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

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UCSB
• 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 $\lambda$

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

Gain Medium

Mode Selection Filter

Mirror-1

L

Mirror-2

Gain Spectrum

Lasing Mode

Mode Selection Filter

Cavity Modes

$\lambda$
Distributed Bragg Reflector Laser

\[ m \lambda/2 = nL \]
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?

$$\Delta \lambda = \frac{\lambda^2}{2n_1L_1}$$

$$\Delta \lambda = \frac{\lambda^2}{2n_2L_2}$$

$$\Delta \lambda = \frac{\lambda^2}{2(n_1L_1 - n_2L_2)}$$
First integrated InP (laser – X) devices

- Coupling mirrors between integrated active and passive sections

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

Early tunable, single-frequency diode lasers

- Coupling mirrors between integrated active and passive sections

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


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

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.
Vernier Tuning Concept in Coupled-Cavity Lasers

Early Tunable DBR Work

Pioneering Active-Passive interfaces

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

• 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)

\[
\frac{\Delta \lambda_g}{\lambda_g} = \frac{\Delta \tilde{n}_{DBR}}{\tilde{n}_{DBR}}. \quad \frac{\Delta \lambda_m}{\lambda_m} = \frac{\Delta \tilde{n}_a L_a + \Delta \tilde{n}_p L_p + \Delta \tilde{n}_{DBR} L_{eff}}{\tilde{n}_{g_a} L_a + \tilde{n}_{g_p} L_p + \tilde{n}_{g_{DBR}} L_{eff}}.
\]
Multi-element Mirror 4-Section Tunable Laser

• Combine vernier with DBR

United States Patent

Coldren

MULTI-SECTION TUNABLE LASER WITH DIFFERING MULTI-ELEMENT MIRRORS

Inventor: Larry A. Coldren, Santa Barbara, Calif.
Assignee: The Regents of the University of California, Berkeley, Calif.
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Filed: Aug. 23, 1988
Int. Cl.4 H01S 3/10
U.S. Cl. 372/20; 372/29; 372/102; 372/31; 372/99; 372/101, 20, 92, 99, 372/102, 29, 32, 38
Field of Search 372/101, 20, 92, 99, 372/102, 29, 32, 38

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

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

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
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.

**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 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

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

Agility Communications formed to Commercialize in 1998.

Sampled-Grating DBR: Monolithic and Integrable

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

- 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

UCSB’90 → Agility’99–’05 → JDSU’05

Super-structure grating DBR laser

Distributed reflector and wavelength-tunable semiconductor laser

Tohmori, Yoshikuni, Ishii, Kano, Tamamura

--filed 3/3/1993
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.
Many other widely-tunables from 1993 onward

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

**GCSR--ADC-Altitun**

SGDBR + GACC

**Syntune-Finisar**

**Bookham-Oclaro**

**Modulated Grating Y-Branch (MG-Y) Laser**

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

Grating reflections add rather than multiply
Monolithic Integration of

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

Select wavelength by selecting which SOA to turn on
**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

**Chip size:** 0.4 x 2.15 mm²

**NEC**

**8 Microarray DFB-LDs**

**S-bent waveguides**

**Gain Phase Rear Mirror**

**DBR**

**Light Out**

**Window**

**SOA**

**MMI**

**AR-coating**
Widely deployed commercial “WDM” PICs

**EML’s:**

- **DFB Laser Section**
- **EA Modulator Section**
- **n-InP Substrate**
- **InGaAsP Grating**
- **Fe:InP Blocking**
- **p-InGaAs/InP Cap**
- **Selective-Area MOCVD Grown MQW-SCH**
- **HR**
- **AR**

Into XFP transceivers, etc.

**Tunables & Selectable Arrays:**

- **Modulated Light Out**
- **Tunable over C or L-band**
- **SG-DBR Laser**
- **Amplifier**
- **Front Mirror**
- **G**
- **Phase**
- **Rear Mirror**

**UCSB**

**AGILITY**

**JDSU**

**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)
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 degree 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

Phase Locked Coherent BPSK Receiver

**Homodyne** OPLL + Costas Loop $\rightarrow$ 1 cm$^2$ footprint

**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

ECOC ’12 with Rodwell and Johansson
Larger scale of integration, 32 channels
- Simpler layout: star coupler splitter; unequal channel length

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

**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

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Hybrid-Si Platform
--Vernier tuning with ring-mirrors

$I_{th} = 132$ mA

45 dB SMSR

41 nm Coarse Tuning

338 kHz linewidth
• 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