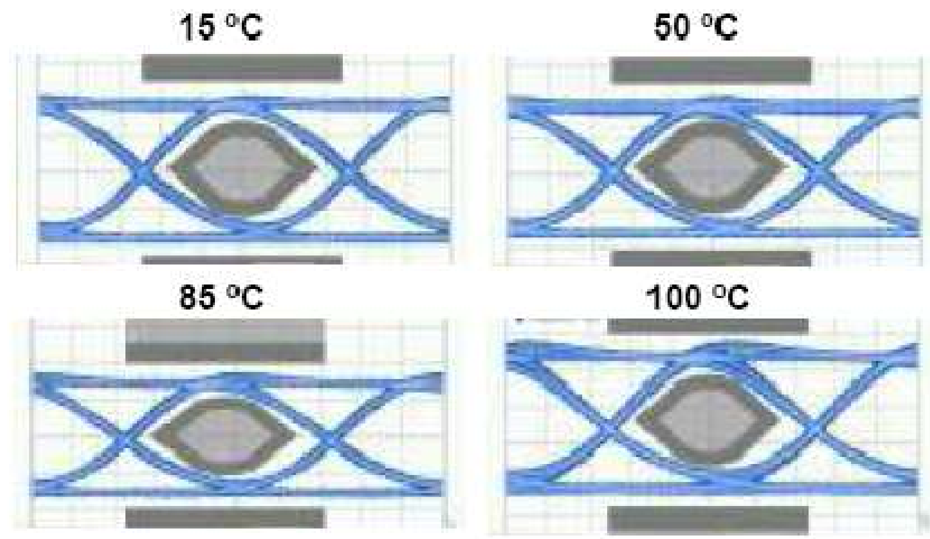


Fig. 4 10.3-Gb/s filtered-eye-diagrams in the fixed driving condition at 15, 50, 85, and 100 °C. The mask margin of more than 48 % was maintained at all temperatures.

200 um long 1.3um ridge FP laser, with amazing performances… on GaAs . Announced to be *"ready for production"….*

… Or real revolution will be Silicon Photonics?

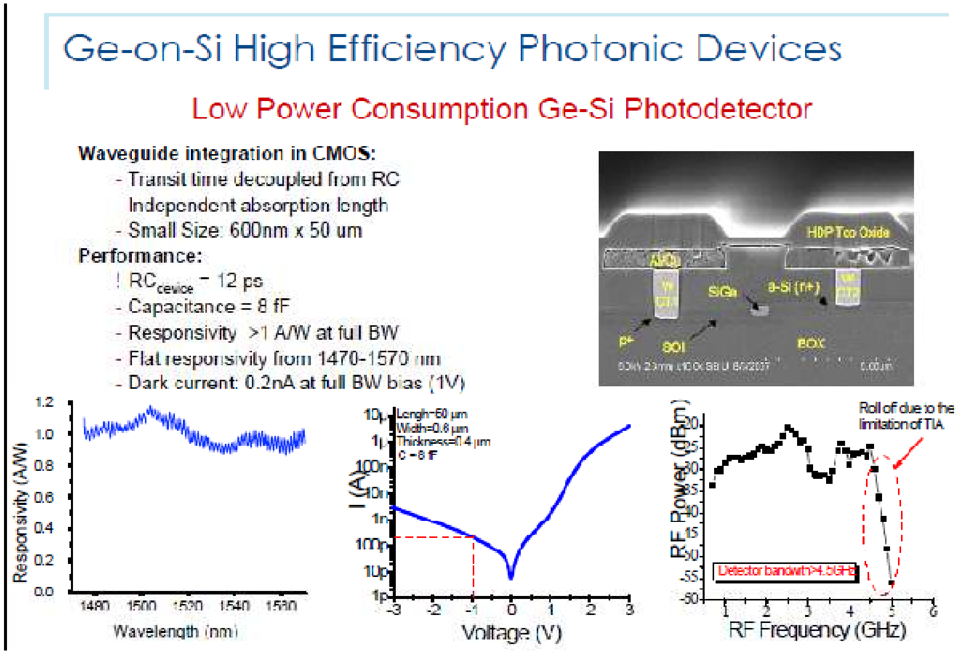
UCSB

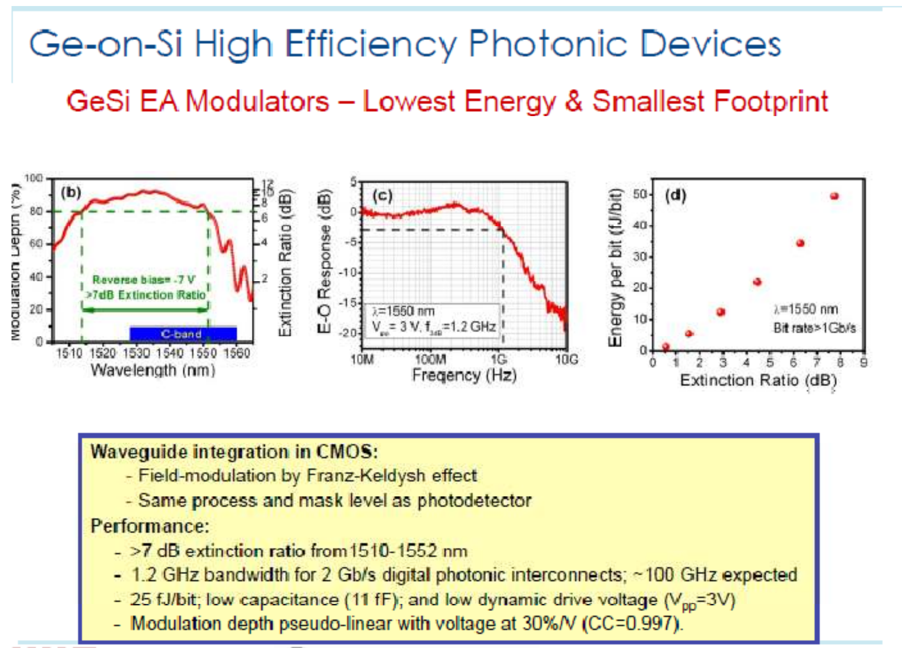
Silicon light emission – How?

