Abstract: Tunable semiconductor lasers continue to be in just about everyone’s list of important components for future fiber optic networks. Various designs will be overviewed with particular emphasis on the widely tunable (>32nm) types.
Contents

■ Why Tunable Lasers?

■ Basic Tuning Mechanisms

■ Examples of Tunable Lasers

■ Control of the Wavelength

■ Reliability Issues
Optical Network Architecture

Core

Edge

More bandwidth and services/$\rightarrow$
Low-cost components and agile architectures
Introduction

- Tunable lasers have been of great interest for some time
  - Dynamic networks with wavelength reconfigurability
    - Networking flexibility
    - Reduced cost
  - One time provisioning (OTP) and sparing seen as side benefits

- Current market conditions....
  - More cautious approach from carriers and system vendors
  - OTP and sparing are now the leading applications

- Tunable lasers are compared with DFB or EML
  - Important to do “apples to apples” comparison
    - Functionality
    - Performance
    - Total Cost of Ownership
Why Tunable Lasers?

- One time provisioning—inventory and sparing
- Field re-provisioning—new services without hardware change or truck roll
- Reconfigurable Optical Add/Drop Multiplexers (ROADM)—Drop and add any channel without demux/mux
- Wavelength conversion—Eliminates wavelength blocking without OEO line cards
- Photonic Switching—Eliminates many OEO line cards
- Wavelength Routing—Use passive optical core
Applications –
One time provisioning—the universal source

■ Laser is provisioned once only
■ Simplifies manufacturing
■ Drastically reduces inventory
■ Minimizes sparing to a manageable level
■ Simplifies forecasting
Applications – Re-provisioning

- Laser is provisioned many times remotely to set up new services
  - Seconds timeframe
  - Point and click or ultimately controlled automatically by software

- Can only be addressed using a widely tunable laser
  - Without severe constraints

- Drastically reduces inventory

- Simplifies forecasting
Applications – Re-configurable OADM

- Drop and Add without Demux and Mux of all channels
- Must be “hitless” filter tuning
- Eliminates mux/demux and OEO
- Tunable lasers are a key enabler
Applications – Photonic Switching 1

- Photonic switches require O-E-O on I/O to prevent blocking
- Tunability reduces O-E-O requirements in half
- Requires moderately fast switching (ms)
Applications – Wavelength Conversion

- Intersection of metro rings
- Wavelengths transition between rings
  - in optical domain
- Tunable lasers used to resolve wavelength blocking
  - Alternative is a bank of fixed wavelength lasers
Applications – Wavelength Routing
(Optical Packet Switching)

- High capacity, high density router function—need wide tuning
- Wavelength used to route traffic through passive device
- For Packets requires very fast switching
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Generic Single-Frequency Laser

\[ m \lambda/2 = \bar{n}L \]
Examples of Single-Frequency Lasers

- **DFB**
  - All-elements combined and distributed along length

- **DBR**
  - Elements separated with individual biases

- **External Cavity**
  - Gain block + external lens & grating

- **VCSEL**
  - Short cavity for mode selection
How Tunable Lasers Tune

Mode wavelength:

\[ m \frac{\lambda}{2} = \bar{n} L \]

Relative change in wavelength:

\[ \frac{\Delta \lambda}{\lambda} = \frac{\Delta \bar{n}}{\bar{n}} + \frac{\Delta L}{L} - \frac{\Delta m}{m} \]

Tuned by mode-selection filter (via index or grating angle)

Tuned by net cavity index change

Tuned by physical length change
Generic Tunable Single-Frequency Laser

\[ m \lambda / 2 = \overline{n}L \]

- Gain
- Cavity phase selection filter (\( \Delta n \))
- Mode-selection filter (\( \Delta m \))
- Tunable output

Possible modes (\( \Delta n, \Delta L \))
Solutions for Tunable Lasers

- **DBR Lasers**
  - Conventional DBR (<8 nm)
  - Extended Tuning DBR’s (≥ 32 nm)

- **External Cavity Lasers (≥ 32 nm)**
  - Littman-Metcalf/MEMs
  - Thermally tuned etalon

