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engineering

September 14, 2016

35 years of widely-tunable single-chip lasers: a pathway to active PICs

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UCSB

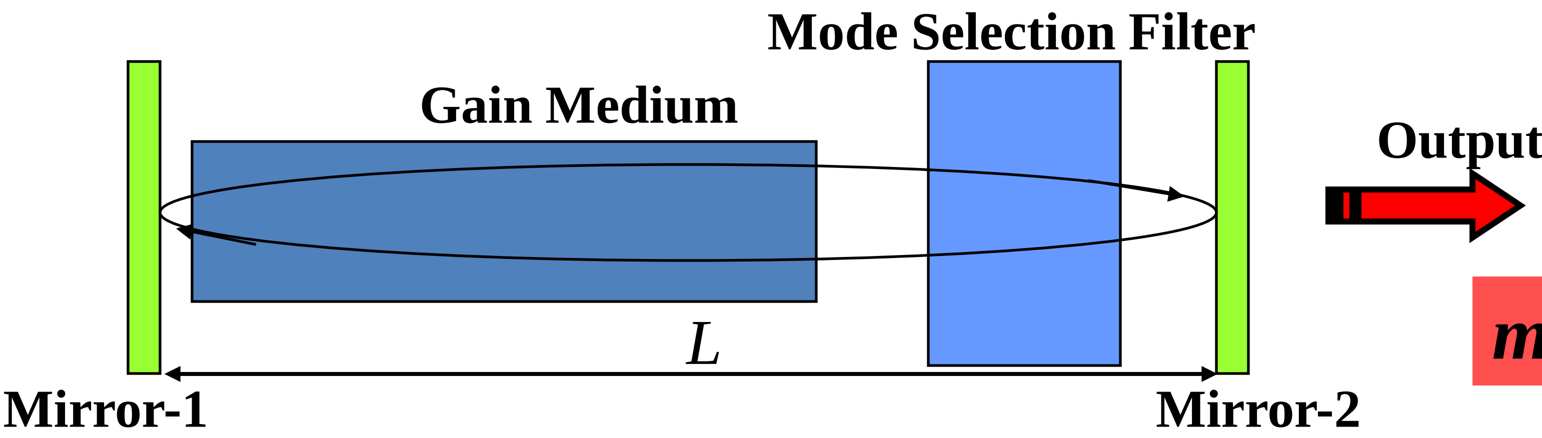
The convergence of research and innovation.

Outline

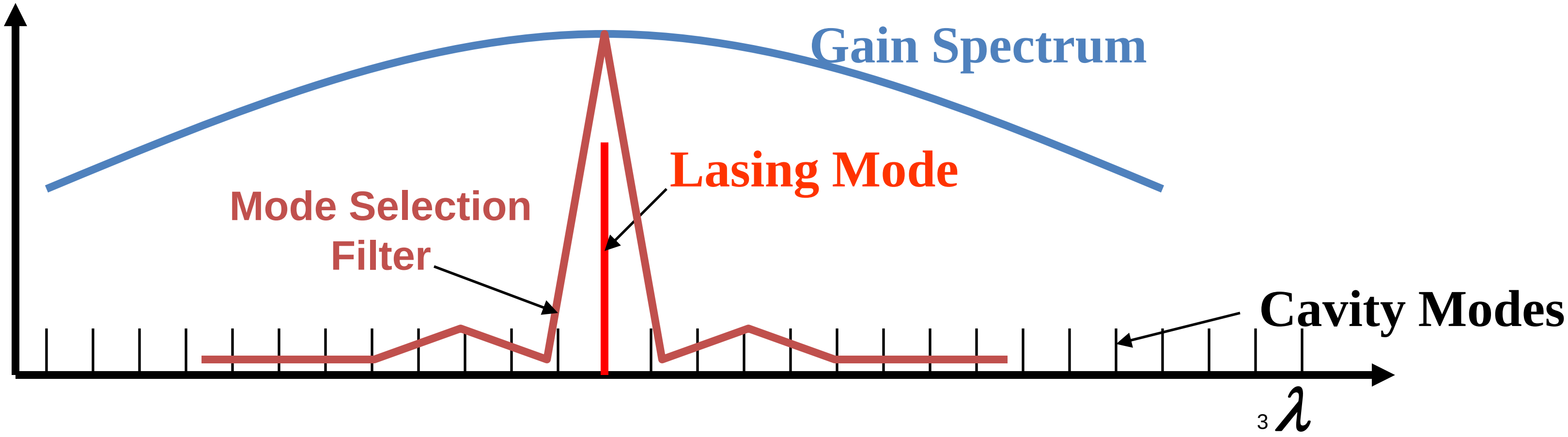
- Early tunable laser results
  - vernier-tuned coupled-cavity lasers
  - DBRs
  - SGDBRs (vernier-tuned DBRs)
- Other widely-tunable laser designs
- Recent advances
- Photonic ICs developed from (and including) tunable laser technology
- Heterogeneous Integration

Single-frequency laser

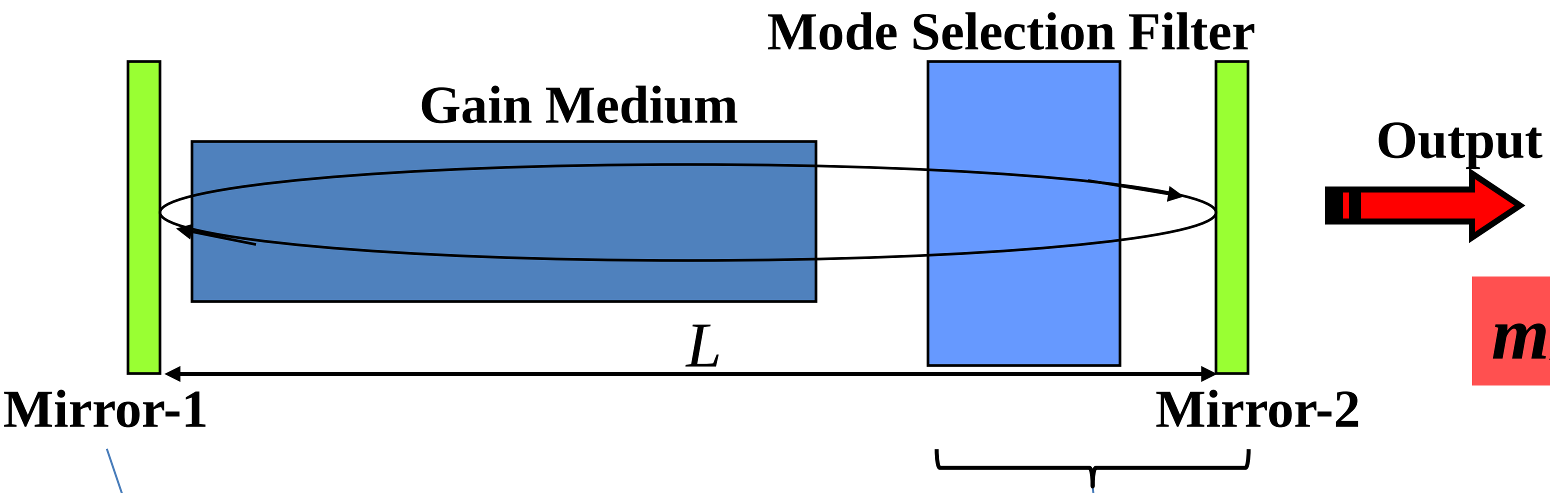
- Change *m*, *n* or *L* to tune λ



$$m\lambda/2 = \bar{n}L$$



Distributed Bragg Reflector Laser



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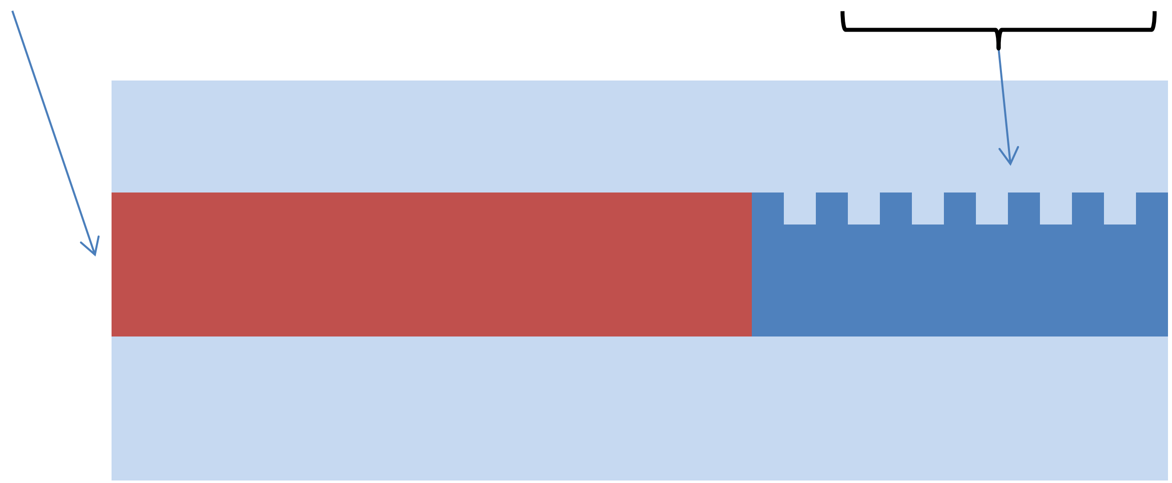
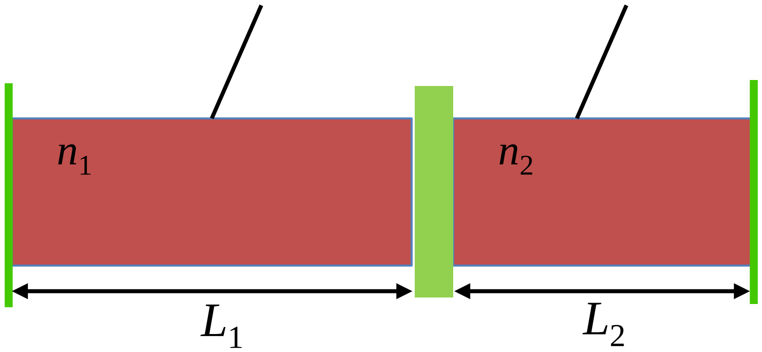
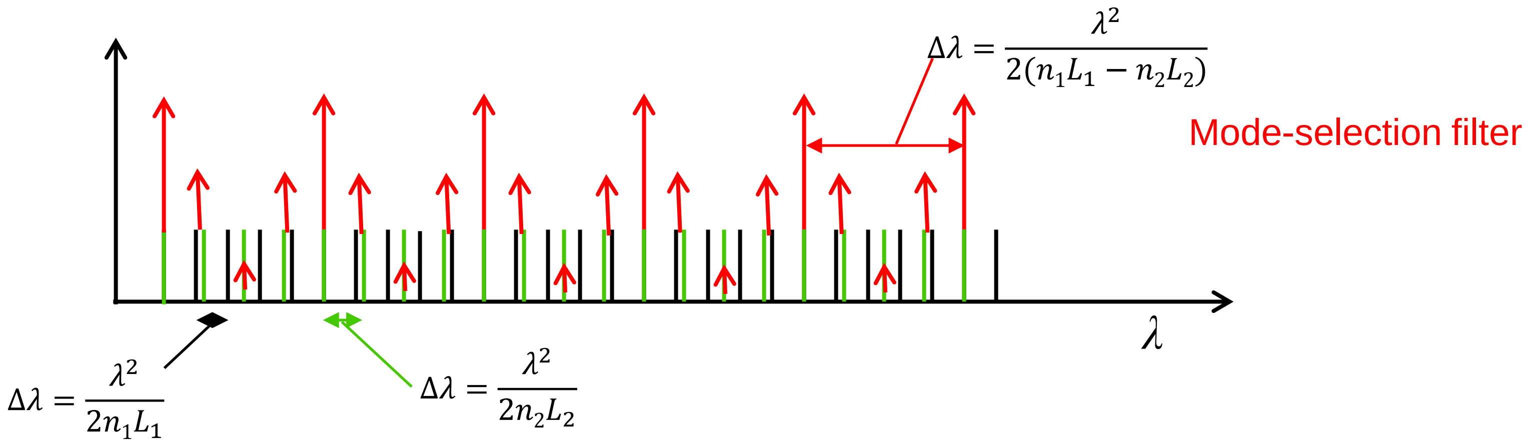


Coupled-Cavity Vernier Tuning

- Tune n_1 or n_2 to tune wavelength location of reinforced modes
- Also possible with coupled ring cavities
- Can provide enhanced AM or FM capability (ISLC ‘84)

Next: Combine vernier tuning with DBR mode selection and continuous tuning?



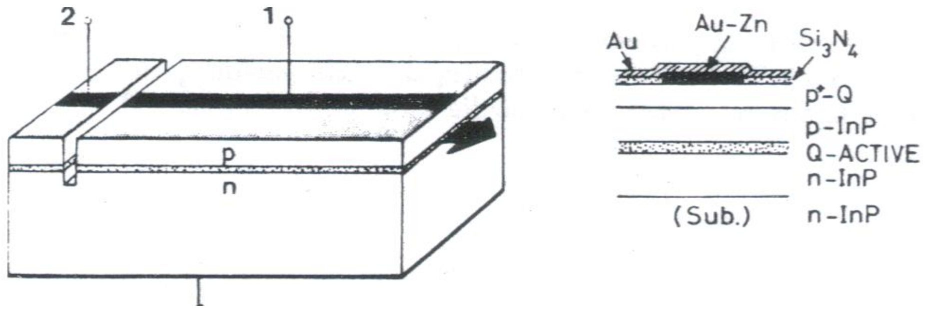


Early tunable, single-frequency diode lasers

- Coupling mirrors between integrated active and passive sections

First integrated InP (laser – X) devices

→ Etched grooves
- Tunable single frequency
- Laser-modulator
- Laser-detector



L.A. Coldren, B.I. Miller, K. Iga, and J.A. Rentschler, "Monolithic two-section GaInAsP/InP active-optical-resonator devices formed by RIE," *Appl. Phys. Letts*., 38 (5) 315-7 (March, 1981).