- Bulk silicon
- Low dimension Silicon
  - Silicon nanocrystal (Pavesi, …)
  - Periodic nanopatterned crystalline silicon (Jimmy Xu)
- Er dopants (Dal Negro,…)
- Avoid direct interband transition
  - Raman laser (UCLA/Intel)
- Another material for gain (hybrid approach)
  - Epitaxial
    - Ge
    - Quantum Dot
    - Pillars
  - Bonding
    - Dice level
    - Wafer level (BCB or Molecular)

ECOC 2010, John Bowers, Dept of Electrical and Computer Engineering, UCSB

Silicon Photonics
EPI: Ge on Silicon





State-of-the-art performances by Ge on Silicon on detectors, improving on modulators

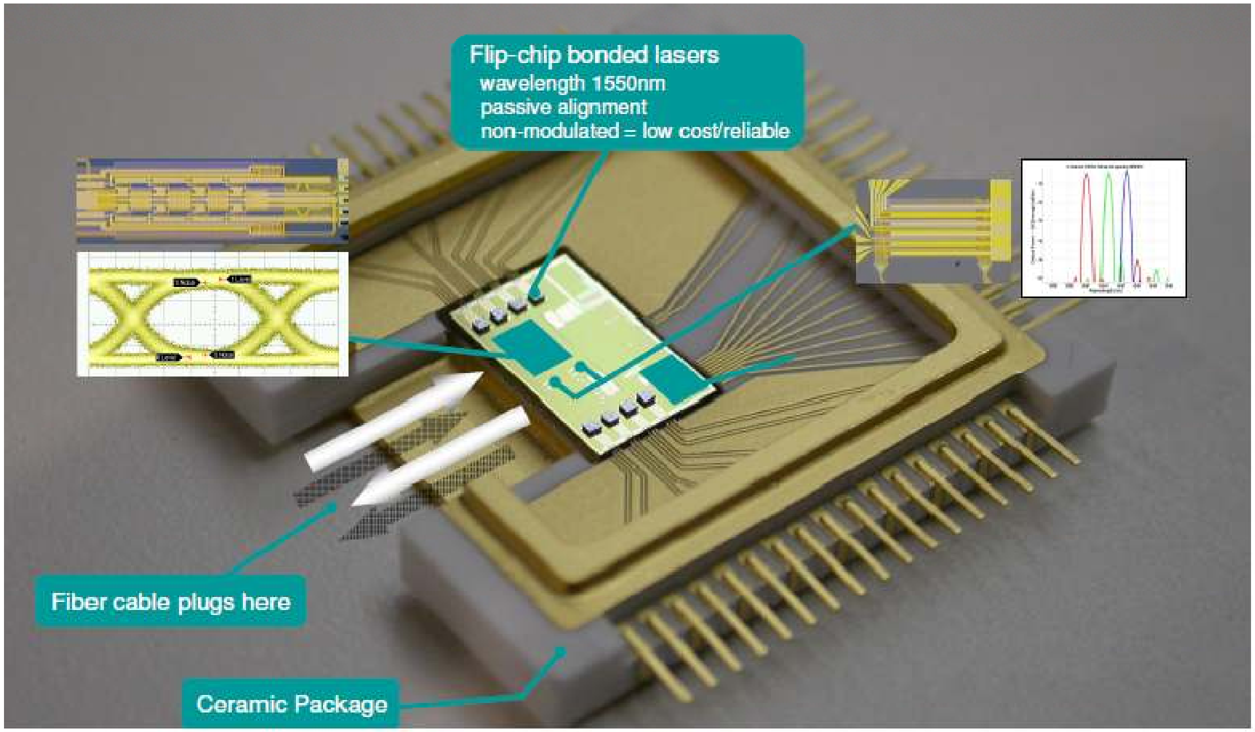
ECOC 2010, Lionel C. Kimerling, MIT

AVAGO TECHNOLOGIES

Silicon Photonics;
Hybrid approach: die level

III-V material for gain (hybrid approach), Si for waveguides and modulators

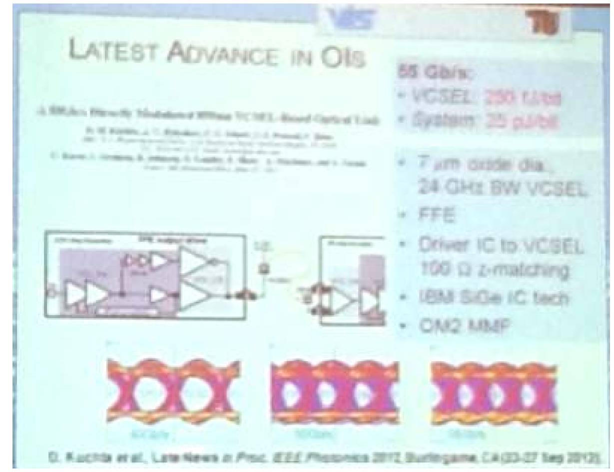
- Bonding: Die level
  - **Flip-chip (Luxtera)**



