Discover Unknown Operating Regimes of the Fabry-Perot Optical Filters:

applications in optical spectrum analyzers and fast tunable semiconductor lasers

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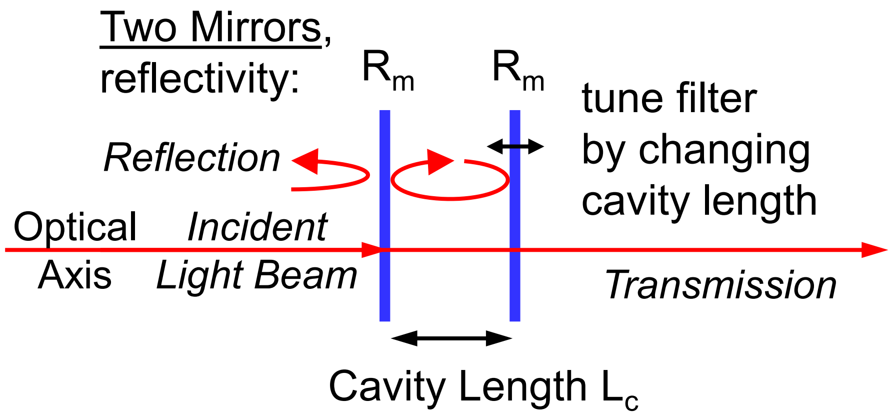
OUTLINE

- Doing science in industry: when tough engineering problems arise, we go beyond known engineering and develop new science to solve the problems.
- Fabry-Perot optical resonators and filters: what we already know about them
- Silicon Micro-Electro-Mechanical System MEMS tunable Fabry-Perot filters
- New by design: Single transverse mode Fabry-Perot optical resonators
  - Theory and measured optical properties
  - Optical spectrum analyzers for channel monitoring in wavelength-division-multiplexed WDM fiber optical networks
- New by discovery: Reflective spectral selection mode of tunable Fabry-Perot filters
  - Modeling: how it works
  - Tunable external cavity semiconductor lasers
  - Narrow linewidth lasers for Swept-Source Optical Coherence Tomography SS-OCT medical imaging
  - Wider linewidth lasers for tunable laser spectroscopy
- Fabry-Perot Resonators - Conclusions
  - More than 125 years after the original publication by Charles Fabry and Alfred Perot, these devices continue to surprise us
  - ”Sur les franges des lames minces argentées et leur application à la mesure de petites épaisseurs d’air ”, Ann. Chim. Phys. (1897).
  - ”Théorie et applications d'une nouvelle méthode de spectroscopie interférentielle ”, Ann. Chim. Phys. (1899).

Fabry-Perot Optical Resonators

(from Textbooks)

Fabry-Perot Interferometer and Tunable Filter: Narrow Peak Transmission + Narrow Notch Reflection



Two Mirrors, reflectivity: R_m R_m

tune filter by changing cavity length

Reflection

Optical Axis

Incident Light Beam

Transmission

Cavity Length L_c

Optical wavelength bands:

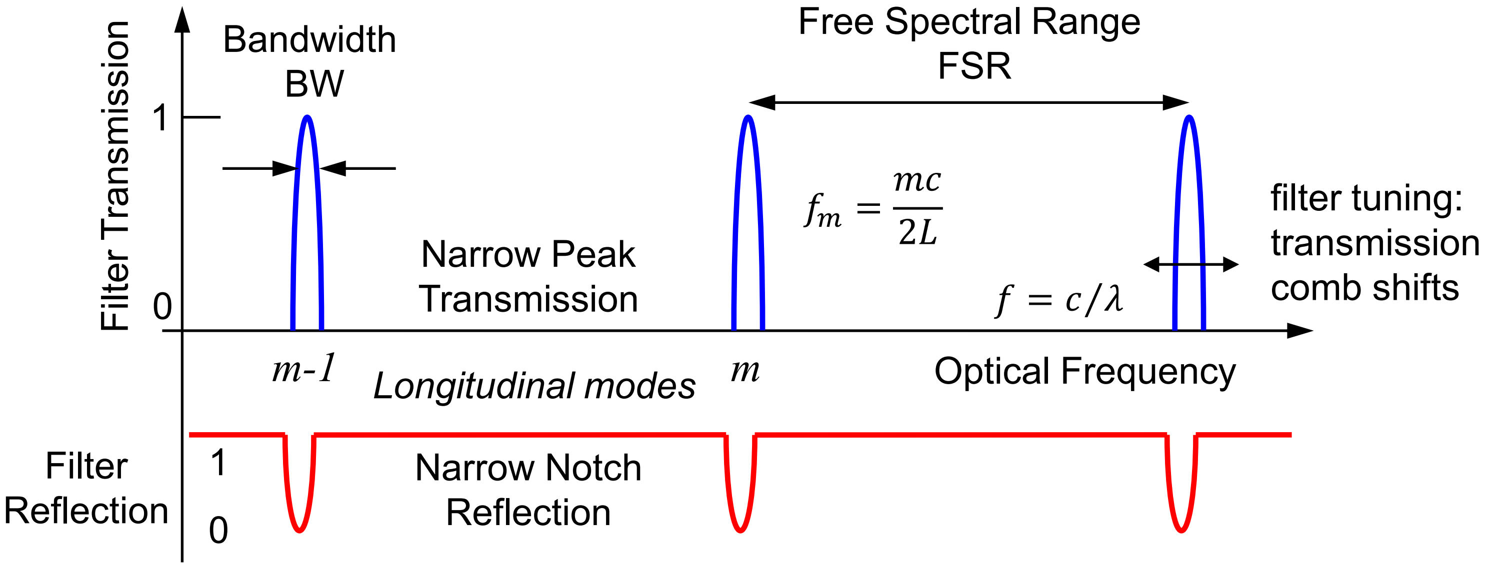
- Optical telecom: 1525 – 1565 nm (40nm - 5,000 GHz)
- Optical coherence tomography: 980 – 1105 nm (125nm - 34,600 GHz)

Filter spectral parameters

- Frequency Tuning Range and FSR: > 100nm (> 35,000 GHz)
- Frequency Resolution: 1 – 10 GHz

Fabry-Perot filter parameters

- Cavity Length: 2 – 30 μm
- Filter Finesse: 5,000 – 10,000



filter tuning: transmission comb shifts

$$\boxed{FSR = \frac{c}{2L_c}}$$

Determines available tuning range

$$\boxed{Finesse = \frac{FSR}{BW} = \frac{\pi\sqrt{R_m}}{1 - R_m}}$$

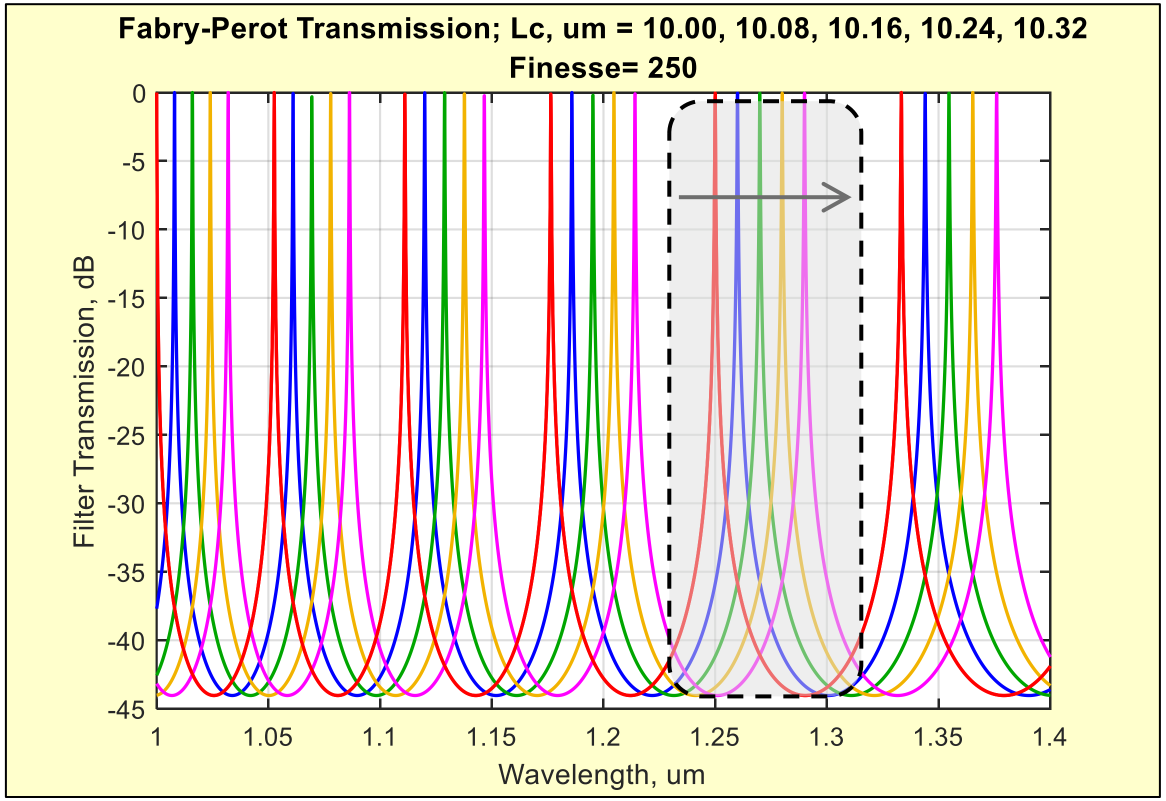
c = speed of light

Finesse:

- mirror reflectivity Rm
- intracavity losses

Fabry-Perot Filter: Tuning of Longitudinal Modes with Cavity Length Change

- Tuning with cavity length change: transmission frequency comb stretches like an accordion
- Make mode spacing FSR large enough, so that only one mode is tuning in the band of interest

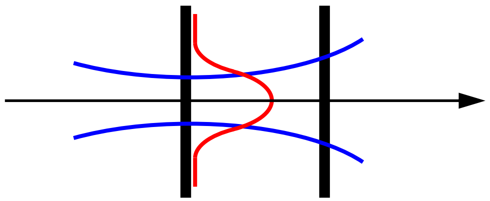


$$\frac{\Delta L_c}{L_c} = \frac{\Delta\lambda}{\lambda} = \frac{-\Delta f}{f}$$

- $\Delta L_c = \lambda/2$ shifts resonance peak by one FSR
  - At λ=1.0 µm need ΔL_c= **0.50 µm** displacement
  - At λ=1.3 µm need ΔL_c= **0.65 µm** displacement
  - At λ=2.0 µm need ΔL_c= **1.00 µm** displacement
- Very small displacements for full range tuning
- Amenable to micro-electro-mechanical system MEMS implementation.

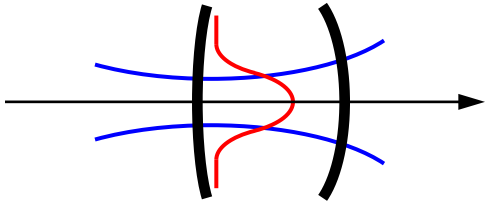
Plane and Curved Mirror Cavities: Filter Frequency Resolution with Finite Size Beams

Plane-Plane Mirror Cavity:
finite size beam limits frequency resolution



$$\Delta f = \frac{2c\lambda}{(\pi w_{dia})^2}$$

Curved Mirror Cavity:
frequency resolution not limited by beam size



- Resonator modes: plane waves of infinite extent at different angles to the optical axis
- Spatial frequency domain: finite size beam has a finite width angular spectrum. Different angular components resonate at different frequencies and broaden the spectral response. (- Diffraction loss)
- For example, 1 GHz filter resolution at λ=1.5µm requires beam diameter > 300 µm

- Resonator modes: transverse modes of finite extent, e.g. Hermite-Gaussian or Laguerre-Gaussian modes for spherical mirrors
- Finesse of a mode and filter frequency resolution are limited only by the mirror reflectivities
- High frequency resolution with smaller diameter beams demands curved mirror cavities for **micro-optical resonators**

Hermite-Gaussian Transverse Modes for Curved Mirror Resonators

Electric Field

$$E_{nm}(x,y,z) = \frac{e^{j(kz-\varphi)}}{w} \underbrace{H_n\left(\sqrt{2}\frac{x}{w}\right) H_m\left(\sqrt{2}\frac{y}{w}\right)}_{\textbf{Hermite polynomials}} \underbrace{\exp\left(-\frac{x^2+y^2}{w^2}\right)\exp\left(-jk\frac{x^2+y^2}{2R}\right)}_{\textbf{Gaussian amplitude and phase front}}$$

Beam Radius and Waist

$$w^2(z) = w_0^2\left[1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2\right]$$

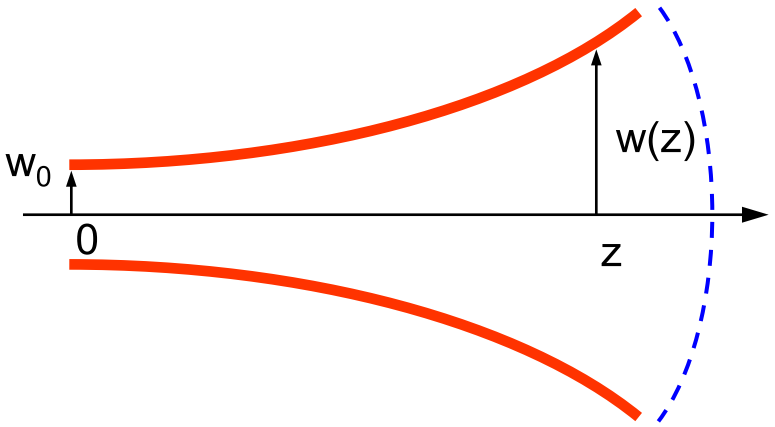
Radius of Curvature

$$\frac{1}{R} = \frac{z}{z^2 + (\pi w_0^2/\lambda)^2}$$

Propagation Phase Shift

$$\varphi = (1+n+m)arctan\left(\frac{z}{\pi w_0^2/\lambda}\right)$$

$$k = 2\pi/\lambda$$



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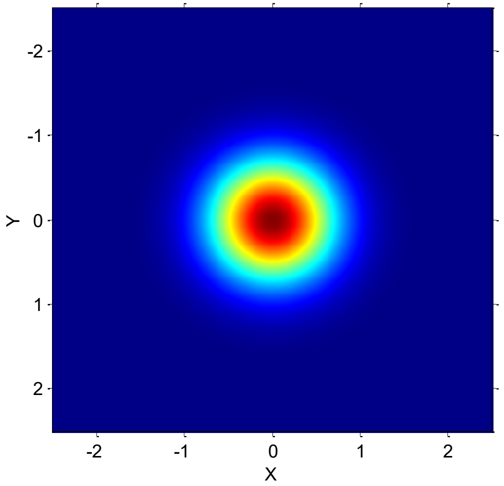
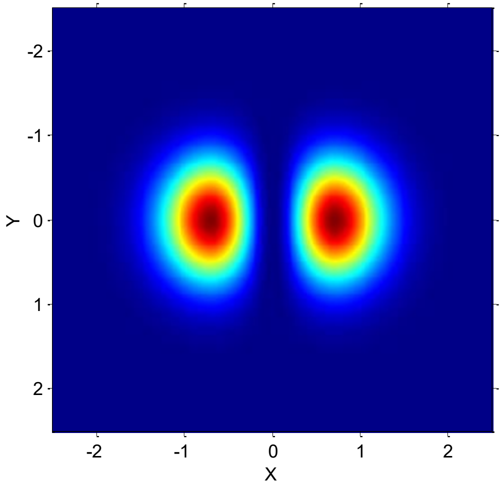
Intensity Profiles: Hermite-Gaussian Modes, X-Y Cartesian Symmetry

- Standard resonator picture: fit a spherical mirror to the spherical phase front of a Gaussian beam
- Fox – Li – Boyd – Gordon – Kogelnik

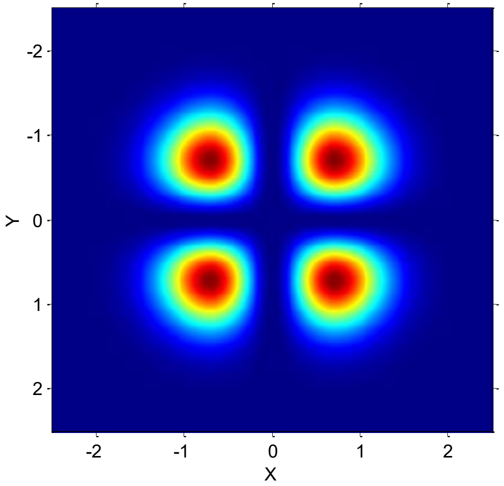
Hermite-Gaussian Mode TEM(0,0)



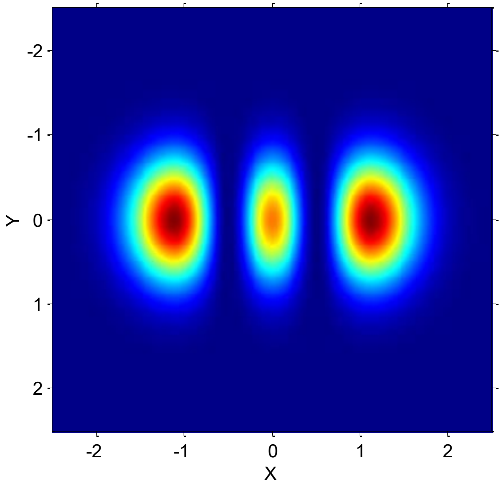
Hermite-Gaussian Mode TEM(1,0)