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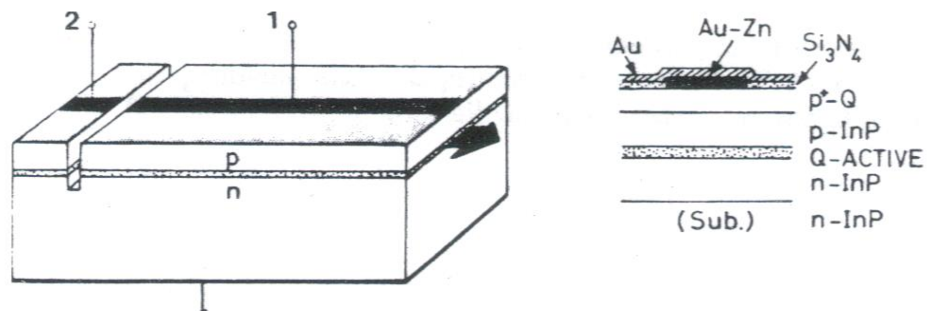
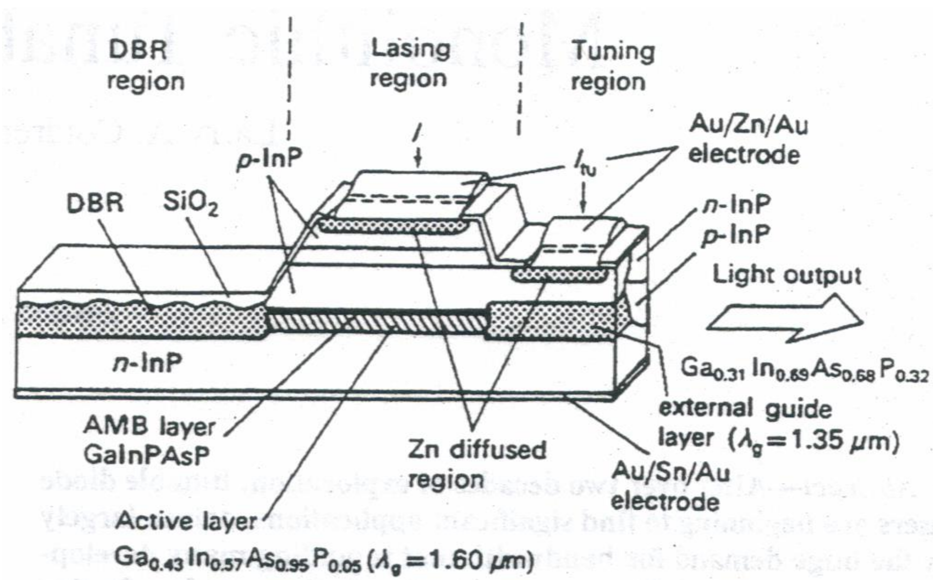


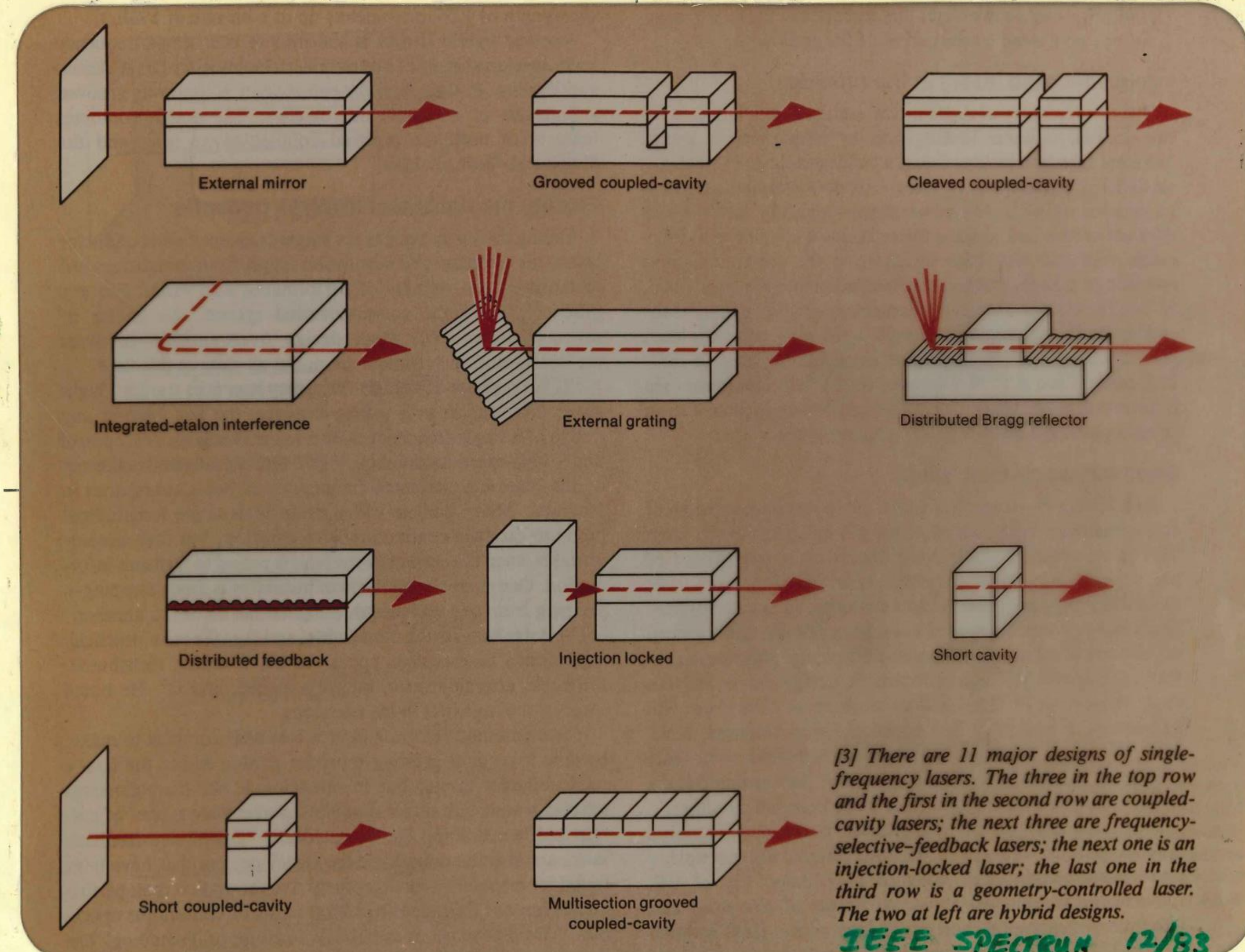
→ DBR gratings and vertical couplers
- Tunable single frequency
- Combined integration technologies

Y. Tohmori, Y. Suematsu, Y. Tushima, and S. Arai, "Wavelength tuning of GaInAsP/InP integrated laser with butt-jointed built-in DBR," *Electron. Lett*., 19 (17) 656-7 (1983).



Single-Frequency and Tunable Lasers; Circa 1983

TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE
VG. NO.



[3] There are 11 major designs of single-frequency lasers. The three in the top row and the first in the second row are coupled-cavity lasers; the next three are frequency-selective-feedback lasers; the next one is an injection-locked laser; the last one in the third row is a geometry-controlled laser. The two at left are hybrid designs.

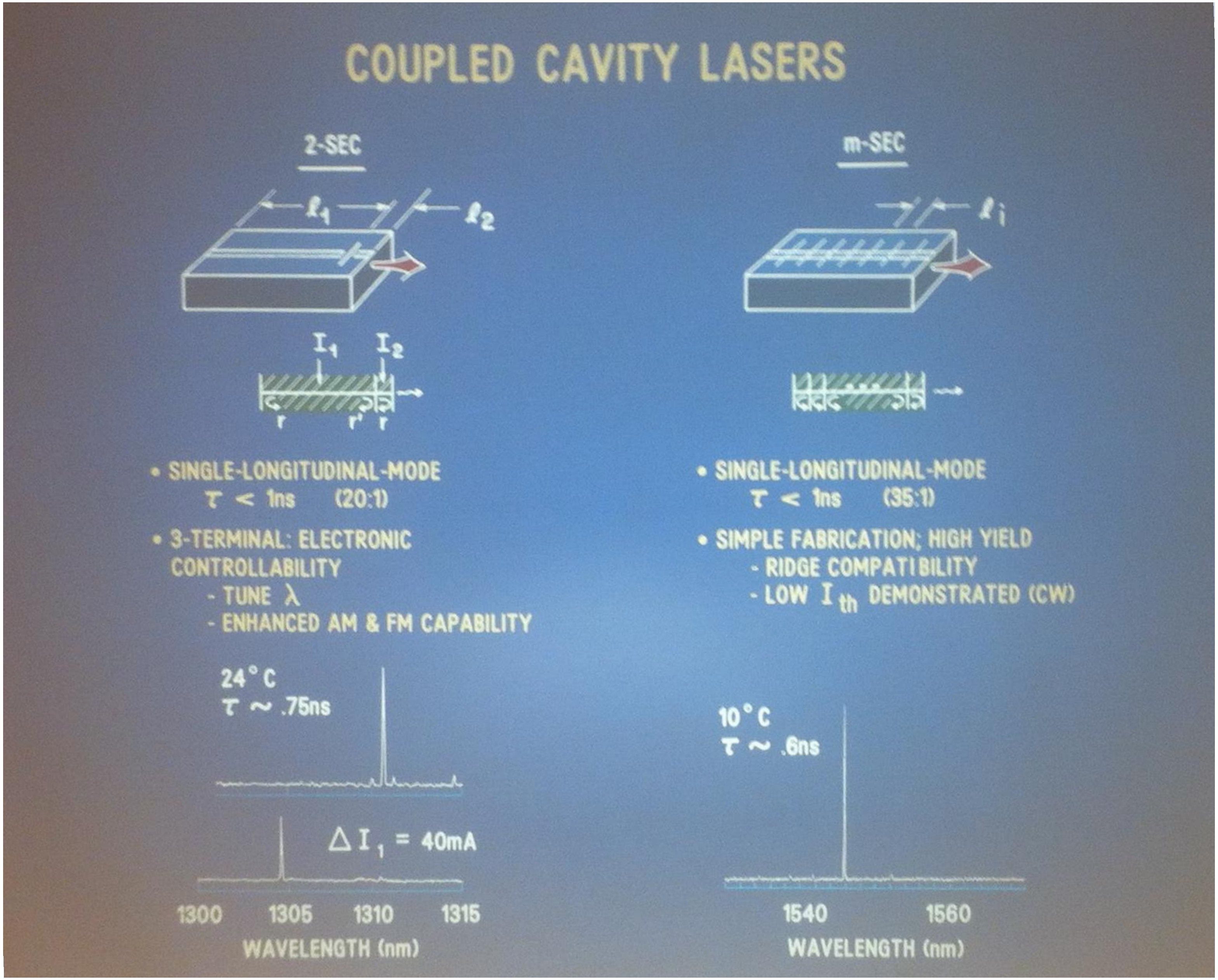
IEEE SPECTRUM 12/83

T..Bell, “Single-frequency semiconductor lasers,” *IEEE Spectrum*, vol 20, 1983

E-9148 (5-78)

Bell Laboratories

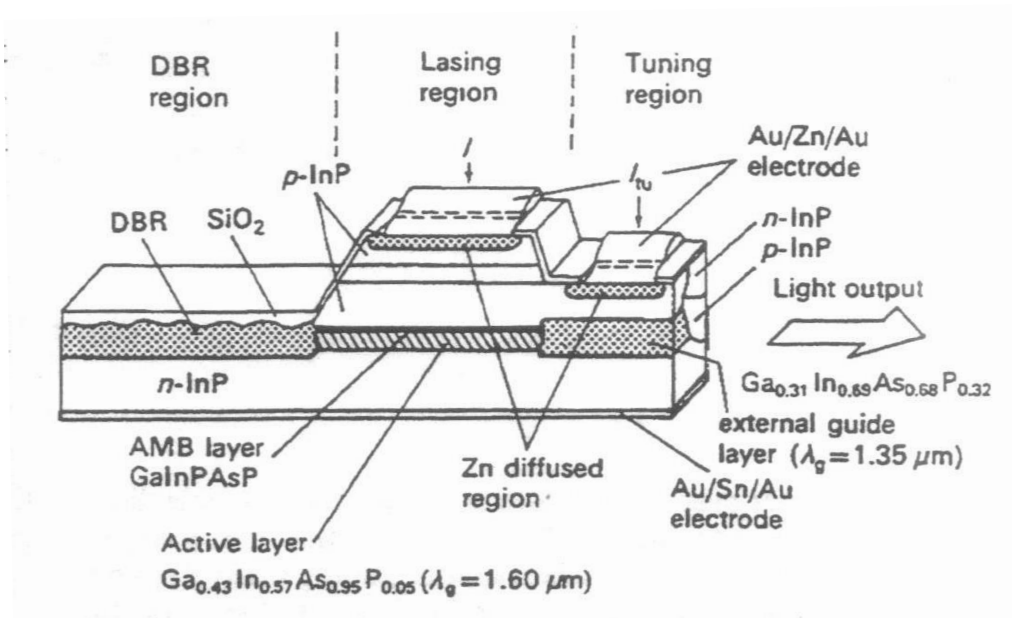
Vernier Tuning Concept in Coupled-Cavity Lasers



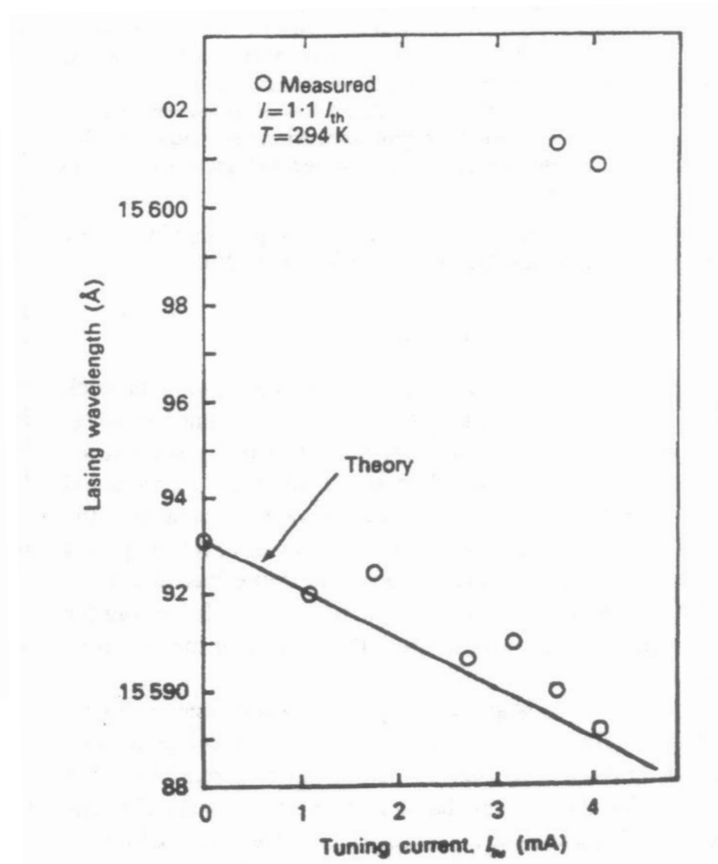
Coldren, Miller, Iga, and Rentschler, *APL*, **38** (Mar, '81); Ebeling, Coldren, Miller, Rentschler, *Electron., Lett.*, **18** ('82)