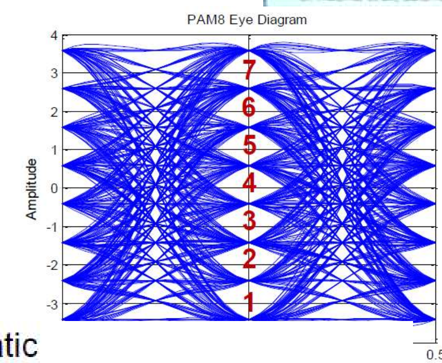
Taking the best from III-V and Si world… Smart guys! Promising solution for advanced modulation format and parallel approach (PSM4)

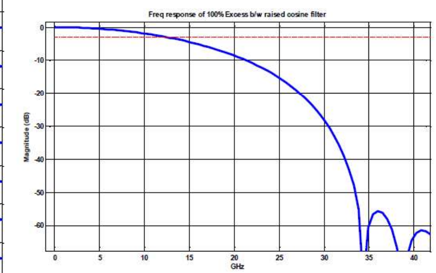
ECOC 2010 - 2012

And electronics can boost optics to higher datarates!

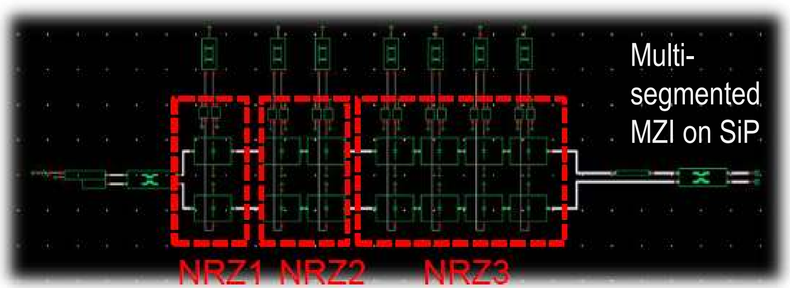


- Using pre-emphasys: 25 Gb VCSEL, 44 Gb using FFE at driver and good electrical matching... (ISLC 2012)
- Using Multilevel coding (IEEE 802 committee)





Opto-electronic Schematic



	Ethernet rate
PAM-2	100.39 Gs/s
PAM-4	50.20 Gs/s
PAM-8	33.46 Gs/s
PAM-16	25.10 Gs/s
PAM-32	20.08 Gs/s

- Or using FEC
  - limiting to 10^{-5} BER and allowing low cost optics: power budget, reflection sensitivity, etc…

Avago Technologies Italy

Acquisition by Agilent Technologies 19 April 2000

Former technology dept. of CSELT; Today XX Eng YY OPer.

Activity: R&D and Production (III-V Team)

- Short term Development projects (transceivers @ 10 Gbit/s and higher)
- Medium term Research projects for active and passive devices
- Development and Production of 10G FP/DFB/EML laser source

Activity: Transceiver R&D (Product Team)

- Design of next generation single mode transceiver

Facilities (III-V team)

- 1350 m^2 of clean room: class 10-10000 (plus R&D Lab, officies).
- EPI (2 MOCVD), material characterization, processing (including EBL), die fab (singulation, coating, testing, assembly and reliability tests)

Expertise: optoelectronic and photonic technologies

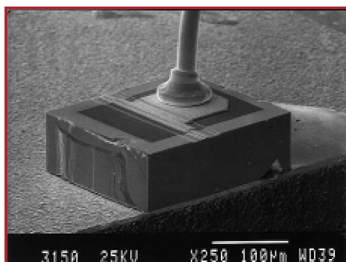
- New transceiver, devices and components conception and design
- Semiconductors
- Device design, prototyping and characterisation