- **MEMS Tunable VCSEL (< 32 nm)**
  - Optically or electrically pumped

- **DFB Array (3-4 nm X #DFBs)**
  - On-chip combiner + SOA
  - Or, off-chip MEMs combiner
  - Thermally tuned
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Examples of Tunable Lasers

■ Narrowly tunable (not discussed further)
  – Temperature tuned DFBs → ~ 3nm
  – Narrowly tunable 2 or 3 section DBR lasers → ~ 8nm

■ DFB selectable arrays
  – Select DFB array element for coarse tuning + temperature tune for fine cavity mode tuning
  – Integrated on-chip combiners + SOAs or off-chip MEMs deflectors

■ External-cavity lasers
  – External grating reflector for mode-selection filter
  – Angle-tune mirror for mode selection—coarse tuning
  – Change length and/or phase section for fine tuning

■ MEMS Tunable VCSELs
  – Move suspended top mirror by electrostatic or thermal tuning
  – Single knob tuning for both coarse and fine

■ Widely tunable DBR lasers
  – Coarse tuning by index tuning of compound mirrors/couplers
  – Fine tuning by index tuning of phase section
  – Dual SGDBR or vertical-coupler + SGDBR mode selection filters
Wavelength-selectable light sources (WSLs) for wide-band DWDM applications

Feature

- DFB-LD-array-based structure
- Wide-band tunability
- Compact & stable
- Multi-λ locker module

Performance

- WSLs for S-, C-, L- bands (OFC’02)
  8 array, Δλ ~ 16 nm (ΔT = 25K) x 6 devices
- Multi λ-locker integrated
  Wide-band WSL module (OFC’02)
  Δλ ~ 40 nm (ΔT = 45K)

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WSLs for S-, C-, L- bands applications
- Lasing spectra -

- Lasing spectra -

$\Delta \lambda \sim 16 \text{ nm (} \Delta T \ 25K \text{)} \ @ 15 - 40 \ ^\circ \text{C}$

6 devices $\rightarrow$ 135 channels @100-GHz ITU-T grid

SMSR > 42 dB

$P_f > \sim 10 \text{ mW} \ @ \ I_{DFB} = 100 \text{ mA}, \ I_{SOA} = 200 \text{ mA}$
Fujitsu DFB Array Integrated Tunable Laser

Monolithic Integration of
- Multi-wavelength DFB laser array
- Passive optical combiner
- Semiconductor optical amplifier

Fujitsu Laboratories Ltd.
Fujitsu Wavelength Tuning Characteristics

Temperature tuning

Spectra at 32 wavelengths

Fujitsu Laboratories Ltd.
Santur Switched DFB Array

- 12 element DFB array, each temperature tuned 3nm for 36nm total tuning range - only one laser on at a time
- MEMS mirror couples the selected laser to fiber

Advantages:
- DFB characteristics (optical quality, reliability, wavelength stability)
- No SOA, tuning sections, phase-sensitive mechanics
- High yield, low cost passive alignment (MEMS does the rest)
- Built-in shutter/VOA
Santur 20 mW Module Performance

- Full band tunability (36nm C-band, 42nm L-band)
- Built-in wavelength locker (25GHz channel spacing)
- >50dB SMSR, 2MHz linewidth
- Typical tuning time ~ 2sec
- Resistant to shock and vibe with no servo (10G causes < 0.2dB fluctuation in power)
Intel External-Cavity Approach
(acquired from New Focus)

- Double sided external cavity laser design, well known in test and measurement applications
- **Temperature tuned etalon** replaces mechanical tuning device
- No moving parts, **but challenging packaging requirements**
Littman-Metcalf Cavity (after New Focus)
Iolon External-Cavity Laser with MEMs Mirror Movement
Tunable VCSELs (optically pumped)

- Cortek-Nortel-Bookham?

