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.

Tunable Semiconductor Lasers

a tutorial

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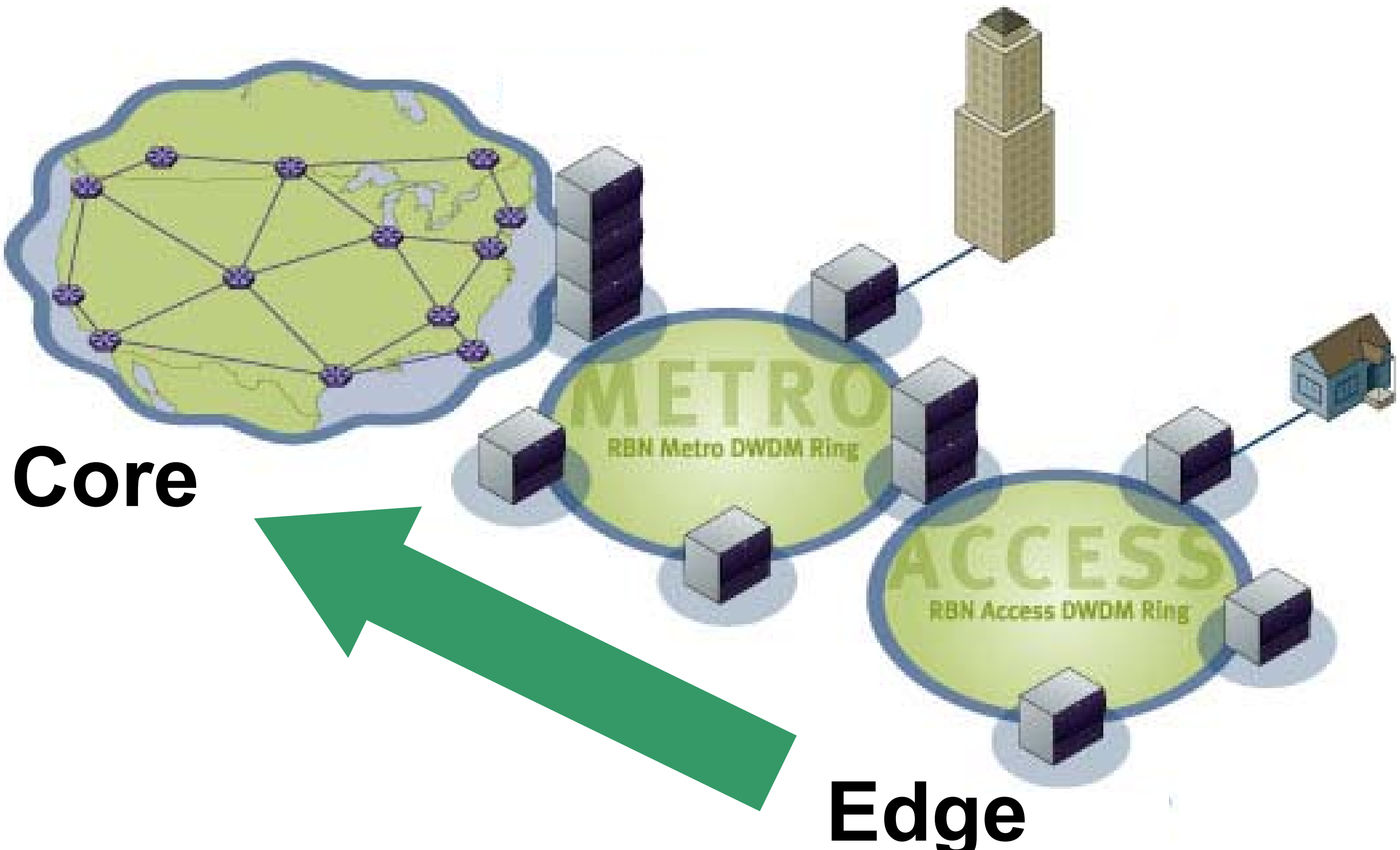
Contents

- Why Tunable Lasers?
- Basic Tuning Mechanisms
- Examples of Tunable Lasers
- Control of the Wavelength
- Reliability Issues

Optical Network Architecture



More bandwidth and services/$→
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

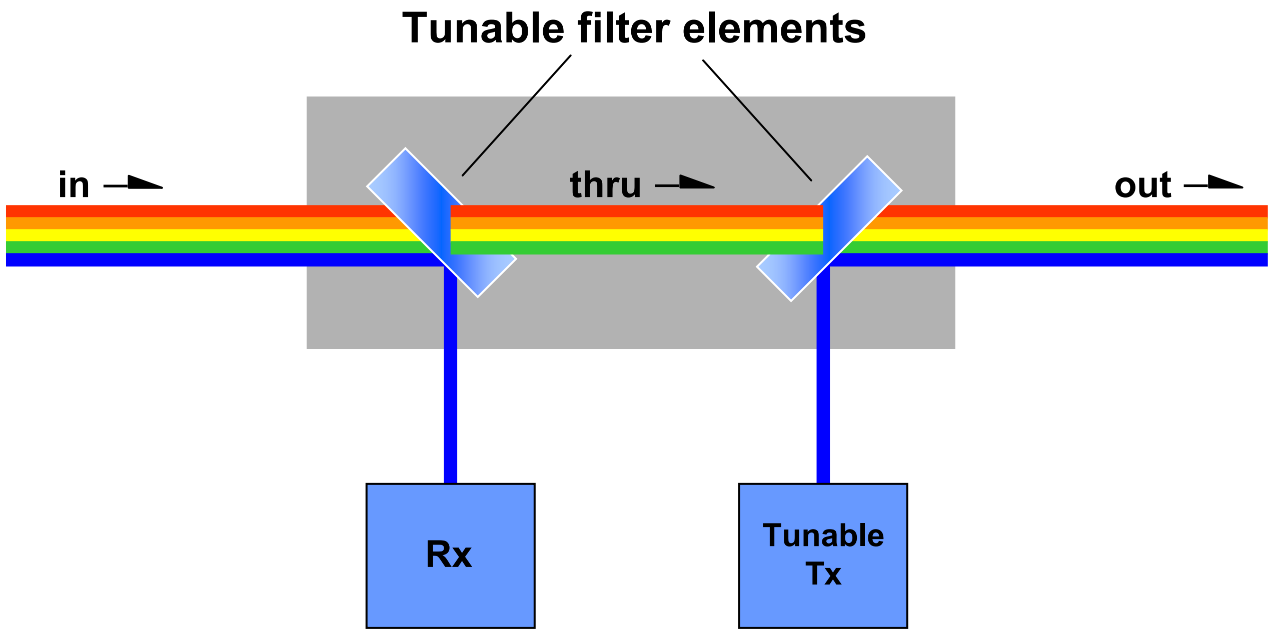
Applications – One time provisioning—the universal source

- Laser is provisioned once only
- Simplifies manufacturing
- Drastically reduces inventory
- Minimizes sparing to a manageable level
- Simplifies forecasting

Applications – Re-provisioning

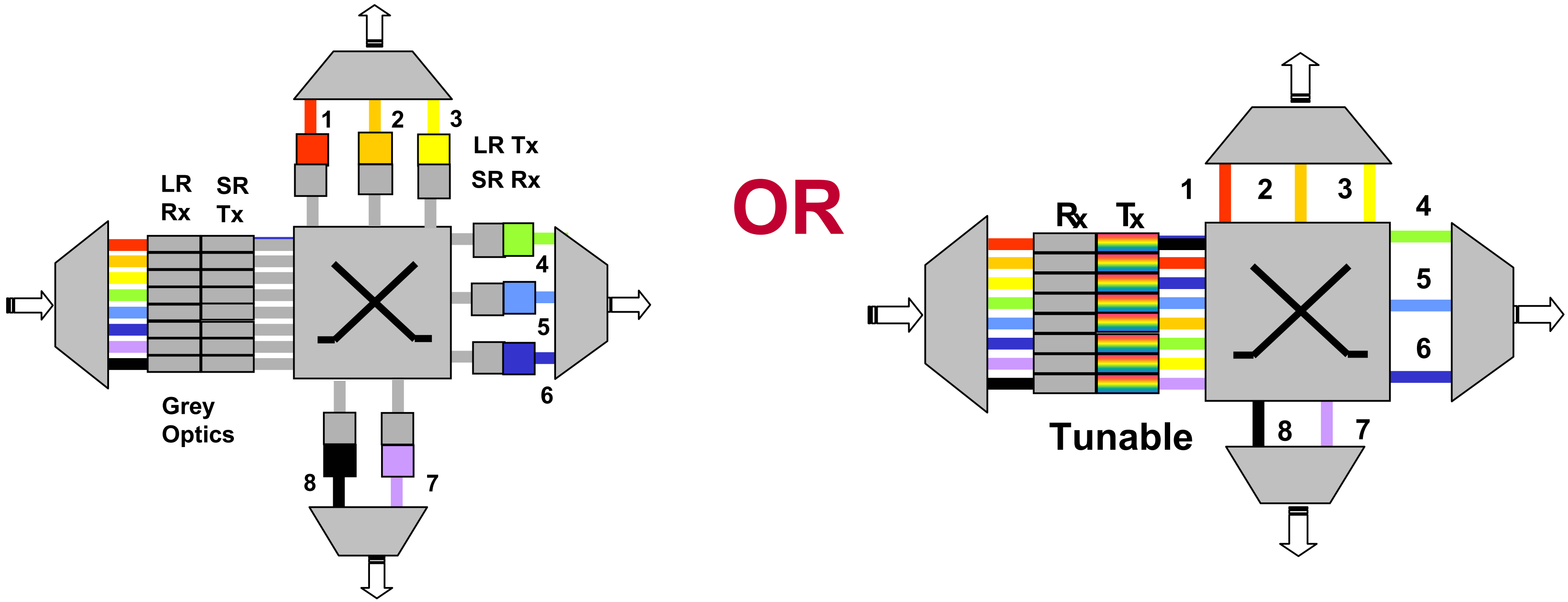
- **Laser is provisioned many times remotely to set up new services**
  - Seconds timeframe
  - Point and click or ultimately controlled automatically by software
- **Can only be addressed using a widely tunable laser**
  - Without severe constraints
- **Drastically reduces inventory**
- **Simplifies 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

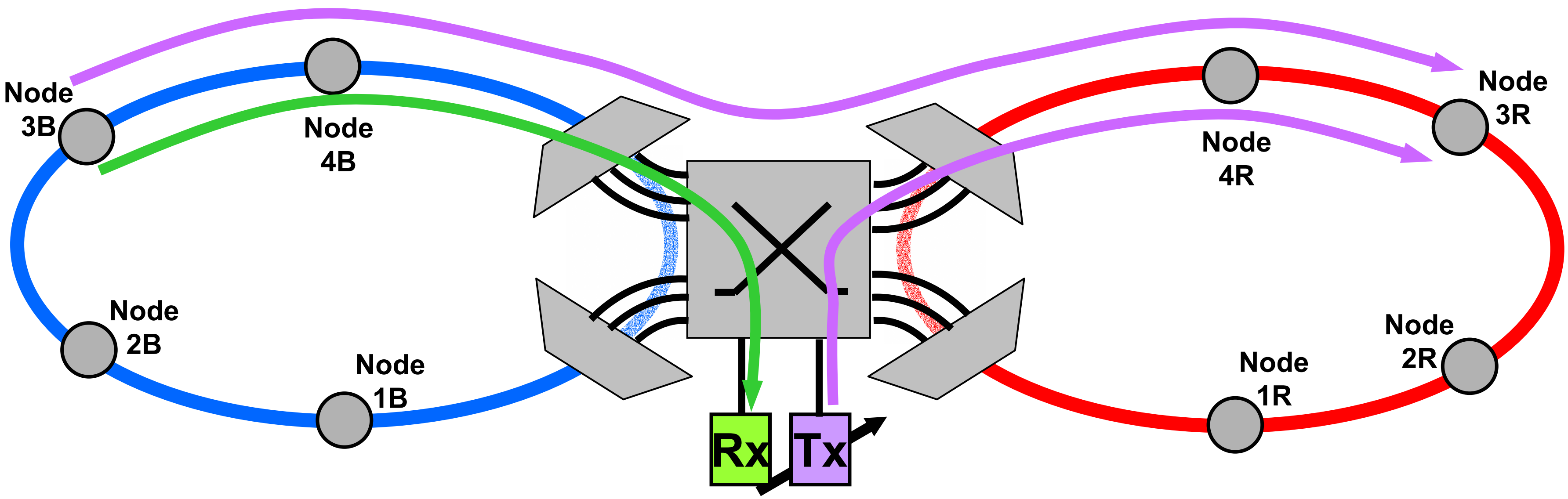
Applications – Photonic Switching 1



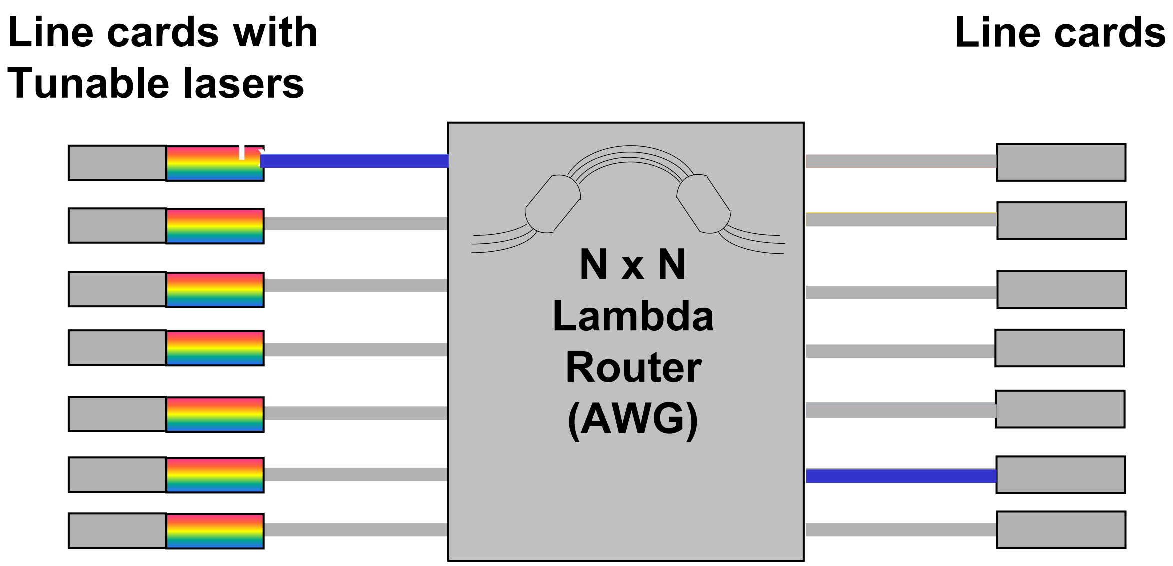
- Photonic switches require O-E-O on I/O to prevent blocking
- Tunability reduces O-E-O requirements in half
- Requires moderately fast switching (ms)

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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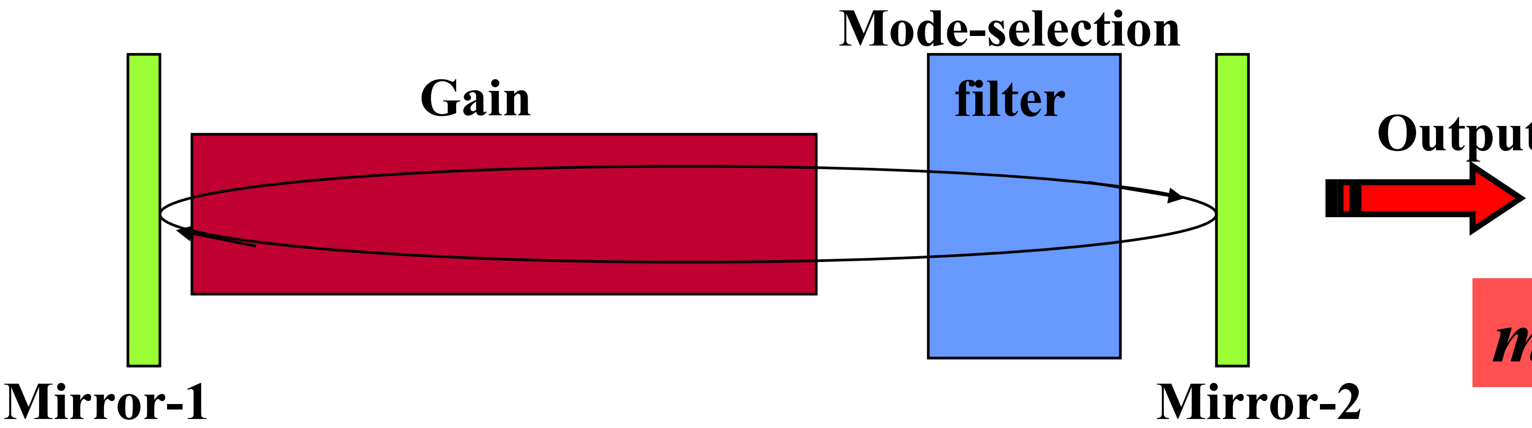
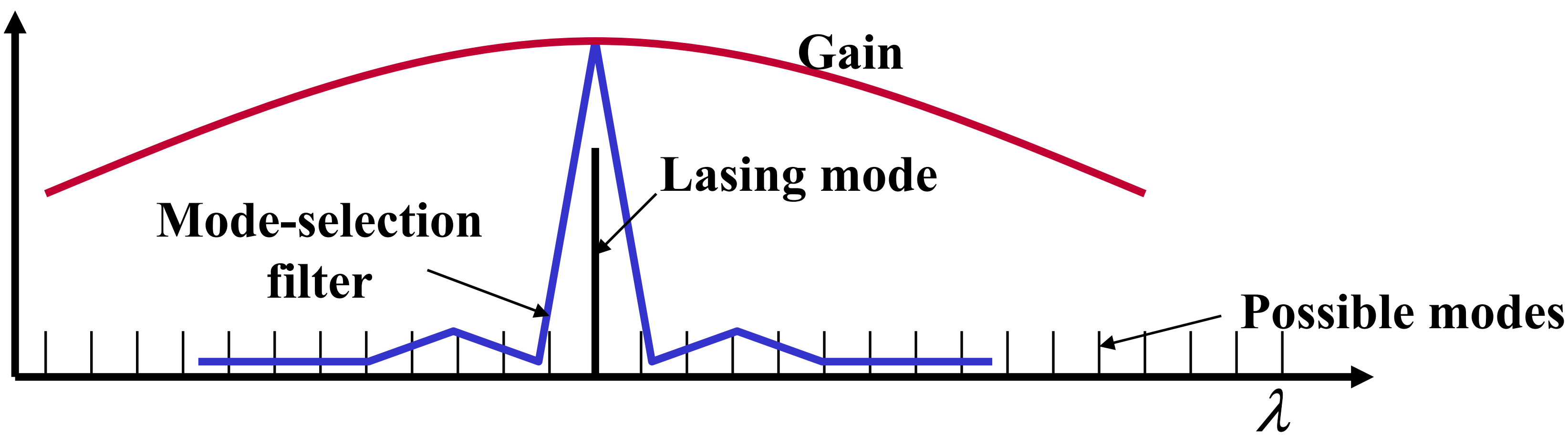
Generic Single-Frequency Laser