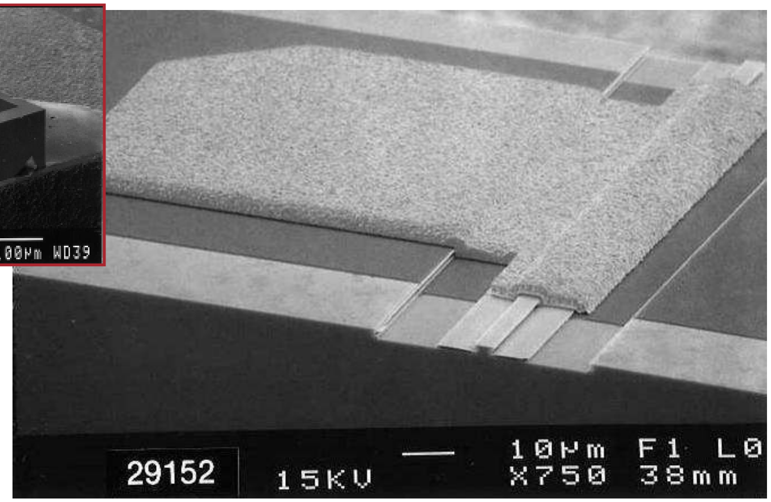
Technology platform for high yield manufacturing

established from 2003 on

- ***high yield***
- ***easy to manufacture***
- ***high performance***

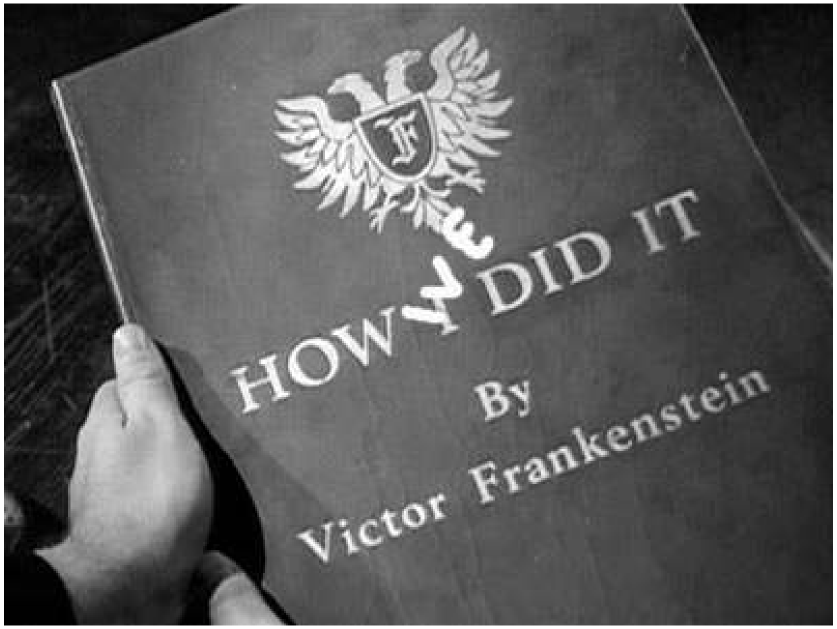
- **Aluminum based MQW material**
  - Superior high T performances
- **Ridge waveguide**
  - High yield; compatible with Al MQW material
- **Quarter wavelength grating**
  - 100% SMSR yield





Proven reliability, with > 50 M devices x hours in 3 years production

How we did it……The III-V Technology in Turin



.. advanced lasers? A teamwork ..

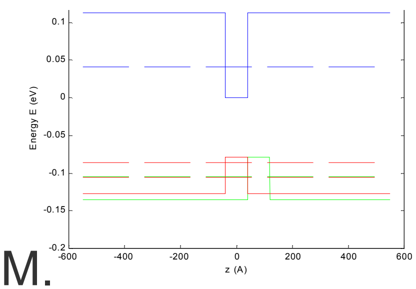
…advanced technologies!

How we did it……

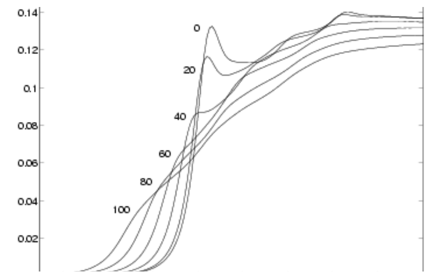
(1) Design/Modeling

1. Material properties (Q.M.)

MQW band profile and levels

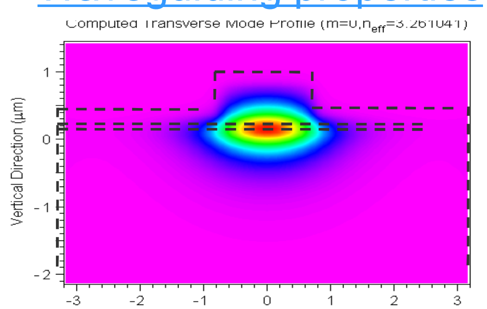


Optical properties: n+ik (I, F, T)