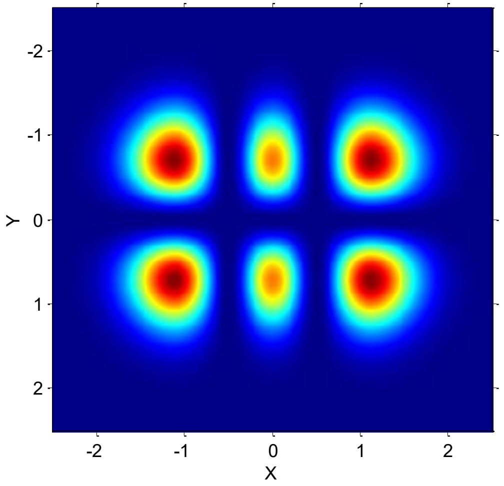
Hermite-Gaussian Mode TEM(1,1)



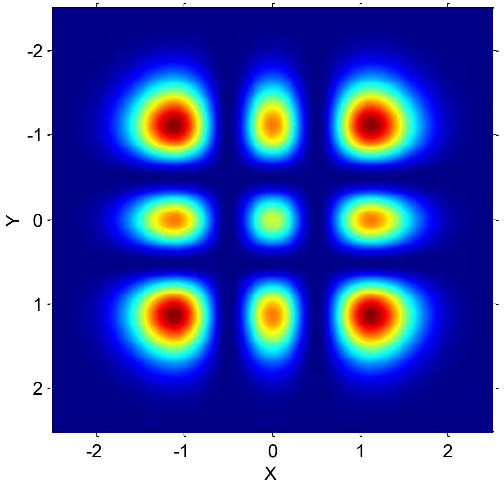
Hermite-Gaussian Mode TEM(2,0)



Hermite-Gaussian Mode TEM(2,1)

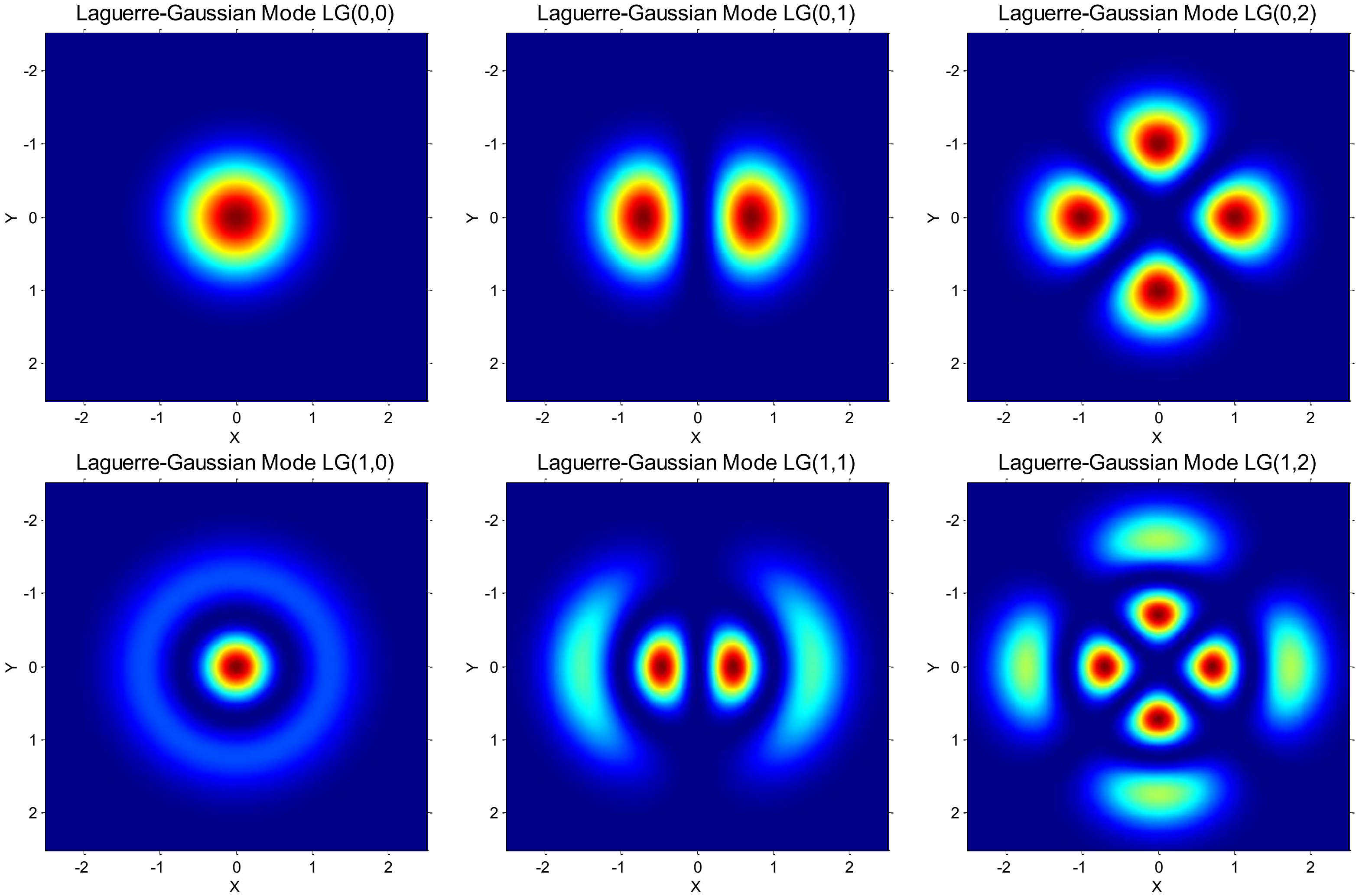


Hermite-Gaussian Mode TEM(2,2)

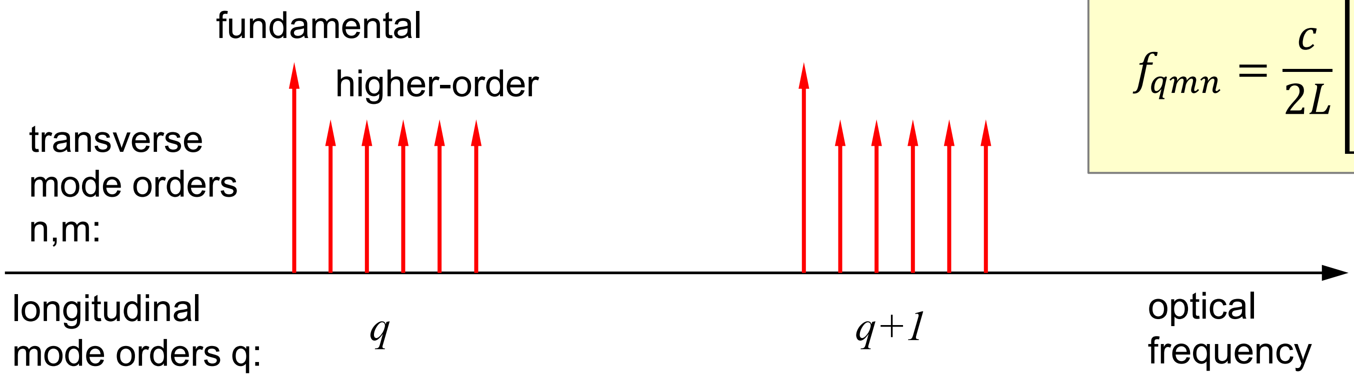


- Different basis sets can be used to expand optical field excitation and the transverse modes of the resonator
- One possible set: Hermite-Gaussian modes with X-Y Cartesian symmetry
- Another possible set: Laguerre-Gaussian modes with R-θ cylindrical symmetry