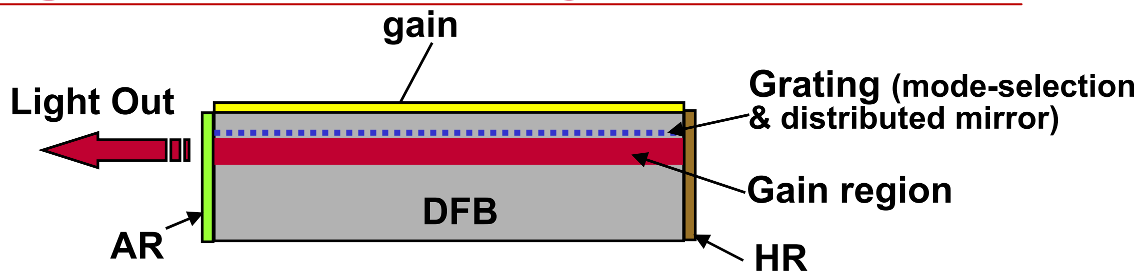


$$m\lambda/2 = \bar{n}L$$

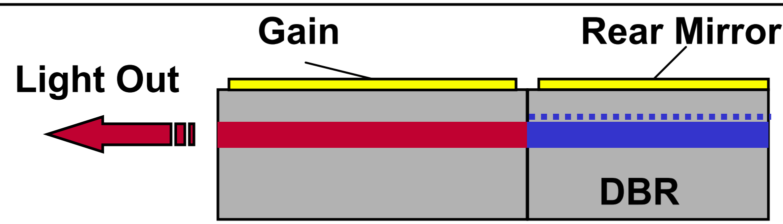


Examples of Single-Frequency Lasers

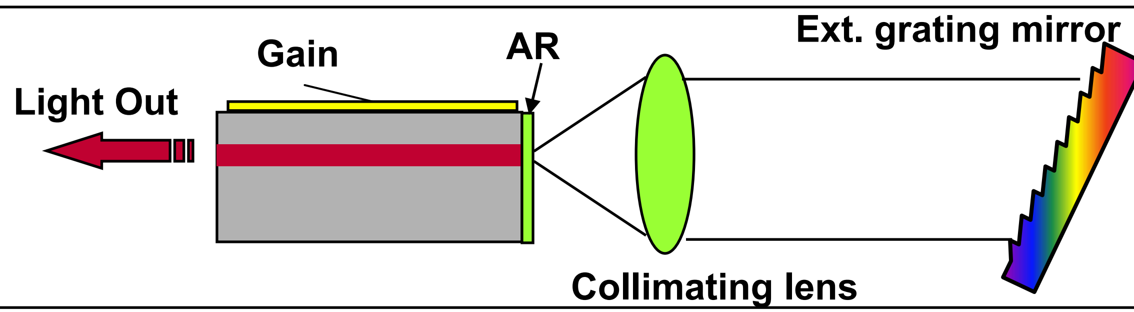
- **DFB**
  - All-elements combined and distributed along length



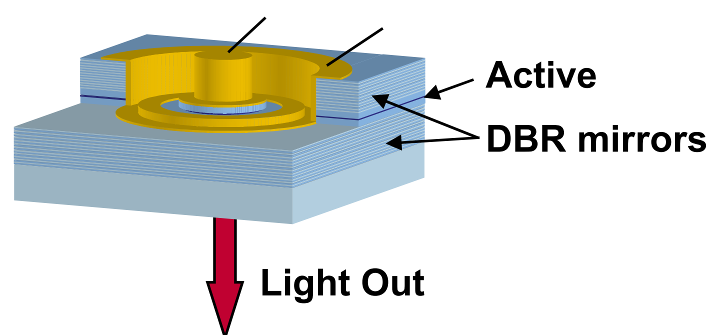
- **DBR**
  - Elements separated with individual biases



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



- **VCSEL**
  - Short cavity for mode selection



How Tunable Lasers Tune

Mode wavelength:

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

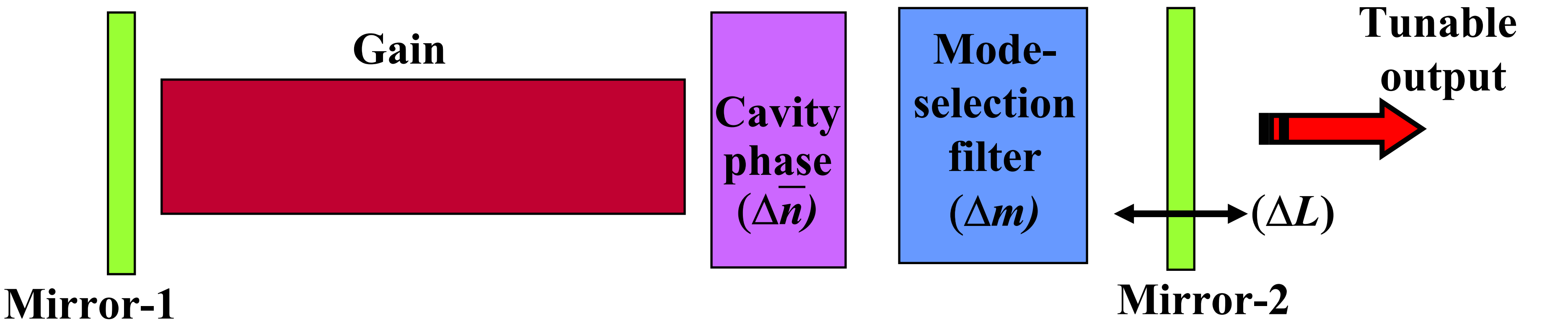
- Mode number: m
- Wavelength: λ
- Effective index: $\bar{n}$
- Effective Cavity length: L

Relative change in wavelength:

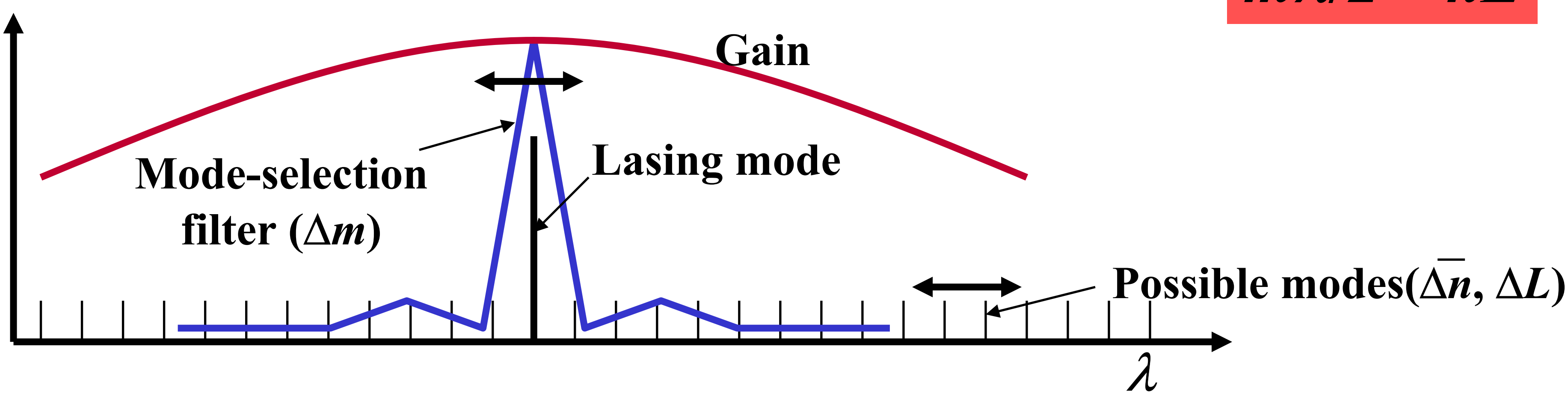
$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\bar{n}}{\bar{n}} + \frac{\Delta L}{L} - \frac{\Delta m}{m}$$

- $\frac{\Delta\bar{n}}{\bar{n}}$: Tuned by net cavity index change
- $\frac{\Delta L}{L}$: Tuned by physical length change
- $\frac{\Delta m}{m}$: Tuned by mode-selection filter (via index or grating angle)

Generic Tunable Single-Frequency Laser

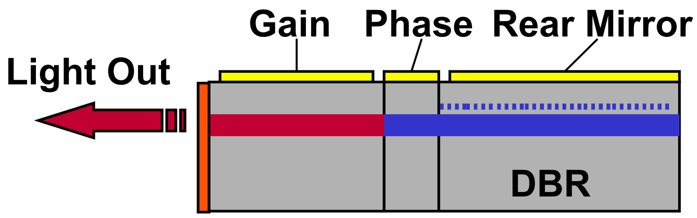


$$m\lambda/2 = \bar{n}L$$

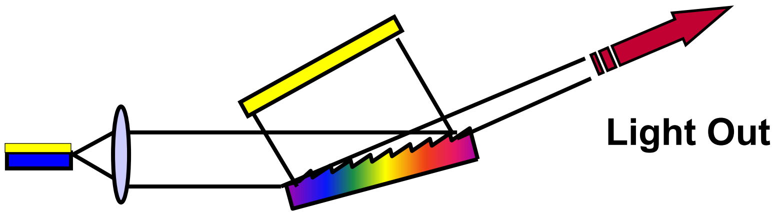


Solutions for Tunable Lasers

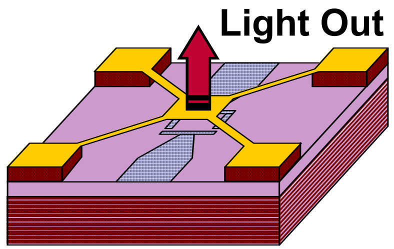
- **DBR Lasers**
  - Conventional DBR (<8 nm)
  - Extended Tuning DBR's (≥ 32 nm)



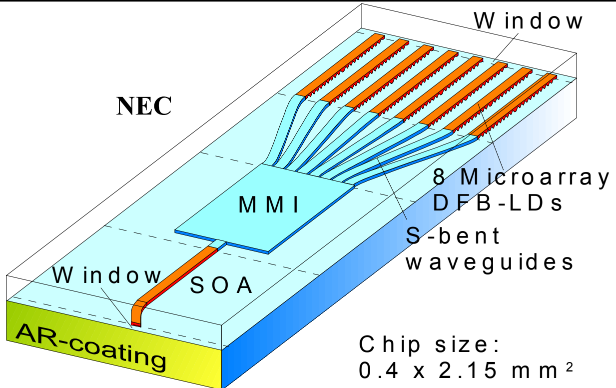
- **External Cavity Lasers (≥ 32 nm)**
  - Littman-Metcalf/MEMs
  - Thermally tuned etalon



- **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

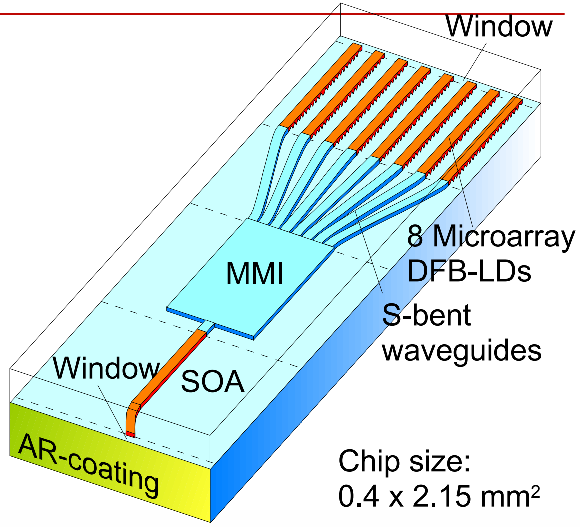
- **Narrowly tunable (not discussed further)**
  - Temperature tuned DFBs→ ~ 3nm
  - Narrowly tunable 2 or 3 section DBR lasers→ ~ 8nm
- **DFB selectable arrays**
  - Select DFB array element for coarse tuning + temperature tune for fine cavity mode tuning
  - Integrated on-chip combiners + SOAs or off-chip 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



Schematic of wide-band WSL

Performance

- *WSLs for S-, C-, L- bands (OFC'02)*

  8 array, Δλ ~ 16 nm (ΔT = 25K) x 6 devices

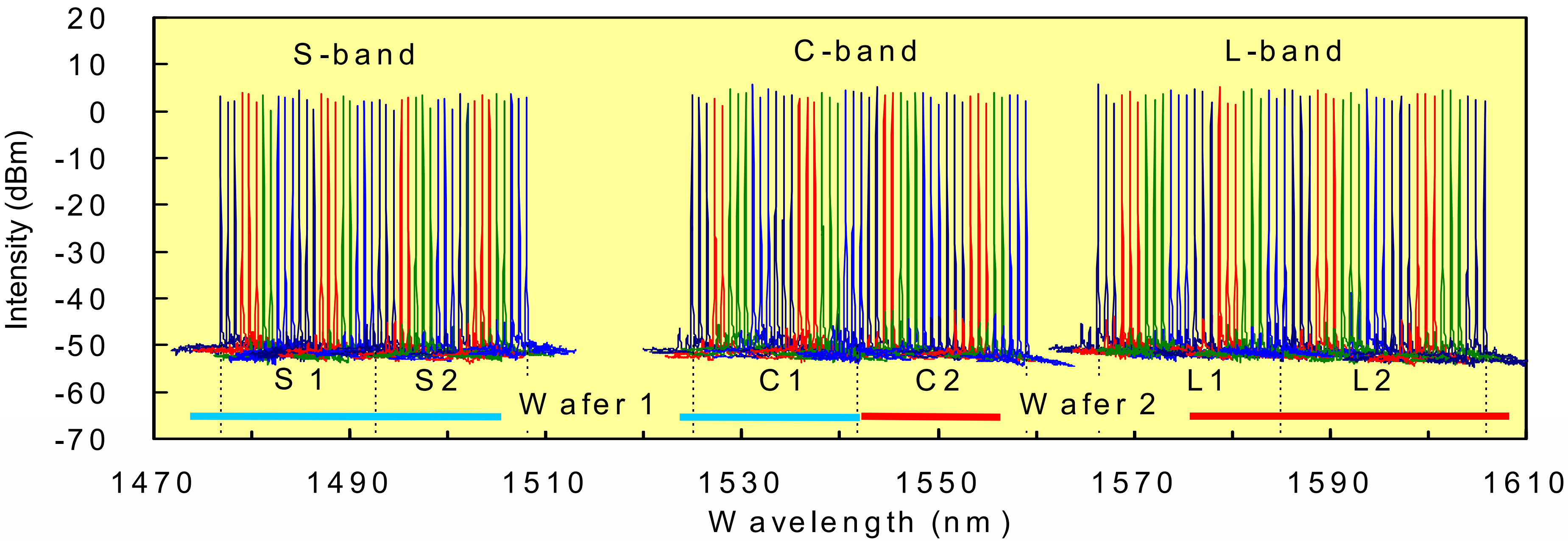
- *Multi λ-locker integrated*

  Wide-band WSL module (OFC'02)

  Δλ ~ 40 nm (ΔT = 45K)