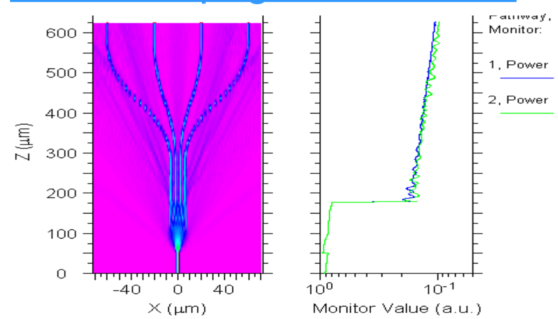


1. E.M.

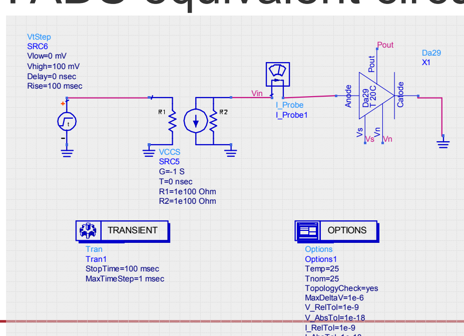
Waveguiding properties

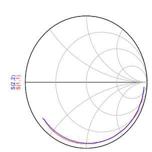


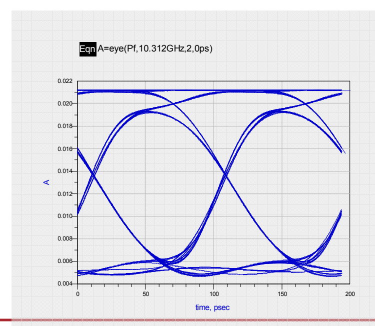
Beam Propagation Method



2. RF: ADS equivalent circuit

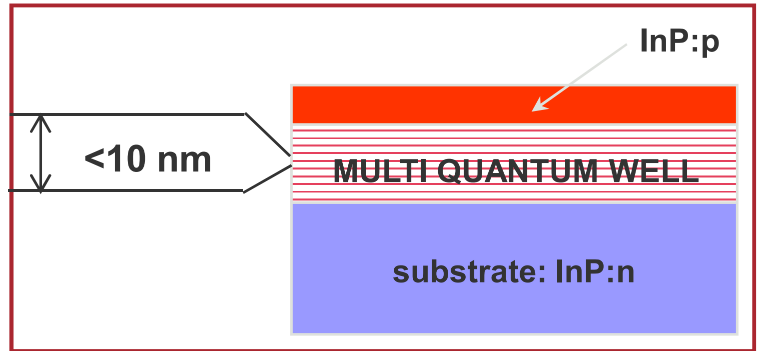




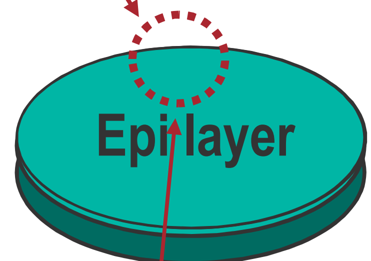


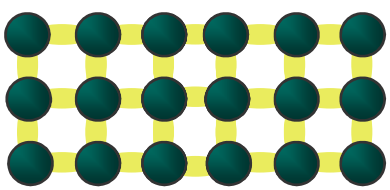
How we did it……

(2) Epitaxial growth

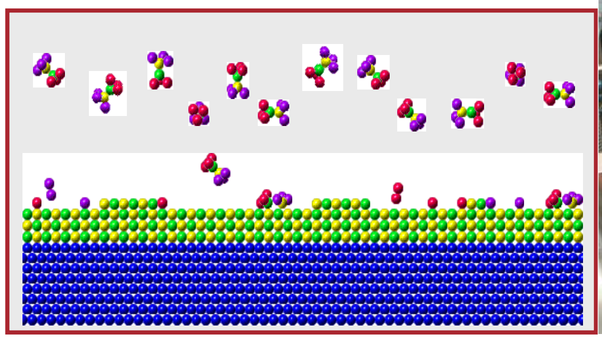


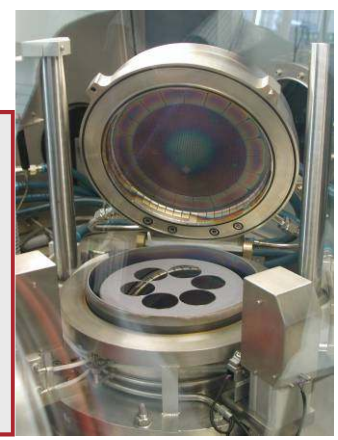
Epi growth

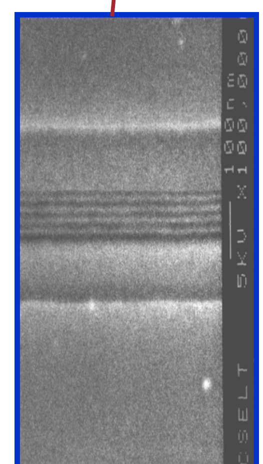




