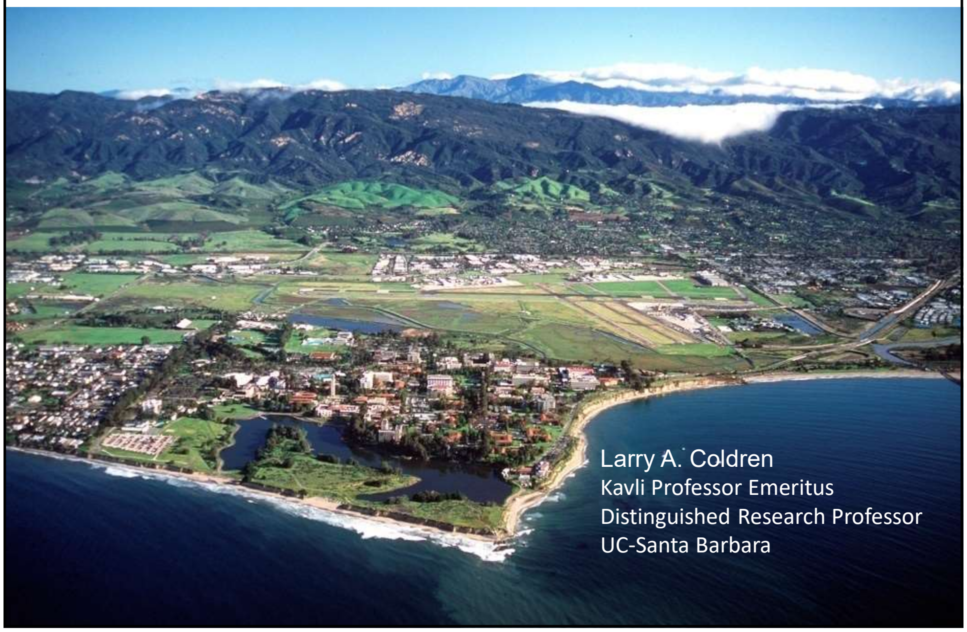
From coupled cavities to photonic ICs—
It didn't begin with lasers



1

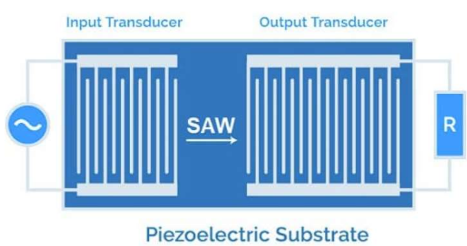
(1968-1978) Surface Acoustic Waves (SAW)

Stanford

Bell Labs

- $v_a \sim 10^{-5}\, v_l$ → ~3 µs/cm vs ~3 µs/km for fiber
- SAW wavelength @ UHF ~ near IR photonic wavelengths
- Large time-bandwidths possible on small crystals → [0.5GHz x 3 µs = 1500]

- Typical SAW filter:



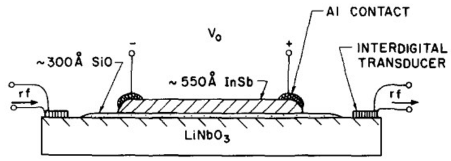
- In this time period, SAW most useful in defense applications—radar, electronic warfare

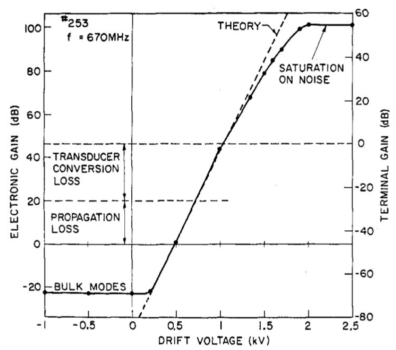
2

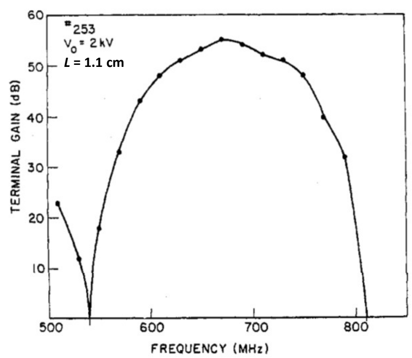
Monolithic Acoustic Surface Wave Amplifier

Stanford **(PhD work: 1969-72)** Bell Labs

- Traveling-wave amplifier—interaction of carriers and the acousto-electric field due to the piezoelectric effect
- Drift carriers faster than the velocity of acoustic waves for gain
- Vacuum deposition of InSb on $LiNbO_3$ (*Heterogeneous integration*)







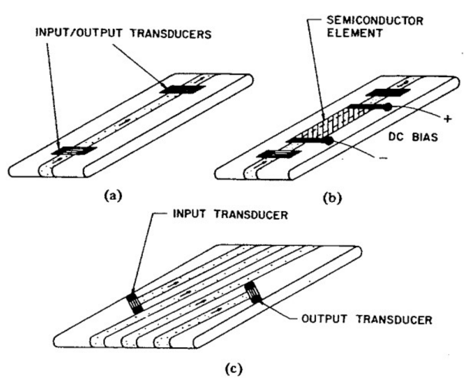
L. A. Coldren, *PhD Thesis Stanford*—same title (1972); also L. A. Coldren and G. S. Kino, " The InSb on piezoelectric Rayleigh wave amplifier, " *IEEE Trans. Electron Devices*, **ED-21** (7), July, 1974.