Multi λ–locker integrated Wide-band WSL module

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



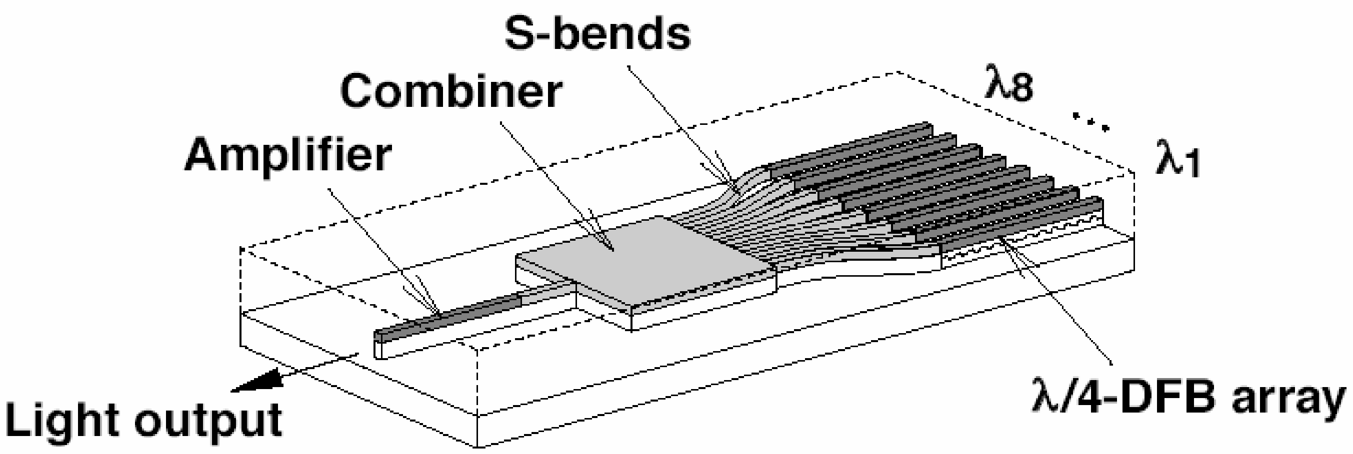
- $\Delta\lambda$ ~ 16 nm (ΔT 25K) @15 - 40 ℃
- 6 devices → 135 channels @100-GHz ITU-T grid
- SMSR > 42 dB
- P_f > ~ 10 mW @ I_{DFB}= 100 mA, I_{SOA}= 200 mA

Empowered by Innovation NEC

Fujitsu DFB Array Integrated Tunable Laser

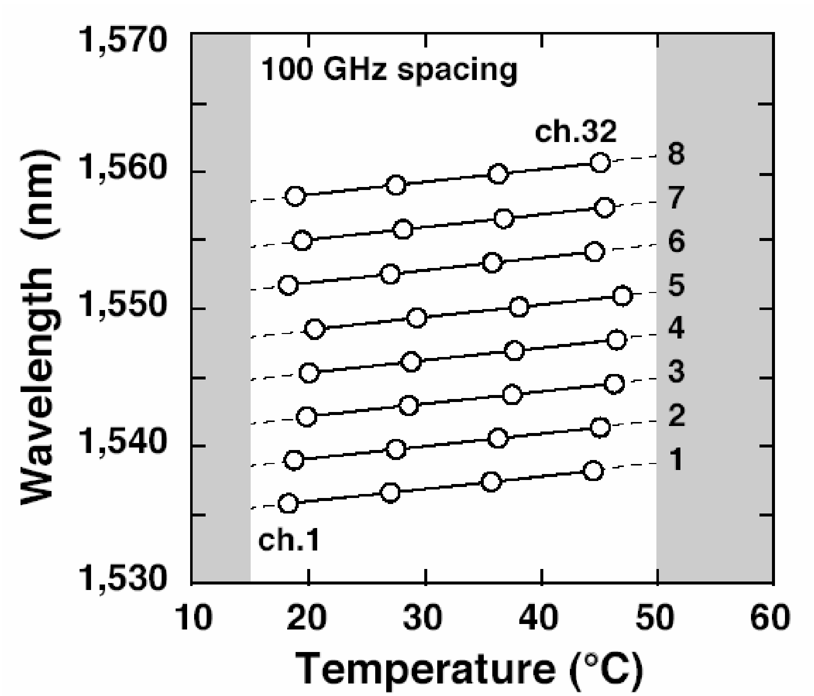
Monolithic Integration of

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

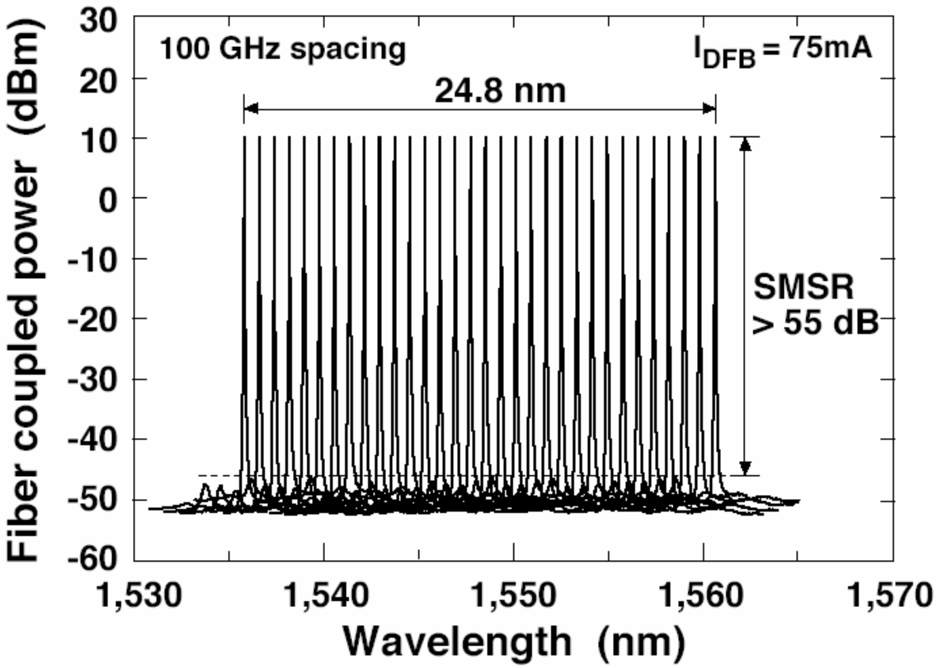


0.5 × 1.8 mm

Fujitsu Wavelength Tuning Characteristics

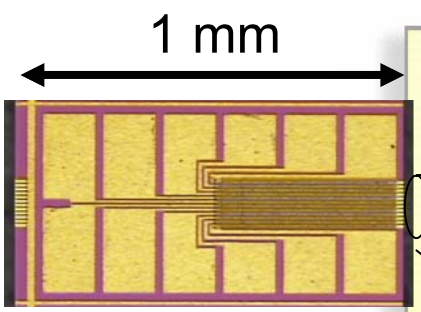


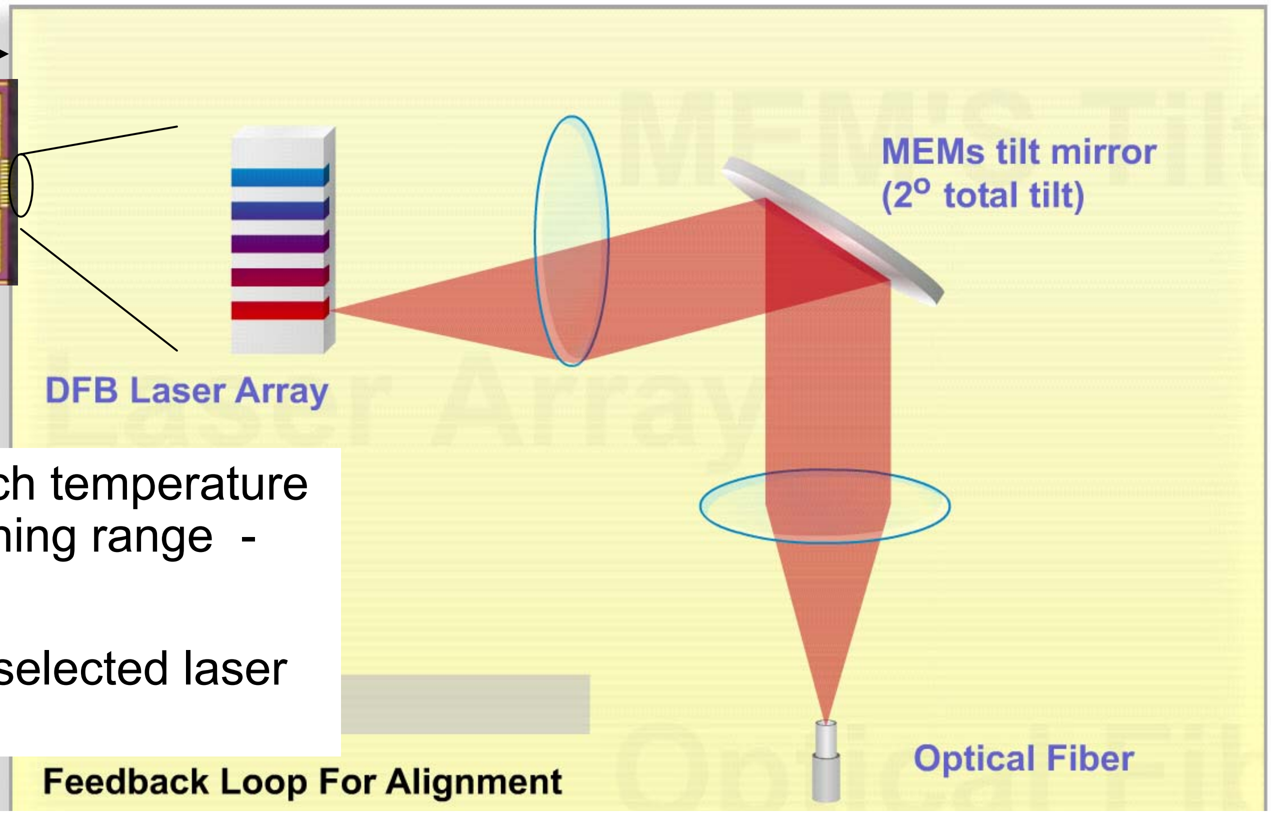
Temperature tuning



Spectra at 32 wavelengths

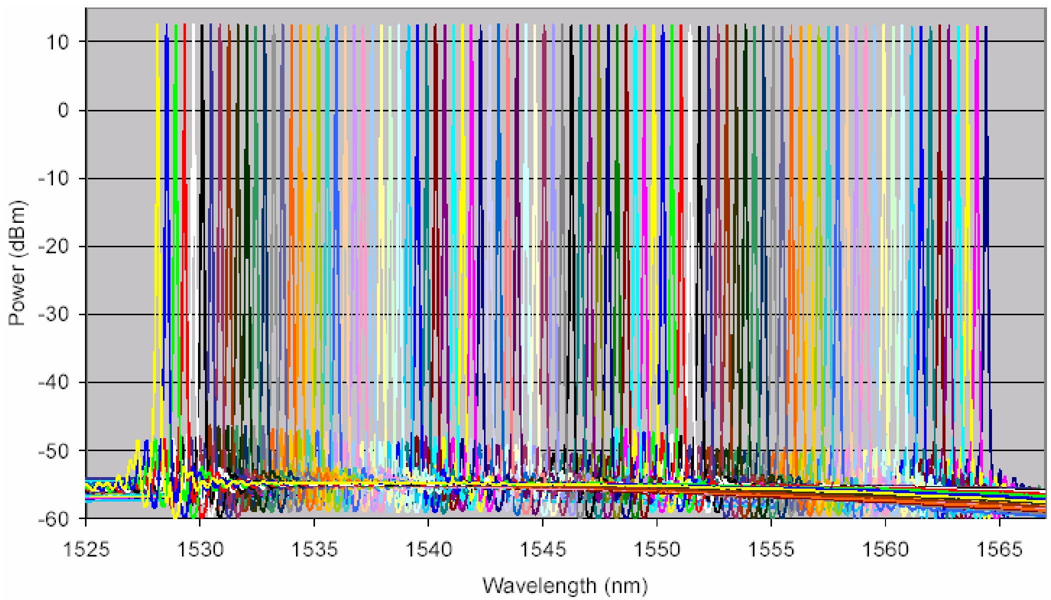
Santur Switched DFB Array





- 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

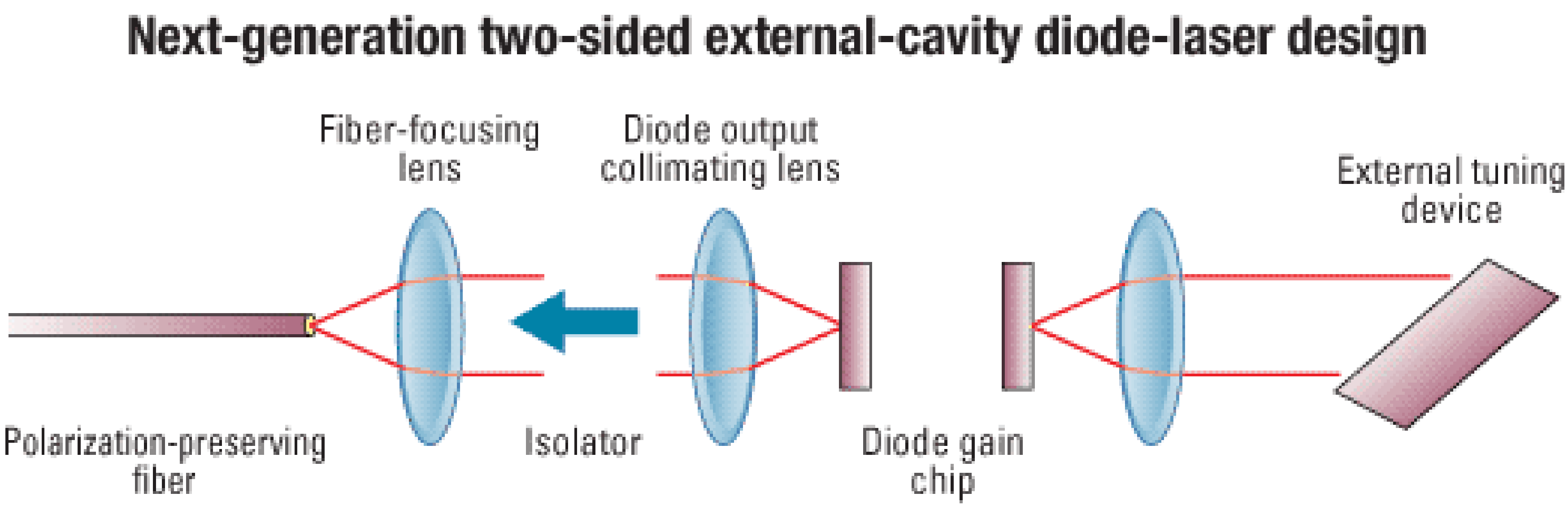
Santur 20 mW Module Performance



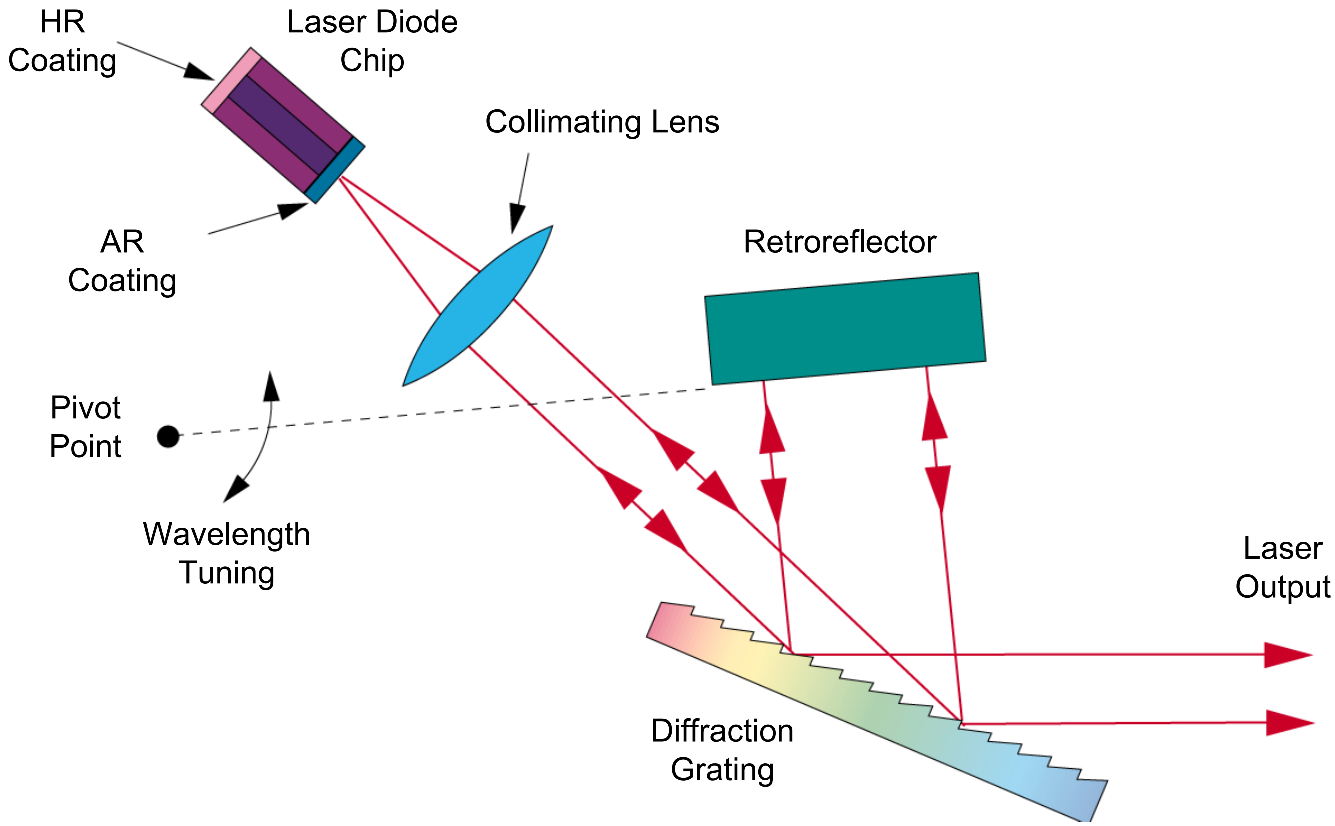
- Full band tunability (36nm C-band, 42nm L-band)
- Built-in wavelength locker (25GHz channel spacing)
- >50dB SMSR, 2MHz linewidth
- Typical tuning time ~ 2sec
- Resistant to shock and vibe with no servo (10G causes < 0.2dB fluctuation in power)