- Component technologies
  - MEMS
  - Thin Film
  - InP Laser
  - Packaging

- Advantages:
  - High Power
  - Wide Tuning Range
  - Continuously Tunable
Core Technologies for Tunable Transmit/Receive

Monolithic MEMS-based tuning
Single cavity VCSEL-based laser
VCSELs tested at a wafer levels before substantial cost and time expended to determine wafer yield

VCSEL: Vertical Cavity Surface Emitting Laser
MEMS: Micro-Electrical Mechanical System
Many more 7 – 10 nm designs
Extended tuning range: SSGDBR--NEL

Phase modulated gratings
Extended tuning range: GCSR--ADC-Altitun

SGDBR + GACC

Gain 400\(\mu\)m
Coupler 600\(\mu\)m
Phase 150\(\mu\)m
Reflector S-DBR 900\(\mu\)m

\(\lambda_g = 1.3\ \mu\)m
\(\lambda_g = 1.55\ \mu\)m
\(\lambda_g = 1.38\ \mu\)m

\text{Wavelength [nm]}

\text{Coupler current [mA]}

\text{Reflector current [mA]}

\text{Extended tuning range: GCSR--ADC-Altitun}
Agility’s Extended Tuning Range Technology: Widely Tunable SGDBR Lasers
Sampled Grating Tunable Lasers

5-10X Tuning Range of DBR
Reliable, Manufacturable InP Technology
Can Cover C band, L band or C + L
Advantages of Monolithic Integration

- Widely Tunable SG-DBR Laser with integrated SOA and EAM

Advantages:
- smaller space (fewer packages)
- lower cost (fewer package components)
- lower power consumption (lower coupling losses)
- high reliability (fewer parts)
Fast Wavelength Switching of SGDBR Lasers

Packet Switching Applications

- Current source rise time can be designed for application.
- Inherent laser limit is in ~ 2-10 ns range.
- Thermal transients can complicate rapid switching.
SG-DBR Laser with Integrated SOA

- High Power Widely Tunable Laser:
  - >100 50 GHz ITU Channels
  - Fiber coupled power = 13dBm = 20mW
  - SMSR > 40 dB
  - SOA: Power leveling, blanking, and VOA w/o degradation of SMSR
  - Channel switching time (software command → verified channel) < 10 ms
- **RIN** is only weakly dependent on output power (SOA current).
- **Linewidth** is less than 2.5 MHz across all wavelengths
  - Scales with Laser Power as expected.
SGDBR-SOA-EAM

Transmission Characteristics

Dispersion penalty at $10^{-10}$ errors/s error rate for 200, 275, and 350 km of standard SMF for 38 ITU channels sampled across C-band.
SGDBR-SOA-EAM
RF-ER, $P_{\text{ave}}$, & VOA Operation

- Ave. power $>5$ dBm and RF ER $>10$ dB across C-band
- Output power dynamic range of $\sim 10$ dB w/ small change in SMSR and Wavelength (open loop operation)
OC-192 Operation of EAM

- Integration technology compatible with higher bit rates
- > 10 dB RF ER across C-band
- Not optimized, improvements to come

PRBS $2^{31}-1$, $V_{p-p} = 3V$
MZ-SGDBR (UCSB)

Curved waveguides 200µm

MMI Length: 96µm

Width: 9µm

Taper: 20µm
Extinction & Chirp: MZ-SGDBR (UCSB)

- > 20 dB extinction with 2V drive
- Negative chirp when increasing reverse bias ‘turns on’ modulator

\[
\alpha_{\text{chirp}} = \frac{\Delta n_{\text{eff (real)}}}{\Delta n_{\text{eff (imag)}}} = \frac{2\Delta \phi}{\Delta \alpha L}
\]

Measured by the Devaux method

**Chirp parameter as function of DC extinction curve for 550µm**
MZ-SGDBR RF Performance: Lumped (UCSB)

- BCB for low capacitance
- Lumped drive—can improve with traveling wave electrodes

10Gbit/s
Eye $10^{15}$-1
PRBS

Normalized S21

-4V Bias

Frequency (GHz)
Control Issues

■ Finding the desired channel
  – Look-up tables vs. channel counting?
  – Is global wavelength monitor required?
  – Must look-up tables be updated over life?