Early Tunable DBR Work

Pioneering Active-Passive interfaces

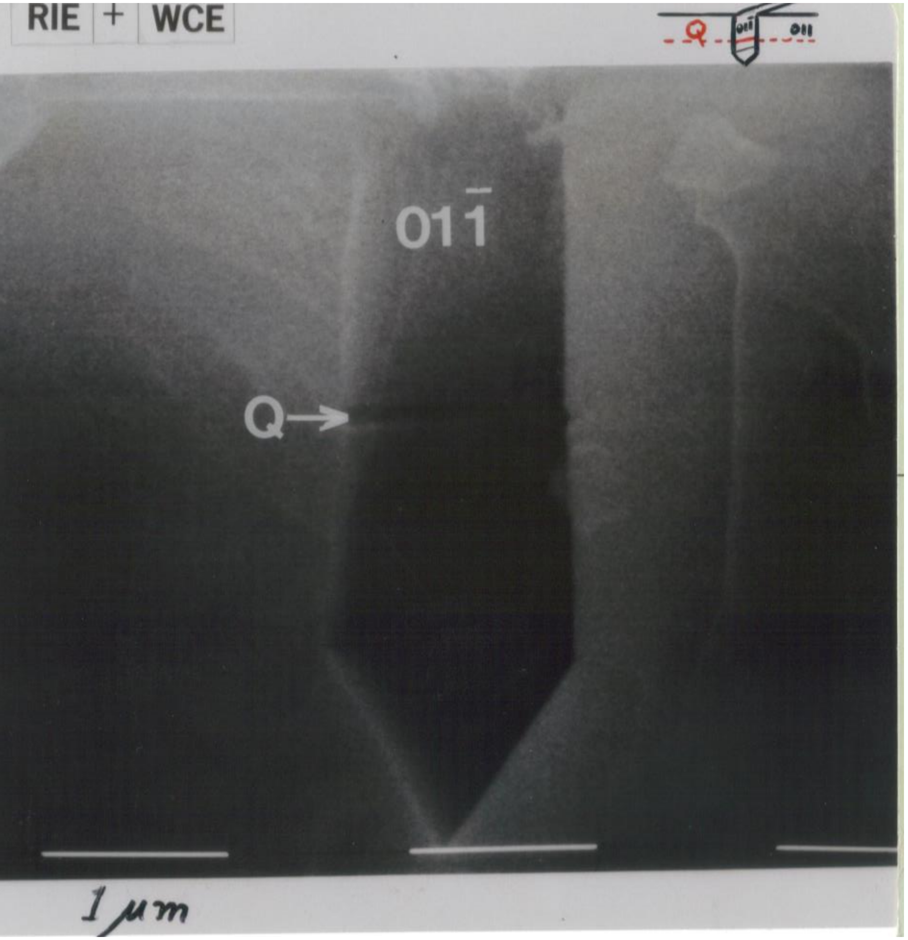


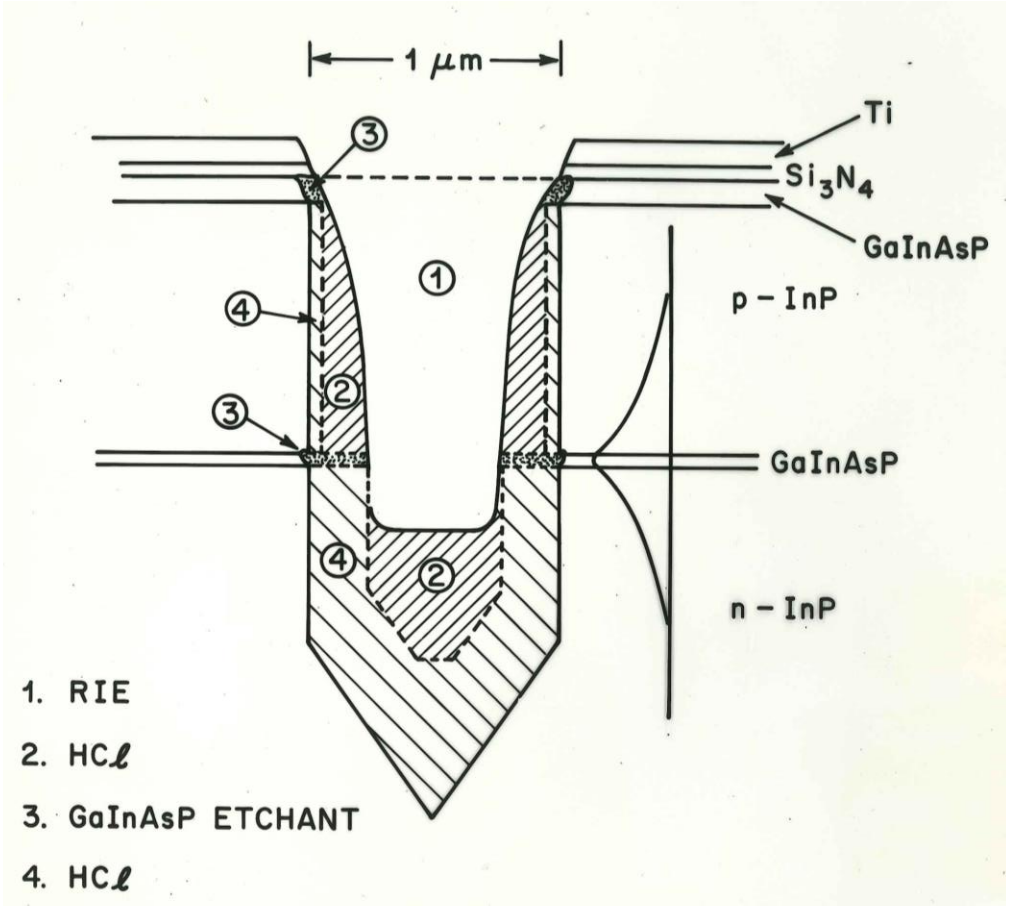
(a)



Tohmori, Suematsu, Tushima, and Arai, TIT, 1983

No-Regrowth Groove Etch: RIE/HCl/Q-etch/HCl

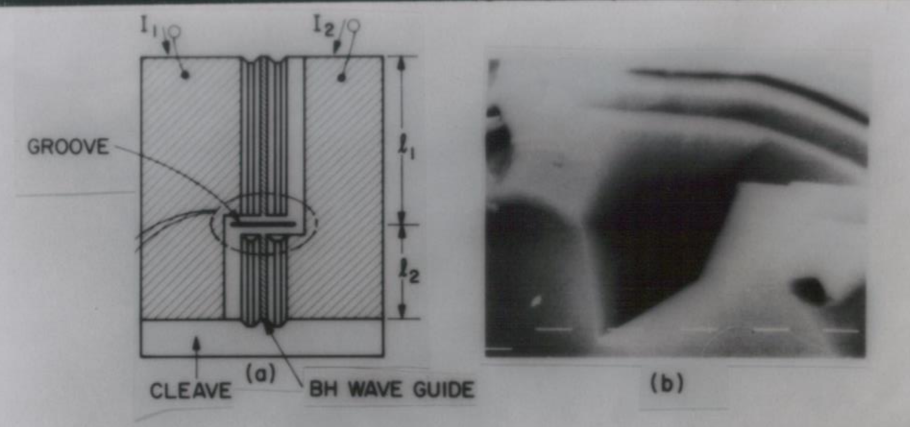




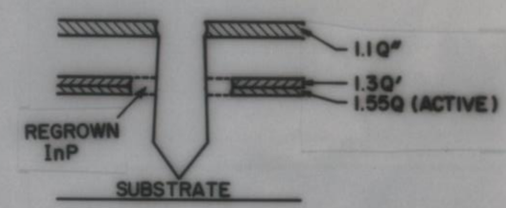
Coldren, Furuya, Miller and Rentschler, *JQE*,**18** ('82)

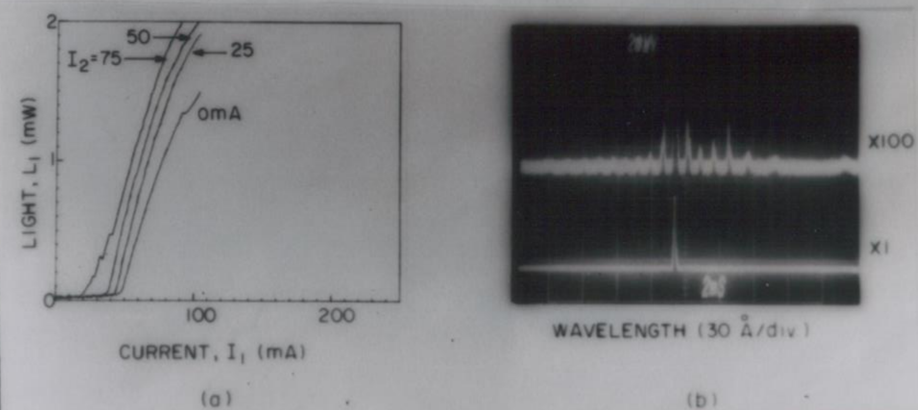
Two-Section Coupled-Cavity Etched-Groove Tunable Laser

ISLC ’84, with T. Koch



RIE etch, Regrow InP, HCl etch

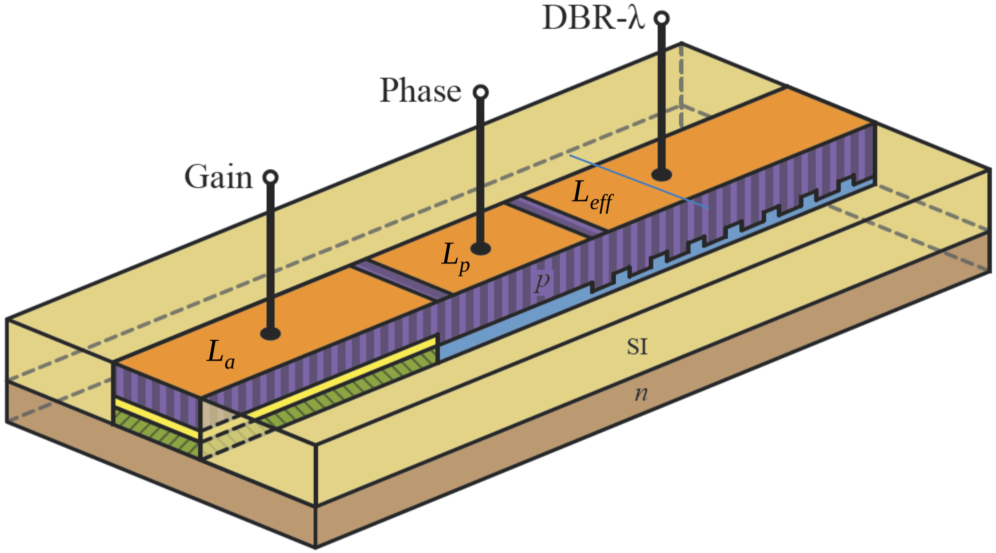




Bell Laboratories

Tunable DBR Lasers (mid-late 1980's)

- Tune cavity modes and selection filter separately (or together)



- The center wavelength of grating, λ_g, will tune in direct proportion to the index change Δn_{DBR}; however this will also tune the mode slightly as well, due to the penetration, L_{eff}.
- Tuning the Phase section electrode will tune only the mode location, λ_m, (tune together with DBR for wide continuous tuning: *JQE* **23** (6) 903, June, 1987)
- There also may be some slight active region index change (due to loss changes)

$$\frac{\Delta\lambda_g}{\lambda_g} = \frac{\Delta\bar{n}_{DBR}}{\bar{n}_{DBR}}. \qquad \frac{\Delta\lambda_m}{\lambda_m} = \frac{\Delta\bar{n}_a L_a + \Delta\bar{n}_p L_p + \Delta\bar{n}_{DBR} L_{eff}}{\bar{n}_{ga} L_a + \bar{n}_{gp} L_p + \bar{n}_{gDBR} L_{eff}}.$$

Multi-element Mirror 4-Section Tunable Laser

- Combine vernier with DBR

United States Patent [19]
Coldren

[11] **Patent Number: 4,896,325**
[45] **Date of Patent: Jan. 23, 1990**

[54] **MULTI-SECTION TUNABLE LASER WITH DIFFERING MULTI-ELEMENT MIRRORS**

[75] Inventor: **Larry A. Coldren,** Santa Barbara, Calif.

[73] Assignee: **The Regents of the University of California,** Berkeley, Calif.

[21] Appl. No.: **235,307**

[22] Filed: **Aug. 23, 1988**

[51] **Int. Cl.**[4] **H01S 3/10**
[52] **U.S. Cl.** **372/20;** 372/99; 372/102; 372/38; 372/31; 372/29
[58] **Field of Search** 372/101, 20, 92, 99, 372/102, 29, 32, 38

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,358,851 11/1982 Scifres et al. 372/6
4,504,950 3/1985 Au Yeung 373/101

OTHER PUBLICATIONS

Akiba et al.; "Self-Focusing Lens as Resonator enables 10 GHz Modulation"; Fiberoptic Technology Oct. 1981, p. 124.

Primary Examiner—Leon Scott, Jr.
Attorney, Agent, or Firm—Donald A. Streck

[57] **ABSTRACT**

An improvement for allowing selective tuning of the emitted beam over a broad bandwidth to a diode laser having an active section for creating a light beam by spontaneous emission over a bandwidth around some center frequency and for guiding and reflecting the light beam between a pair of mirrors bounding the active on respective ends thereof to create an emitted beam of laser light. The mirrors each have narrow, spaced reflective maxima with the spacing of the reflective maxima of respective ones of the mirrors being different whereby only one the reflective maxima of each of the mirrors can be in correspondence and thereby provide a low loss window at any time. The preferred mirrors each include a plurality of discontinuities to cause the narrow, spaced reflective maxima wherein the spacing of the discontinuities of one mirror is different from the spacing of the discontinuities of the other mirror so as to cause the wavelength spacing of the maxima to be different. Additionally, the preferred embodiment includes a vernier circuit operably connected to the mirrors for providing an electrical signal to the mirrors which will cause continuous tuning within a desired frequency band, an offset control circuit operably connected to the mirrors for providing a voltage signal to the mirrors which will shift the reflective maxima of the mirrors into alignment at a desired frequency mode, and a phase control circuit for adjusting the laser mode wavelength to be in correspondence with the low loss window.

27 Claims, 3 Drawing Sheets

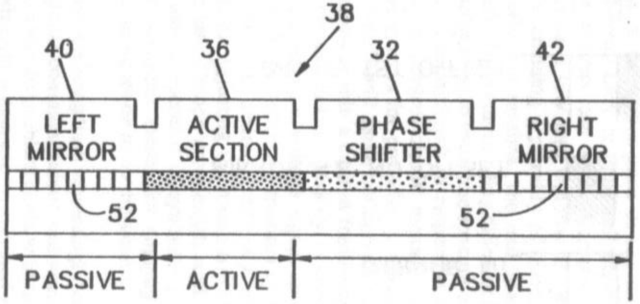


FIG. 5

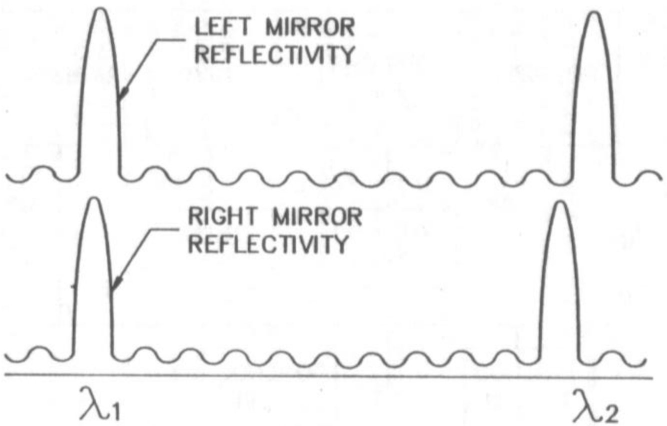


FIG. 7

Multi-element Mirror 4-Section Tunable Laser

United States Patent [19] — Coldren

[11] Patent Number: 4,896,325

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[58] Field of Search 372/101, 20, 92, 99, 372/102, 29, 32, 38

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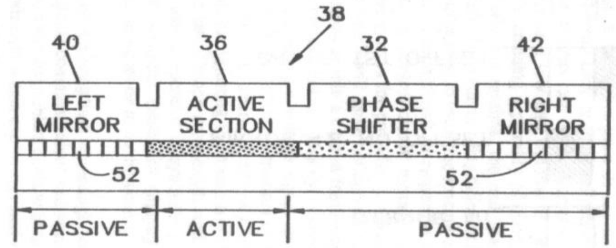


FIG. 5

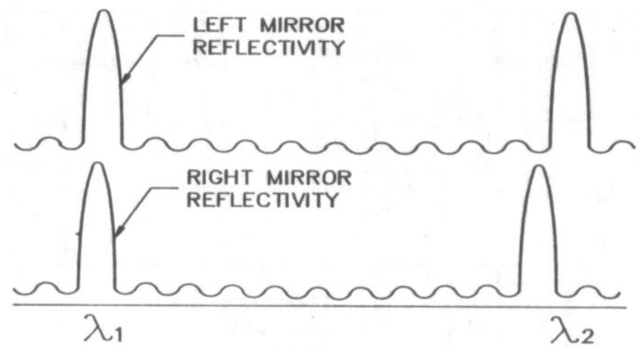
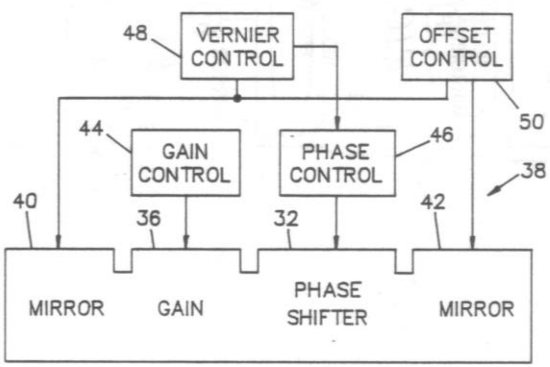