Intensity Profiles: Laguerre-Gaussian Modes, R-θ Cylindrical Symmetry



Resonant Frequencies
of Hermite-Gaussian Resonator Modes

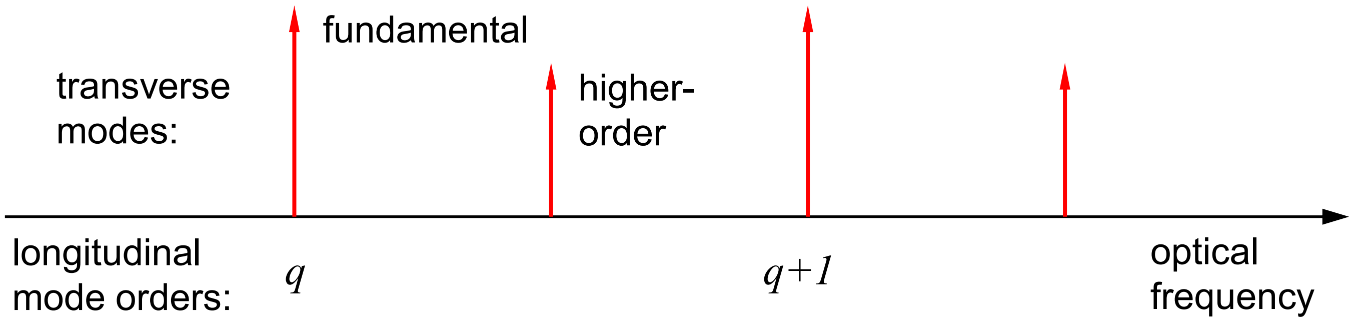


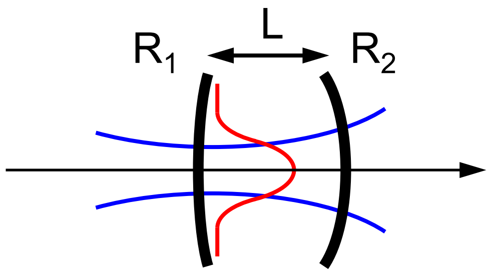
$$f_{qmn} = \frac{c}{2L}\left[q + \frac{(n+m+1)}{\pi} arccos\left(\sqrt{\left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right)}\right)\right]$$

$$\Delta f_t = \frac{\lambda^2}{2\pi\sqrt{R_c L_c}}$$

q = longitudinal modes
n,m = transverse modes
$R_{1,2}$ = mirror radius of curvature
L = cavity length

Special Case: Confocal Optical Resonator (R_{c1}=R_{c2}=L)
widely used for scanning confocal Fabry-Perot interferometers
impractical for 30 µm long micro-optical cavities (very small radius of curvature and mode spot size)



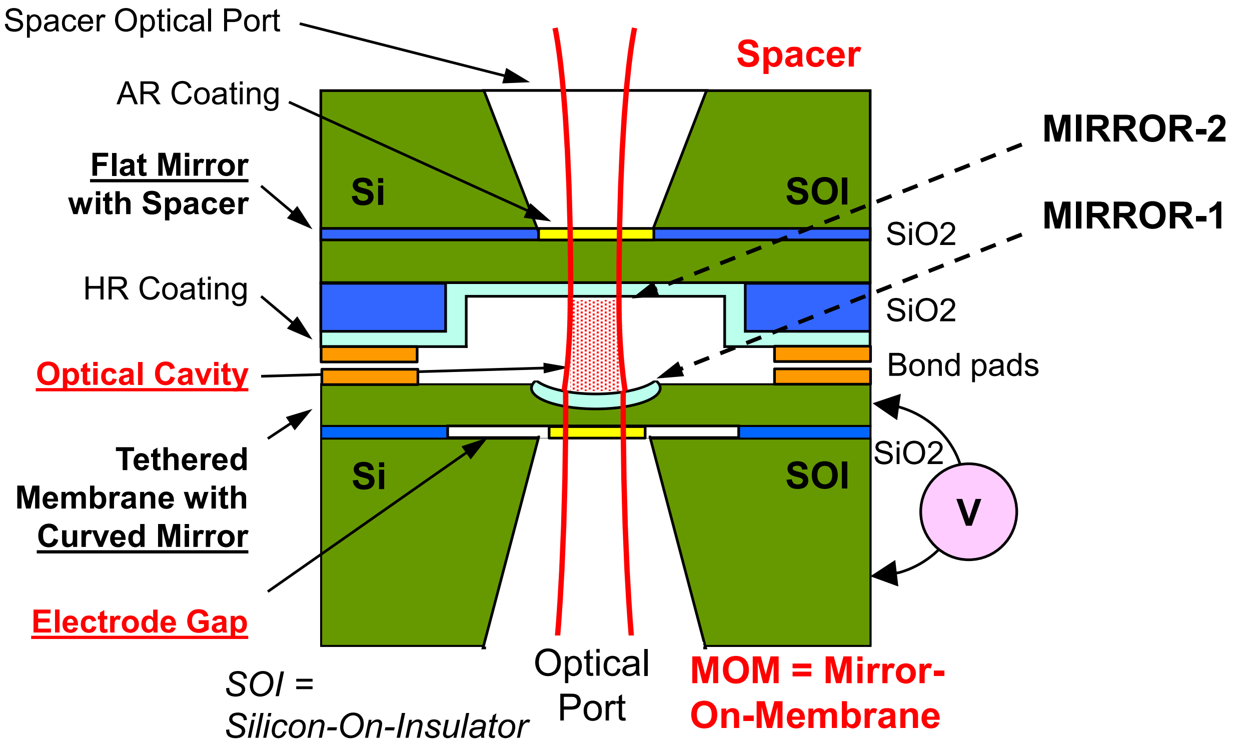


Fabry-Perot Tunable Filters Implemented in Silicon Micro-Electro-Mechanical System MEMS Technology

Silicon MEMS Tunable Fabry-Perot Filter

- High reflectivity HR mirrors: dielectric multi-layer coatings
- Curved mirror on a movable Si membrane (~ 11 μm thick)
- Applied voltage actuates membrane motion by electrostatic force
- Silicon die ~ 1 mm on a side, Electrical gap = 3 μm, Optical gap = 2 μm
- Membrane motion: 1/3 electrical gap. Voltage ~ 200 V

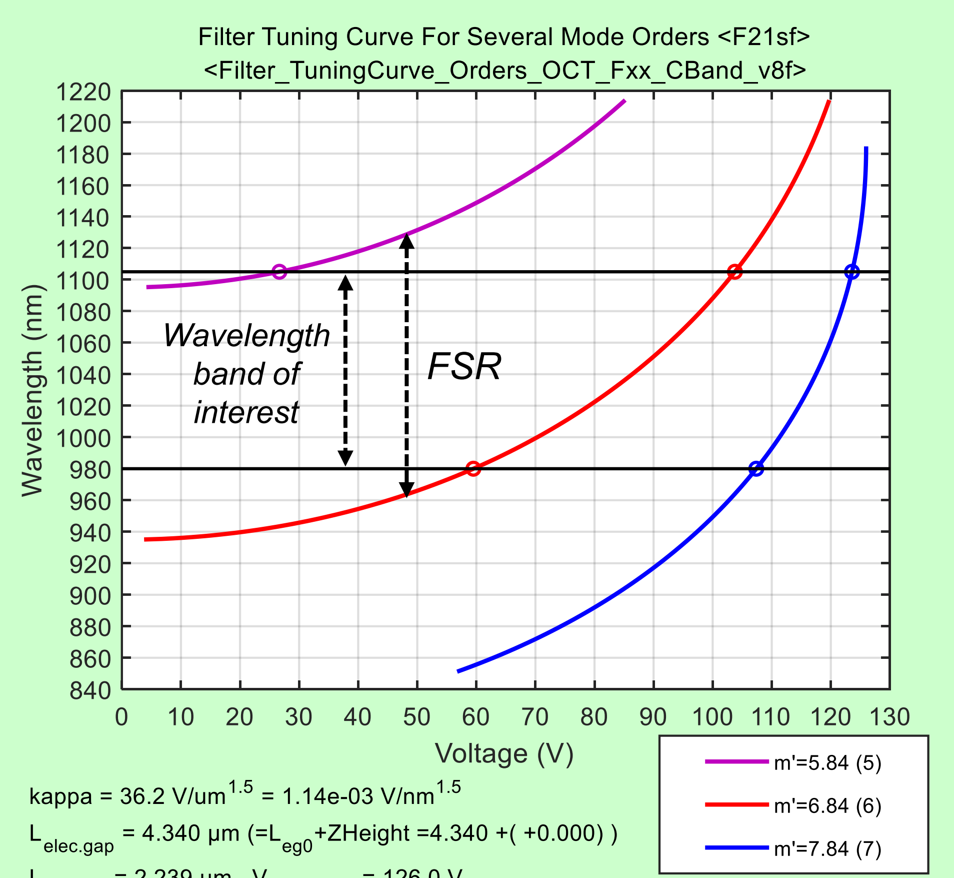
MEMS Tunable Fabry-Perot Filter



SOI = Silicon-On-Insulator

MOM = Mirror-On-Membrane

Mode Wavelength Tuning with Applied Voltage



kappa = 36.2 V/um$^{1.5}$ = 1.14e-03 V/nm$^{1.5}$

$L_{elec.gap}$ = 4.340 μm (=L_{eg0}+ZHeight =4.340 +(+0.000))