■ Staying on the desired channel
  – Is locker required to meet spec?
  – Is single knob control from locker sufficient over life?
Generic Tunable Single-Frequency Laser

\[ m \lambda / 2 = \bar{n}L \]
# Control comparison across types

<table>
<thead>
<tr>
<th>Laser</th>
<th>$\lambda_{\text{coarse}}$</th>
<th>$\lambda_{\text{fine}}$</th>
<th>Amplitude</th>
<th>VOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFB Array/SOA</td>
<td>$V_{\text{array}}(j)$</td>
<td>$T$</td>
<td>$I_{\text{gain}}(j)$</td>
<td>$\Delta I_{\text{SOA}}$</td>
</tr>
<tr>
<td>DFBs/MEMs</td>
<td>$V_{M1}, V_{M2}(j)$</td>
<td>$T$</td>
<td>$I_{\text{gain}}(j)$</td>
<td>$V_{M1}, V_{M2}(j)$</td>
</tr>
<tr>
<td>SGDBR/SOA</td>
<td>$I_{m1}, I_{m2}$</td>
<td>$I_\phi$</td>
<td>$I_{\text{SOA}}$</td>
<td>$\Delta I_{\text{SOA}}$</td>
</tr>
<tr>
<td>Ext. Cavity</td>
<td>$V_{M\theta}$</td>
<td>$V_{ML}, I_\phi$</td>
<td>$I_{\text{gain}}$</td>
<td>$V_{\text{Mshutter}}$</td>
</tr>
<tr>
<td>VCSEL/MEMs</td>
<td>$V_{M1}$</td>
<td>$V^*_{M1}$</td>
<td>$I_{\text{gain}}$</td>
<td>$\text{--------}$</td>
</tr>
</tbody>
</table>
Iolon Control Scheme for Ext. Cavity Laser
Agility Control of SG-DBR Lasers

Control Circuitry

- DWDM DBR
  - Power Control
  - Temperature Control (fixed)
  - Wavelength Locking
  - Mirror Control (Locking?)

- DWDM DFB comparison
  - Power Control
  - Temperature Control
  - Wavelength Locking

Light Out

Wavelength Locking
Mirror Control
Power Control

SOA Front Mirror Gain Phase Rear Mirror

SG-DBR
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Wavelength Reliability

■ It’s not enough to just put out the right power in a single mode for a long time (old criterion)

■ Prior to end-of-life of a multi-channel DWDM source, power & wavelength must be in spec.

■ Intimately linked to wavelength control (or lack of it)
  - Finding the desired channel
    - Look-up tables vs. channel counting?
    - Is global wavelength monitor required?
    - Must look-up tables be updated over life?
  - Staying on the desired channel
    - Is locker required to meet spec?
    - Is single knob control from locker sufficient over life?

■ If look-up tables must be updated, how can this be done reliably?
What causes the wavelength to change

\[ \frac{\Delta \lambda}{\lambda} = \frac{\Delta \bar{n}}{\bar{n}} + \frac{\Delta L}{L} - \frac{\Delta m}{m} \]

- Tuned by mode-selection filter (via index or grating angle)
- Tuned by net cavity index change
- Tuned by physical length change

**Physical Causes, assuming a fixed look-up table:**
- \( \Delta \bar{n} \) – Changes in internal temperature, \( T_{\text{int}} \), or carrier lifetime, \( \tau_c \)
- \( \Delta L \) – Physical movements—solder relaxation, MEMs charging
- \( \Delta m \) – \( \Delta n \) of DBR, \( \Delta \theta \) of ext. grating, or MEMs charging
## Critical issues for wavelength stability

<table>
<thead>
<tr>
<th>Laser</th>
<th>Variables in Table</th>
<th>*Critical $\Delta \lambda$ issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFB Array/SOA</td>
<td>$j, I_g(j), T, I_{SOA}$</td>
<td>$\Delta n(T_{int}) \leftrightarrow \Delta I_g$</td>
</tr>
<tr>
<td>DFBs/MEMs</td>
<td>$j, I_g(j), T, V_{M1}(j), V_{M2}(j)$</td>
<td>$\Delta n(T_{int}) \leftrightarrow \Delta I_g$</td>
</tr>
<tr>
<td>SGDBR/SOA</td>
<td>$I_{m1}, I_{m2}, I_\phi, I_{SOA}$</td>
<td>$\Delta n_{DBR}(\tau_c) \rightarrow \Delta m$</td>
</tr>
<tr>
<td>Ext. Cavity</td>
<td>$V_{M\theta}, V_{ML}, I_\phi, I_{gain}, V_{Mshut}$</td>
<td>$\Delta L(V_M), \Delta m(V_M), \Delta n(T_{int}) \leftrightarrow \Delta I_g$</td>
</tr>
<tr>
<td>VCSEL/MEMs</td>
<td>$V_{M1}, I_g$</td>
<td>$\Delta L(V_M)$</td>
</tr>
</tbody>
</table>