3

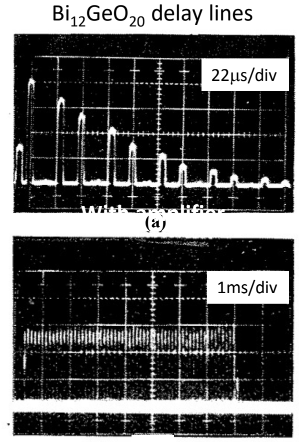
Wrap-around Long-delay Lines

Stanford Bell Labs

- ~3 µs/cm
- Bell Labs interested in Frame store for Picture Phone
- Digital storage limited to 1 kb/DIP package in 1972 → entire 6 ft cabinet for frame



$Bi_{12}GeO_{20}$ delay lines



(b)

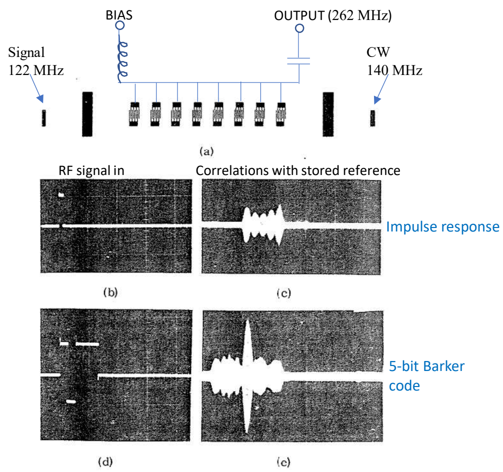
L. A. Coldren and H. J. Shaw, *Proc. of the IEEE*, **64** (5) 1976

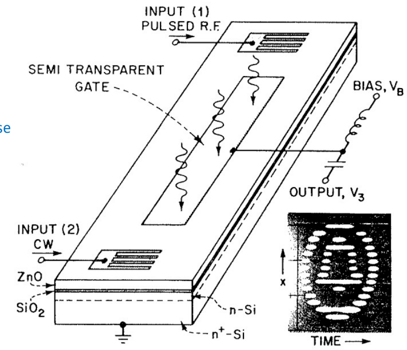
4

ZnO/Si Signal/Image Storage Read by Two Interfering SAWs

Bell Labs

Nonlinear SAW correlators weighted by stored charge at ZnO/SiO2 interface (charge could be modulated by light)





L. A. Coldren, *Appl. Phys. Letts*, **26** (4) (1975)

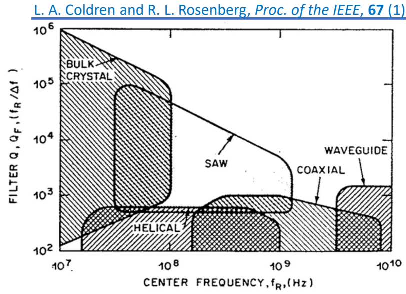
L. A. Coldren, *Appl. Phys. Letts*, **27** (1) (1975)

See also, L. A. Coldren, *Proc. of the IEEE*, **64** (5) (1976)

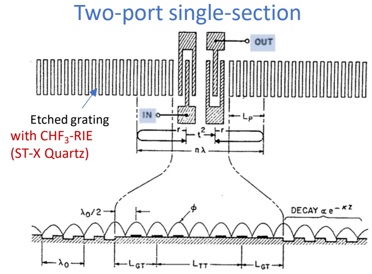
SAW Resonator Filters (1974-1979)

L. A. Coldren and R. L. Rosenberg, *Proc. of the IEEE*, **67** (1) 1979

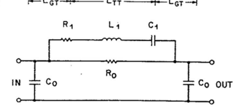
Bell Labs



Two-port single-section

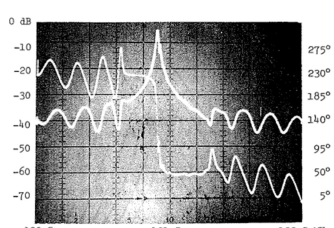


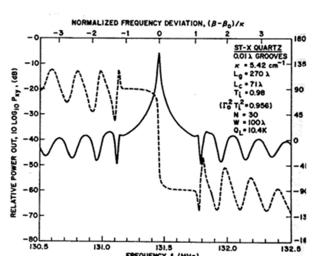
Transfer function from Scattering Theory (C_0 resonated out):



$$T \approx \frac{t^2(1+r)^2}{1 - r^2t^4[1 - S_{13}^2(2 + 1/r + 1/rt^4)]}\, S_{13}^2, \qquad |S_{13}|^2 << 1.$$

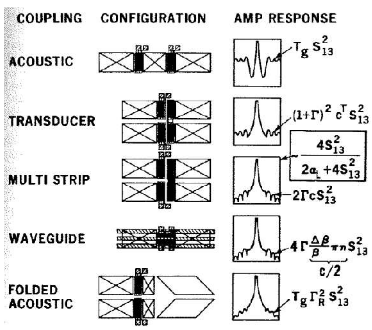
Example:

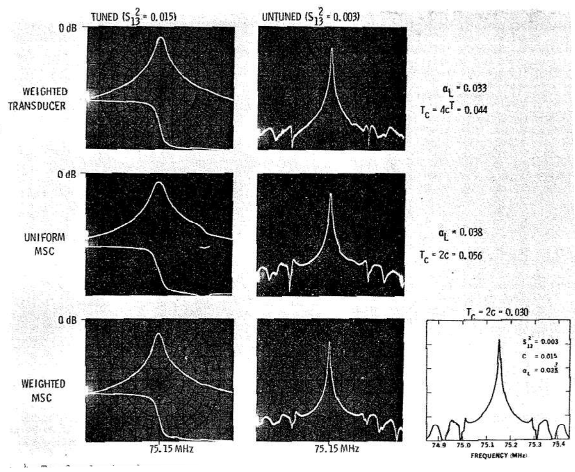


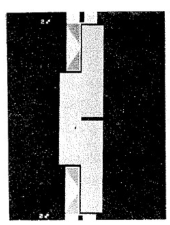


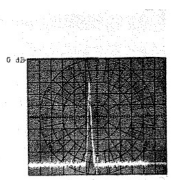
Two-section SAW Resonator Filters (and higher-order)