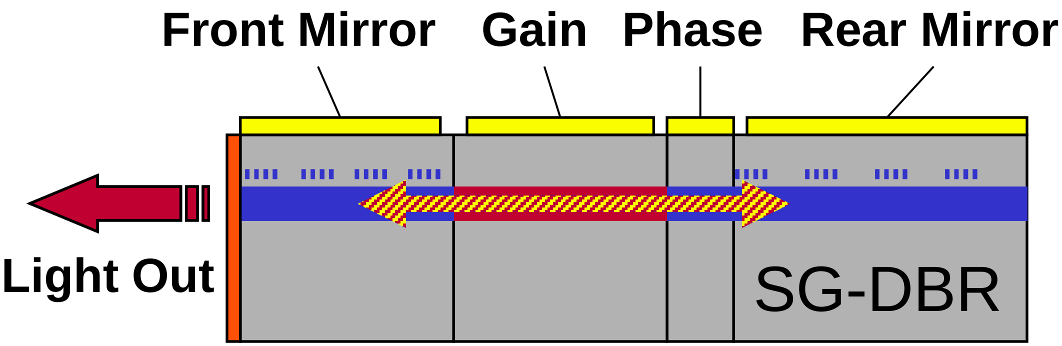
FIG. 7

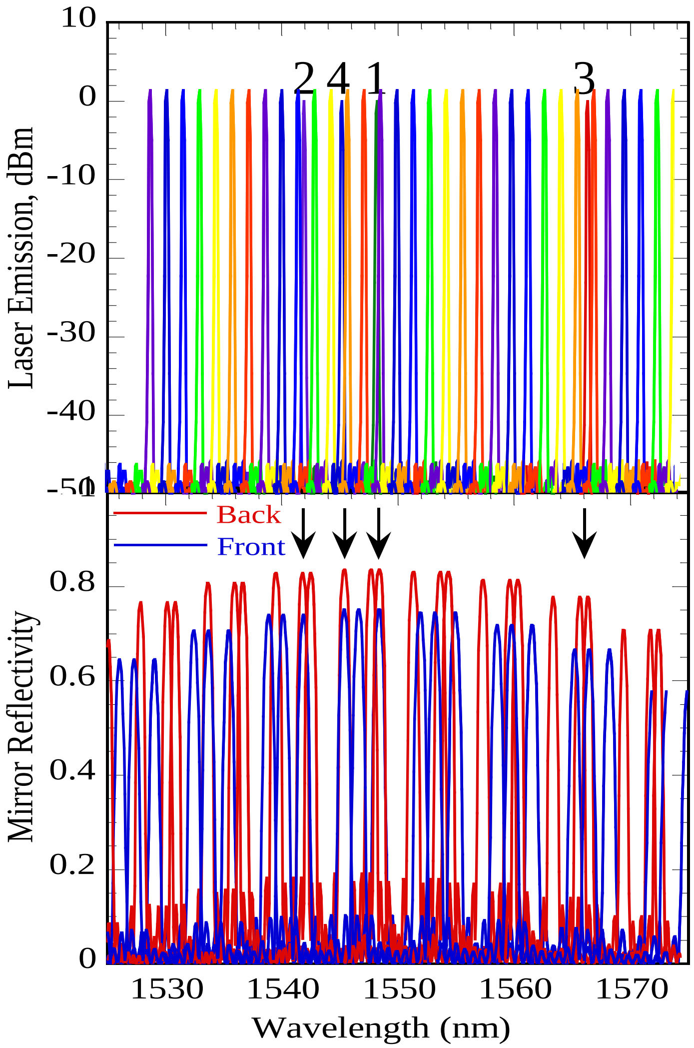


DESCRIPTION OF THE PREFERRED EMBODIMENT

The novel four section tunable laser of the present invention is shown in simplified form in FIG. **5** where it is generally indicated as **38**. By combining discrete mode-jump tuning with continuous tuning, it will be seen that this design allows the relative tuning range to be extended by at least an order of magnitude larger than $\Delta n/n$. To achieve the objectives, two multi-element mirrors **40**, **42** are employed, one at each end of the laser **38**. The gain section **36** and phase shifter section **32** are as described above with respect to the three-section laser of FIG. **3**, of which this is an improvement.

Sampled-Grating DBR Tunable Lasers

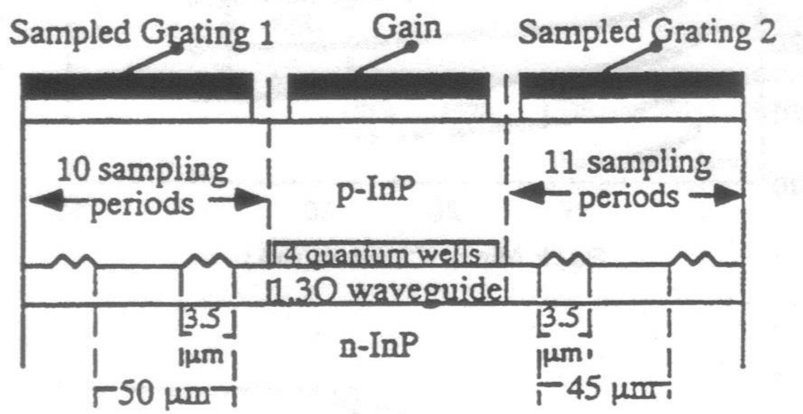


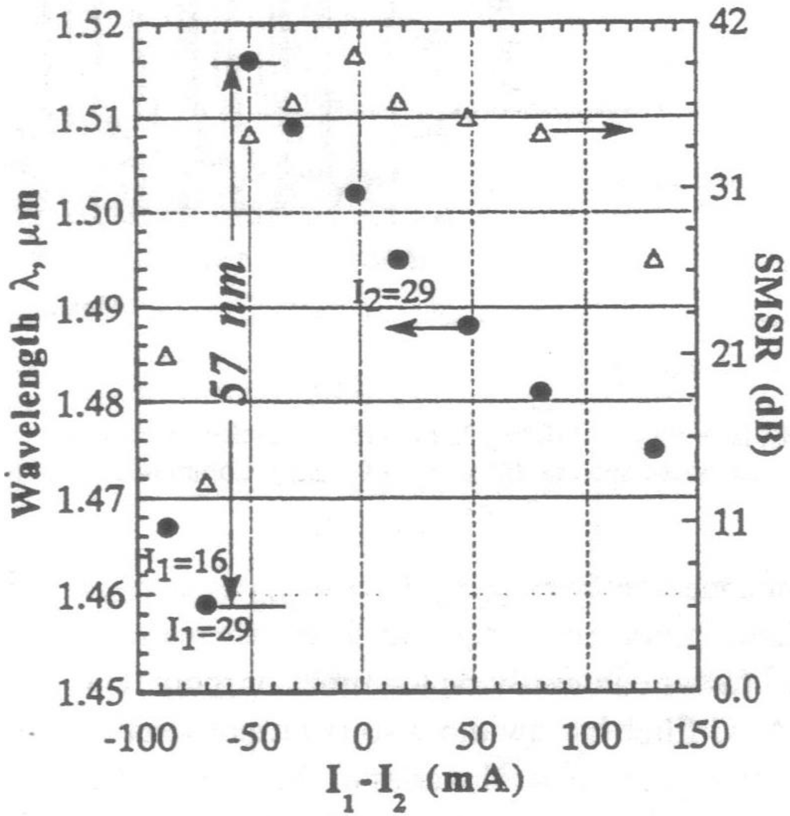


- 5-10X Tuning Range of DBR
- Reliable, Manufacturable InP Technology
- Can Cover C band, L band or C + L
- Easily Integrates Monolithically with Other Components (e.g. EAM, SOA)

Sampled-Grating DBR Tunable Laser

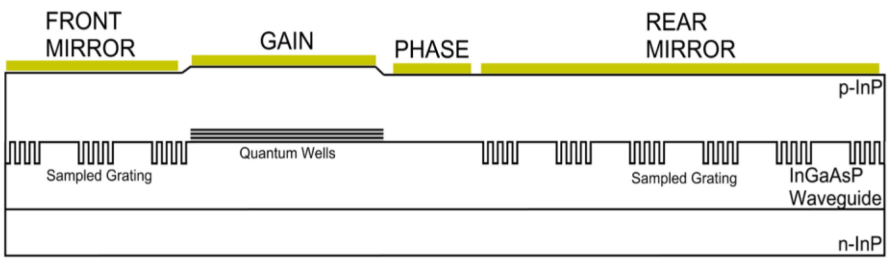
- **Initial results**
- **3 sections—vernier tuning**

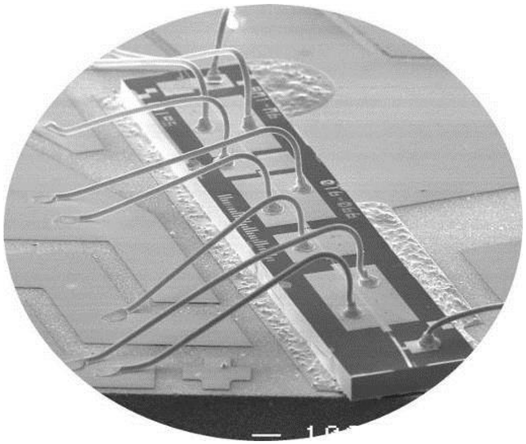




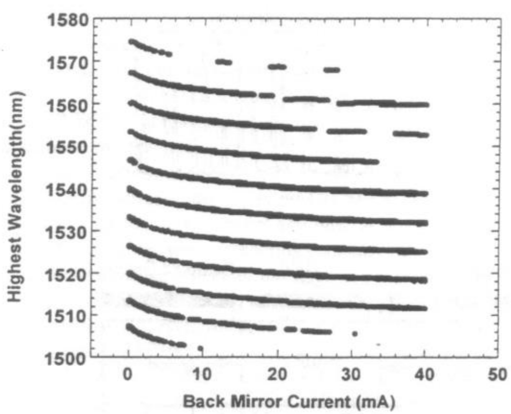
V. Jayaraman, A. Mathur, L.A. Coldren and P.D. Dapkus, ISLC 1992

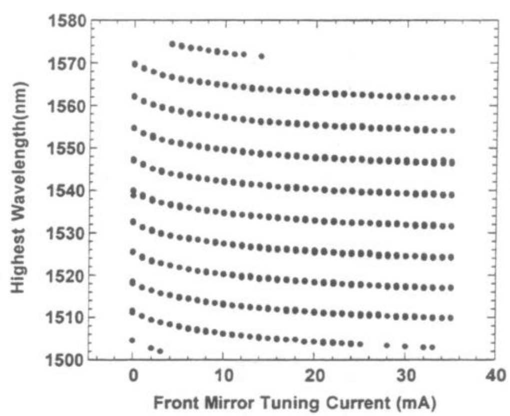
SGDBR wide-tuning, high-power, high-reliability



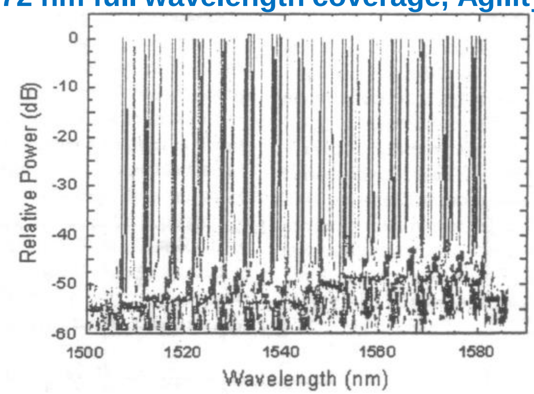


Agility Communications formed to Commercialize in 1998.

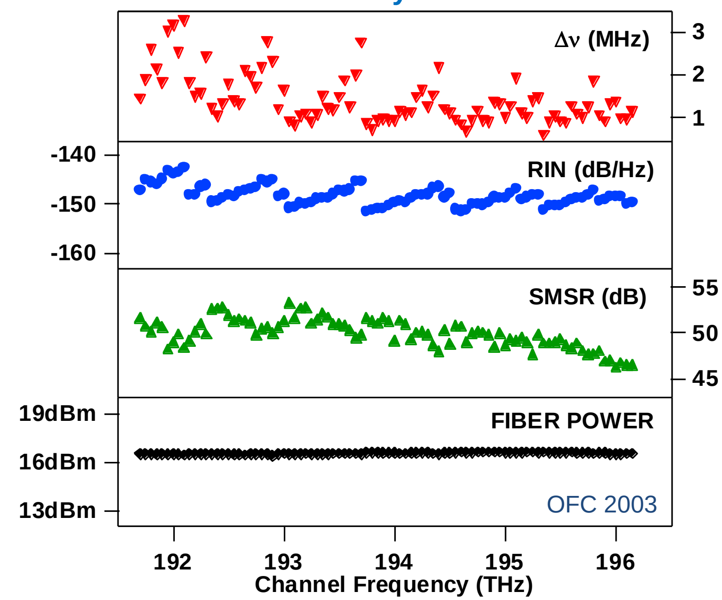




72 nm full wavelength coverage, Agility, 2001.



> 300 yr MTTF

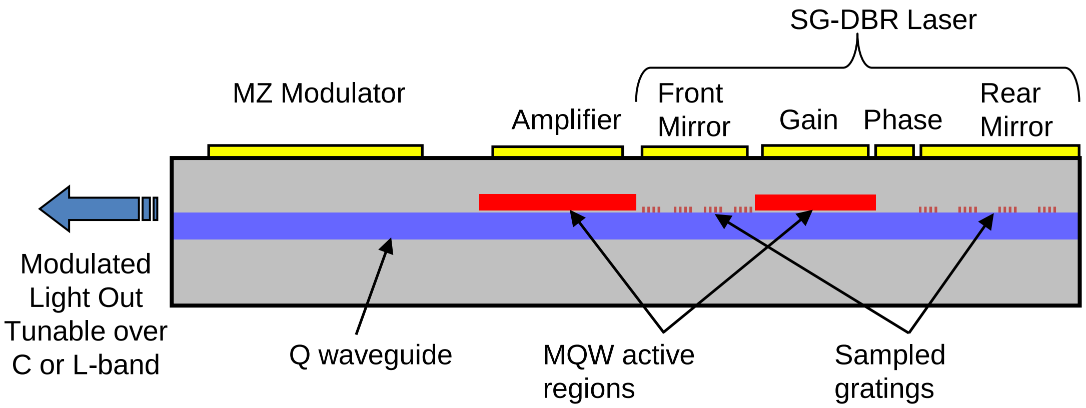


Sampled-Grating DBR: Monolithic and Integrable

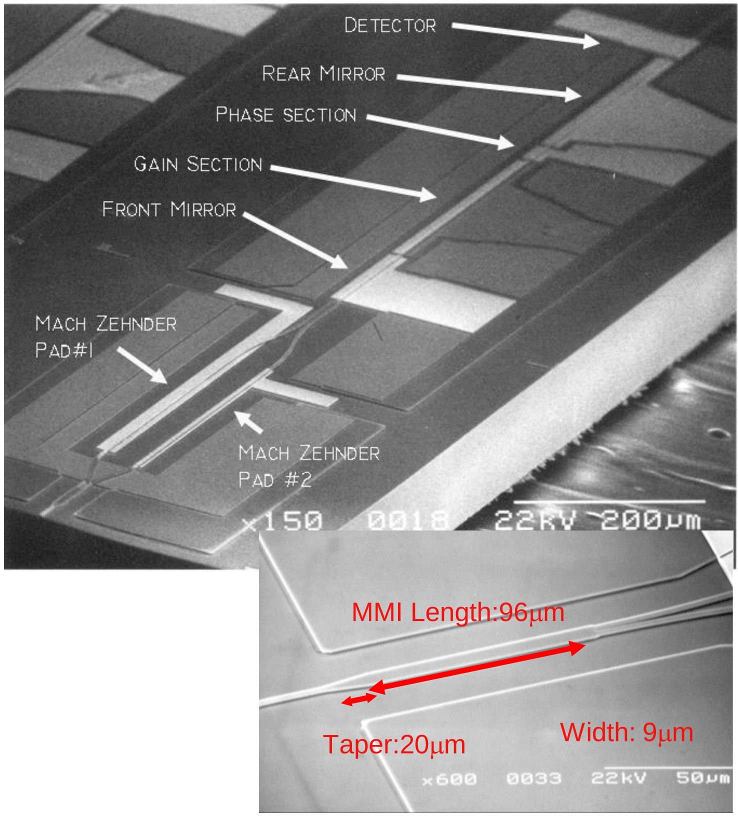
SGDBR+X widely-tunable transmitter:

- Foundation of PIC work at UCSB

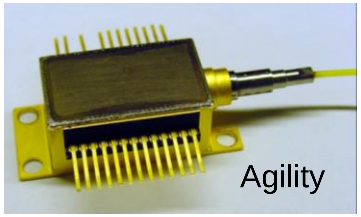
UCSB'90-- → Agility'99-'05 → JDSU'05→



6 section InP chip



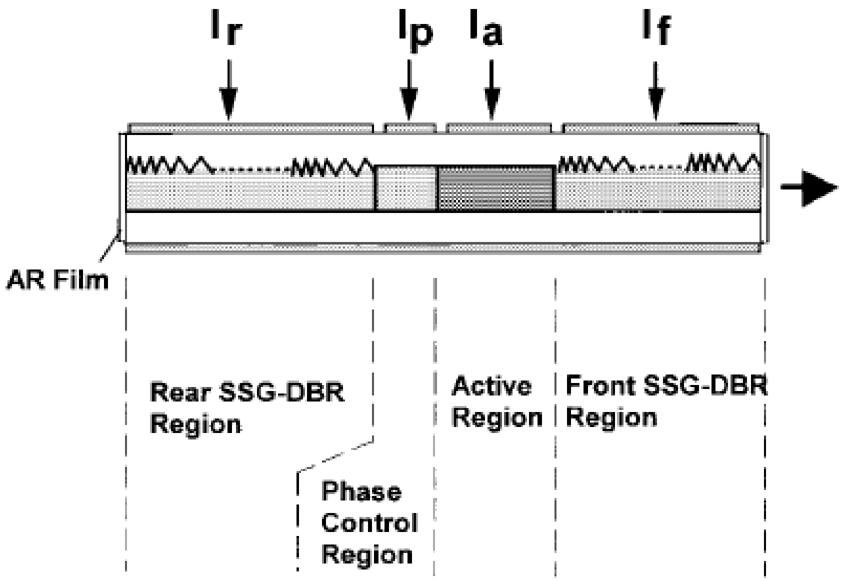
- Vernier tuning over 40+nm near 1550nm
- SOA external to cavity provides power control
- Currently used in many new DWDM systems (variations)
- Highly reliable— < 10% of SGDBR is grating
- Integration technology for much more complex PICs

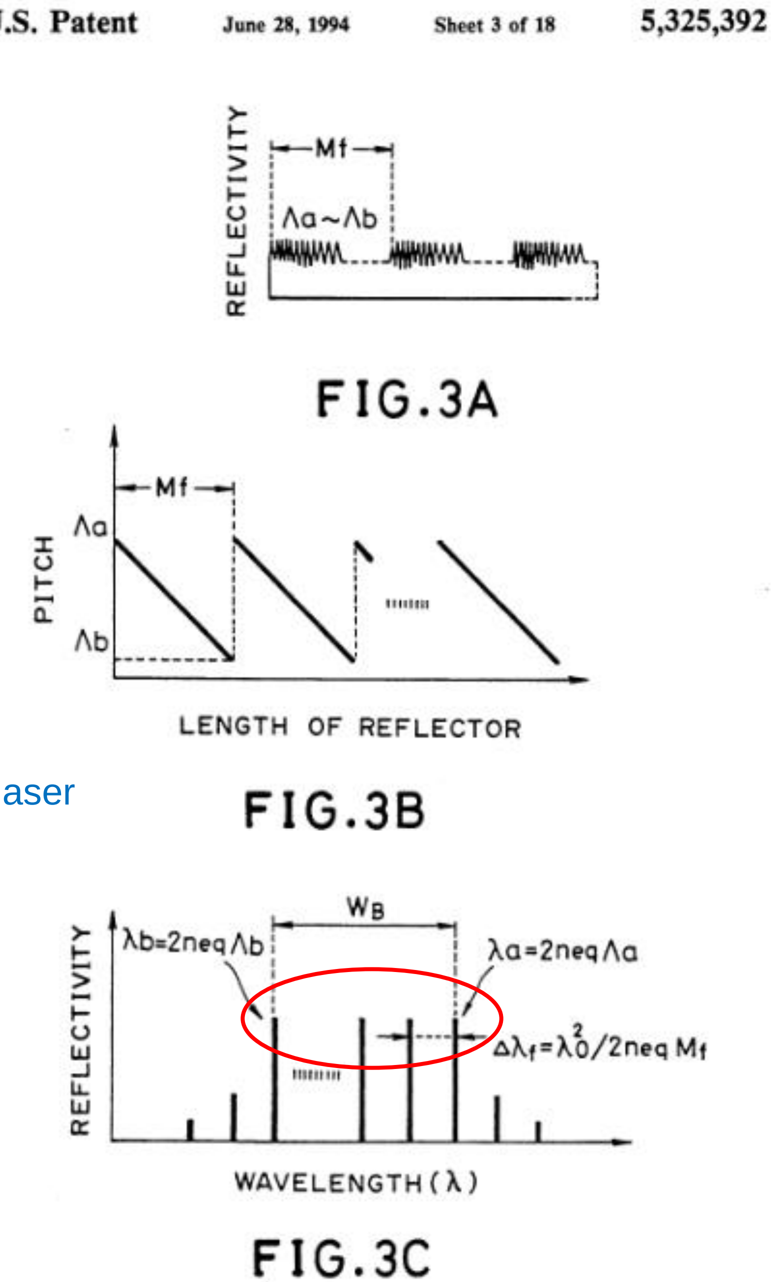


JDSU-ILMZ TOSA (~ 18mm)

J. S. Barton, et al, *ISLC,* TuB3, Garmish, (Sept, 2002)

Super-structure grating DBR laser





Distributed reflector and wavelength-tunable semiconductor laser

Tohmori, Yoshikuni, Ishii, Kano, Tamamura

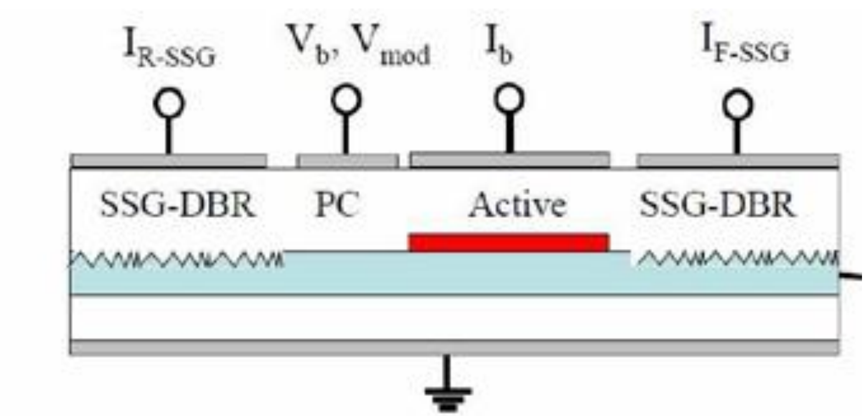
--filed 3/3/1993

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 32, NO. 3, MARCH 1996

Quasicontinuous Wavelength Tuning in Super-Structure-Grating (SSG) DBR Lasers

Hiroyuki Ishii, Hiromasa Tanobe, Fumiyoshi Kano, *Member, IEEE*, Yuichi Tohmori, *Member, IEEE*, Yasuhiro Kondo, *Member, IEEE*, and Yuzo Yoshikuni, *Member, IEEE*

NTT-NEL



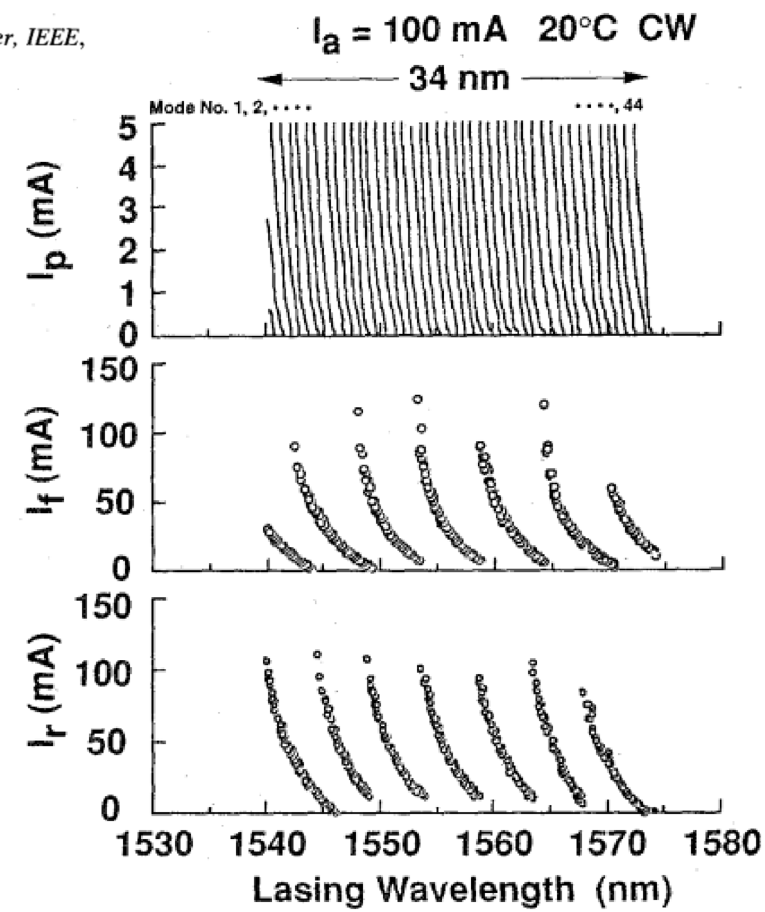
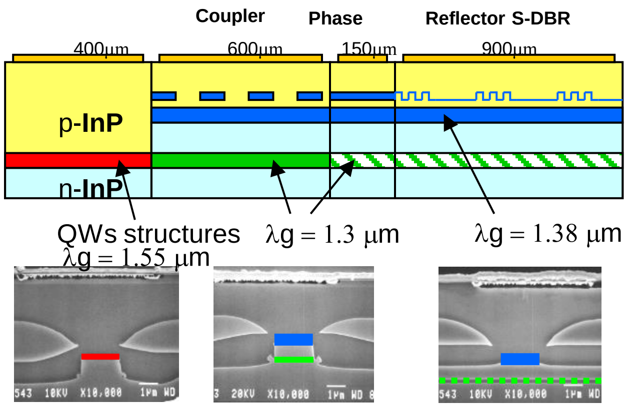


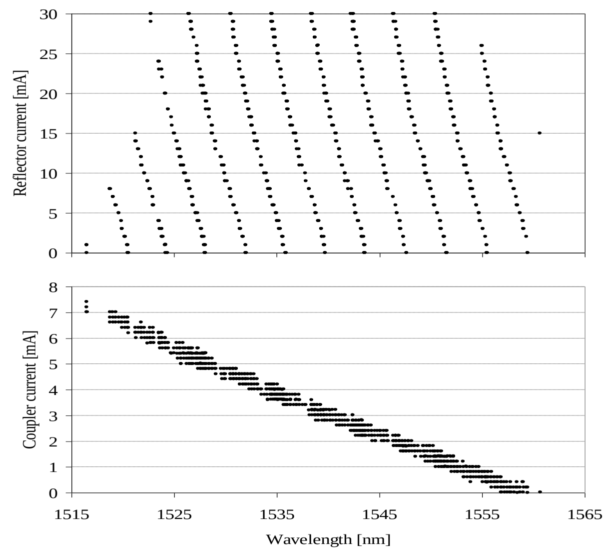
Fig. 12. Quasicontinuous wavelength tuning characteristics with three-tuning-current control.

Many other widely-tunables from 1993 onward

GCSR--ADC-Altitun

SGDBR + GACC





- **Vertical coupler filter (wideband)**
- **+ SGDBR or SSGDBR (narrow)**

Modulated Grating Y-Branch (MG-Y) Laser

Syntune-Finisar

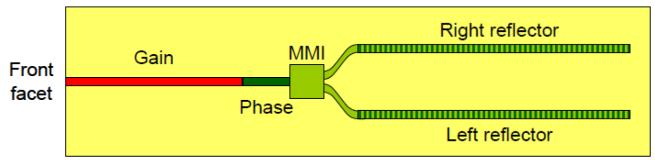
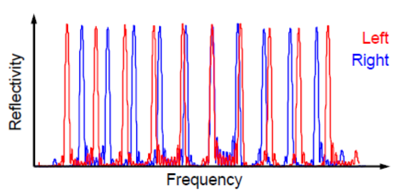
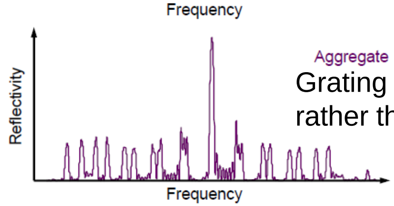


Fig. 3 Schematic top view of the modulated grating Y-branch (MG-Y) laser





Grating reflections add rather than multiply

Bookham-Oclaro

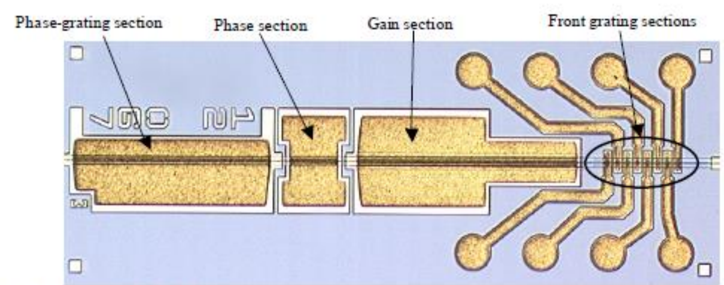
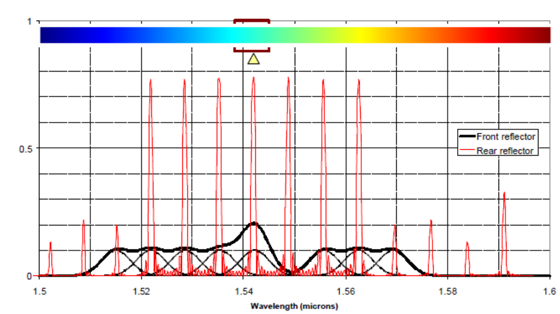


Figure 3.2: Top view of a DS-DBR laser chip.