$L_{opt.gap}$ = 2.239 μm, $V_{snapdown}$ = 126.0 V

λ_0,nm = 815.7/ 934.9/ 1095.0/ 1321.2/ 1665.3 ; Wav.Band=[980 1105] nm

FSR(nm)= 226.2(up), 160.1(dn) (@980nm: 167.8(o6)/ 143.3(o7) nm)

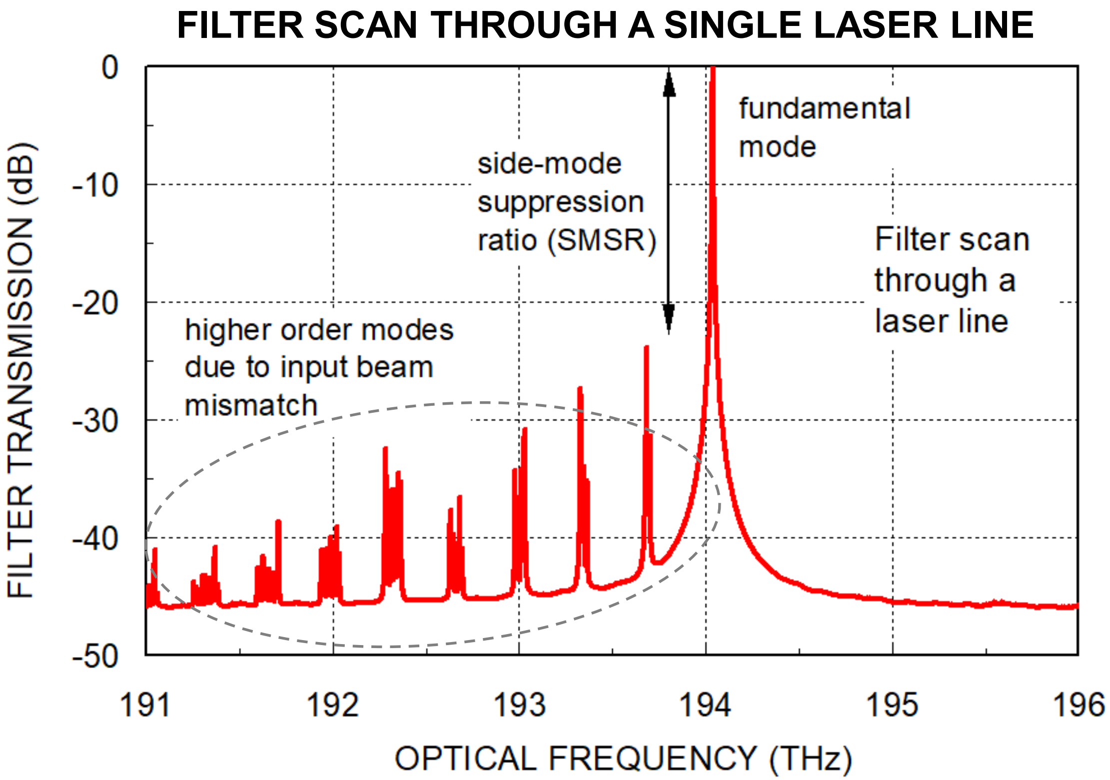
m'=4.840, V_b(V) =

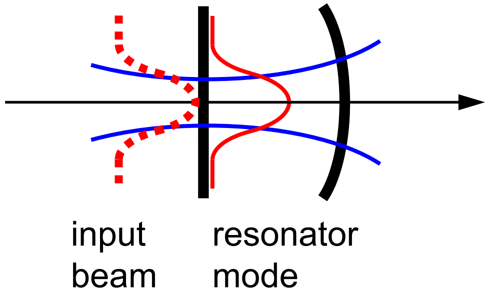
m'=5.840, V_b(V) = 26.7(21.2%),

m'=6.840, V_b(V) = 59.5(47.2%), 103.8(82.4%), $V_{ac/ctr}$(V) = 44.3 / 81.6

Scan Tunable Filter Across a Laser Line: Attempt to Match Input Beam to Fundamental Resonator Transverse Mode

- Try to match incoming beam profile to the resonator fundamental transverse mode profile
- Any beam size, shape, position, or phase front mismatch will excite higher order transverse modes
- Require robust side mode suppression > 30 dB (optical spectrum analyzer applications)
- **HOW CAN WE GET RID OF THE HIGHER ORDER TRANSVERSE MODES?**


FILTER SCAN THROUGH A SINGLE LASER LINE



Intensity Profiles: Hermite-Gaussian Modes, X-Y Cartesian Symmetry

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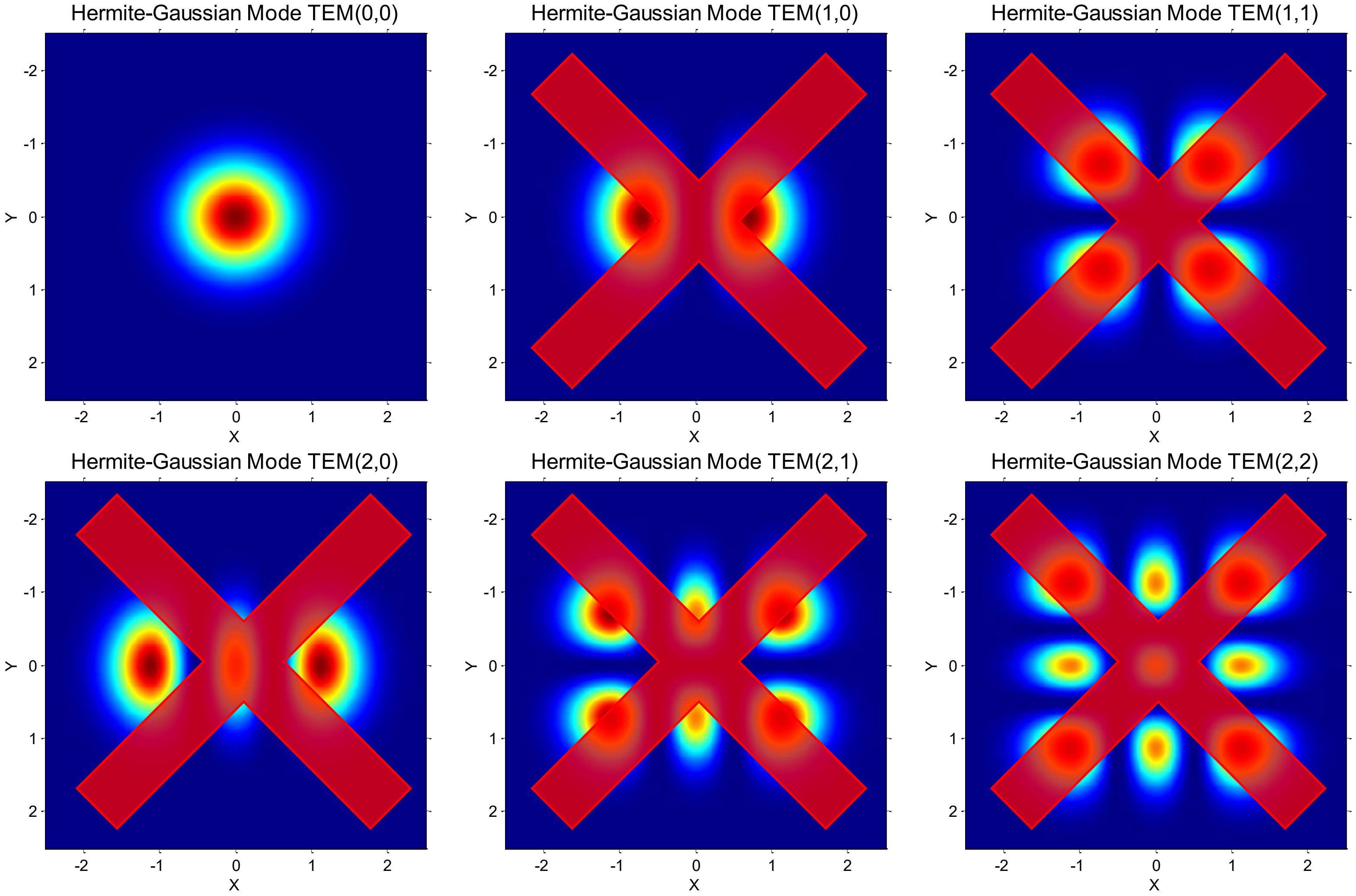


SINGLE TRANSVERSE MODE RESONATOR ?