Bell Labs









4-section MSC result

- Scattering theory worked well

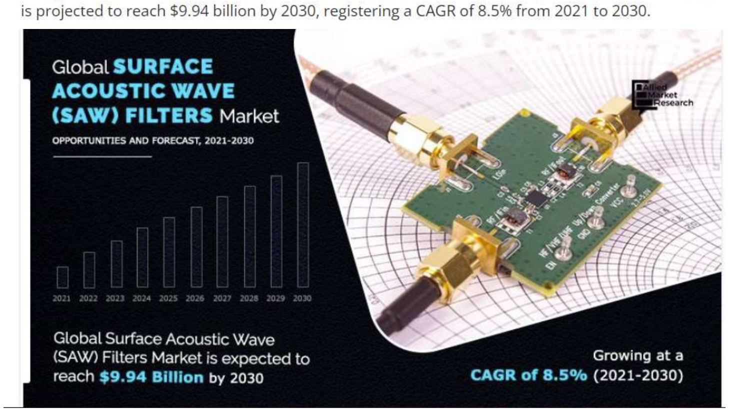
L. A. Coldren and R. L. Rosenberg, *Proc. of the IEEE*, **67** (1) 1979

SAW Filters (Today) > $5B market

Applications:

Smart phones and tables	Radar
GPS	Aerospace
WiFi	RFID sensors
Wireless Sensing	Digital TV
Base Stations	

The global surface acoustic wave (SAW) filters market size was valued at $4.56 billion in 2020, and is projected to reach $9.94 billion by 2030, registering a CAGR of 8.5% from 2021 to 2030.

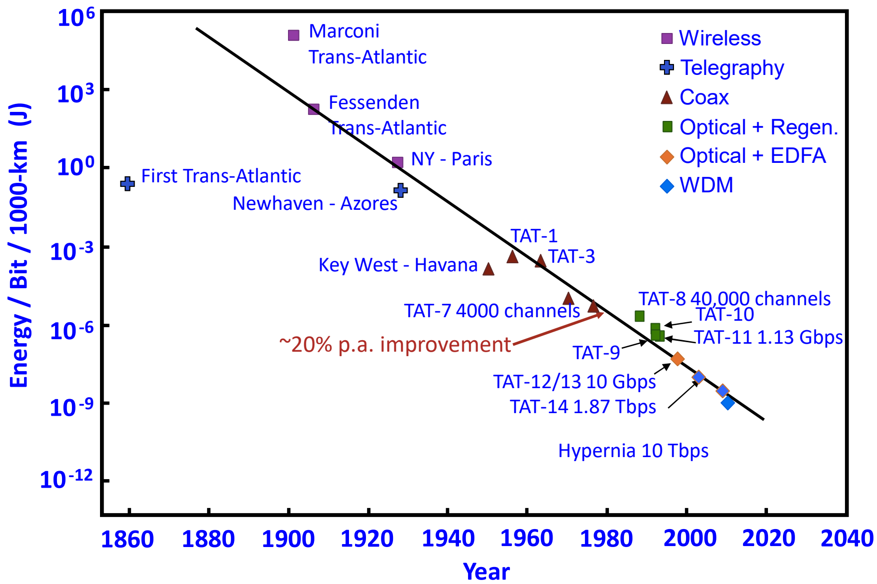


Allied Market Research®

Author(s) : N N Kundan, Asavari Patil , Vineet Kumar

UCSB

Energy to transport a bit across the ocean—TAT-8 first optical system (used SAW—TR filters)



9

IEEE Fellow

- 1982
- No mention of photonics

The Institute of Electrical and Electronics Engineers, Inc.

Certifies that

LARRY A. COLDREN

has been elected to the grade of

Fellow

for contributions to surface acoustic wave resonator filters, long delay lines, and monolithic acoustoelectric signal processing devices.

January 1, 1982

President

Secretary

10

Early Tunable, Single-Frequency Diode Lasers

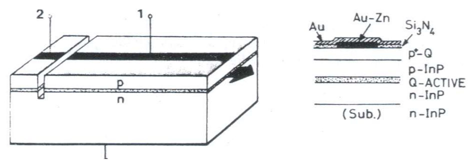
Bell Labs

- Coupling mirrors between integrated active and passive sections

First integrated InP (laser – X) devices

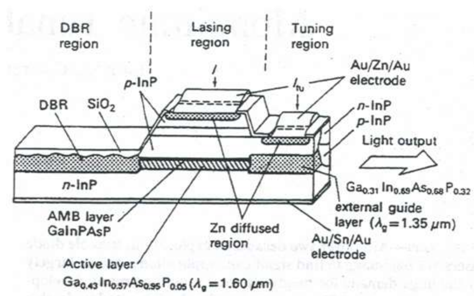
→ Etched grooves/RIE: Cl-Ar-O_2
- Tunable single frequency @ 1.3 µm
- Laser-modulator
- Laser-detector

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).