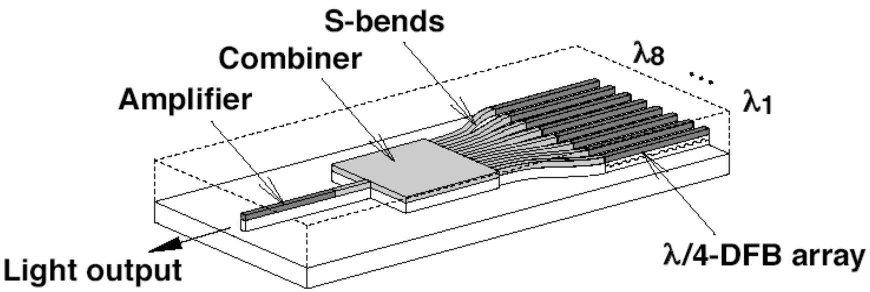


Wavelength selectable "widely-tunables"

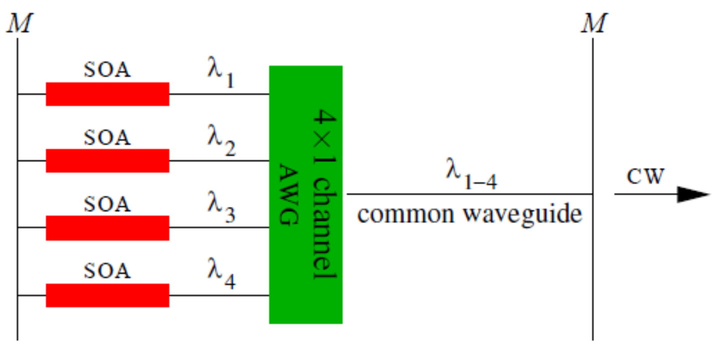
Fujitsu Laboratories Ltd.

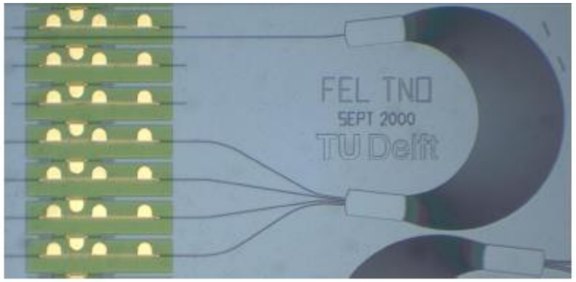
Monolithic Integration of

- **Multi-wavelength DFB laser array**
- **Passive optical combiner**
- **Semiconductor optical amplifier**

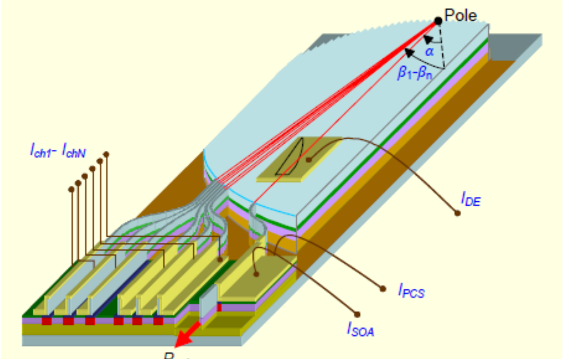


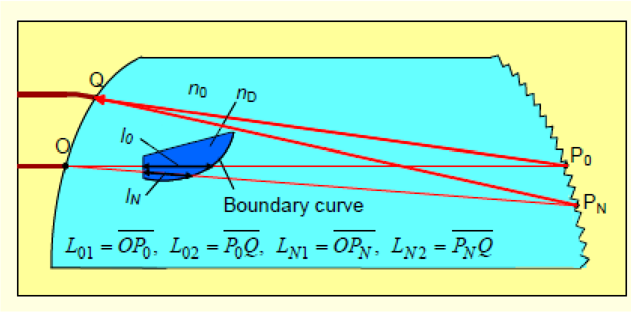
Select wavelength by selecting which SOA to turn on

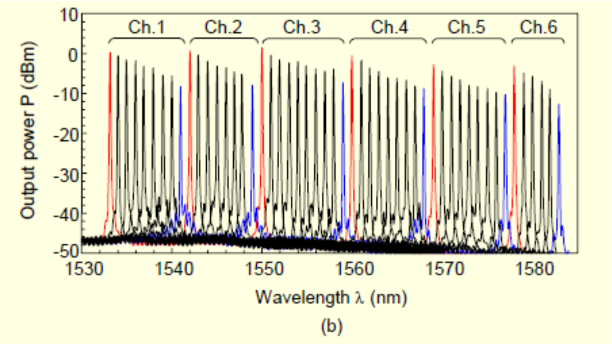




Eschelle Grating Laser

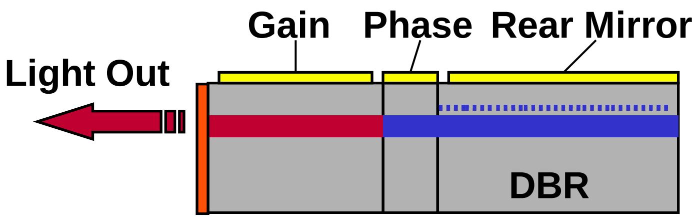




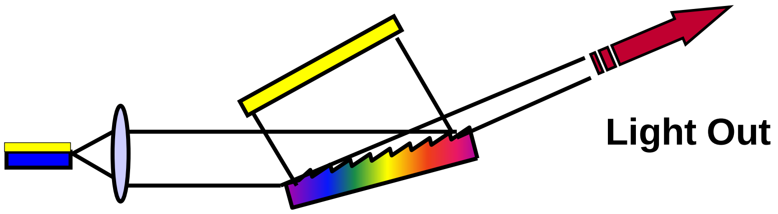


Solutions for Tunable Lasers (summary ~2005)

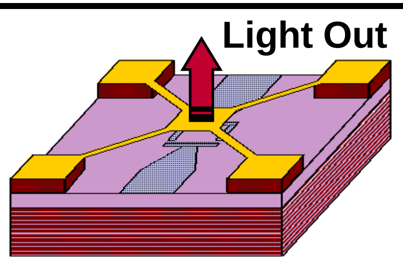
- **DBR Lasers**
  - Conventional DBR (<8 nm) [mid '80s]
  - Extended Tuning DBR's (≥ 32 nm) [early '90s]



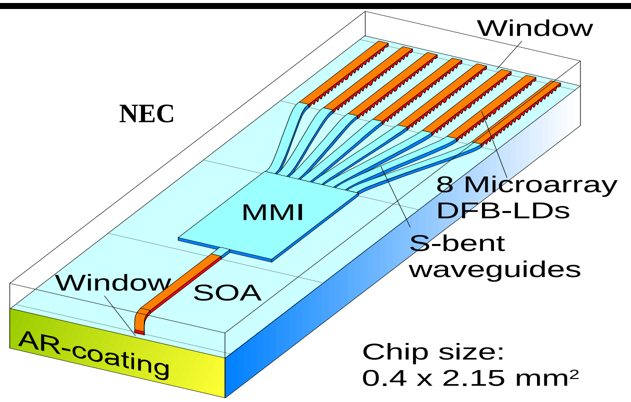
- **External Cavity Lasers (≥ 32 nm)**
  - Littman-Metcalf/MEMs [late '90s]
  - Thermally tuned etalon



- **MEMS Tunable VCSEL (~ 32 nm)**
  - Optically or electrically pumped [late '90s]

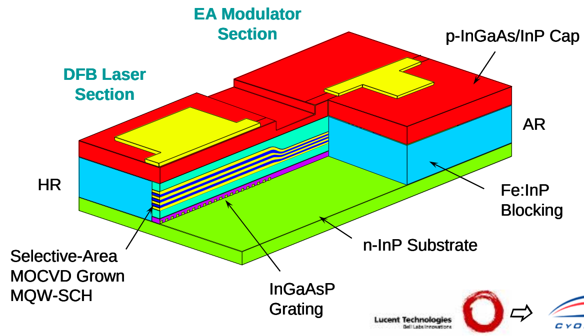


- **DFB Array (~4nm X #DFBs)**
  - On-chip combiner + SOA [mid '90s]
  - Or, off-chip MEMs combiner
  - Thermally tuned



Widely deployed commercial "WDM" PICs

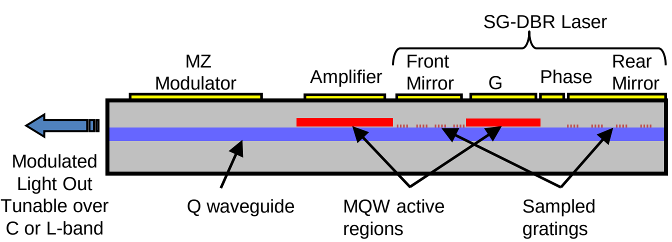
EML's:



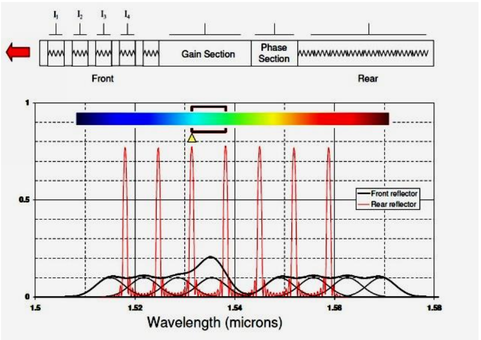
Lucent Technologies ⇨ CyOptics

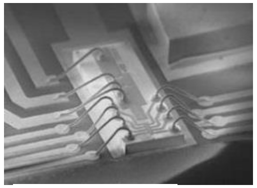
into XFP transceivers, etc.

Tunables & Selectable Arrays:

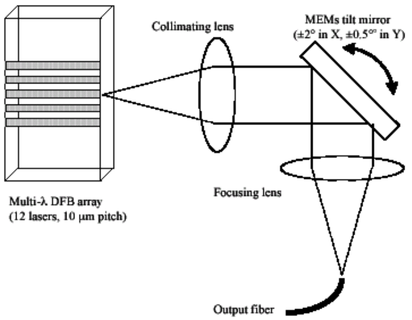


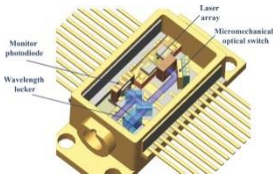
UCSB ⇨ AGILITY ⇨ JDSU



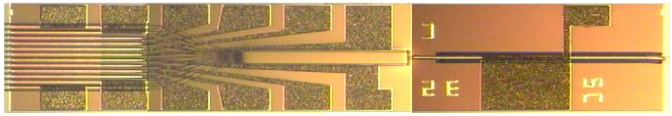


Bookham Technology ⇨ oclaro

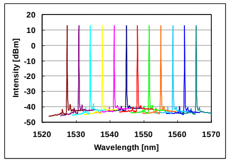




Santur Corporation



1 x 12 DFB **S-Bent** **MMI** **SOA**



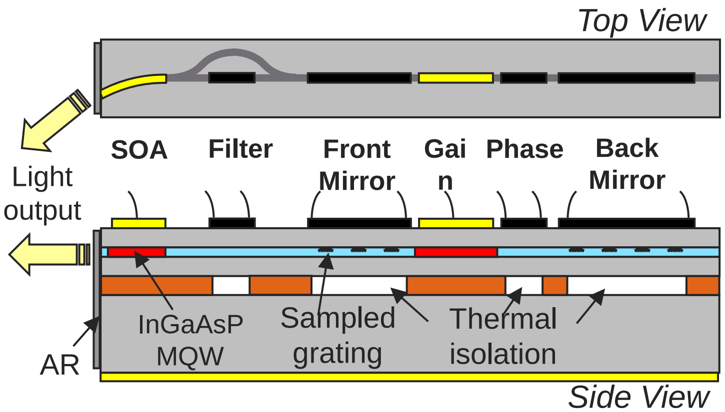
FURUKAWA ELECTRIC

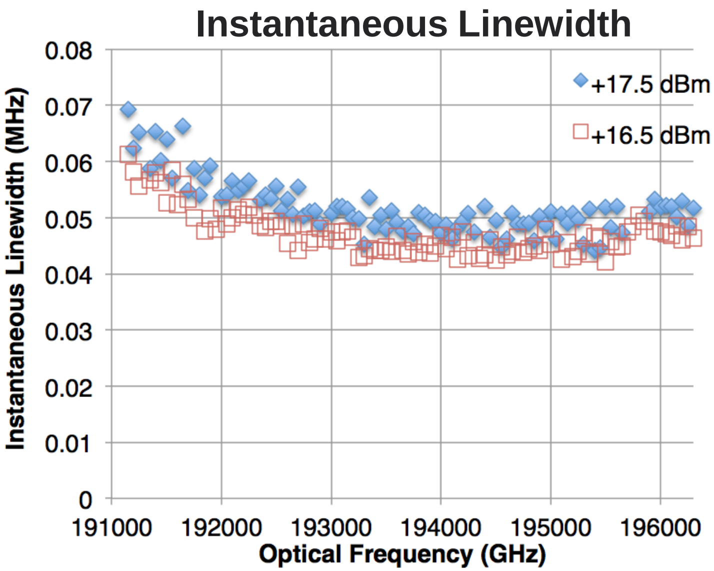
courtesy of T. Koch 2012

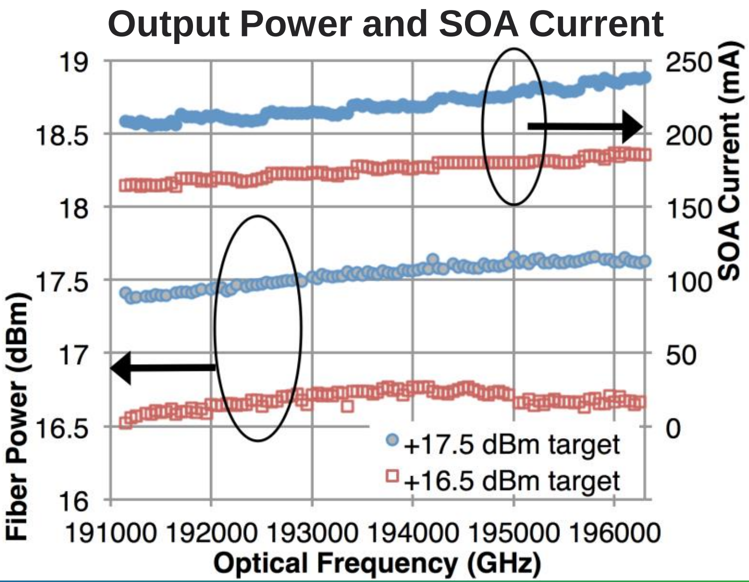
Narrow linewidth thermally-tuned SGDBR Laser

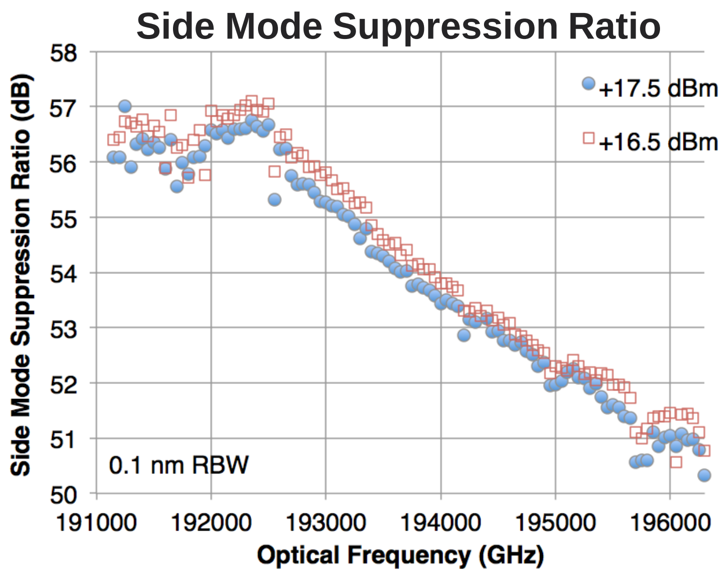
Mike Larson (TuC2)