*Requiring table update or global channel locator
## Estimated Open-loop Wavelength Shifts

<table>
<thead>
<tr>
<th>Laser</th>
<th>Critical $\Delta \lambda$ issues</th>
<th>$\Delta \lambda$ @ EOL$_{\text{gain}}$ (No table update)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFB Array/SOA</td>
<td>$\Delta n(T_{\text{int}}) \leftrightarrow \Delta I_g$</td>
<td>40GHz (10GHz/SOA feedback)</td>
</tr>
<tr>
<td>DFBs/MEMs</td>
<td>$\Delta n(T_{\text{int}}) \leftrightarrow \Delta I_g$</td>
<td>40GHz</td>
</tr>
<tr>
<td>SGDBR/SOA</td>
<td>$\Delta n_{\text{DBR}}(\tau_c) \rightarrow \Delta m$</td>
<td>&lt;10GHz</td>
</tr>
<tr>
<td>Ext. Cavity</td>
<td>$\Delta L(V_M)$, $\Delta m(V_M)$, $\Delta n(T_{\text{int}}) \leftrightarrow \Delta I_g$</td>
<td>100GHz (MEMs charging)</td>
</tr>
<tr>
<td>VCSEL/MEMs</td>
<td>$\Delta L(V_M)$</td>
<td>1000GHz</td>
</tr>
</tbody>
</table>

- Only SGDBR lands on correct mode near EOL Open-loop
- Others require global channel monitor or the like
Effects of SGDBR Mirror Aging: Measurement

- Corresponds to > 100 yrs of operation
- Aging gives fixed amount of root current increase to provide a shift in the “mode map” to higher current.
Very High SGDBR Wavelength Stability and Reliability

- ~ $10^6$ Device Hours measured.
- Very low Bragg Wavelength Aging Rates < 0.5 pm/year at worse case.
- Gain and SOA sections have similar MTTF and failure distribution.
- OK for open-loop operation → no mode hops or incorrect channels

**Figure:**
- MTTF ~ 350 yrs
- $\sigma \sim 0.56$
- $E_a = 0.55$ eV, $n=2$
- $\lambda_{\text{FITS}} @ 25$ yrs < 1

**Graph:**
- Cumulative Failures, %
- Mirror Life Time (yrs)
- $0.1 \ 1 \ 5 \ 20 \ 50 \ 80 \ 95 \ 99 \ 99.9$
- $10^1 \ 10^2 \ 10^3 \ 10^4$
- Exponential distribution fit

**Legend:**
- + Mirrors - Experimental
- - Mirrors - Least Squares Fit
SGDBR Laser/SOA FITs vs. Time

- Open-loop failure rate vs. time
- Gain section determines EOL
- Closed-loop mirror control has also been implemented to monitor any drift
SGDBR vs DFB Chip Reliability

- Historically, DBR Reliability WAS Poor…

- Defects in the grating area, found to be primary cause of DBR failure.

- Improvement to re-growth (InP/InP) and minimal grating area of SG-DBR, allow equivalent or better performance vs. DFB’s.

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Summary

- Tunable lasers can reduce operational costs
- Narrowly tunable versions have some short term inventory/sparing cost advantages but newer full-band types offer many further opportunities
- Several configurations have emerged for current applications
- Monolithic integration offers significant potential for reducing size, weight, power, & cost
- Wavelength control issues still exist for many configurations. Look-up table updating and/or global channel monitors are necessary in some cases.
- Reliability has been proven for the SGDBR version without any updating of the look-up tables or need for channel searching