MOCVD reactor







⇒ How we did it……

(3) Material characterization

X-Ray diffraction: crystal quality +composition

Photoluminescence: alloy composition

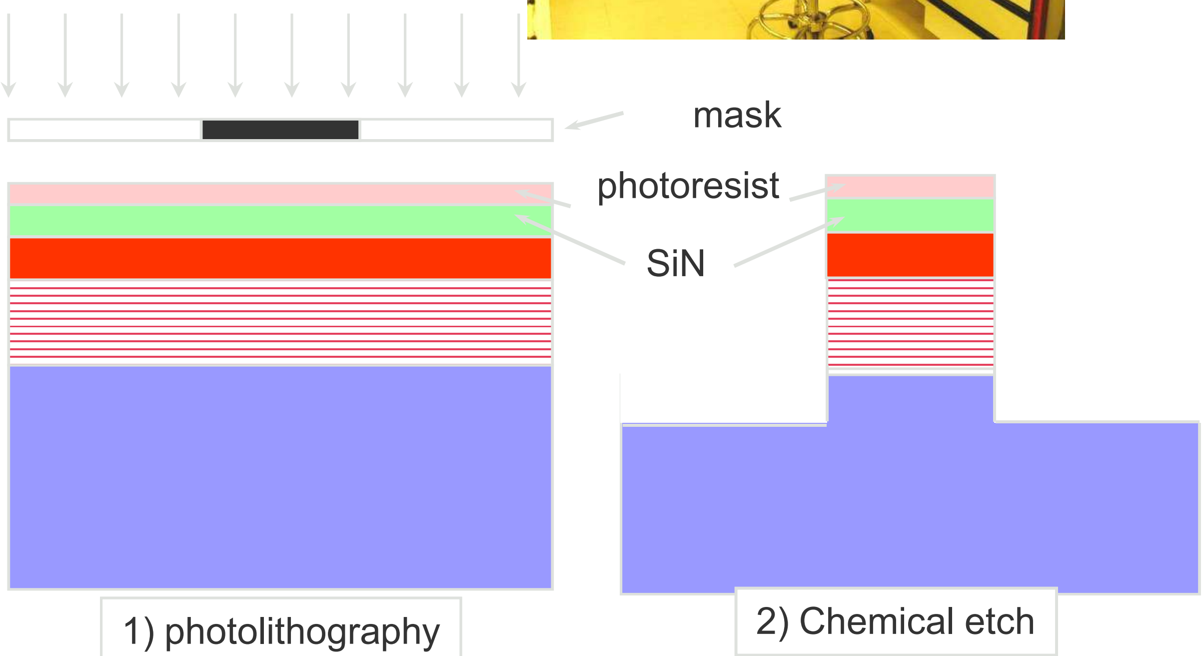
Scanning Electron Microscope (SEM)

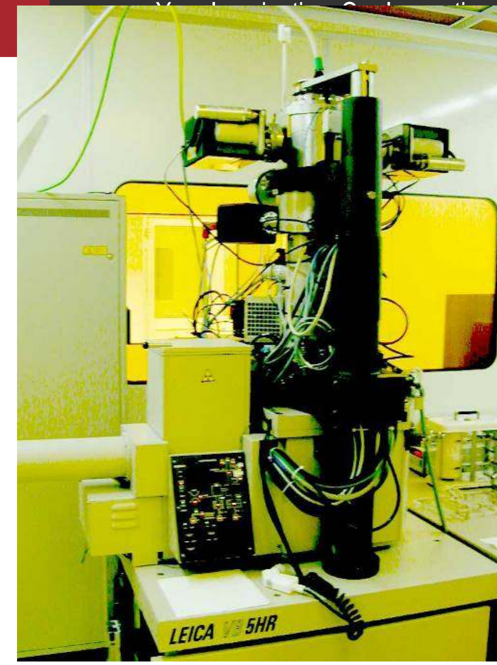
C-V profilers: doping profile

How we did it……

(4) Processing

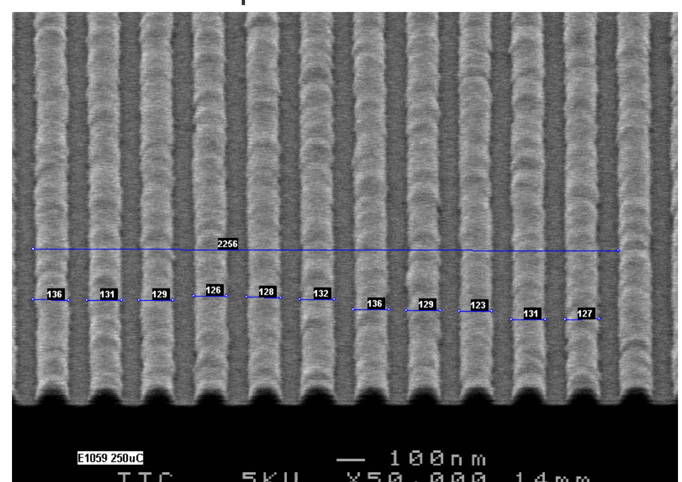
Photolithography





Electron Beam Lithography

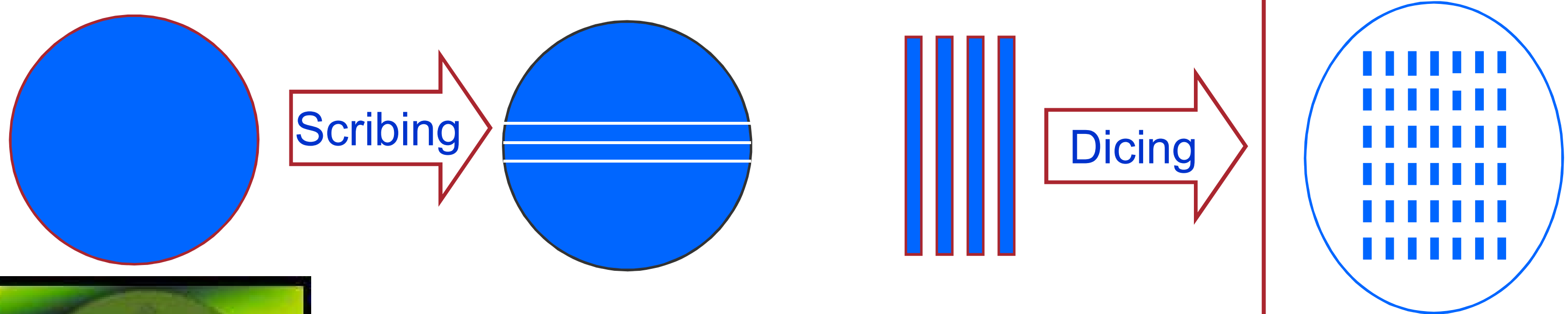
- ✓ 70 nm line in 75 nm thick resist
- ✓ 200 nm pitch lines