→ DBR gratings
- Tunable single frequency @ 1.55 µm
- Combined integration technologies

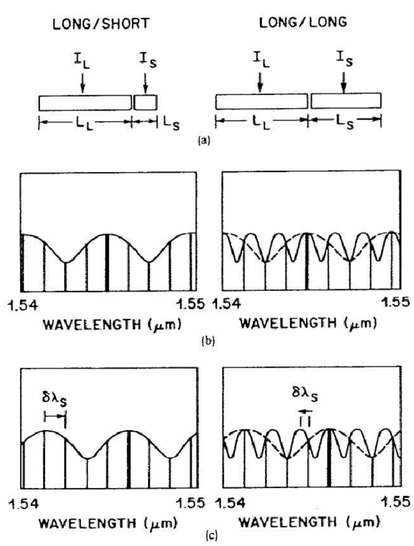
Y. Tohmori, Y. Suematsu, Y. Tushima, and S. Arai, "Wavelength tuning of GaInAsP/InP integrated laser with butt-jointed built-in DBR," *Electron. Lett.*, 19 (17) 656-7 (1983).

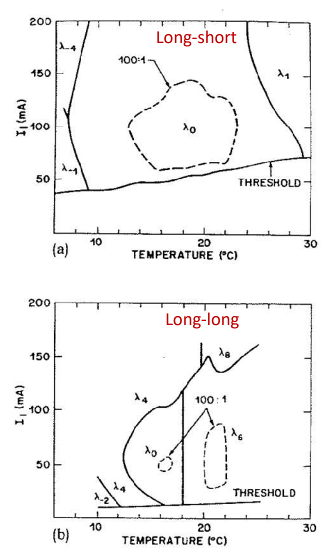


Vernier Tuning Between Modes of Two Cavities

Bell Labs

- **Long-short configuration more stable**





Early Tuning Result with Etched Coupling Grooves

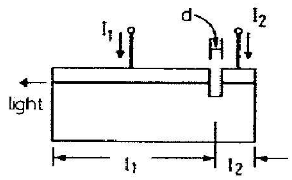
Bell Labs

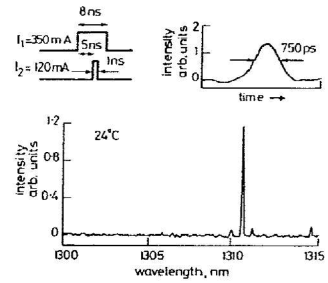
Monolithic two-section tunable laser

-- Broad-area lasers

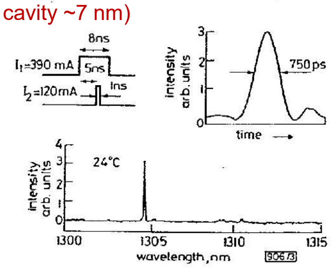
-- No regrowth required

-- Single longitudinal mode (> 20:1) with short pulses





Tuning between two modes of short cavity ~7 nm)

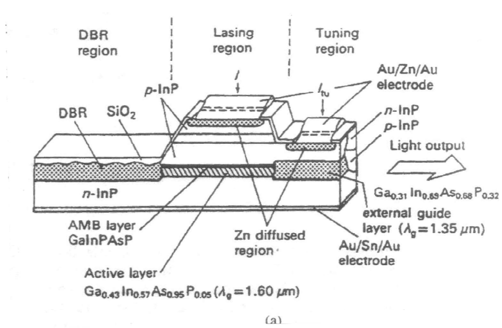


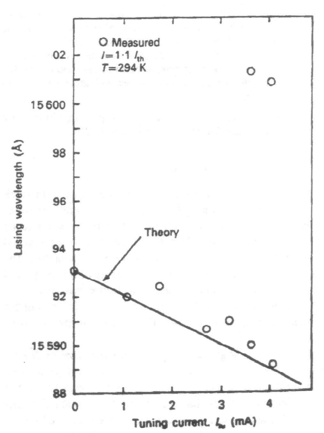
K. J. Ebeling, L. A. Coldren, B. I. Miller, J. A. Rentschler, "Generation of single-longitutional mode subnanosecond light pulses by high-speed current modulation of monolithic two-section semiconductor lasers," *Electronic Letts*., **18** (21) 901-902 (Oct.,1982).

13

Early Tunable DBR Work

Pioneering Active-Passive interfaces



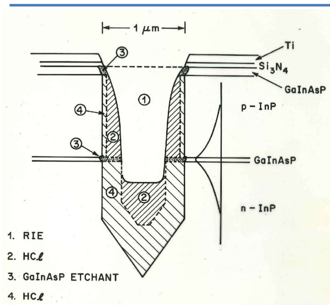


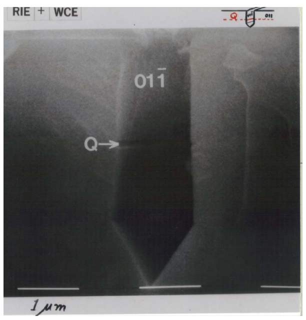
Tohmori, Suematsu, Tushima, and Arai, TIT, 1983

14

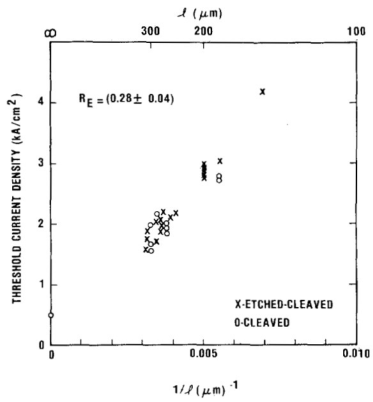
No-Regrowth Groove Etch: RIE/HCl/Q-etch/HCl

Bell Labs





Threshold current density versus reciprocal cavity length (1/*l*) for cleaved and etched facet broad-area lasers.



→ Kaz also demonstrated integrated polymer waveguide external cavity.