Intel External-Cavity Approach
(acquired from New Focus)

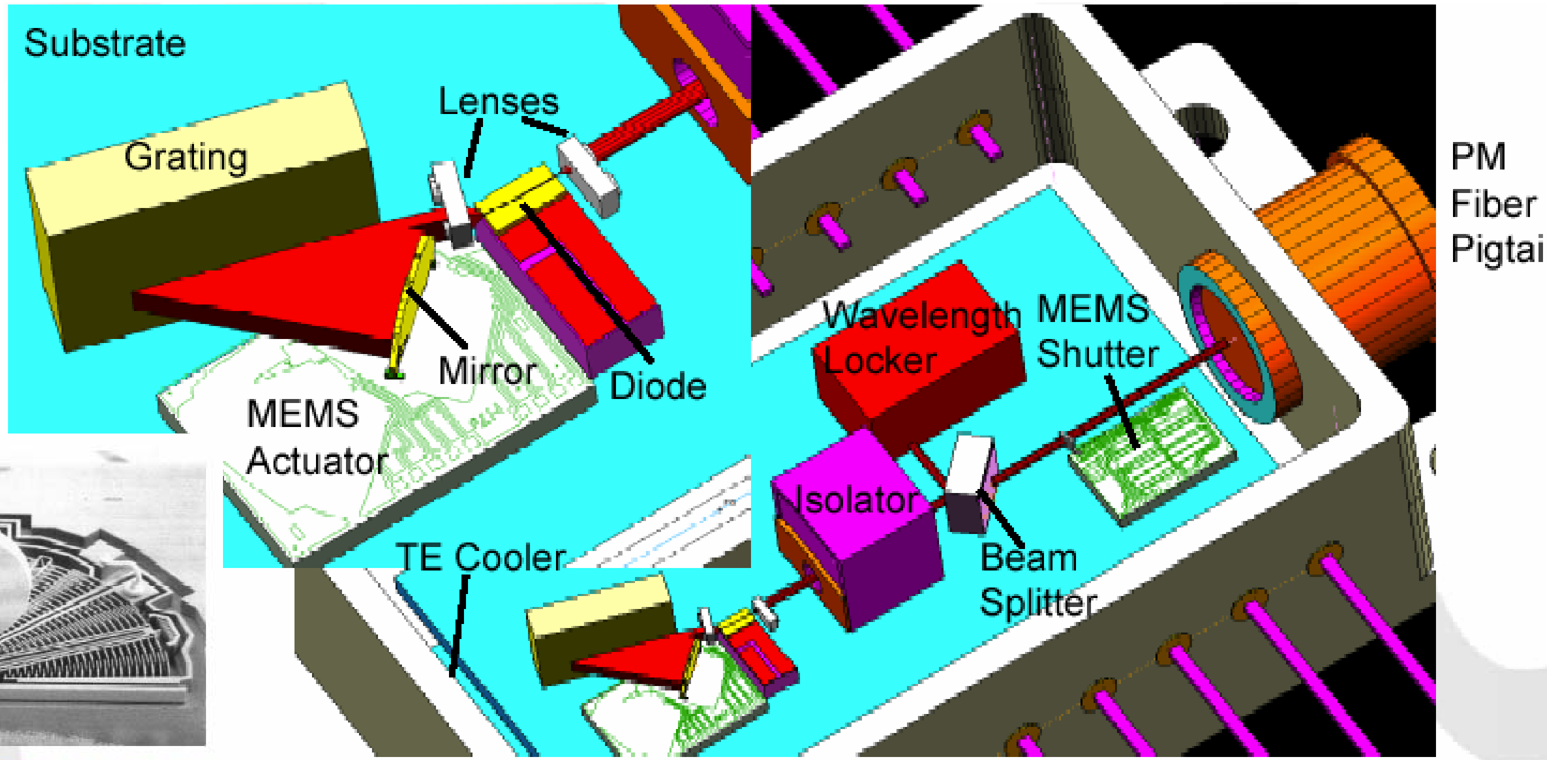
- Double sided external cavity laser design, well known in test and measurement applications
- **Temperature tuned etalon** replaces mechanical tuning device
- No moving parts, **but challenging packaging requirements**

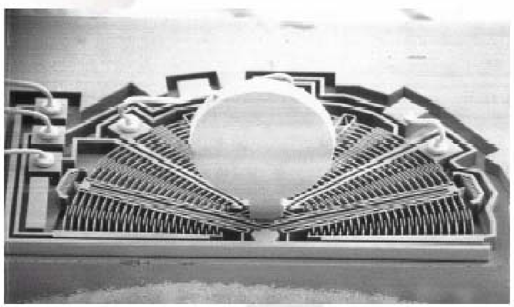


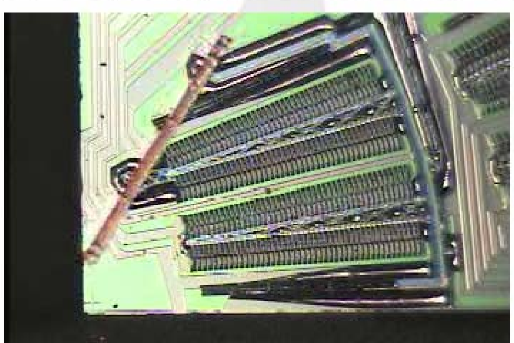
Littman-Metcalf Cavity (after New Focus)



Iolon External-Cavity Laser with MEMs Mirror Movement



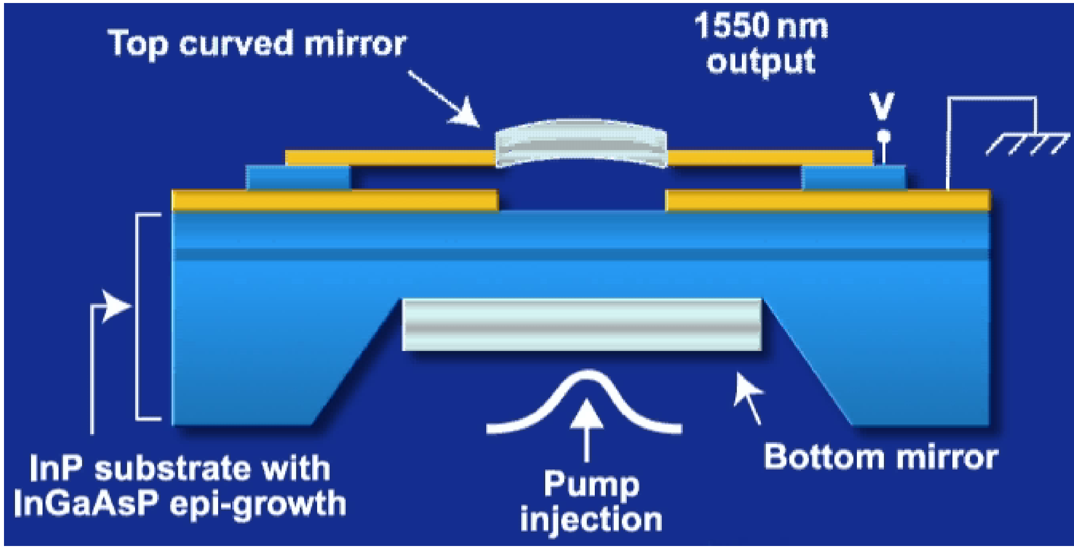




ioλon

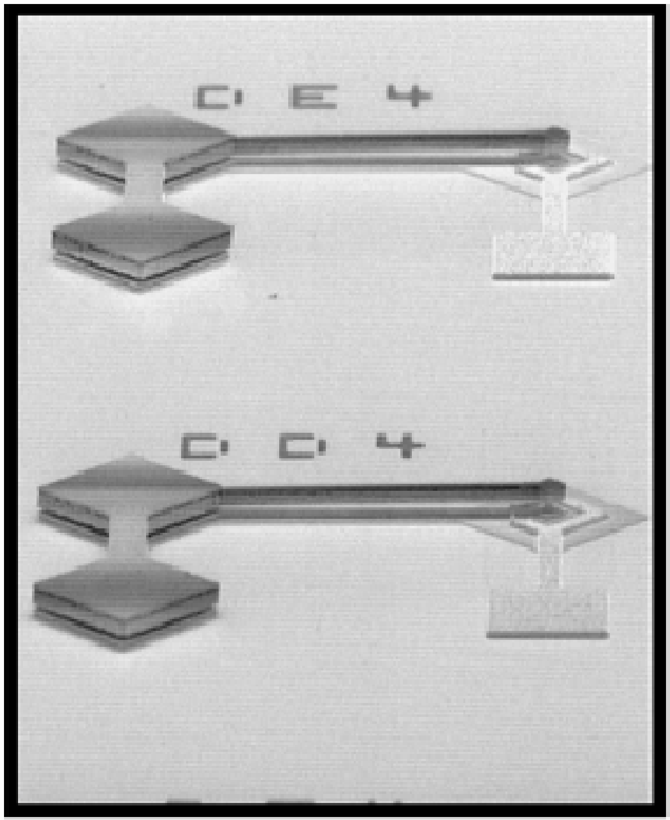
Tunable VCSELs (optically pumped)

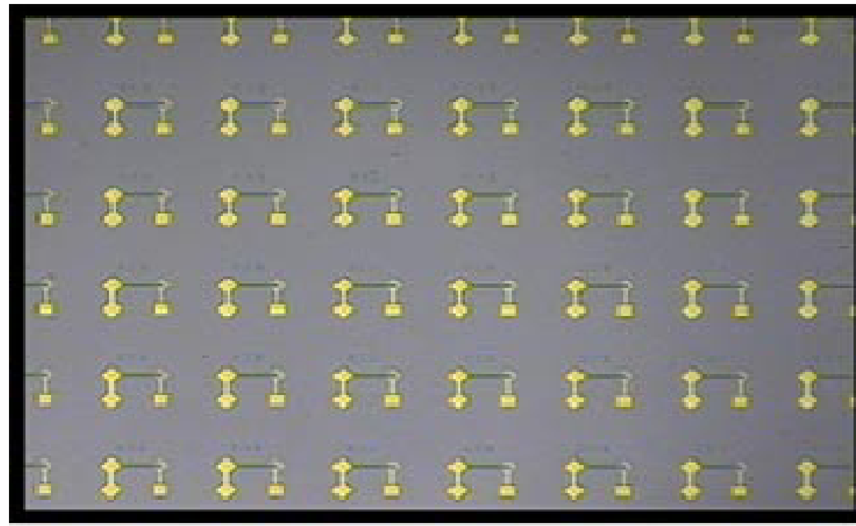
- **Cortek-Nortel-Bookham?**
- **Component technologies**
  - MEMS
  - Thin Film
  - InP Laser
  - Packaging
- **Advantages:**
  - High Power
  - Wide Tuning Range
  - Continuously Tunable



BANDWIDTH9

Core Technologies for Tunable Transmit/Receive



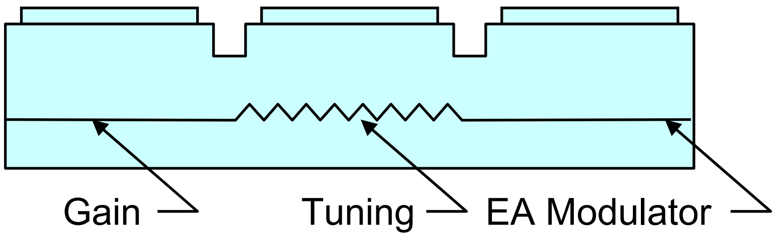


Monolithic MEMS-based tuning
Single cavity VCSEL-based laser
VCSELs tested at a wafer levels before substantial cost and time expended to determine wafer yield

VCSEL: Vertical Cavity Surface Emitting Laser
MEMS: Micro-Electrical Mechanical System

