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

Larry A. Coldren
Kavli Professor Emeritus
Distinguished Research Professor
UC-Santa Barbara

• $v_a \sim 10^{-5} v_l \rightarrow \sim 3 \mu s/cm$ vs $\sim 3 \mu s/km$ for fiber
• SAW wavelength @ UHF $\sim$ near IR photonic wavelengths
• Large time-bandwidths possible on small crystals $\Rightarrow [0.5GHz \times 3 \mu s = 1500]$

• Typical SAW filter:

• In this time period, SAW most useful in defense applications—radar, electronic warfare
Monolithic Acoustic Surface Wave Amplifier
(PhD work: 1969-72)

- 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 LiNbO₃ (Heterogeneous integration)


Wrap-around Long-delay Lines

- ~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

L. A. Coldren and H. J. Shaw, Proc. of the IEEE, 64 (5) 1976
ZnO/Si Signal/Image Storage Read by Two Interfering SAWs

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

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

SAW Resonator Filters (1974-1979)


Transfer function from Scattering Theory ($C_0$ resonated out):

$$T \approx \frac{z^2(1 + r)^2}{1 - r^2} \left| 1 - S_L a_2 + i n + i r^2 \right|$$

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

Bell Labs


• Scattering theory worked well

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

IEEE Fellow

- 1982
- No mention of photonics
Early Tunable, Single-Frequency Diode Lasers

• Coupling mirrors between integrated active and passive sections

→ Etched grooves/RIE: Cl-Ar-O₂
  - Tunable single frequency @ 1.3 µm
  - Laser-modulator
  - Laser-detector

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

Vernier Tuning Between Modes of Two Cavities

• Long-short configuration more stable
Early Tuning Result with Etched Coupling Grooves

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,

Bell Labs

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Early Tunable DBR Work

Pioneering Active-Passive interfaces

Tohmori, Suematsu, Tushima, and Arai, TIT, 1983
No-Regrowth Groove Etch:  RIE/HCl/Q-etch/HCl

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.


1984—One Year After Bell System Breakup
1980s: MBE; more MBE; and founding of Materials Dept.

Early MBE/Kroemer  Later MBE: 2 Gen-2s

Electronic Materials Founders

Slightly later (’87)

Art Gossard
Director of MBE Lab

John Bowers

Evelyn Hu
later

Materials Department (1986)

Electronic Materials Founders

Excellent MBE Enables Good Vertical-Cavity Modulators and Lasers

Reflection Modulator (’86-’91)  VCSEL (’87→)

Asymmetric Resonant-cavities


**Tunable DBR Lasers (mid-late 1980’s)**

- The center wavelength of grating, $\lambda_g$, will tune in direct proportion to the index change $\Delta n_{DBR}$; 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, $\lambda_m$ (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)

$$\Delta \lambda_g = \frac{\Delta n_{DBR}}{\tilde{n}_{DBR}} \approx 0.5\% \quad \Delta \lambda_m = \frac{\Delta \tilde{n}_L + \Delta \tilde{n}_p + \Delta \tilde{n}_{DBR} L_{eff}}{\tilde{n}_{DBR} L + \tilde{n}_p L + \tilde{n}_{DBR} L_{eff}}$$

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**Multi-element Mirror 4-Section Tunable Laser**

- Vernier tuning of DBR mirror ‘super modes’
  
  (much wider spacing than cavity modes)
Sampled-Grating DBR Tunable Laser

- Initial results
- 3 sections—vernier tuning


Super-structure Grating DBR laser

Distributed reflector and wavelength-tunable semiconductor laser

Tohmori, Yoshikuni, Kano, Marumura —filed 3/3/1993

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

Tohmori, Kish, Tonomura, Kato, Marumura, SGR, Osaka, Ueno, Kusumoto, SGR, Osaka, Ueno

I_b = 100 mA 20°C CW

Fig. 12. Quasicontinuous wavelength tuning characteristics with three-tuning current control.
SGDBR wide-tuning, high-power, high-reliability

Agility Communications formed to Commercialize in 1998.


UCSB

Sampled-Grating DBR: Monolithic and Integrable

SGDBR+X widely-tunable transmitter:

- Foundation of PIC work at UCSB

UCSB’90→ Agility’99-’05 → JDSU’05→

- 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)

J. S. Barton, et al, ISLC, TuB3, Garmish, (Sept, 2002)
PICs (2005-2013)

Wavelength converters/switches

OPLL-Coherent RX & Beam Sweepers

- 4.3 mm
- 3.5 mm
- 0.54 mm


 PICs (2015-2022)

RF/fiber & trace gas detection

Rapid locking to narrowline microresonator

- < 1 kHz linewidth

**Improved Dry etching & Flattened Ring Resonator Laser**

- Cl/H₂/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.


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

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

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 is the picture, in the photonic circuit. The whole structure is passivated with BCB after transfer printing.

Fig. 2. SEM image of the front side of the main mesa. The trenches inside the mesa define the central waveguide. The trenches in the mesa 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.
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.
### Narrow-linewidth Thermally-tuned SGDBR Laser

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

### Instantaneous Linewidth

![Graph showing instantaneous linewidth](image)

### Side Mode Suppression Ratio

![Graph showing side mode suppression ratio](image)

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### Coupled-Cavity Etched-Groove Tunable Laser with Regrowth

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

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