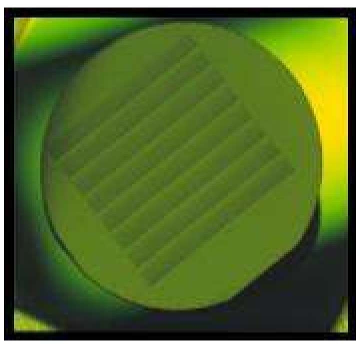


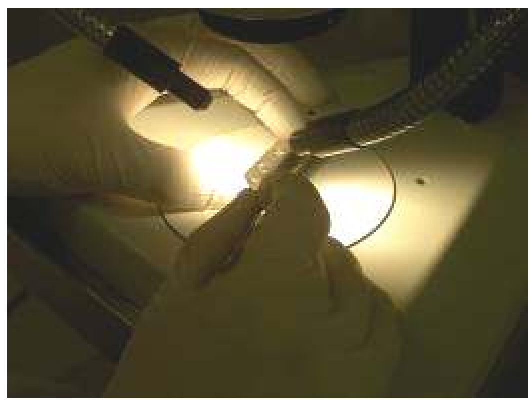
How we did it……

(5) Scribing: from wafer to chip

Wafer **bars** **Coating /cleave** **Dies**







From 2” wafer:
up to 20.000 lasers (Yield!!)

How we did it……

(6) Automatic testing

What are LDIs?

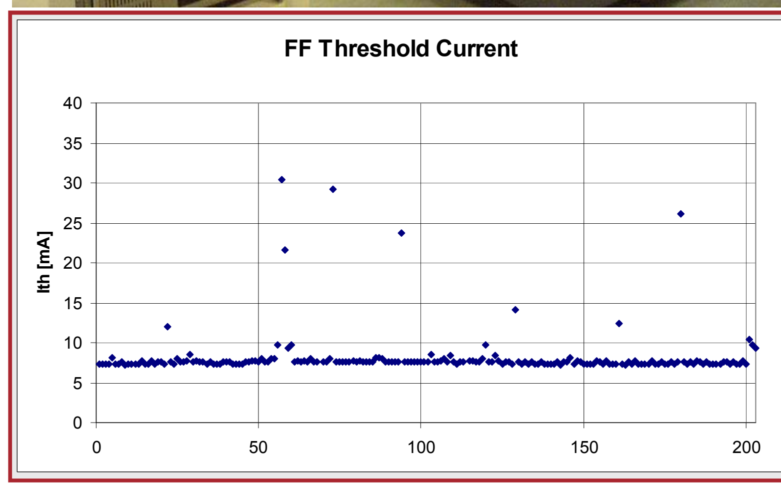
Laser Device Inspectors are automatic systems for 100% device testing and screenings.

System capabilities and scope:

•Test: pulsed measurements on chip @ R.T.:

•F/B LIV, spectrum, rev. leakage, chip size and tilt

•10G FP, 10G DFB, EML



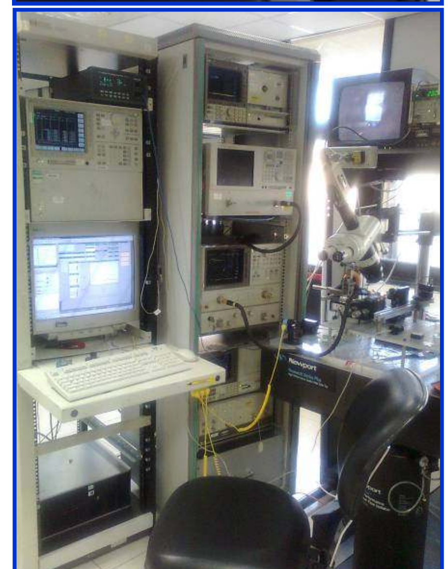
MOV001

Statistics of main parameters

How we did it……

(7) R&D lab characterizations (new products dev.)

- **Dedicated area (130m^2), large set of characterization techniques**
- **Measurement benches for:**
  - FP and DFB lasers; Multi-electrodes (EML, Tunable) lasers
- **Static measurements on tile (10 - 100 C) and Headers**
  - F/B LIV, spectrum, low current, rev. leakage, Far Field, ...
- **Dynamic characterization: "directly on chip" probing (10 - 100 C)**
  - Small signal S_{21}, S_{11}, parasitics and active dynamics up to 20 GHz
  - Large signal dynamic characterization:
    - Pattern generators at 1-12 Gb/s and 4-60 Gb/s (SHF); up to 32GFC complete eye diagram measurement set-up (including optical receiver)
    - Up to 12 Gb/s BERT test (200 km fiber)
- **…plus standard production testing / validation line**
  - LDI for screening, statistic and process debug purposes
  - Stress tests (BI/ESD/ALT) for reliability assessment and qualification