L. A. Coldren, K. Furuya, B. I. Miller and J. A. Rentschler, "Etched mirror and groove-coupled laser devices for integrated optics," *J. Quantum Electron.* **QE-18** (10) 1679-1688, Oct., 1982

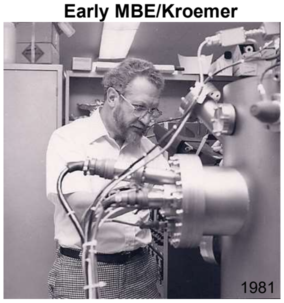
UCSB

1984—One Year After Bell System Breakup

1980s: MBE; more MBE; and founding of Materials Dept.

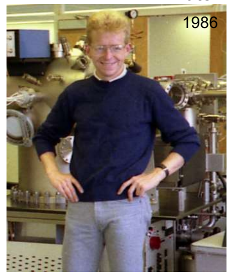
UCSB

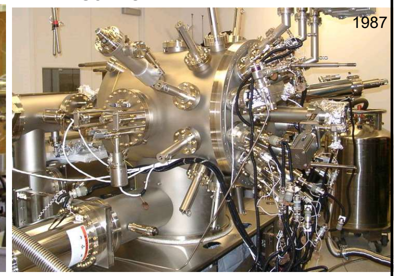
Early MBE/Kroemer



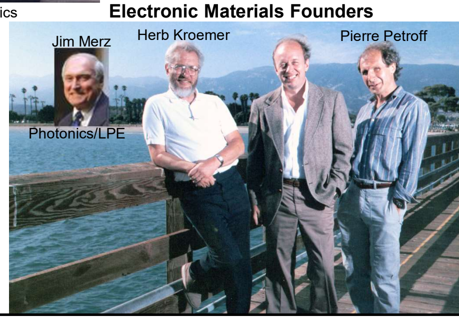
Physics/Electronics

Later MBE: 2 Gen-2s





Electronic Materials Founders



Materials Department (1986)

Slightly later ('87)

Art Gossard
Director of MBE Lab

John Bowers

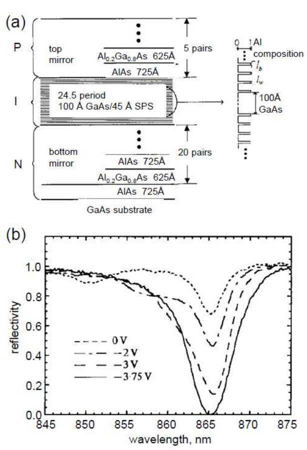
Evelyn Hu later

17

Excellent MBE Enables Good Vertical-Cavity Modulators and Lasers

UCSB

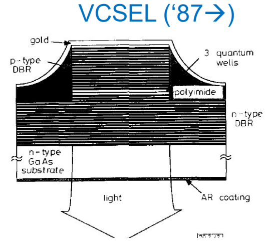
Reflection Modulator ('86-'91)



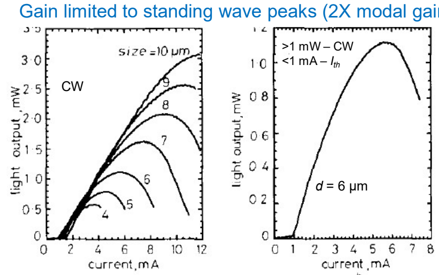
Asymmetric Resonant-cavities

K. K. Law, M. Whitehead, J. L. Merz, and L. A. Coldren, *Electron. Lett.* **27**, 1863 (1991).

VCSEL ('87→)



Gain limited to standing wave peaks (2X modal gain)



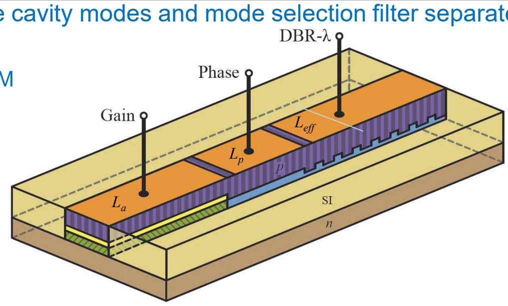
R. S. Geels & L. A. Coldren, *Electron. Letts*.,vol 27, no. 21, Oct., 1991

Recent Review: Larry A. Coldren, "Review of key vertical-cavity laser and modulator advances enabled by advanced MBE technology," JVST-A **39,** 010801 (2021); doi: 10.1116/6.0000574—tribute to Prof. A.C. Gossard.

18

Tunable DBR Lasers (mid-late 1980's)

- One cavity: tune cavity modes and mode selection filter separately (or together)
- Coherent and WDM



- 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)

Limit on tuning range →

$$\frac{\Delta\lambda_g}{\lambda_g} = \frac{\Delta\bar{n}_{DBR}}{\bar{n}_{DBR}}. \approx 0.5\%$$

~ 7 nm @ 1.5 μm

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

Multi-element Mirror 4-Section Tunable Laser

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

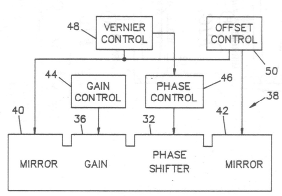
Akiba et al.; "Self-Focusing Lens as Resonator enables 10 GHz Modulation"; Fiberoptic Technology Oct. 1981, p. 124.