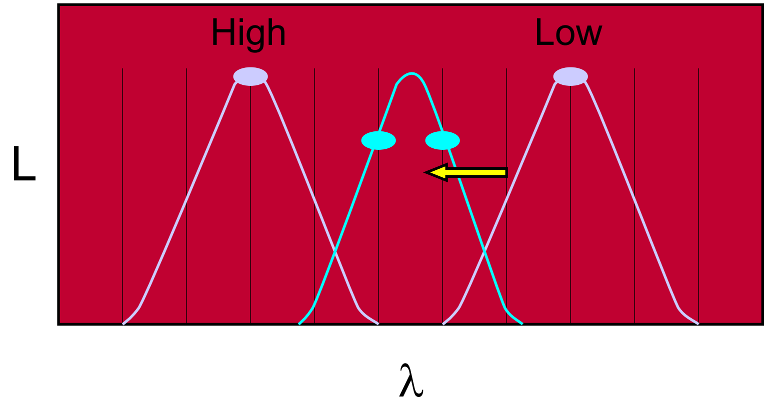
Agere "Narrowly" Tunable DBR/SOA/EAM

EA-DBR Operation

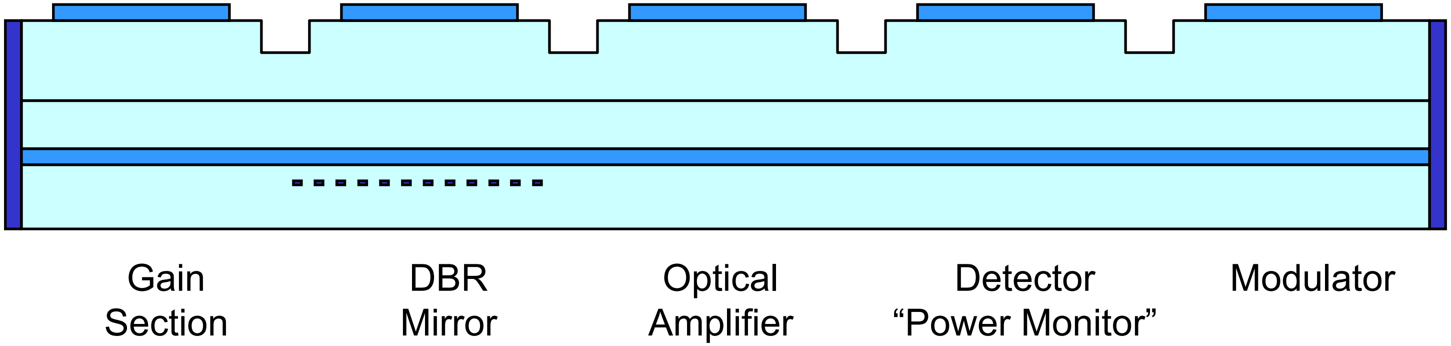


Bragg mirror select FP mode
Tuning current moves Bragg mirror

Tuning Current



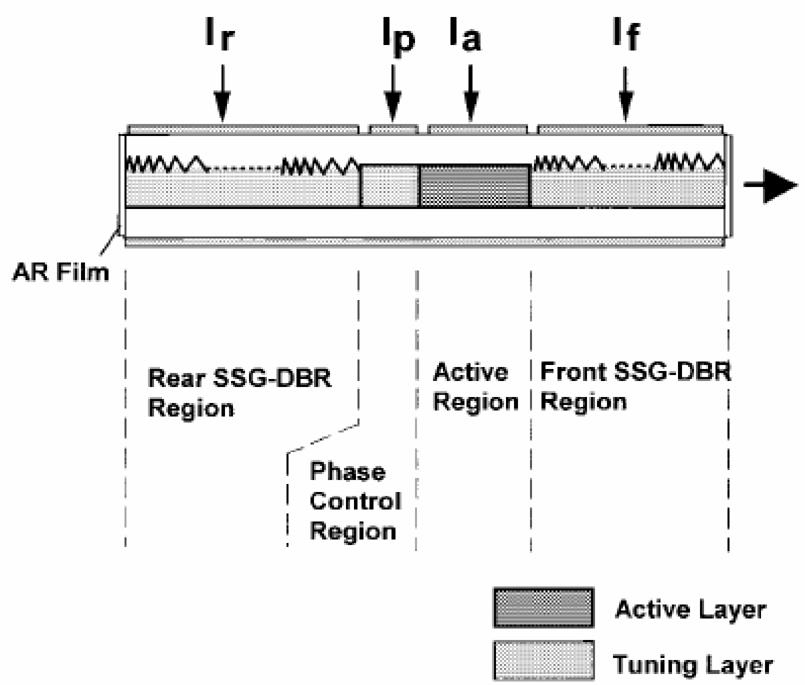
A Five Stage Bell Labs Design

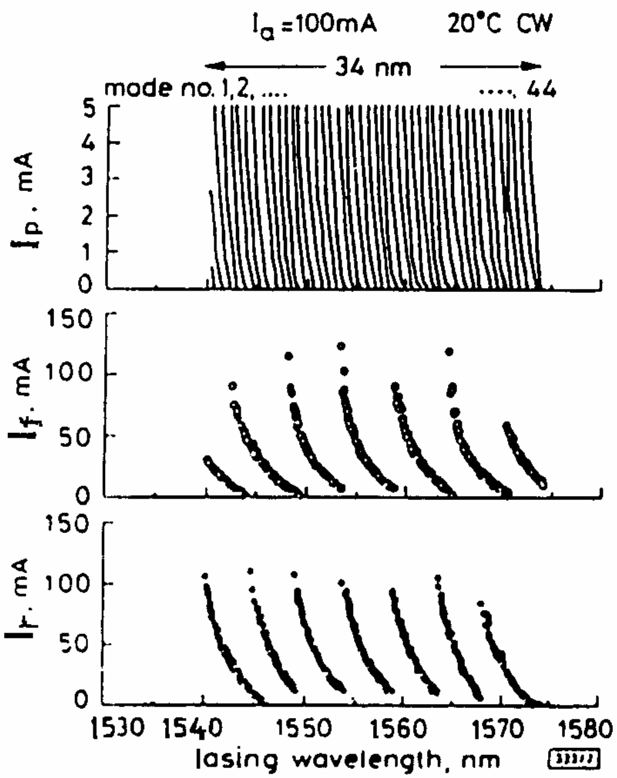


Many more 7 – 10 nm designs

Extended tuning range: SSGDBR--NEL

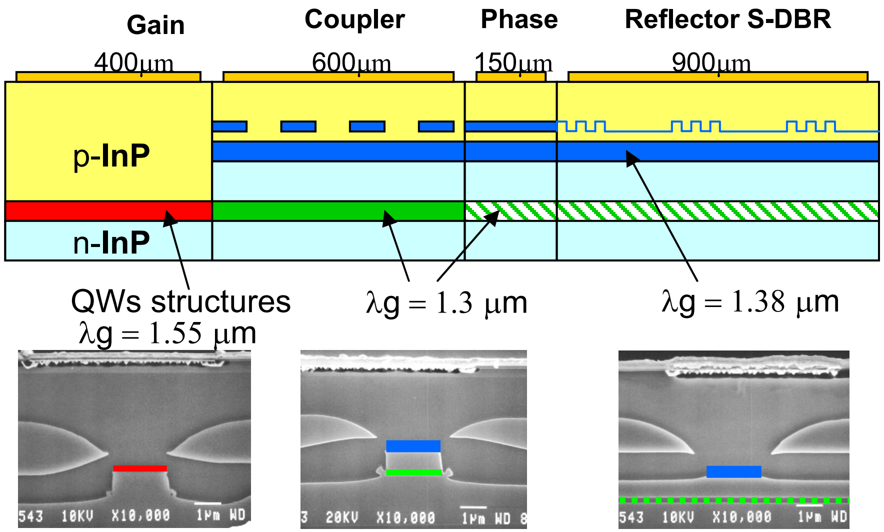
Phase modulated gratings

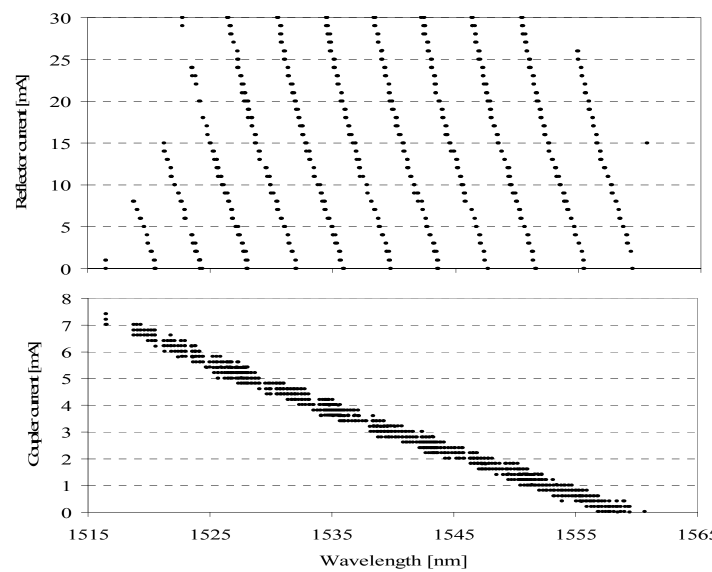




Extended tuning range: GCSR--ADC-Altitun

SGDBR + GACC

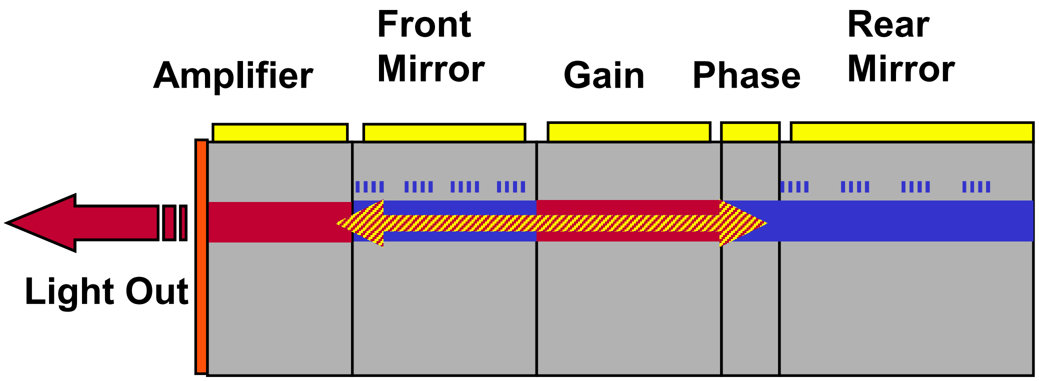


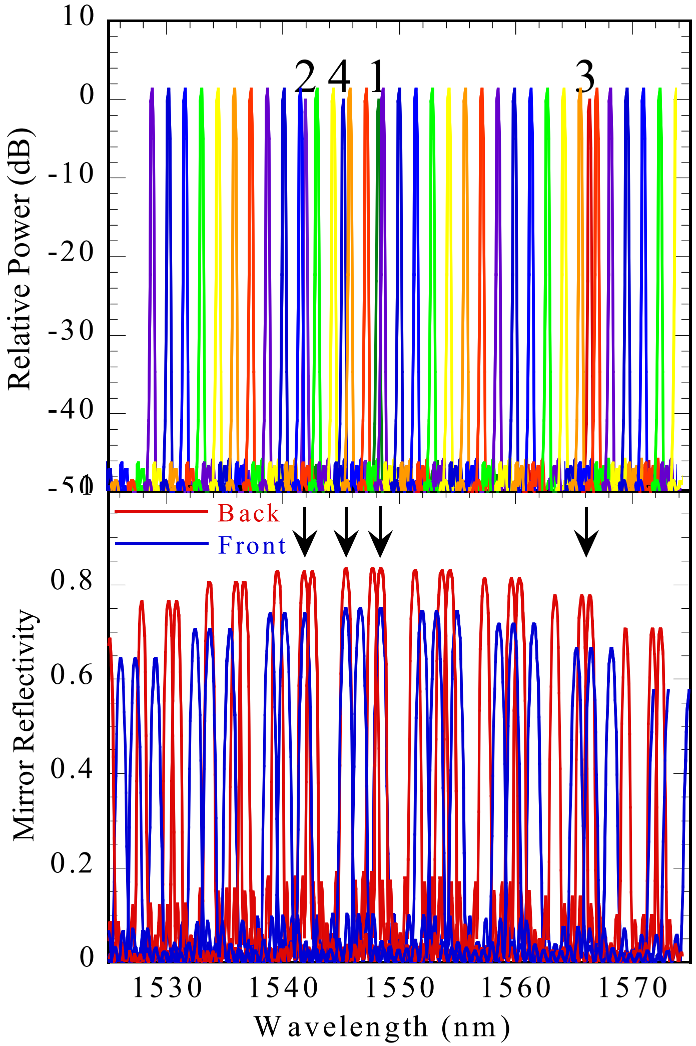


Agility's Extended Tuning Range Technology: Widely Tunable SGDBR Lasers

AGILITY

Sampled Grating Tunable Lasers





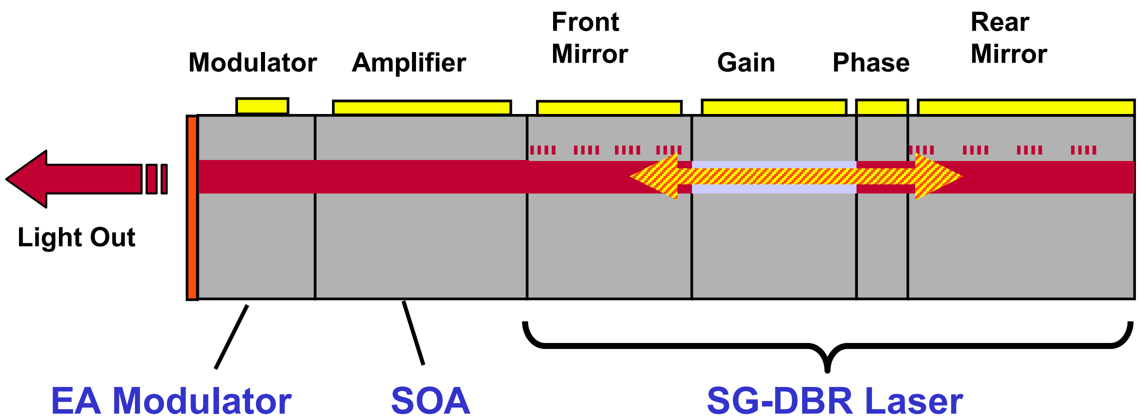
5-10X Tuning Range of DBR

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**

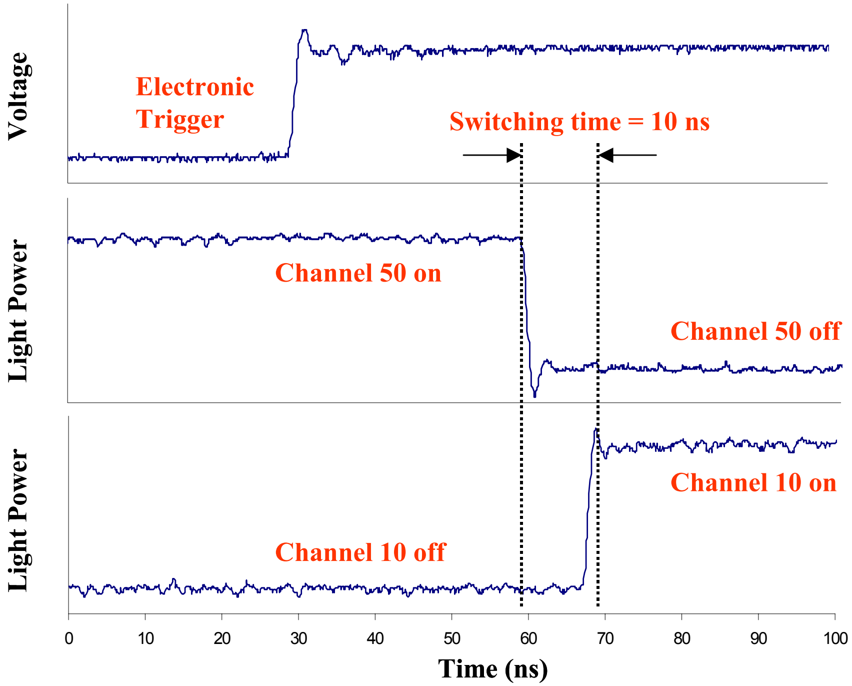


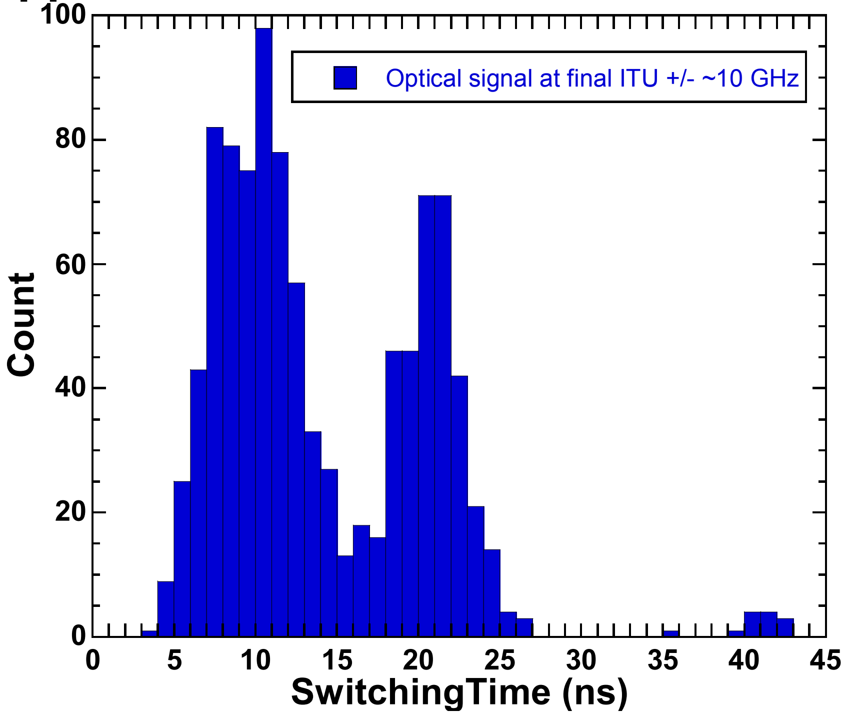
Advantages:

- 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

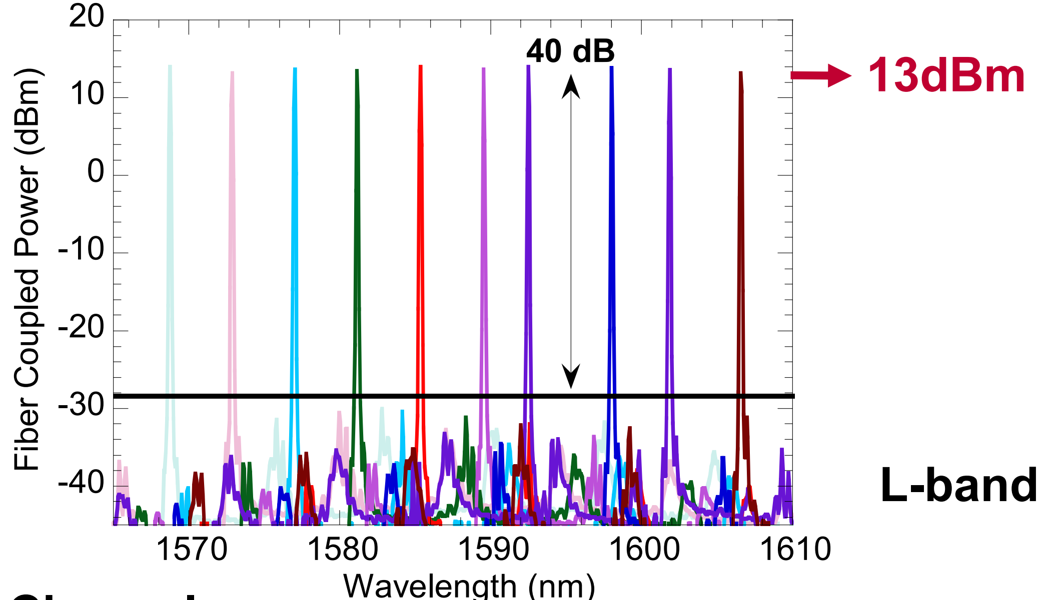




- Current source rise time can be designed for application.
- Inherent laser limit is in ~ 2-10 ns range.
- Thermal transients can complicate rapid switching.