AVAGO TECHNOLOGIES

From R&D to production

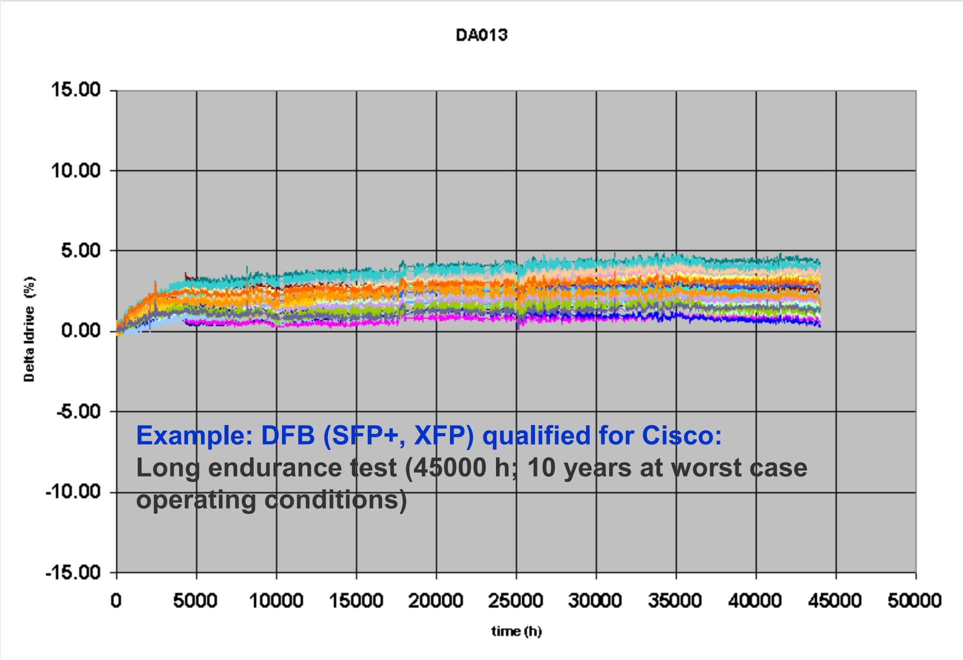
Developing a reliable technology….

- 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

DFB (SFP+, XFP) qualified for Cisco:
- many million devices* hours
- Long endurance test

Enormous investments…

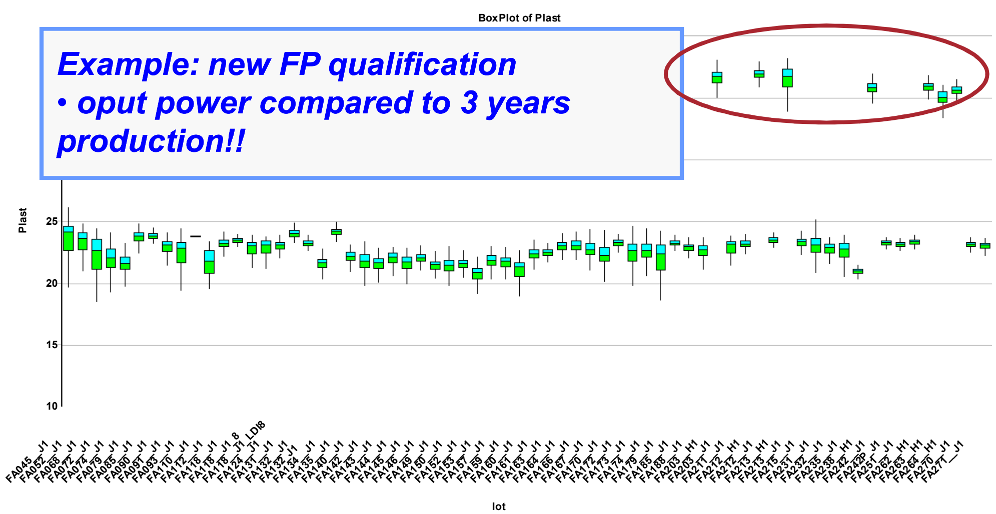


From R&D to production

Testing a production volume....

- **Testing is one of the most expensive part in the III-V production, which require 100% testing of laser chip!**
- **Only key team have testing capability suitable for mass-production (not for start up..)**

⇒ R&D design for Testing



R&D Avago VCSEL Tester: 1 sec/die

R&D Avago DFB Tester: 20 sec/die

The end!

Books

- Ramo Winnery Van Duzer, "Fields and waves in communication electronics", John Wiley.,
- G. Guekos, *Photonic Devices*, Springer, 1999, ISBN 3-540-64318-4
- L. A. Coldren, S. W. Corzine, "*Diode lasers and photonic integrated circuits*", John Wiley and sons, inc.,
- P. Vasil'ev, "U*ltrafast diode laser*", Artec House Boston-London
- K. Petermann, "Laser Diode Modulation" and Noise, Dordrecht, The Netherlands: Kluwer Academic Publishers

Application Notes

- Application Note 1550-6, HP
- Application Note 1287-1
- Network Analyzer Basics
- The Art of Measuring 40G Eye Patterns

Related published paper

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