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



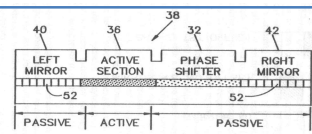
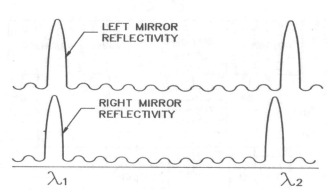


FIG. 5



- **Vernier tuning of DBR mirror 'super modes'**
  (much wider spacing than cavity modes)

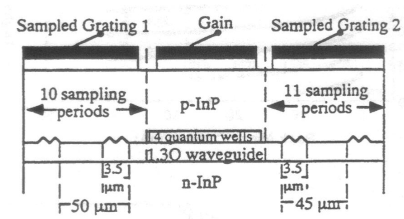
DESCRIPTION OF THE PREFERRED EMBODIMENT

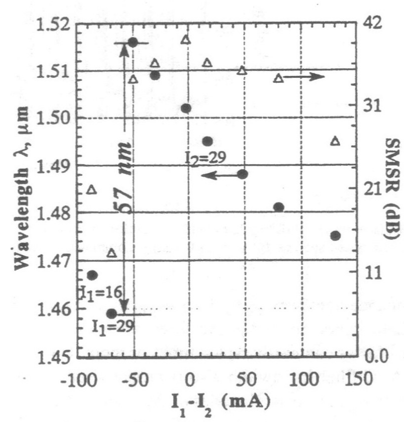
The novel four section tunable laser of the present invention is shown in simplified form in FIG. 5 where it is generally indicated as 38. By combining discrete mode-jump tuning with continuous tuning, it will be seen that this design allows the relative tuning range to be extended by at least an order of magnitude larger than Δn/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 Laser

UCSB

- Initial results
- 3 sections—vernier tuning





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

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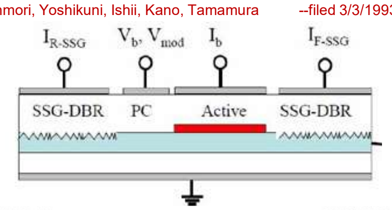
Super-structure Grating DBR laser

UCSB

Distributed reflector and wavelength-tunable semiconductor laser

Tohmori, Yoshikuni, Ishii, Kano, Tamamura --filed 3/3/1993



U.S. Patent June 28, 1994 Sheet 3 of 18 5,325,392

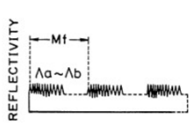


FIG.3A

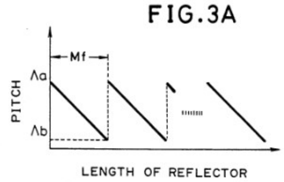


FIG.3B

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

NTT-NEL

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*

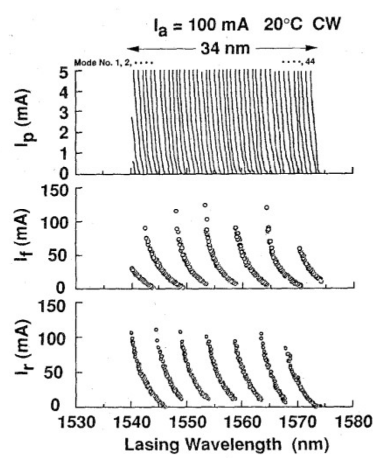
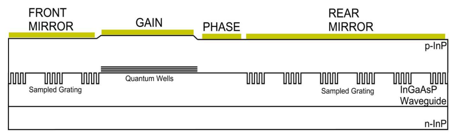


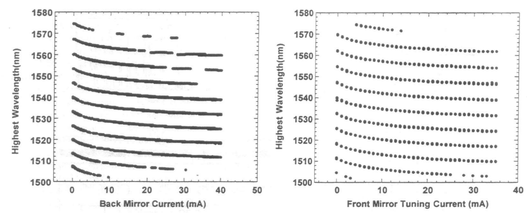
Fig. 12. Quasicontinuous wavelength tuning characteristics with three-tuning-current control.

22

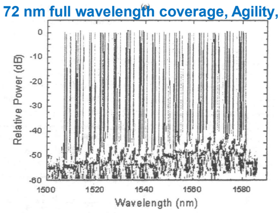
SGDBR wide-tuning, high-power, high-reliability



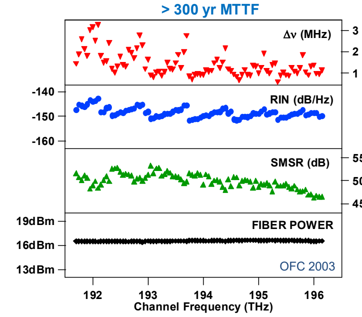
Agility Communications formed to Commercialize in 1998.



72 nm full wavelength coverage, Agility, 2001.



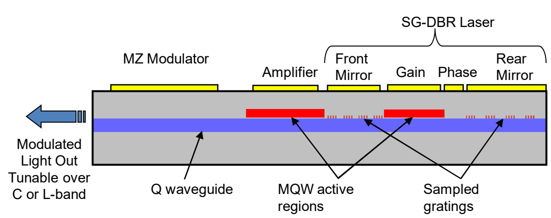
> 300 yr MTTF



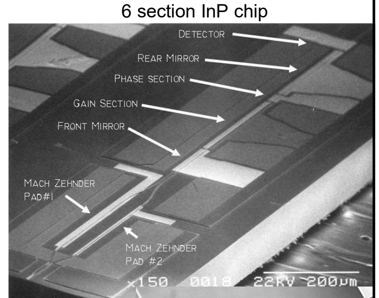
Sampled-Grating DBR: Monolithic and Integrable

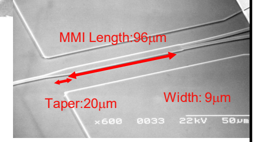
SGDBR+X widely-tunable transmitter:
- Foundation of PIC work at UCSB

UCSB'90-- → Agility'99-'05 → JDSU'05→

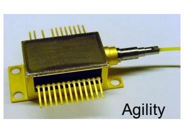


6 section InP chip





- Vernier tuning over 40+nm near 1550nm
- SOA external to cavity provides power control
- Highly reliable— < 10% of SGDBR is grating
- Integration technology for much more complex PICs*