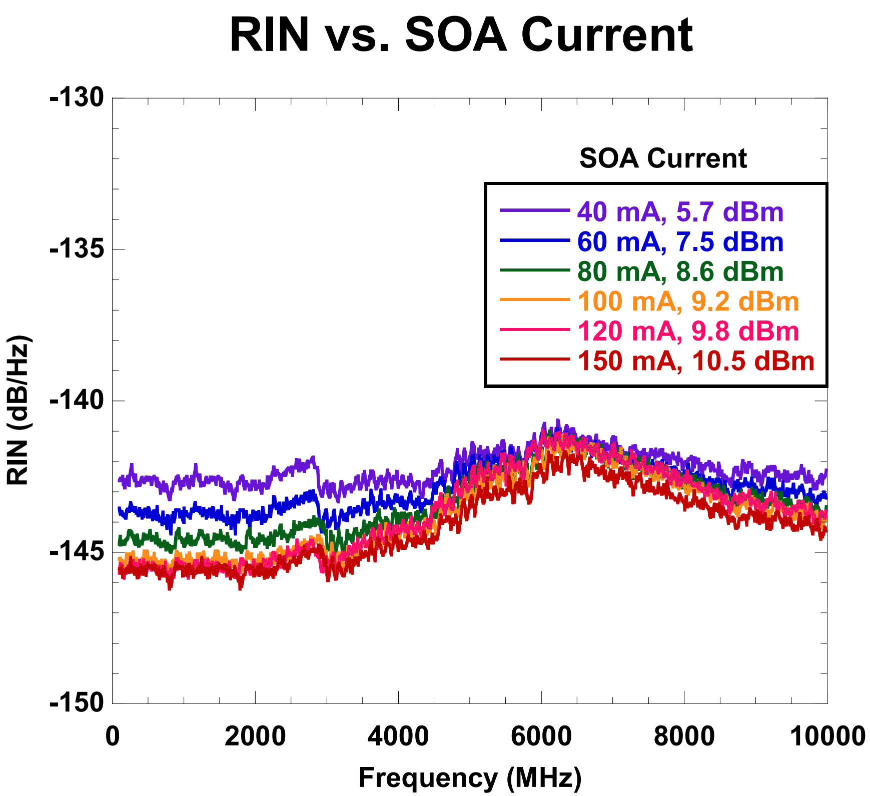
SG-DBR Laser with Integrated SOA

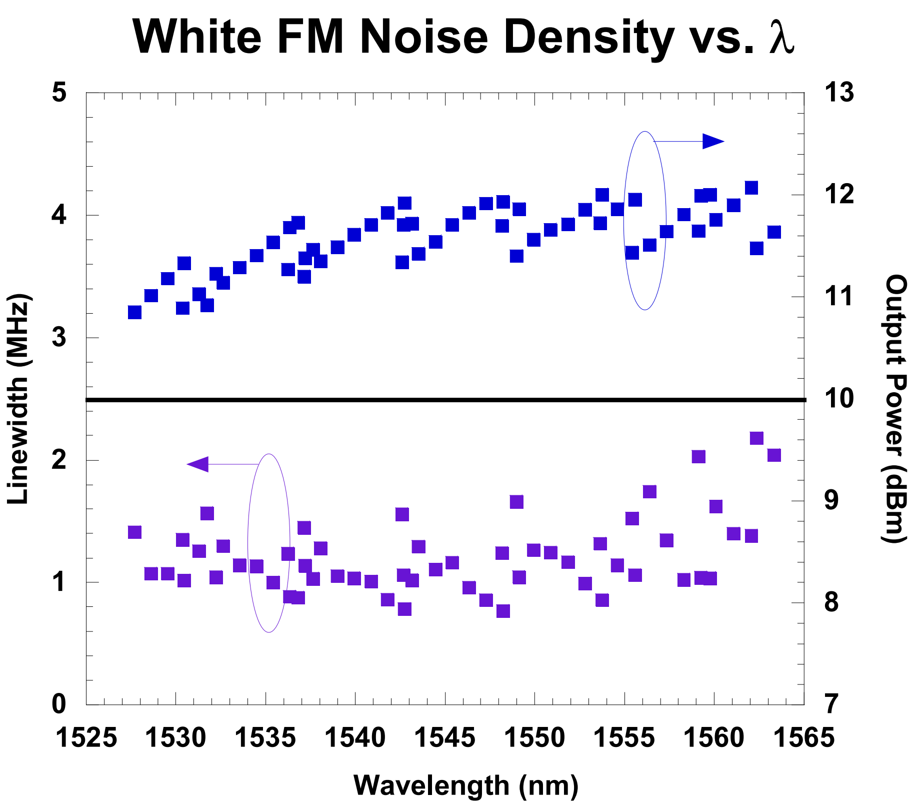
- High Power Widely Tunable Laser:



- >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

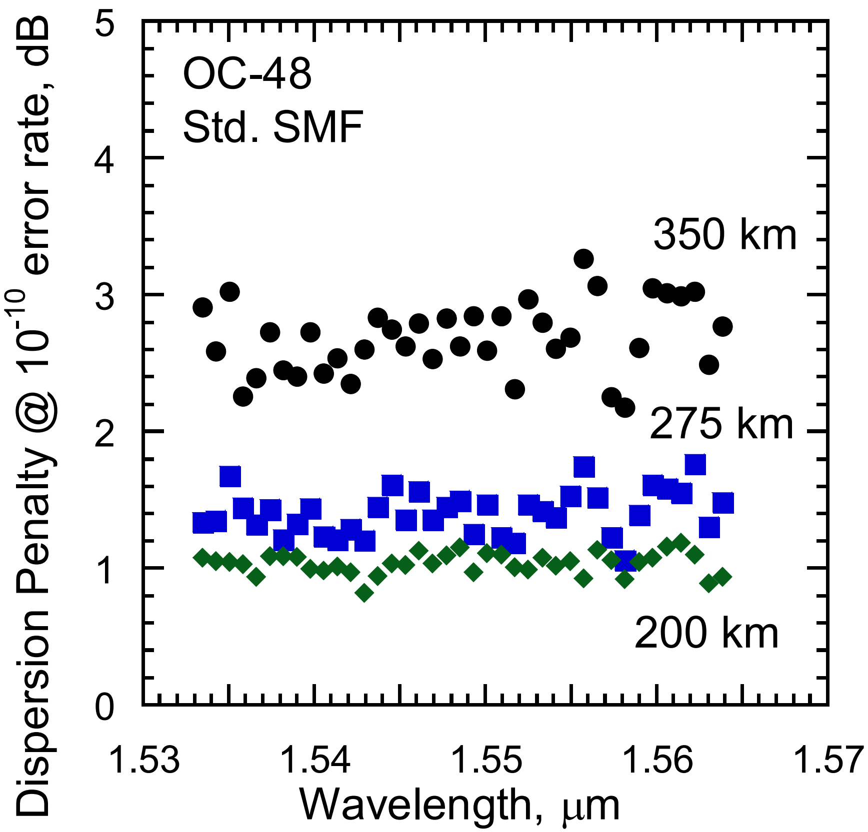
RIN & Linewidth Dependence on Power





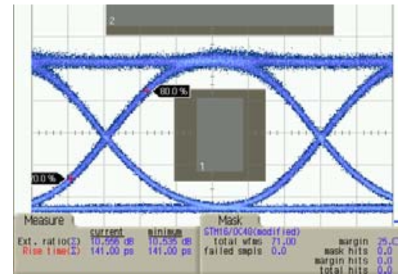
- RIN is only weakly dependent on output power (SOA current).
- Linewidth is less than 2.5 MHz across all wavelengths
  - Scales with Laser Power as expected.

SGDBR-SOA-EAM Transmission Characteristics

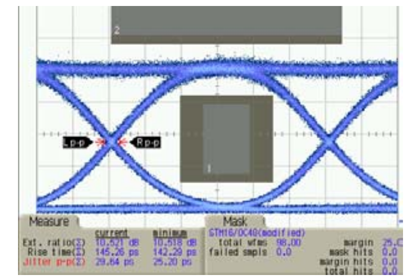


Dispersion penalty at 10^{-10} errors/s error rate for 200, 275, and 350 km of standard SMF for 38 ITU channels sampled across C-band.

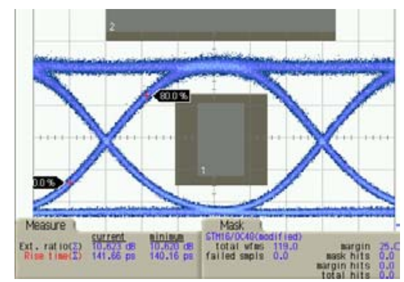
1528 nm



1560 nm



1540 nm

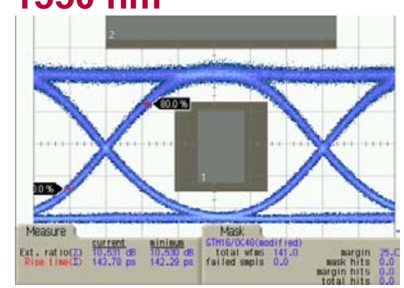


PRBS 2^{31}-1 at 2.5 Gb/s

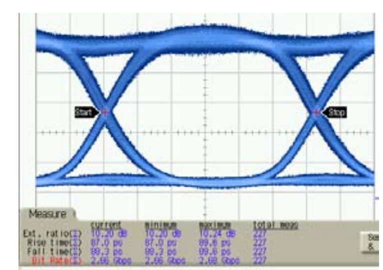
4^{th} order Bessel-Thomson filter

SONET mask with 25% margin

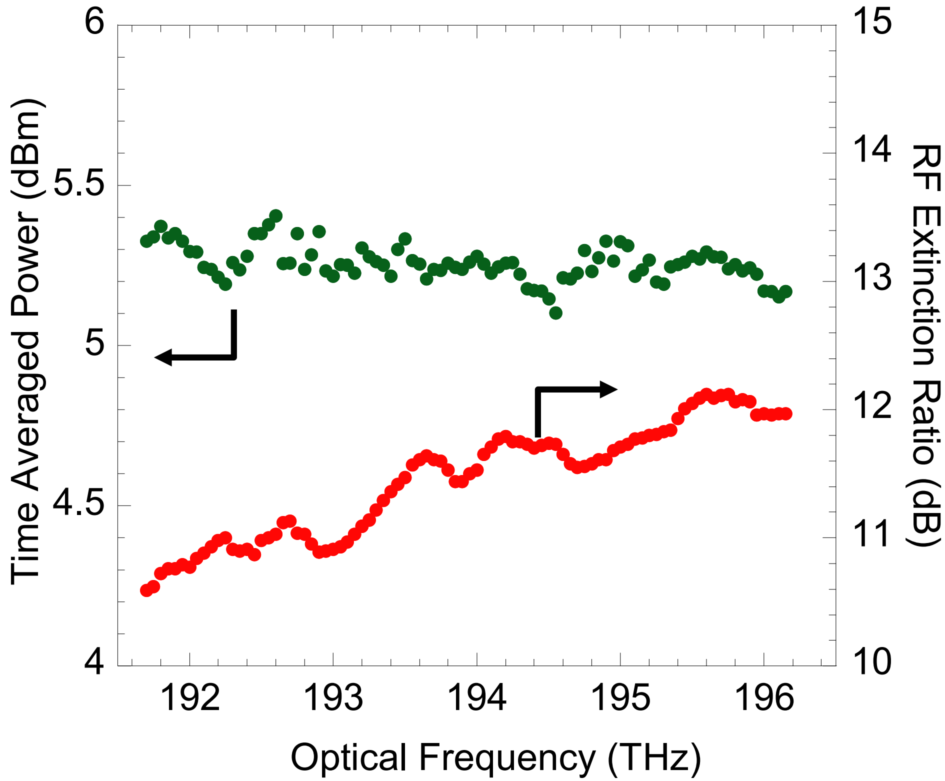
1550 nm

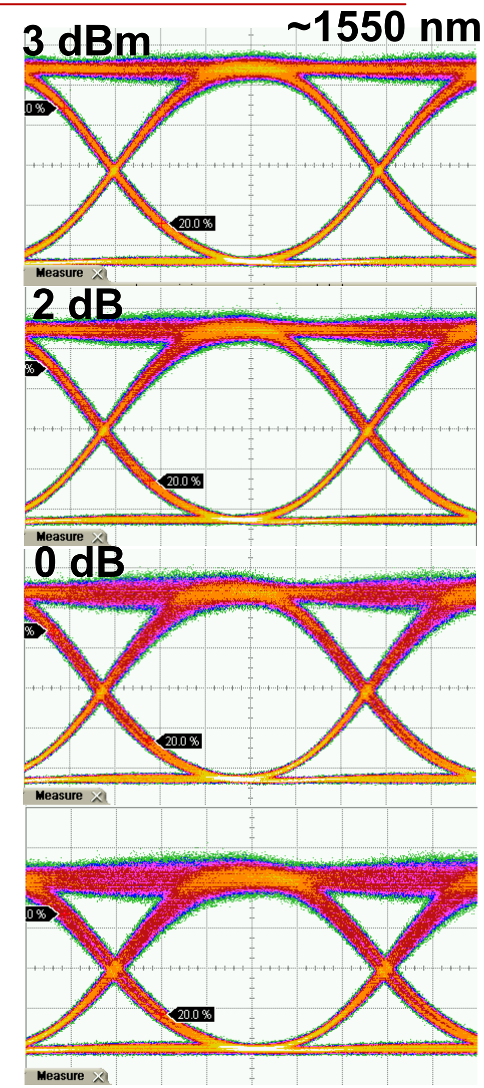


Unfiltered 2.7 Gb/s



SGDBR-SOA-EAM
RF-ER, P_{ave}, & VOA Operation

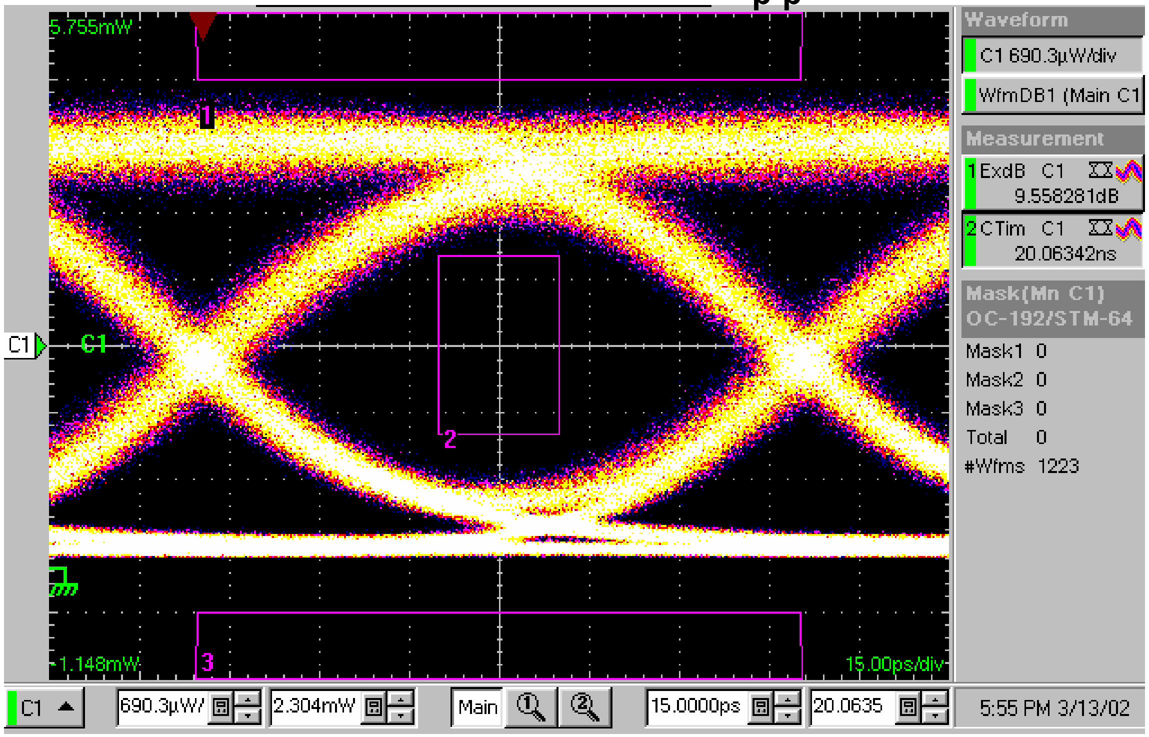




- **Ave. power >5 dBm and RF ER > 10 dB across C-band**
- **Output power dynamic range of ~10 dB w/ small change in SMSR and Wavelength (open loop operation)**

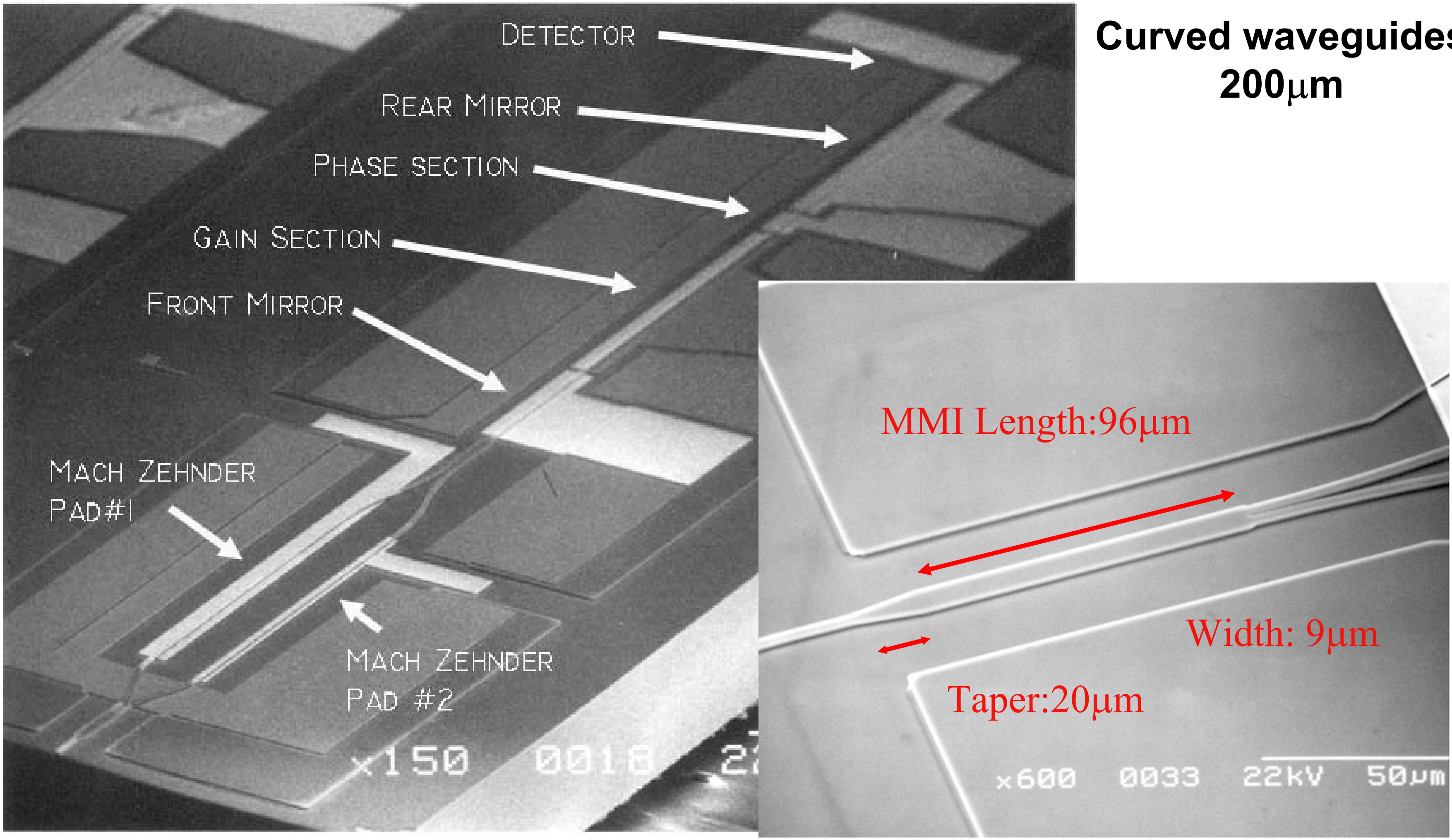
OC-192 Operation of EAM

PRBS 2^{31}-1, V_{p-p} = 3V



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

MZ-SGDBR (UCSB)