- 70kHz linewidth and 50dB SMSR at +17dBm fiber power over 41nm range in C-band



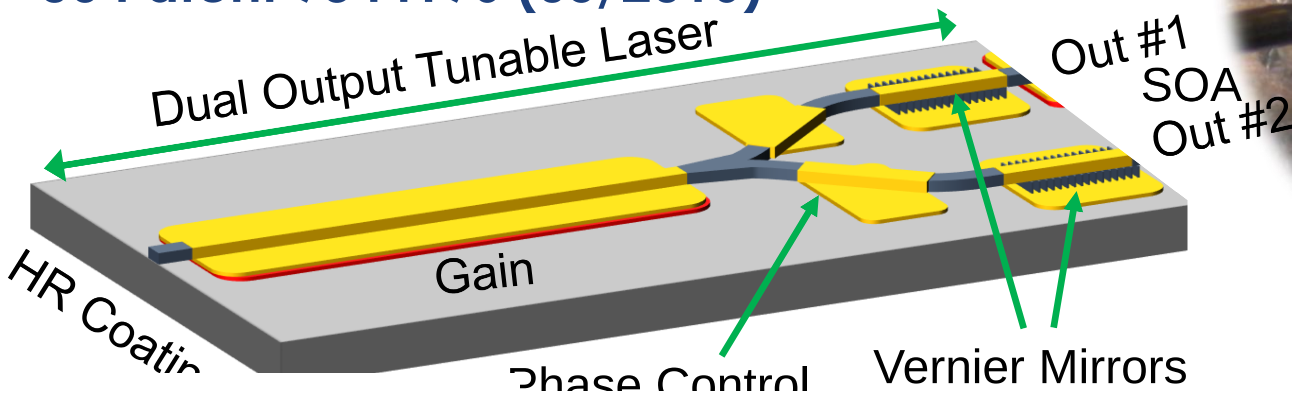


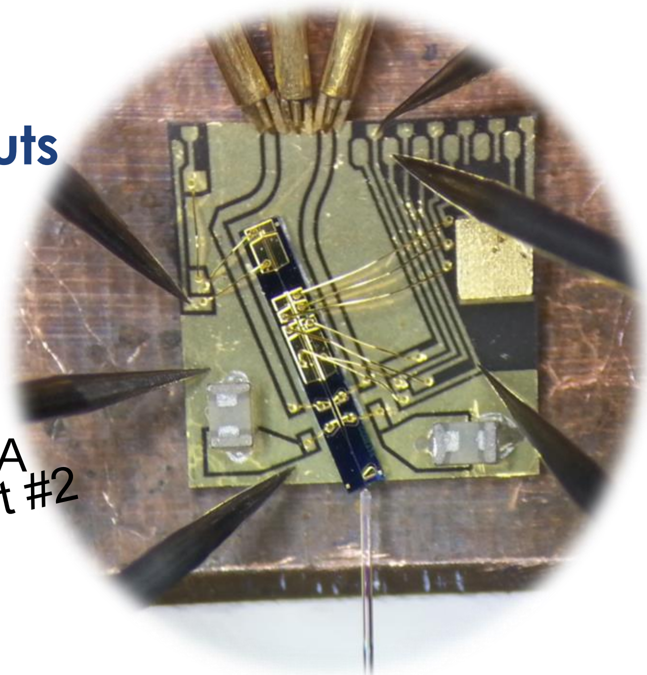




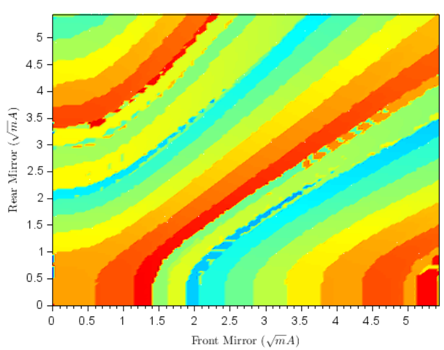
Tunable Interferometric Transmitter (Tunit)

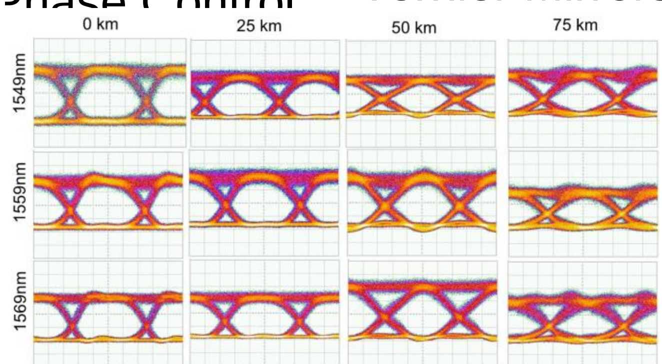
- Dual output Vernier tunable laser
  - 50 dB SMSR, well behaved tuning, 50nm
- Interferometrically combined modulator outputs
  - 12.5 Gbps operation, chirp control
  - 80+ km reach, SMF-28
- US Patent 9344196 (05/2016)





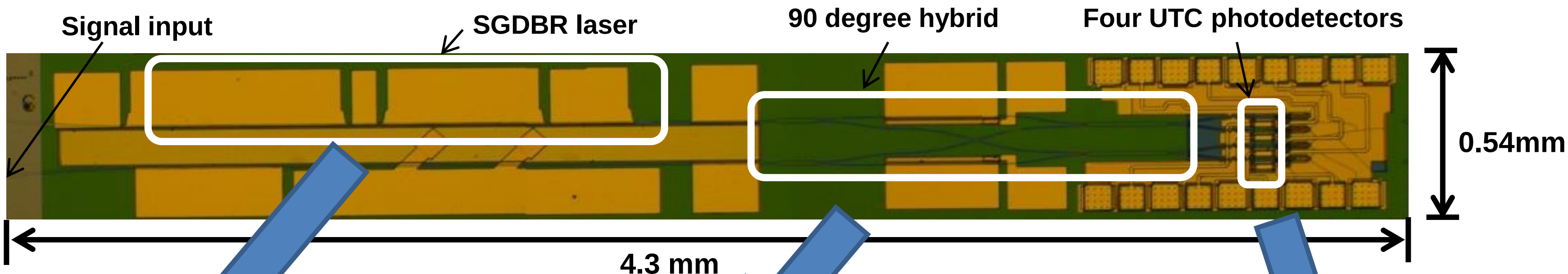
Hig… …ators



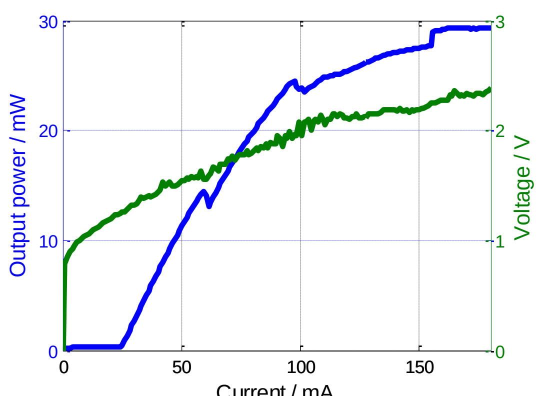


InP Widely-tunable Coherent Receiver PIC

(Homodyne or Intradyne—also for Optical Synthesis)



- **SG-DBR laser**



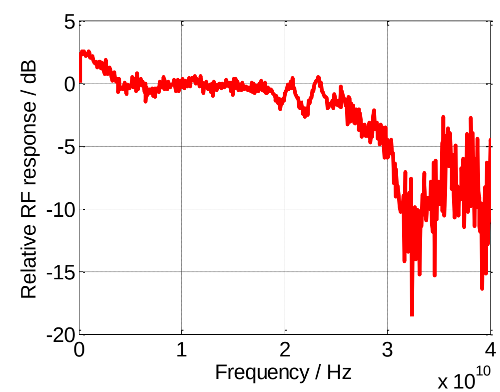
- **30 mW output power**
- **40 nm tuning range**
- **25 mA threshold current**

- **90 deg hybrid**

- ***1x2 MMI couplers***
- ***Directional couplers***
- ***Phase shifters***

No phase error
4% power imbalance

- **UTC photodetectors**



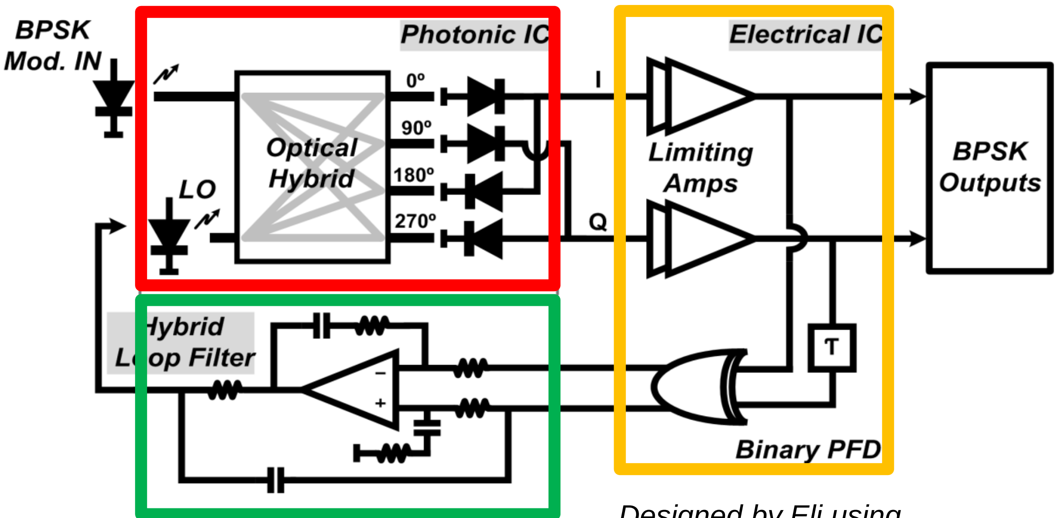
- ***29 GHz 3-dB bandwidth with -2V bias***
- ***18 mA saturation current at -5V bias.***

Mingzhi Lu, et. al., Optics Express, Vol. 20, Issue 9, pp. 9736-9741 (2012)

Phase Locked Coherent BPSK Receiver

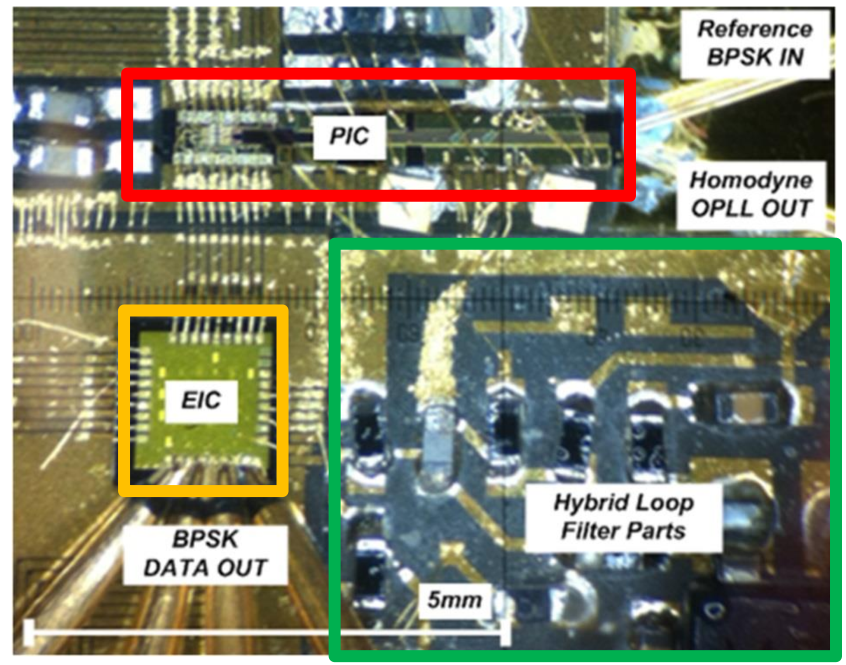
Homodyne OPLL + Costas Loop → 1 cm^2 footprint

Fabricated by Mingzhi



Designed by Eli using Teledyne 500nm HBT Process

Loop filter and system designed by Hyunchul



Photonic IC: SGDBR laser, optical hybrid, and un-balanced PDs

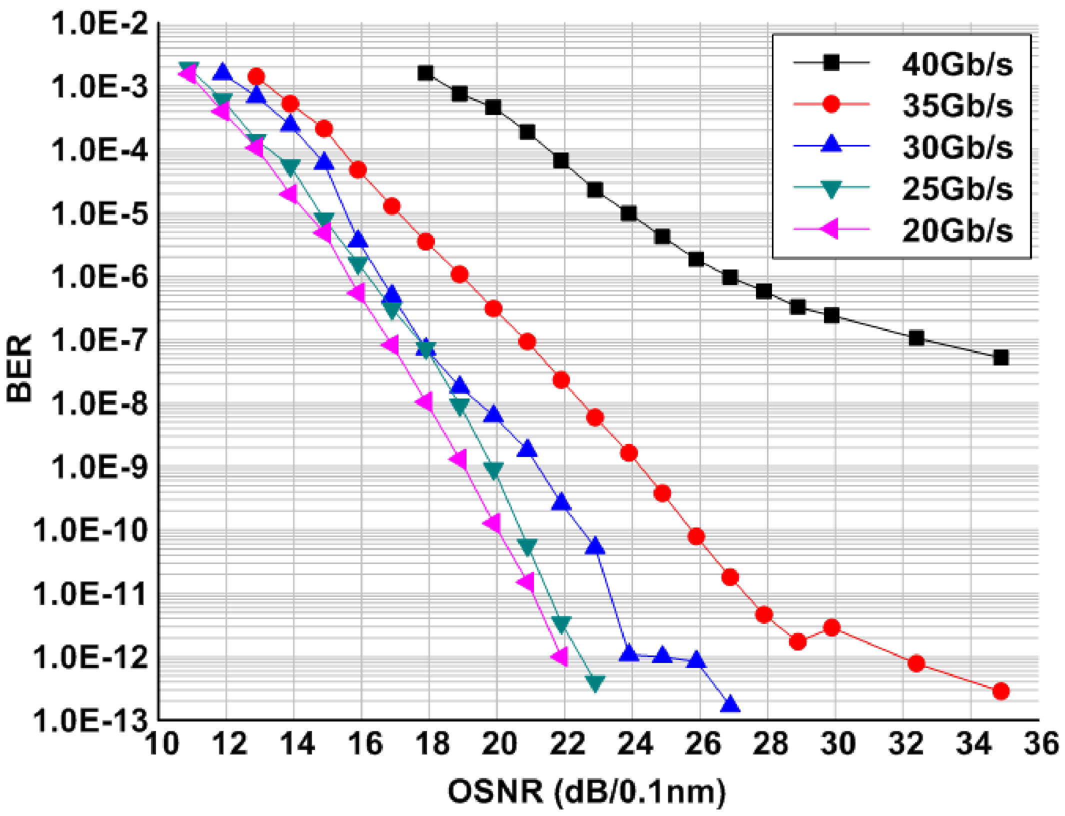
Electrical IC: limiting amplifiers and phase & frequency detector (PFD)

Hybrid loop filter: Feed-forward technique, op-amplifier and 0603 SMDs

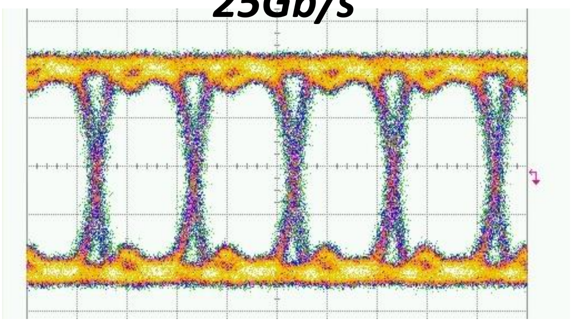
Mingzhi Lu, et. al., Optics Express, ***20****, (9), pp. 9736-9741 (2012)*

"Analog" Coherent OPLL BPSK Receiver

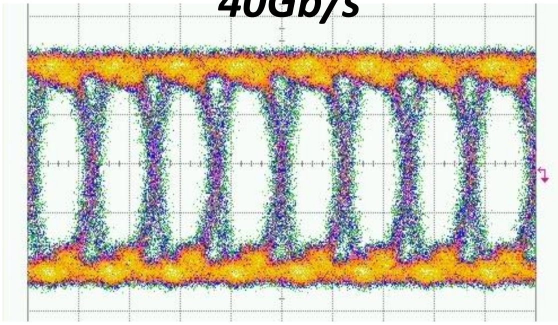
- BER vs. OSNR (20Gb/s to 40Gb/s)—> No ADC—No DSP
- *Error-free up to 35Gb/s , < 1.0E-7 @ 40Gb/s*
- PRBS 2^{31}-1 signals – up to 40Gb/s
- *Open eye diagrams for 25Gb/s and 40Gb/s*