JDSU-ILMZ TOSA (~ 18mm)

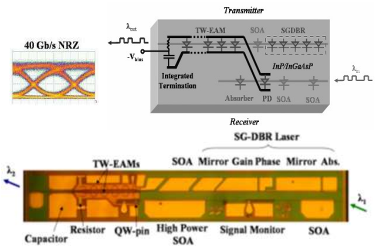
~2008

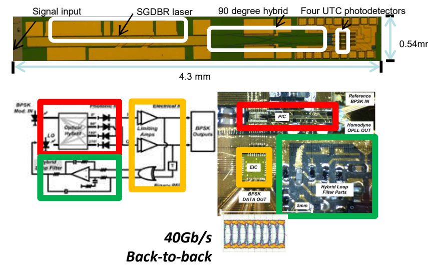
J. S. Barton, et al, *ISLC,* TuB3, Garmish, (Sept, 2002)

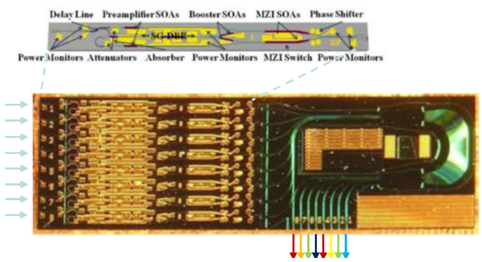
PICs (2005-2013)

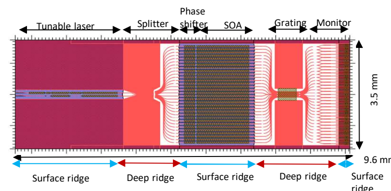
UCSB

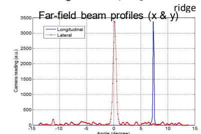
Wavelength converters/switches | **OPLL-Coherent RX & Beam Sweepers**









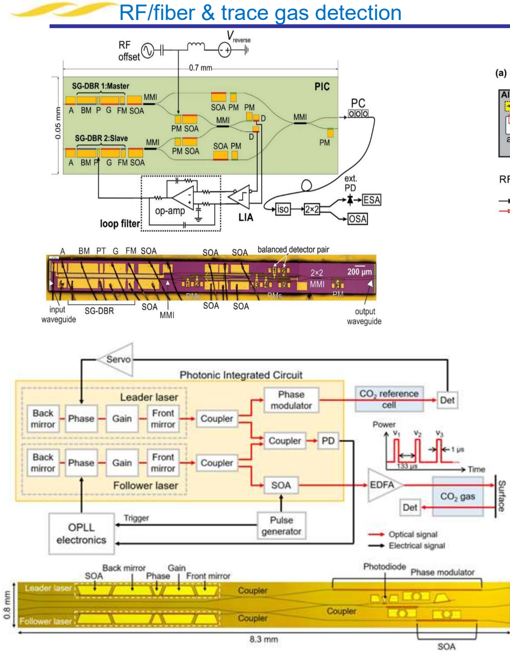


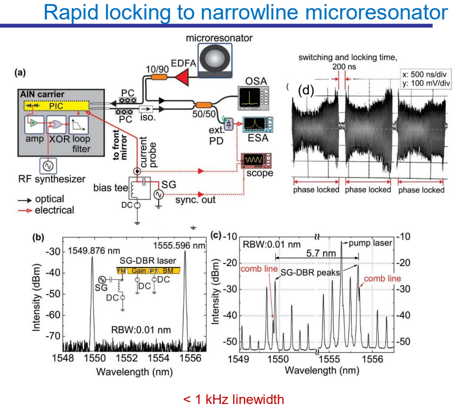
*For more information see: L. A. Coldren, et al, "A Review of Photonic Systems-on-Chip Enabled by Widely-Tunable Lasers," *IEEE J. Quantum Electron.*, **58**(4):1-1 August 2022; doi: 10.1109/JQE.2022.3168041

PICs (2015-2022)

UCSB

RF/fiber & trace gas detection | **Rapid locking to narrowline microresonator**



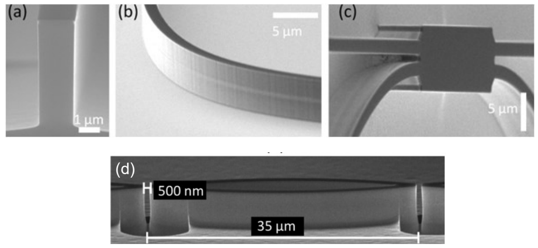


*For more information see: L. A. Coldren, P.A. Verrinder, J. Klamkin, "A Review of Photonic Systems-on-Chip Enabled by Widely-Tunable Lasers," *IEEE J. Quantum Electron.*, **58**(4):1-1 August 2022; doi: 10.1109/JQE.2022.3168041

UCSB

Improved Dry etching & Flattened Ring Resonator Laser

- $Cl_2/H_2/Ar$ (9/18/2 sccm) ICP (Inductively-Coupled Plasma) etching at a chamber pressure of 1.5 mT.



Scanning electron microscope (SEM) images of the etched waveguides showing: (a) 5 µm deep etch with vertical sidewalls, (b) waveguide bends with smooth sidewalls, (c) multimode interference (MMI) couplers, and (d) flattened ring-resonator laser with frustrated total-internal-reflection mirrors.