Curved waveguides 200µm

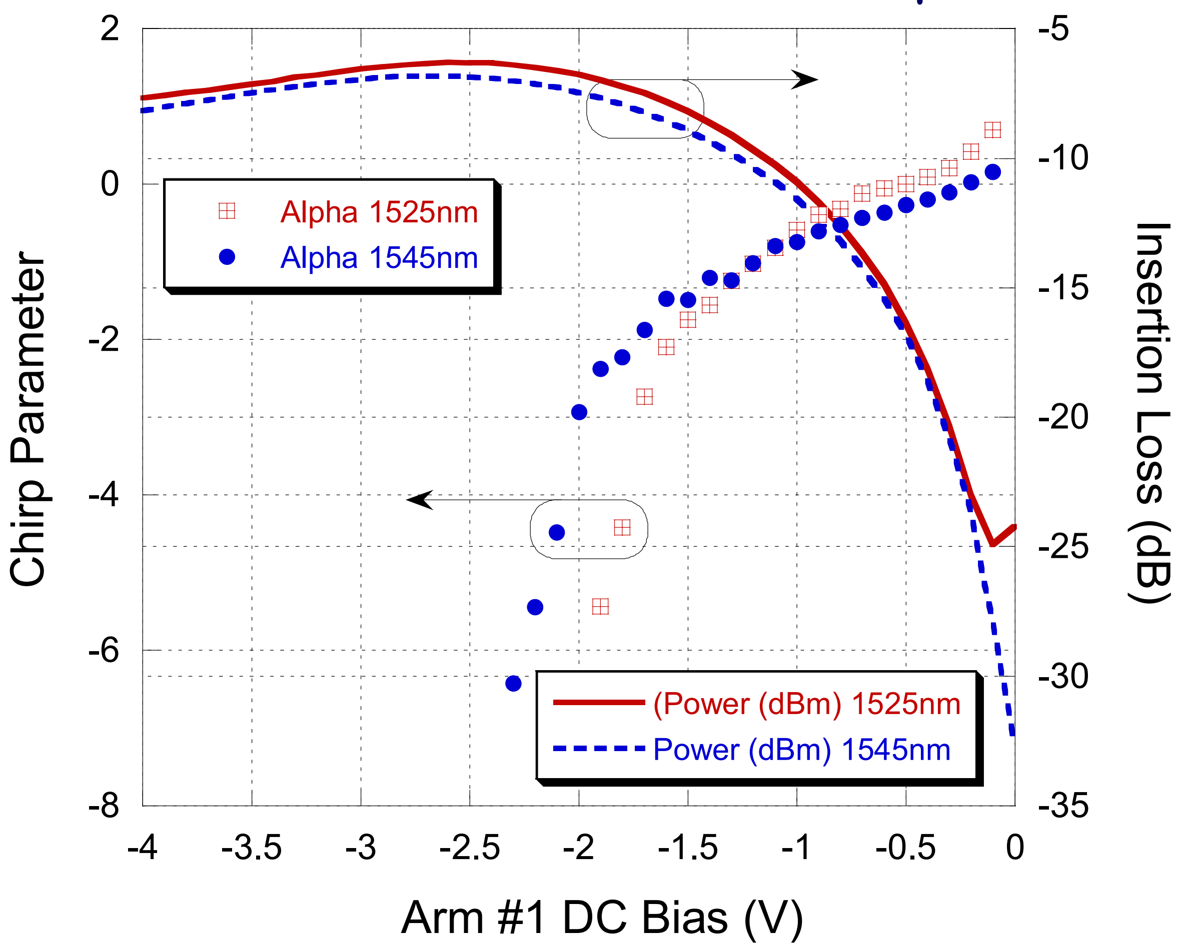
Extinction & Chirp: MZ-SGDBR (UCSB)

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

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

Measured by the Devaux method

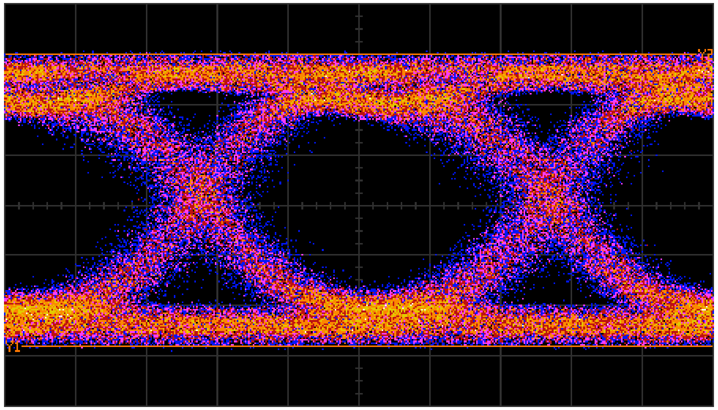
Chirp parameter as function of DC extinction curve for 550µm

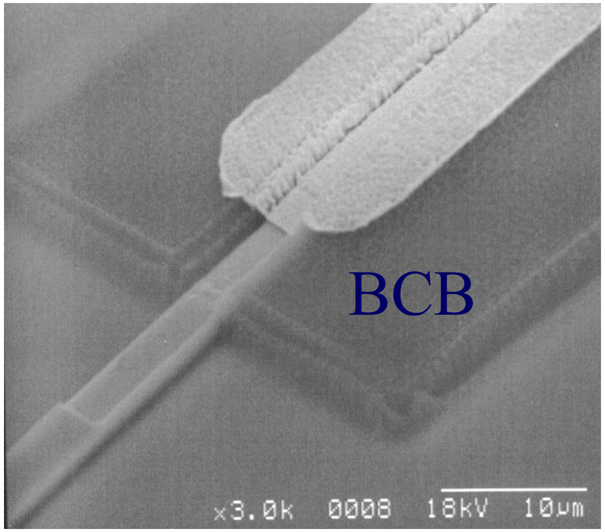


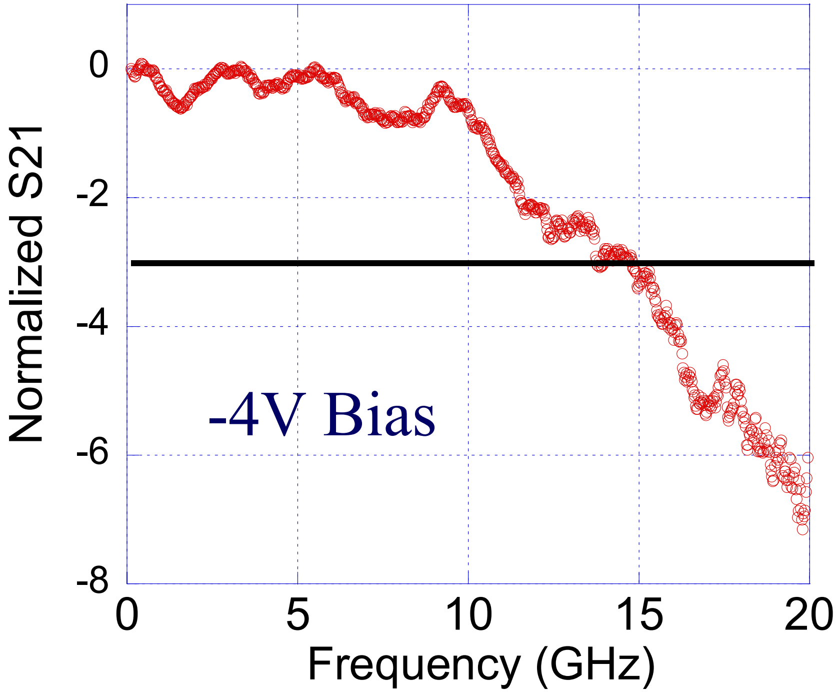
MZ-SGDBR RF Performance: Lumped (UCSB)

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

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







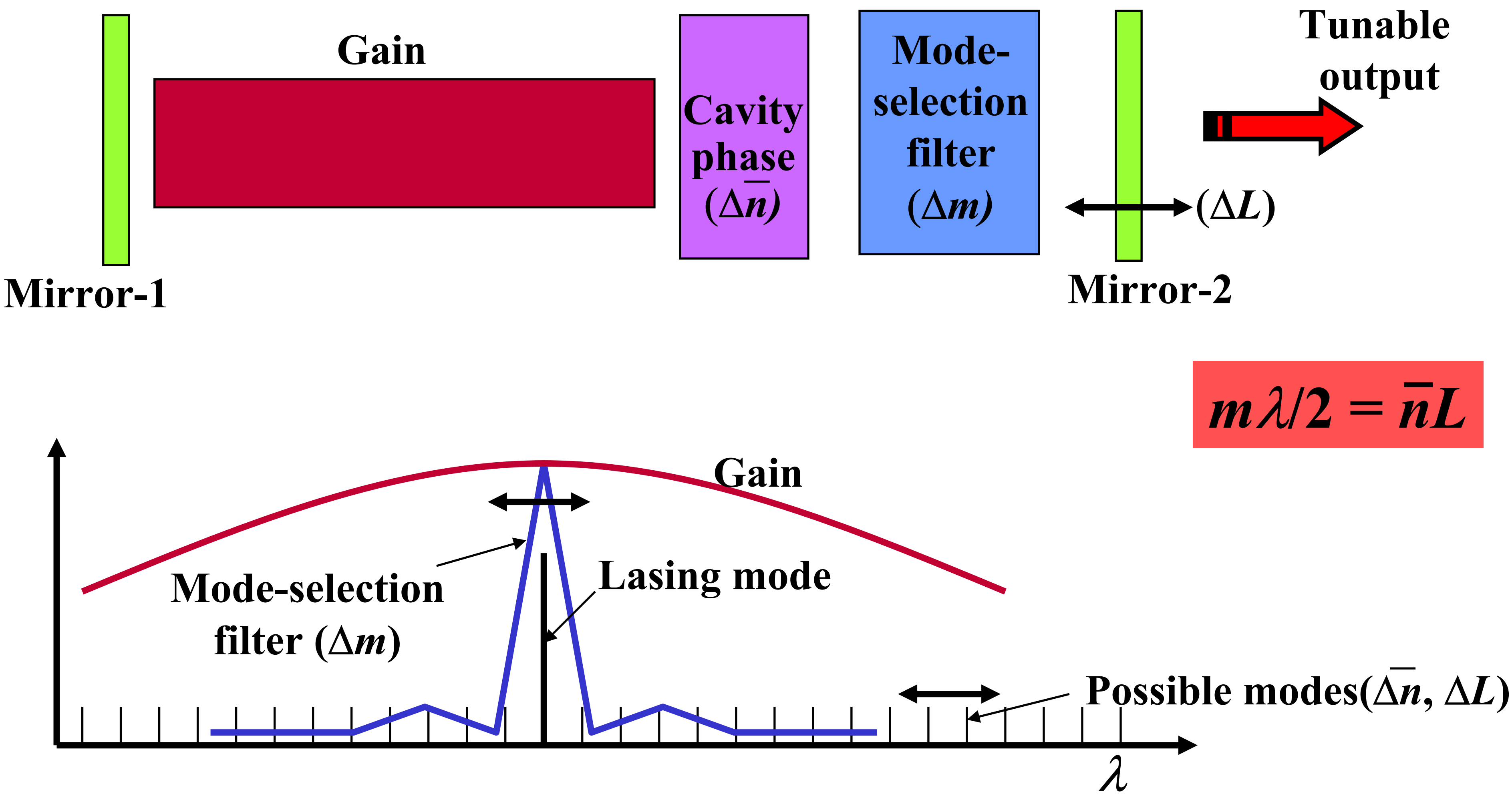
Contents

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

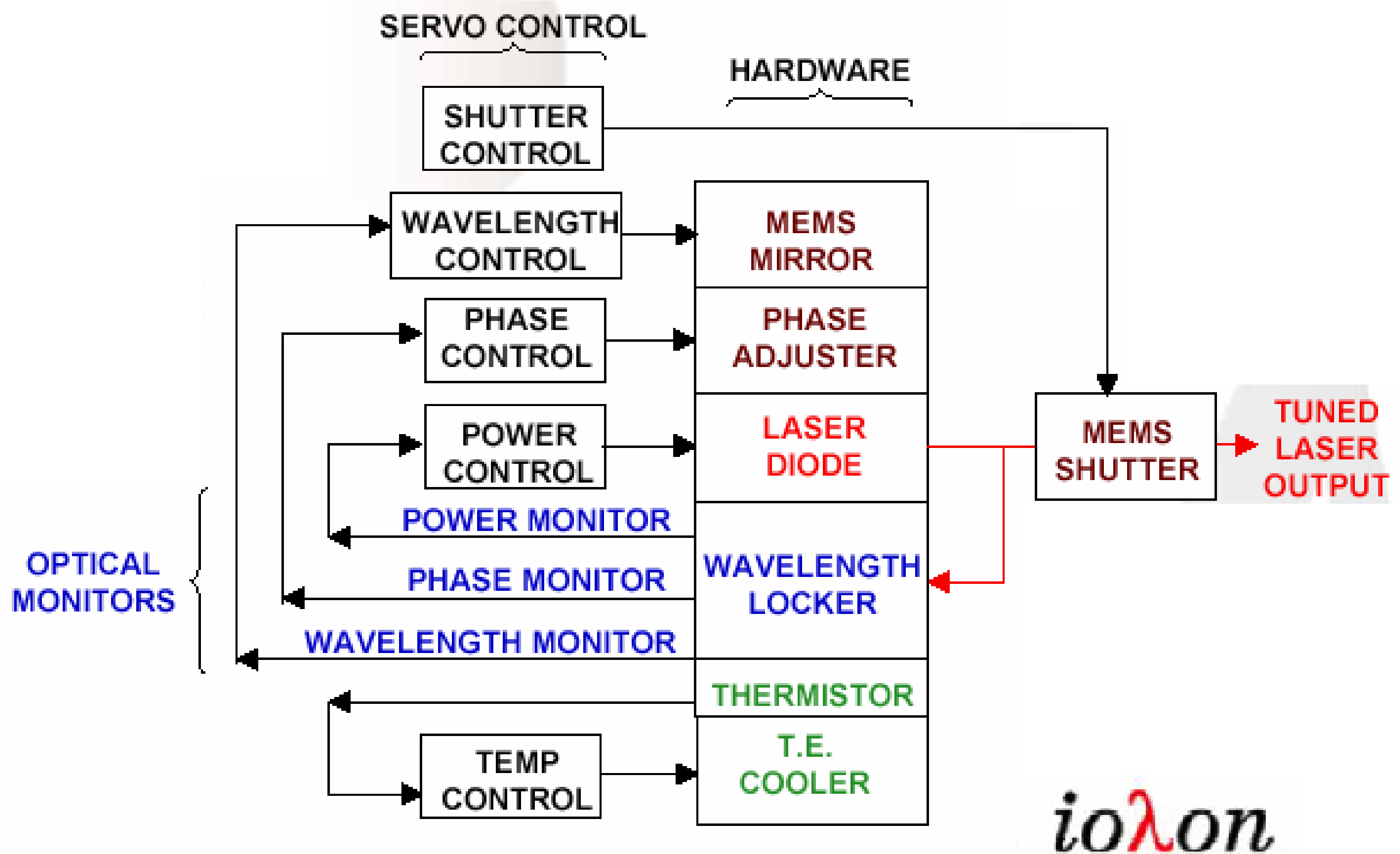


$$m\lambda/2 = \bar{n}L$$

Control comparison across types

Laser	λ_{coarse}	λ_{fine}	Amplitude	VOA
DFB Array/SOA	$V_{array}(j)$	T	$I_{gain}(j)$	ΔI_{SOA}
DFBs/MEMs	$V_{M1}, V_{M2}(j)$	T	$I_{gain}(j)$	$V_{M1}, V_{M2}(j)$
SGDBR/SOA	I_{m1}, I_{m2}	I_{ϕ}	I_{SOA}	ΔI_{SOA}
Ext. Cavity	$V_{M\theta}$	V_{ML}, I_{ϕ}	I_{gain}	$V_{Mshutter}$
VCSEL/MEMs	V_{M1}	V^*_{M1}	I_{gain}	--------