Single Transverse Mode Optical Resonators:

New, by Design

(This is not in your Textbook)

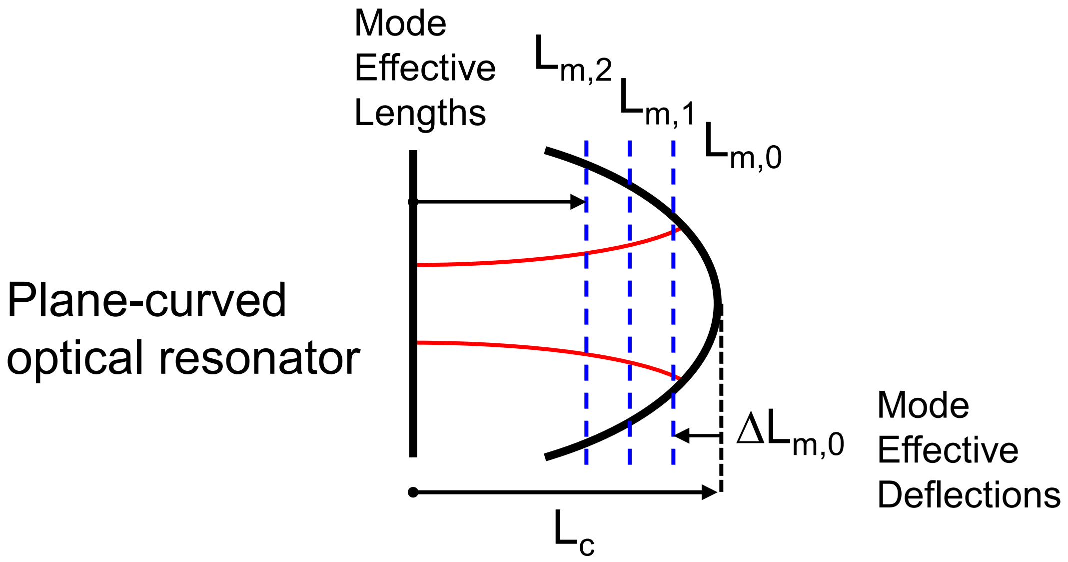
Define Effective Length of Transverse Modes in Optical Resonators

Longitudinal mode frequencies $$f_m = m\frac{c}{2L_c}$$

Transverse mode frequencies $$f_{m,t} = f_m + \Delta f_{m,t} \equiv m\frac{c}{2L_{m,t}} > f_m$$

Effective length of transverse modes $$L_{m,t} \equiv \frac{mc}{2f_{m,t}} < L_c$$

Effective deflection of transverse modes $$\Delta L_{m,t} \equiv L_c - L_{m,t}$$

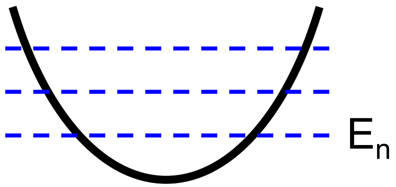


The Harmonic Oscillator Analogies

Parabolic potential:

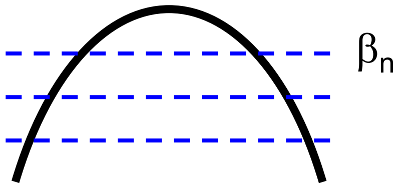
- Hermite-Gaussian eigenmodes
- Equally-spaced eigenvalues

Harmonic Oscillator



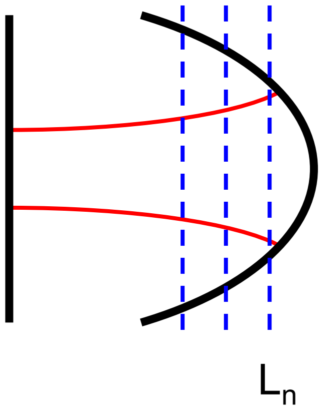
Particle states with
equally-spaced
energy levels

Parabolically Graded-Index Optical Fiber



Waveguide modes
with equally-spaced
propagation constants

Spherical Mirror Resonator

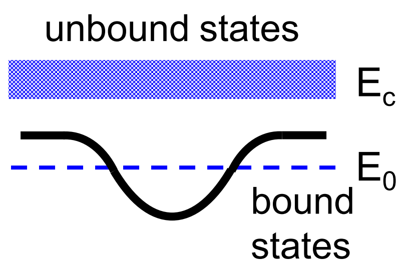


Resonator modes
with equally-spaced
effective lengths

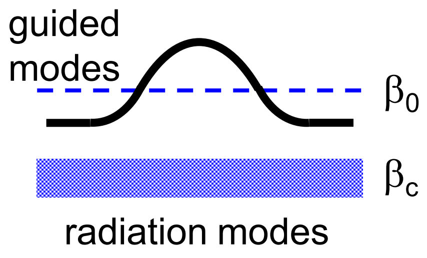
Transverse Mode Stability in Potential Wells, Optical Waveguides and Optical Resonators

- The harmonic oscillator supports a multitude of discrete bound states whose energies fall within the depth of the parabolic potential well.
- A finite depth potential well supports only a finite number, potentially just one, of bound states, There is also a continuum of unbound states with energies above the edge of the potential well.
- An optical waveguide with a finite refractive index step support a finite number, potentially just one, of guided modes, plus unbound radiation modes.
- We conjecture that optical resonators behave analogously to potential wells and optical waveguides: the multitude of stable transverse modes is caused by the “unlimited” depth of the spherical mirror, where a multitude of mode deflections fits within the mirror depth.
- Optical resonator with finite depth mirrors should have a finite number of discrete spatially confined (stable) modes whose deflections fall within the mirror depth. There should be a continuum of unconfined (unstable) modes with deflections beyond the depth of the mirror.

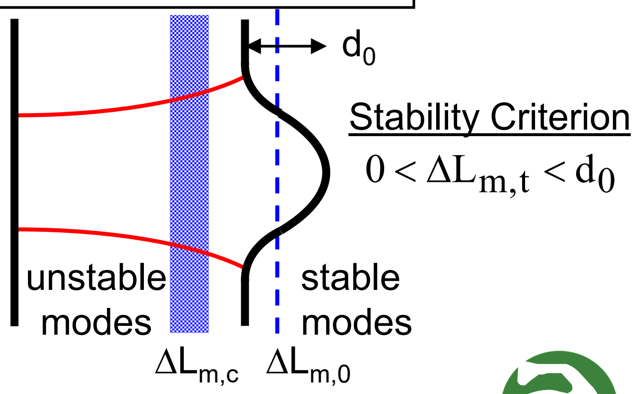
POTENTIAL WELL



OPTICAL WAVEGUIDE



OPTICAL RESONATOR

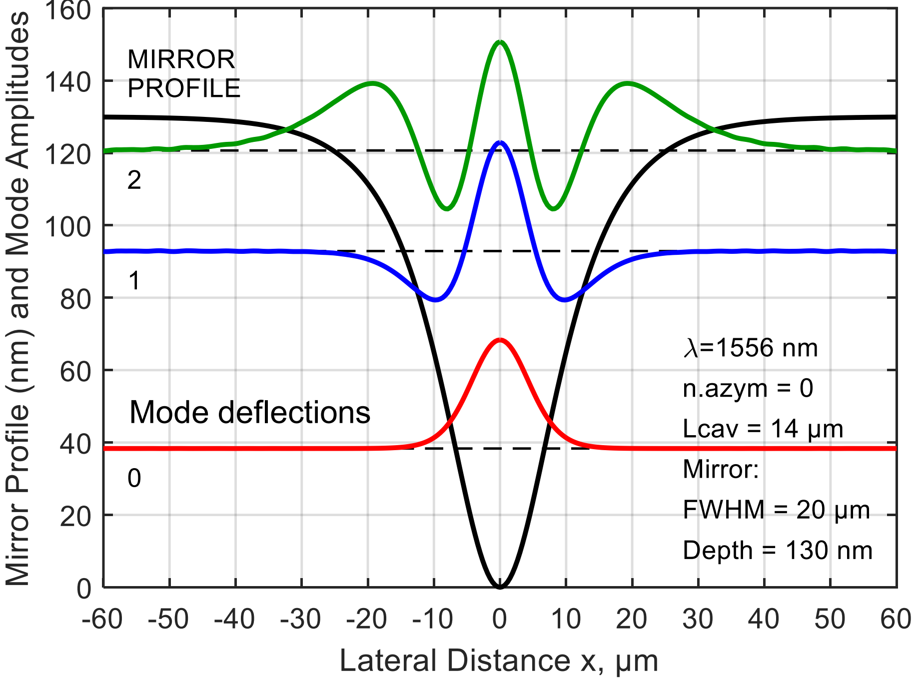


Calculated Transverse Mode Profiles for Fabry-Perot Resonators with Finite Depth Mirrors

Resonator eigenvalue equation
for cylindrical symmetry:

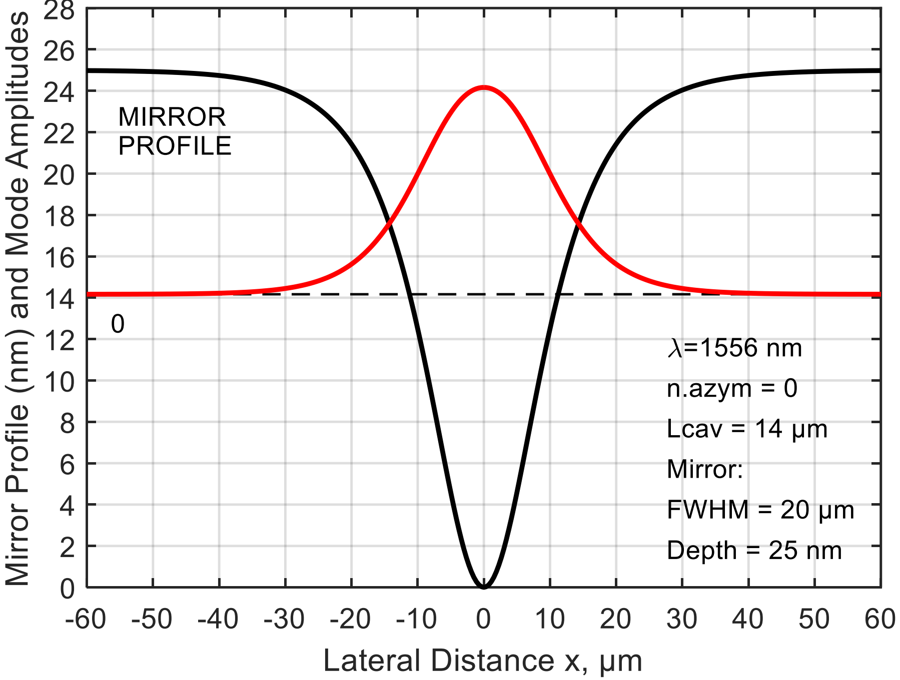
$$\int dk_r E_k(k_r) A(k_r\,, r) = \mu \int dk_r E_k(k_r) B(k_r\,, r)$$

Transverse Modes
of a Finite Deflection Mirror Fabry-Perot Resonator



- Deep mirror, 130 nm, sech(r) profile
- **Three confined modes**
- Mode n_r=2 approaching cutoff, losing confinement – broad spatial wings, diffraction loss, spectral linewidth broadening

Transverse Modes
of a Finite Deflection Mirror Fabry-Perot Resonator



- Shallow mirror, 25 nm, sech(r) profile
- Phase front follows the mirror profile
- Mode has distinct exponential, rather than Gaussian, tails
- **Single confined mode !!!**

Single Transverse Mode Condition for Optical Resonators

- Fit a spherical mirror passing through the apex and the full-width-half-max FWHM points of the finite depth mirror
- We know mode frequencies and deflections of the spherical mirror resonator. Single transverse mode condition: the first higher order mode of the spherical mirror is cut off, its effective deflection $\Delta L_{m,1}$ reaches the mirror profile edge d_0:

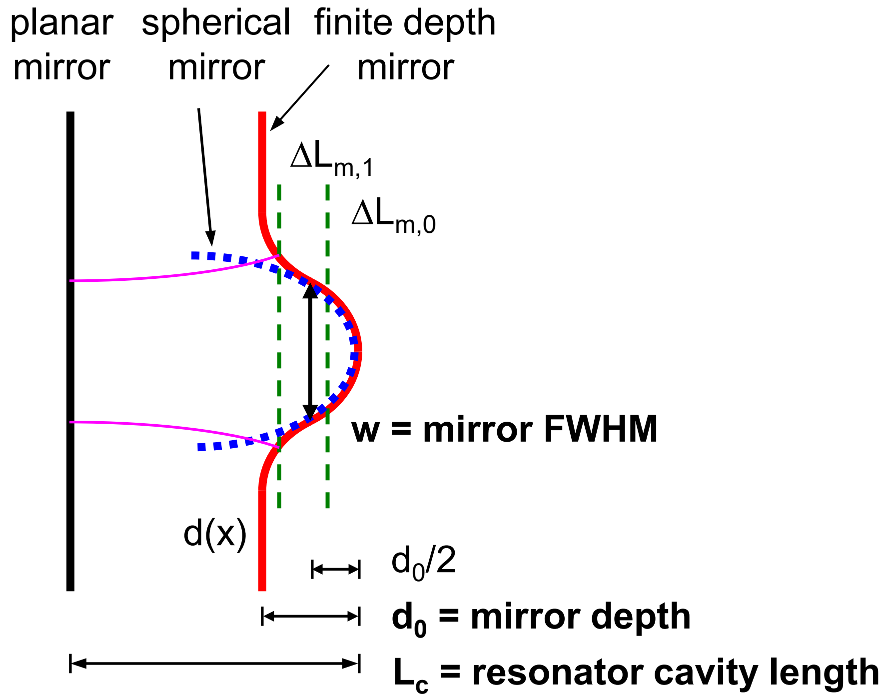
$$\frac{\pi w}{\lambda}\sqrt{d_0/L_c} < 2$$

- Optical fiber single mode condition and the V-number:

$$V_f \approx \frac{\pi w}{\lambda}\sqrt{2n_{clad}\Delta n} < 2.405$$

- In analogy with optical fibers, define a dimensionless V-parameter for optical resonators:

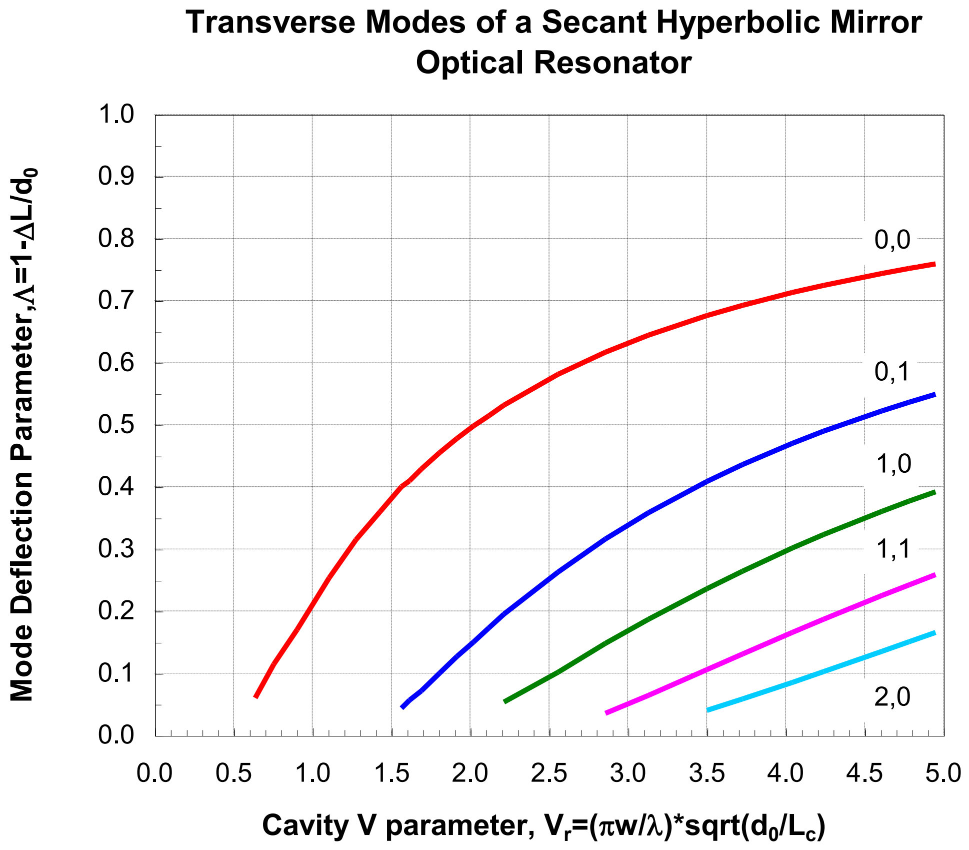
$$\boxed{V_r \equiv \frac{\pi w}{\lambda}\sqrt{d_0/L_c}}$$