J.S. Parker, E.J. Norberg, Y.J. Hung, B. Kim, R.S. Guzzon, L.A. Coldren, "InP/InGaAsP Flattened Ring Lasers with Low-loss Etched Beam Splitters", *Photonics Technology Letters*, **23**, (9), pp. 573-575 (May 2011)

Micro-transfer Printing of III-V chips on Si-Photonics
(etched facets inherent)

Integration of III-V light sources on a silicon photonics circuit by transfer printing

Joan Juvert, Tommaso Cassese, Sarah Uvin, Andreas De Groote, Brad Snyder, Peter De Heyn, Peter Verheyen, António José Trindade, Christopher Bower, Marco Romagnoli, Günther Roelkens, and Dries Van Thourhout

2017 IEEE 14th International Conference on Group IV Photonics (GFP)
23-25 August 2017, Berlin, Germany

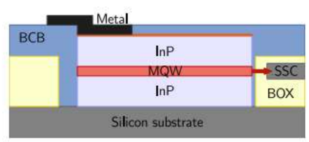


Fig. 1. Sketch of the integration approach. The III-V coupon is transfer printed directly in a trench in the buried oxide. No adhesive layer is used for the bonding. The output of the MQW device is directly coupled to a trident spot-size converter, SSC in the picture, in the photonic circuit. The whole structure is passivated with BCB after transfer printing.

- Many other recent publications on µTP. [These guys are not the originators.]
- Current DARPA—LUMOS program is based upon use of this approach

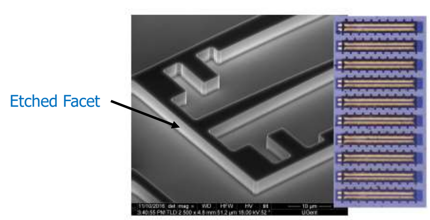


Fig. 2. SEM image of the front side of the main mesa. The trenches inside the mesa define the central waveguide. The notches in the trenches are used for pattern recognition during transfer printing. On the right, an optical image of an array of encapsulated coupons on their native III-V substrate is shown.

UCSB

Summary
(for students?)

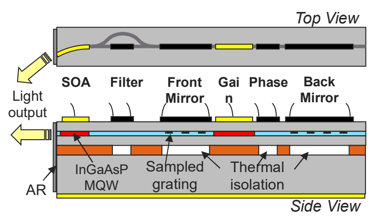
- Etched facets are needed for micro-transfer printing, and they now appear to function as well as cleaved facets.
- You never know where your current project will lead you, so best to be enthusiastic about it and learn what you can from it.
- The things that are different from the mainstream about your project may be the most important. Don't always follow the crowd.
- Unexpected results are not failed results, they provide learning opportunities. If your experiment gives the expected results, you may be happy, but you probably haven't learned anything new.

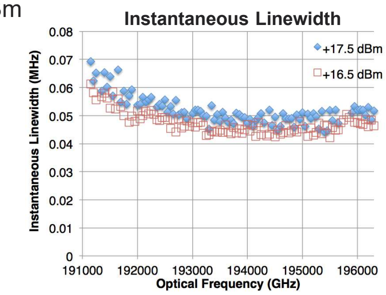
UCSB

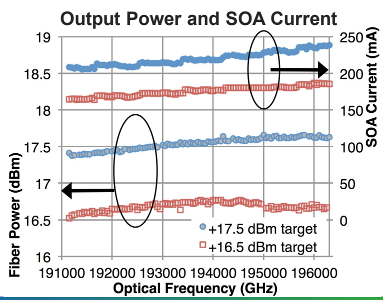
Backup

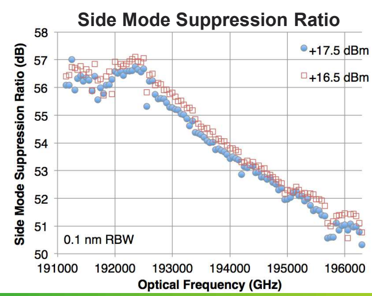
UCSB — Narrow-linewidth Thermally-tuned SGDBR Laser

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









LUMENTUM

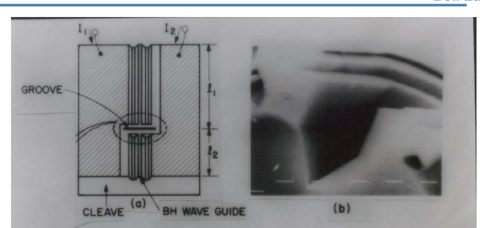
M.C. Larson et al., OFC 2015, M2D.1

Coupled-Cavity Etched-Groove Tunable Laser with Regrowth

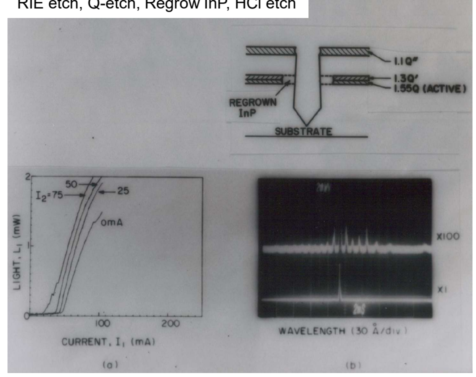
Bell Labs

Monolithic two-section tunable laser

-- BH stripe lasers (CW)
-- BH regrowth simultaneously fills slots
-- Single HCl etch of only InP at mirrors
-- Planar etched facets and slots (all InP)
-- Single longitudinal mode
-- Tunable



RIE etch, Q-etch, Regrow InP, HCl etch



L. A. Coldren, T. L. Koch, T. J. Bridges, E. G. Burkhardt, B. I. Miller, and J. A. Rentschler, "Vapor-phase regrown monolithic two-section window lasers exhibiting DSM operation at 1.55 um," *ISLC*, Rio de Janeiro, Brazil, Sept., 1984