Iolon Control Scheme for Ext. Cavity Laser

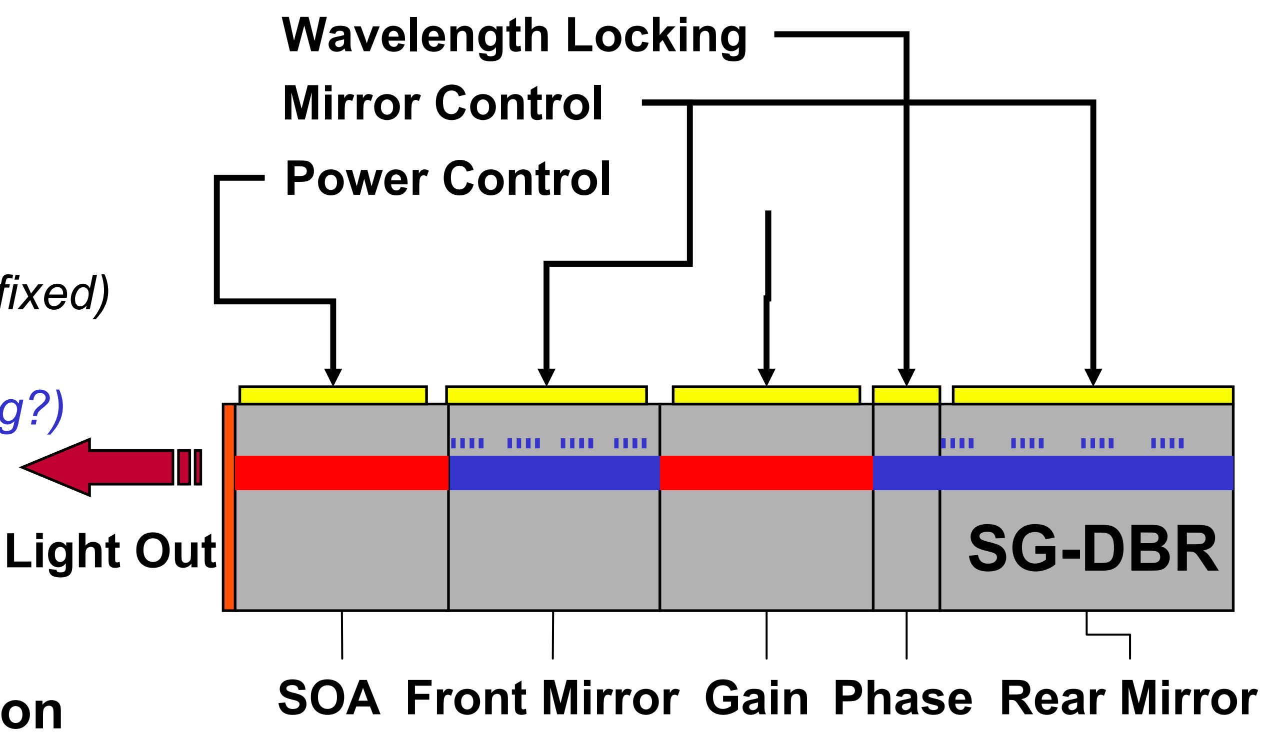


ioλon

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

Contents

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

<u>Physical Causes, assuming a fixed look-up table:</u>

$\Delta\bar{n}$ – Changes in internal temperature, T_{int}, or carrier lifetime, τ_c

ΔL – Physical movements—solder relaxation, MEMs charging

Δm – Δn of DBR, $\Delta\theta$ of ext. grating, or MEMs charging

Critical issues for wavelength stability

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

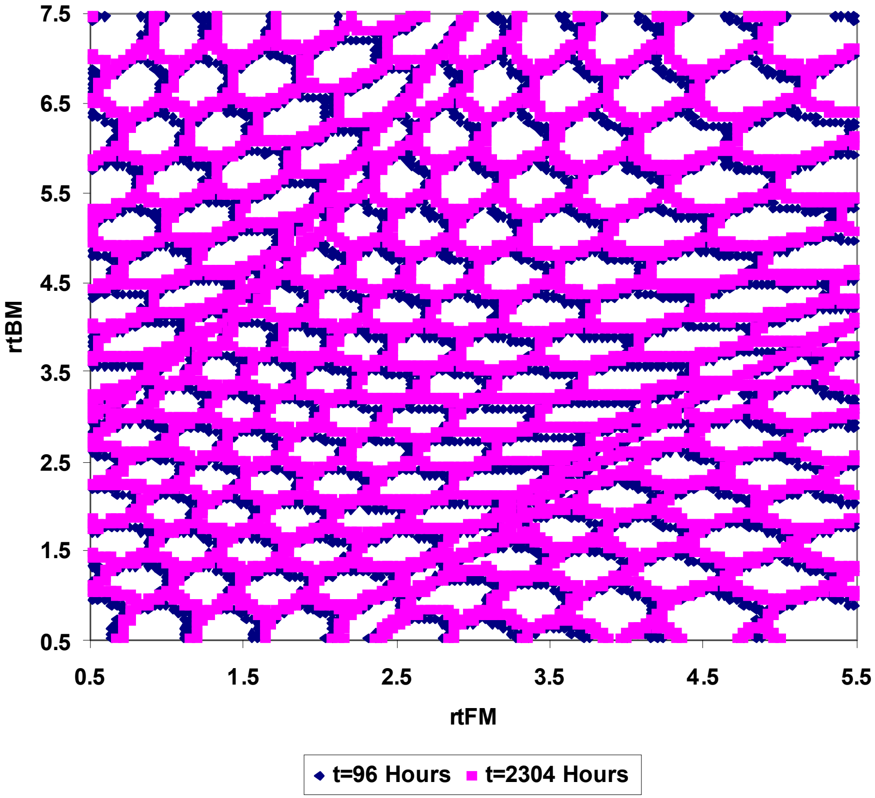
*Requiring table update or global channel locator

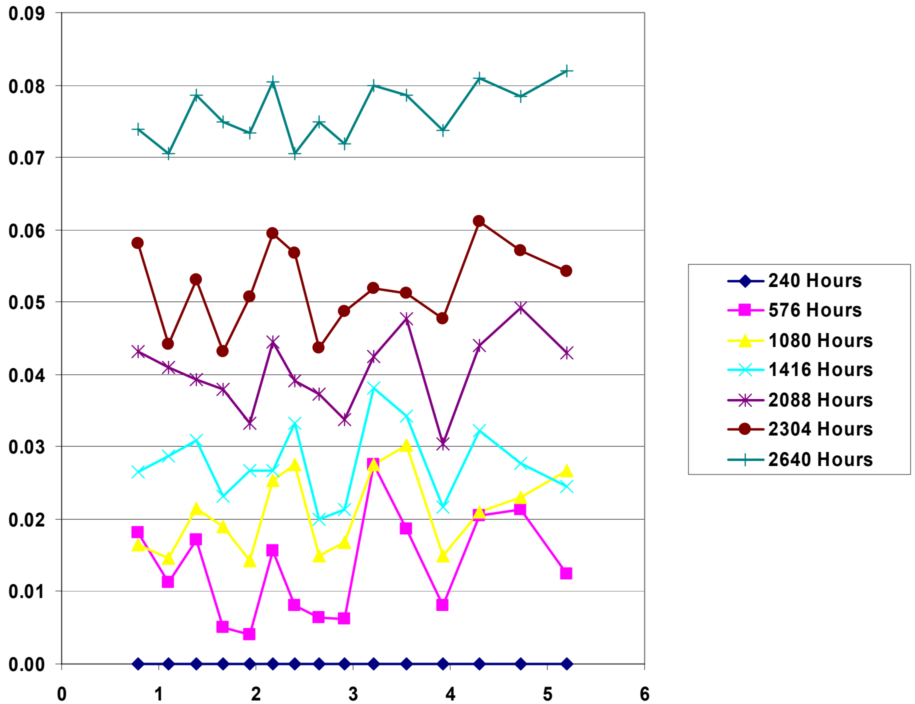
Estimated Open-loop Wavelength Shifts

Laser	Critical $\Delta\lambda$ issues	$\Delta\lambda$ @ EOL_{gain} (No table update)
DFB Array/SOA DFBs/MEMs	$\Delta n(T_{int}) \leftarrow \Delta I_g$ $\Delta n(T_{int}) \leftarrow \Delta I_g$	40GHz (10GHz/SOA feedback) 40GHz
SGDBR/SOA	$\Delta n_{DBR}(\tau_c) \rightarrow \Delta m$	<10GHz
Ext. Cavity	$\Delta L(V_M)$, $\Delta m(V_M)$, $\Delta n(T_{int}) \leftarrow \Delta I_g$	100GHz (MEMs charging)
VCSEL/MEMs	$\Delta L(V_M)$	1000GHz

- **Only SGDBR lands on correct mode near EOL Open-loop**
- **Others require global channel monitor or the like**

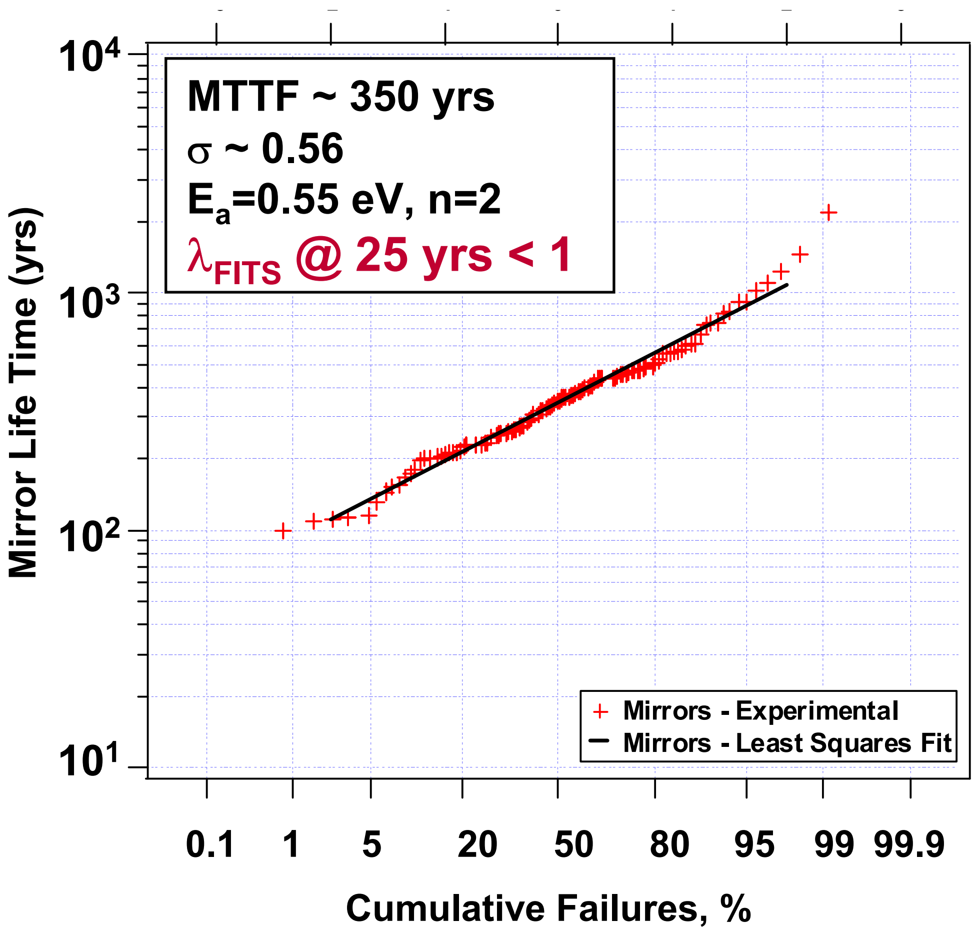
Effects of SGDBR Mirror Aging: *Measurement*





- 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



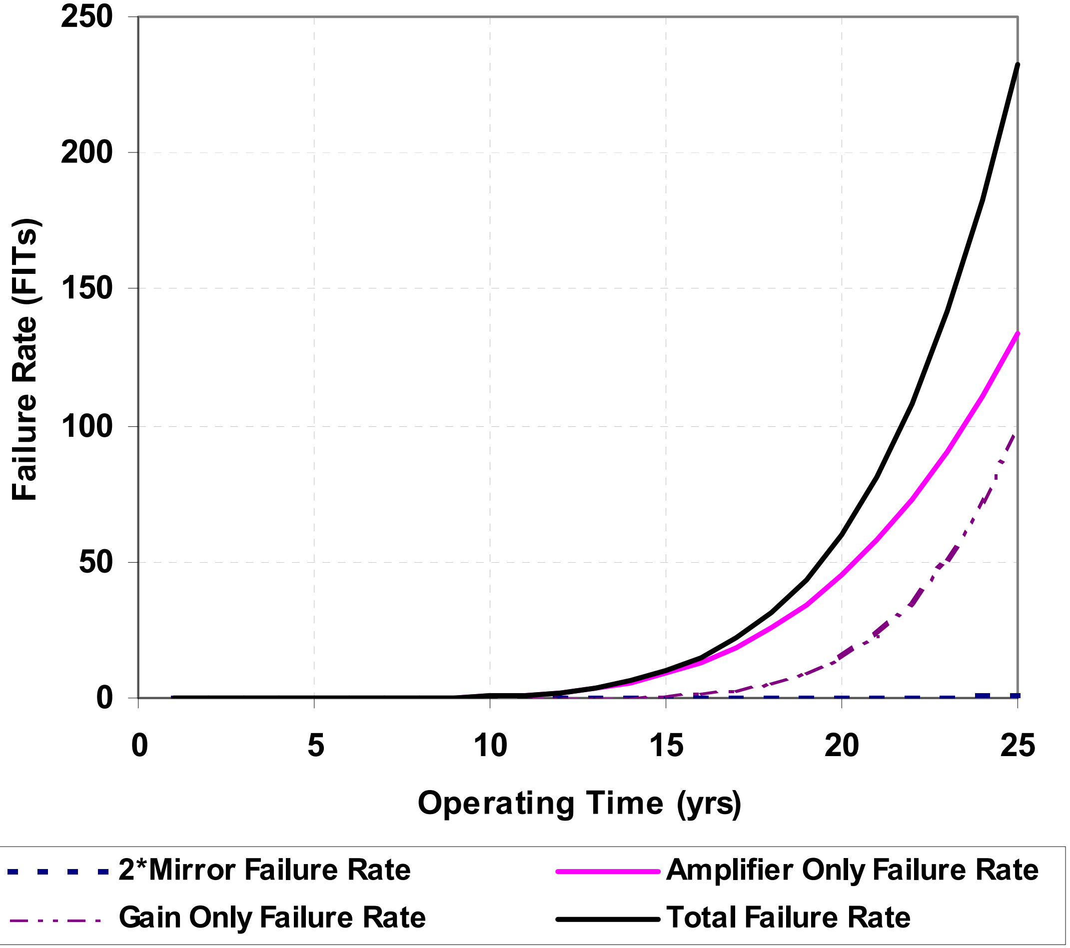
- ~ 10^6 Device Hours measured.
- Very low Bragg Wavelength Aging Rates < 0.5 pm/ year at worse case.
- Gain and SOA sections have similar MTTF and failure distribution.
- OK for open-loop operation→ no mode hops or incorrect channels

SGDBR Laser/SOA FITs vs. Time

- Open-loop failure rate vs. time

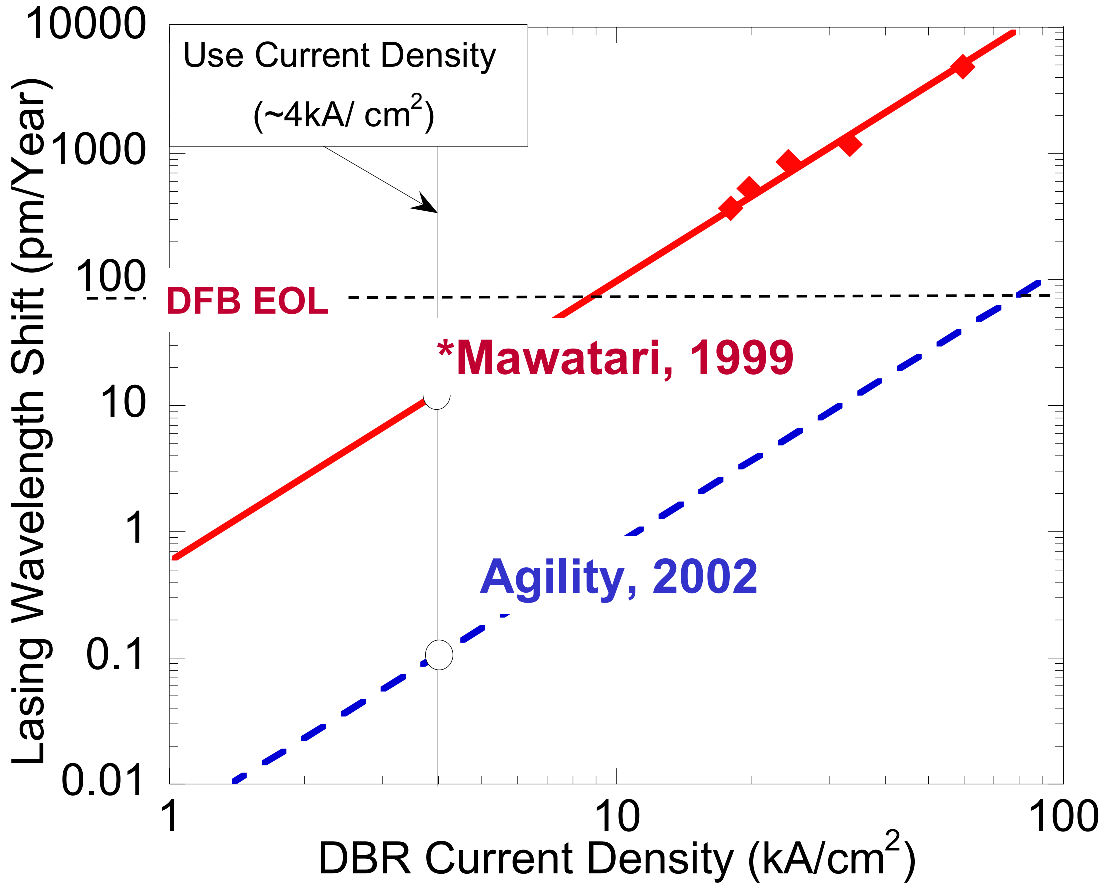
- Gain section determines EOL

- 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.



*Mawatari et al, "Lasing Wavelength Changes Due to Degradation in Buried Heterostructure DBR Laser", Journal of Lightwave Technology, v.17, no.5 1999

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**