25Gb/s

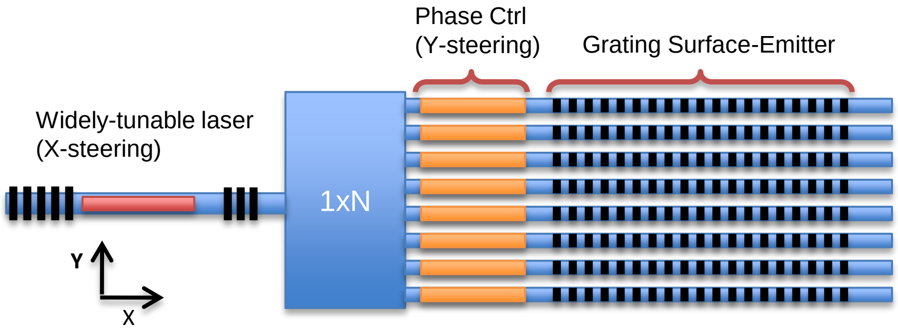


40Gb/s

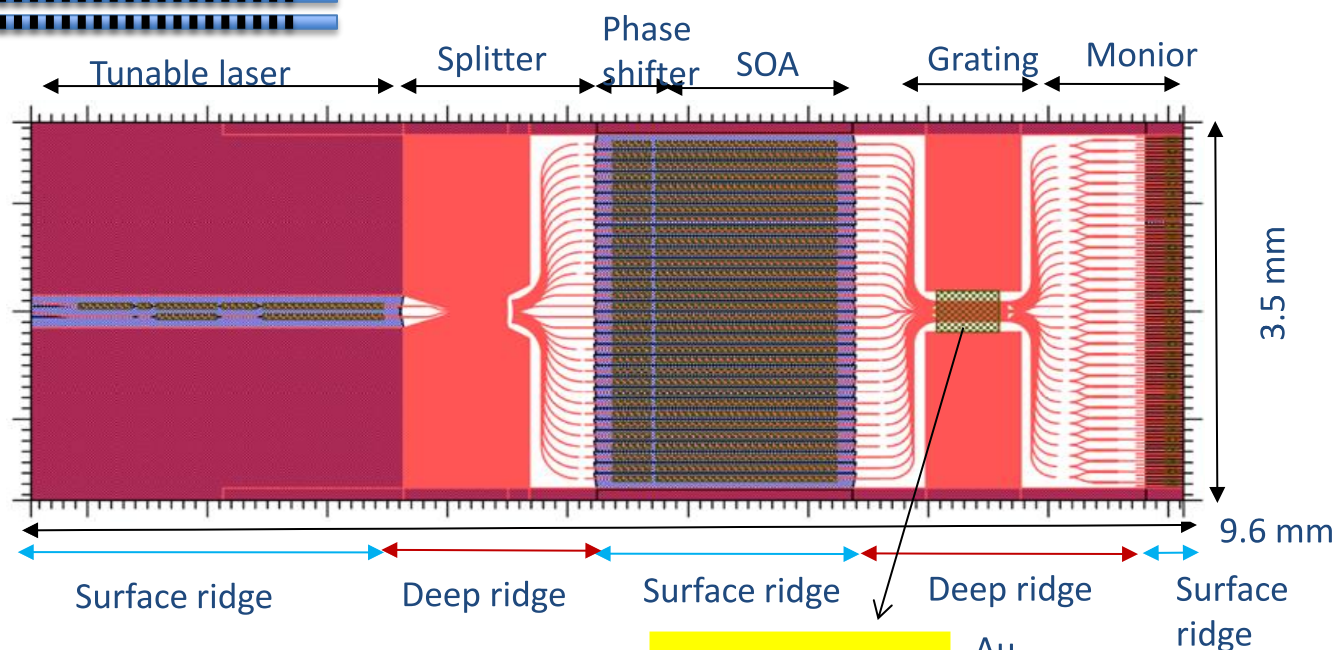


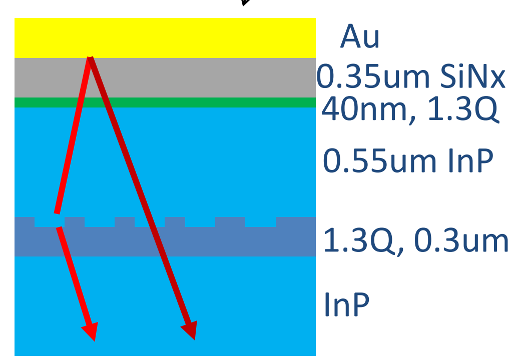
ECOC '12 with Rodwell and Johansson

SWEEPER PIC layout (32 waveguides)



1-D phased array (y-scan)
+ wavelength (x-scan)

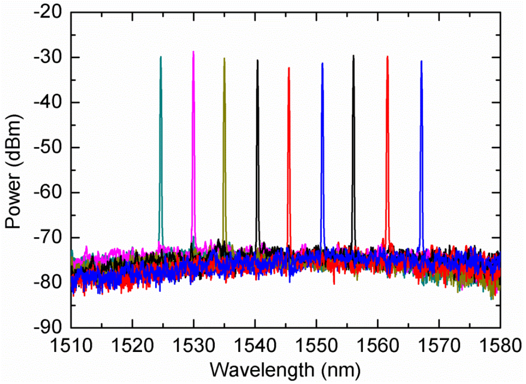




- **Larger scale of integration, 32 channels**
- **Simpler layout: star coupler splitter; unequal channel length**

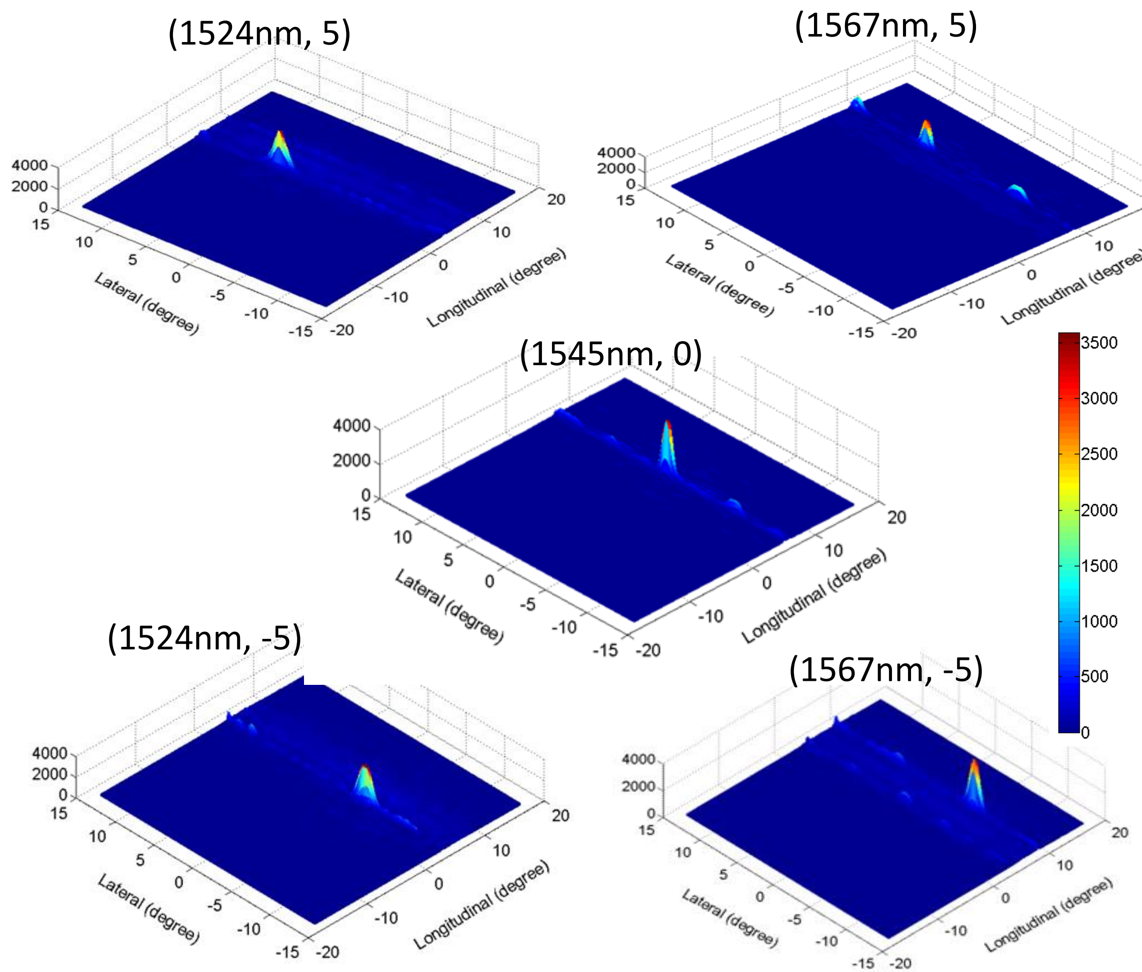
W-H Guo, et al,, *JSTQE*, **19** (4) 6100212, (2013)

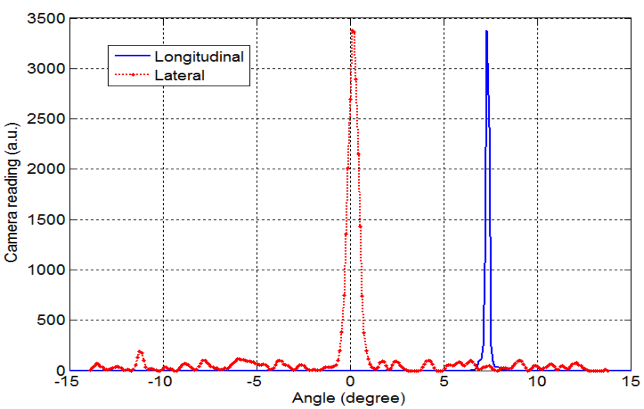
SWEEPER Results (32 x N)



Super modes of tunable laser

- **On chip tunable laser >40 nm**
- **2D beam steering demonstrated**





Integration Platforms

Indium Phosphide
- Excellent active components
- Mature technology
- Complexity/propagation losses for passive elements
- Foundries evolving

Silica on Silicon (PLC)
- Excellent passive components
- Mature technology
- Lack of active elements

Polymer Technology
- Low loss
- Passive waveguides
- Modulators
- No laser

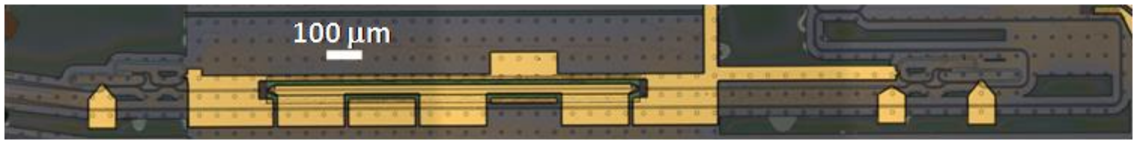
Hybrid Solutions

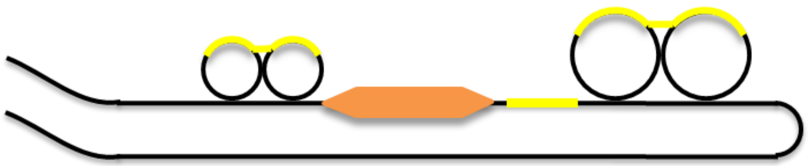
Silicon Photonics
- Piggy-back on Si-CMOS technology
- Integration with electronics?
- Constantly improving performance
- No laser

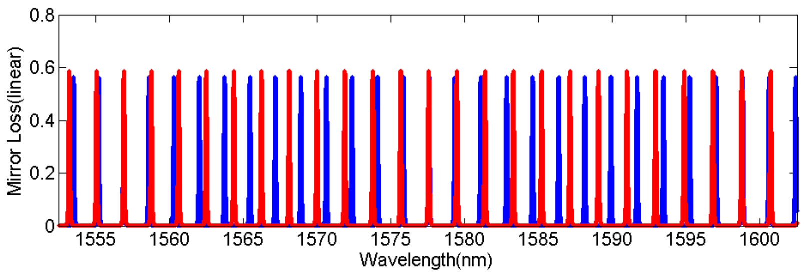
"Heterogeneous Integration Technology"

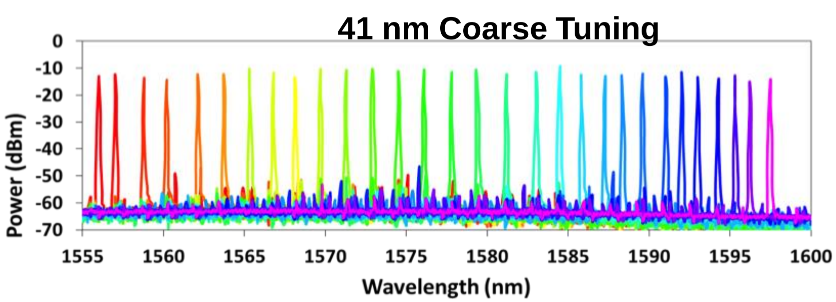
Narrow linewidth tunable laser using coupled resonator mirrors

Tin Komljenovic, Michael Davenport, Sudharsanan Srinivasan, Jared Hulme, and John E. Bowers
Electrical & Computer Engineering, University of California Santa Barbara, CA 93106.
tkomljenovic@ece.ucsb.edu



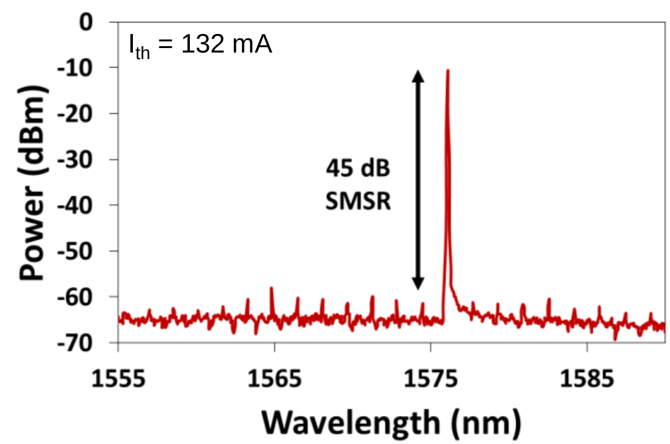


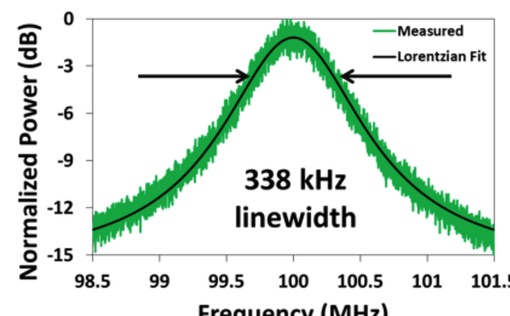




Hybrid-Si Platform

--Vernier tuning with ring-mirrors





T. Komljenovic, et al, *IEEE JSTQE*, Vol: 21 Nov 2015

Summary

- **Early vernier-tuned coupled-cavity laser concepts together with those of DBRs led to the creation of a four-section widely-tunable vernier-tuned design that is still in wide use today**

- **Many other widely-tunable laser designs have been developed over the years driven mainly by the need for a universal WDM source**

- **Integration technology developed for such lasers enabled many more complex Photonic Integrated Circuits**

- **Close integration of control/feedback electronics will be desirable in many future PIC applications**

- **Heterogeneous integration enables compatibility with different technologies—e.g., Si-photonics**