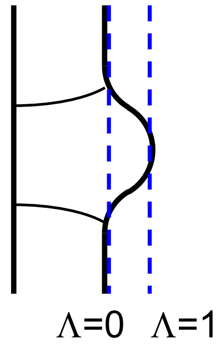


Transverse Mode Structure of Optical Resonators: the Λ-V Diagram

- Define a dimensionless mode deflection parameter Λ:
- Λ = 0 at mode cutoff, Λ →1 for a well confined mode
- Universal Λ – V diagram: a point on the diagram represents all the different resonators with the same V-parameter
- Weak dependence on the mirror shape

$$\boxed{\Lambda \equiv 1 - \Delta L_{m,t}/d_0}$$


Transverse Modes of a Secant Hyperbolic Mirror Optical Resonator

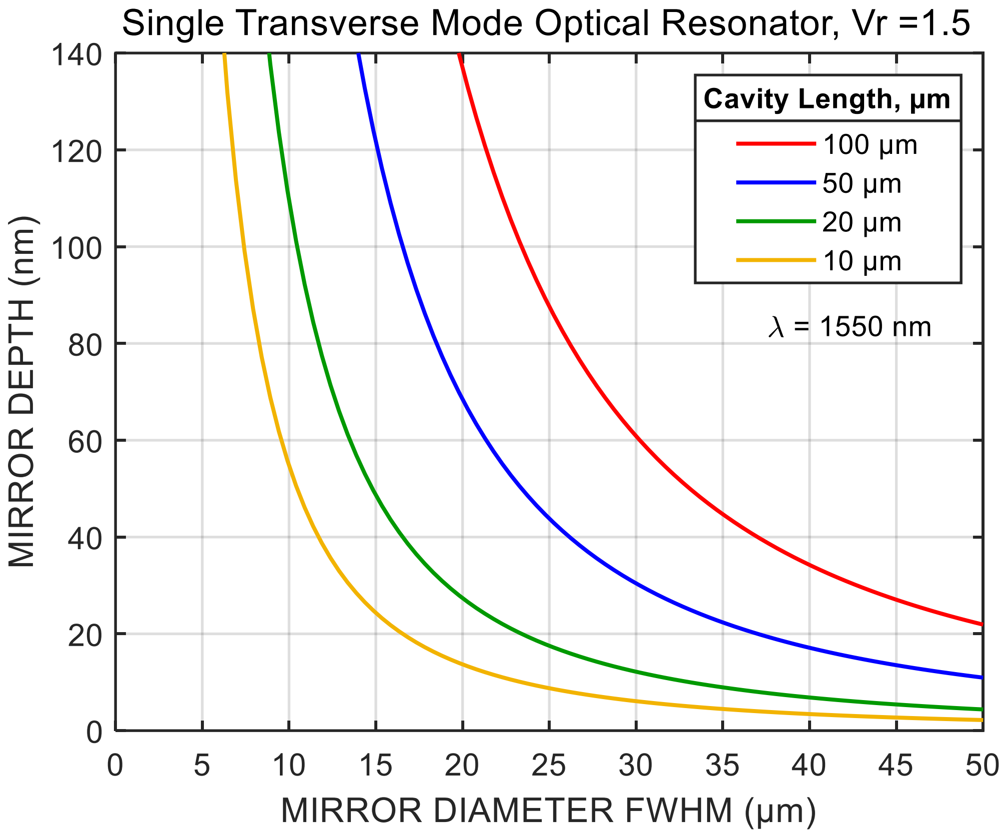


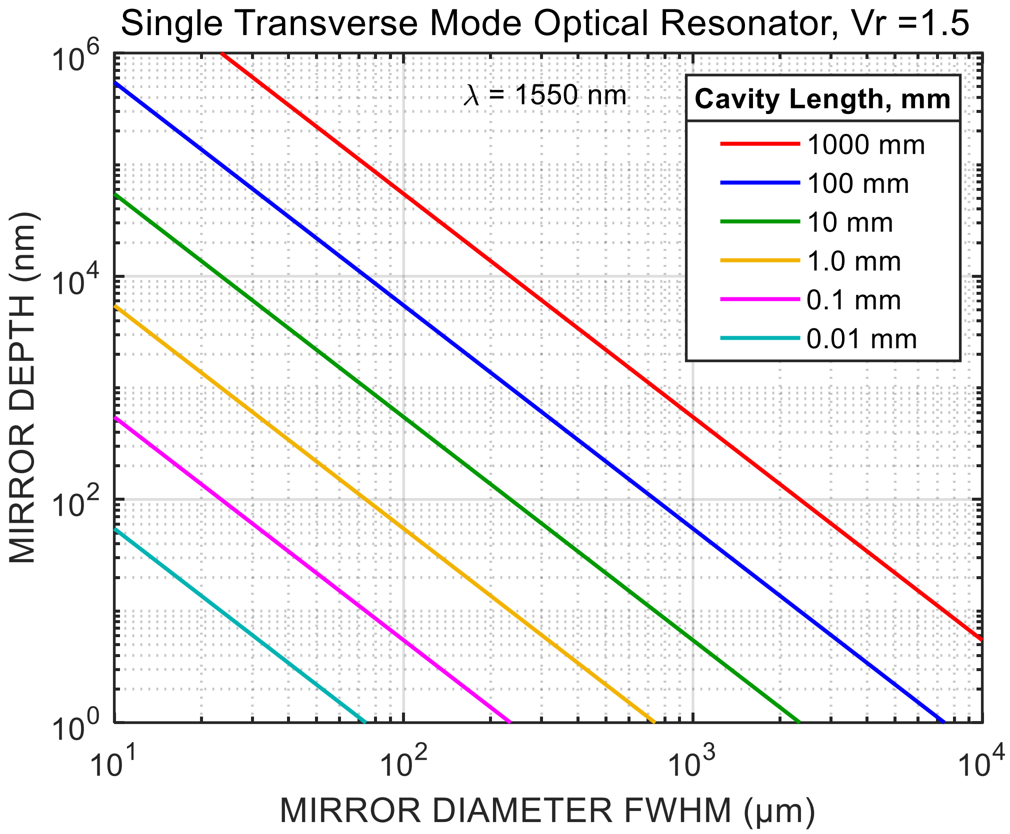
- Secant hyperbolic mirror profile
- Radial and azimuthal mode numbers (n_r,n_{azim})
- Universal dimensionless resonator parameter V_r

$$\boxed{V_r \equiv \frac{\pi w}{\lambda}\sqrt{d_0/L_c}}$$

- Single mode condition: **$V_r < 1.5$**

Mirror Dimensions for Single Mode Resonators:
Excellent Match for Micro-Optical MEMS Tunable Filters



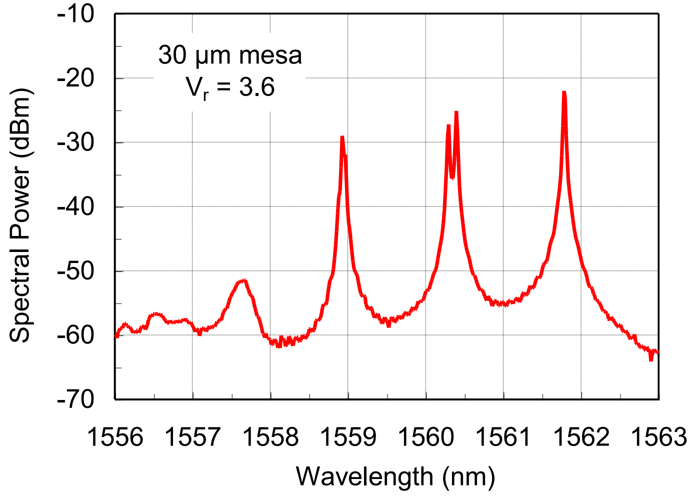


For single mode micro-optical resonators, the mirrors are small:

- mirror diameter ~ 10 – 30 µm
- mirror depth ~ 20 – 80 nm

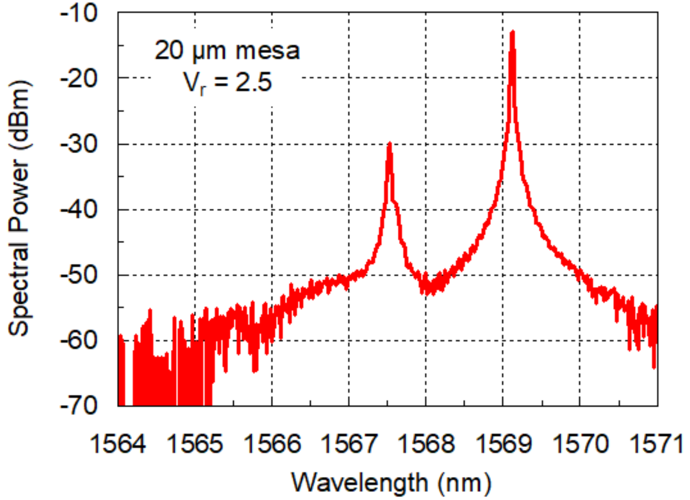
Measured Micro-Optical Cavity Transmission for Different Mirror Sizes

Vr = 3.6, 4 modes

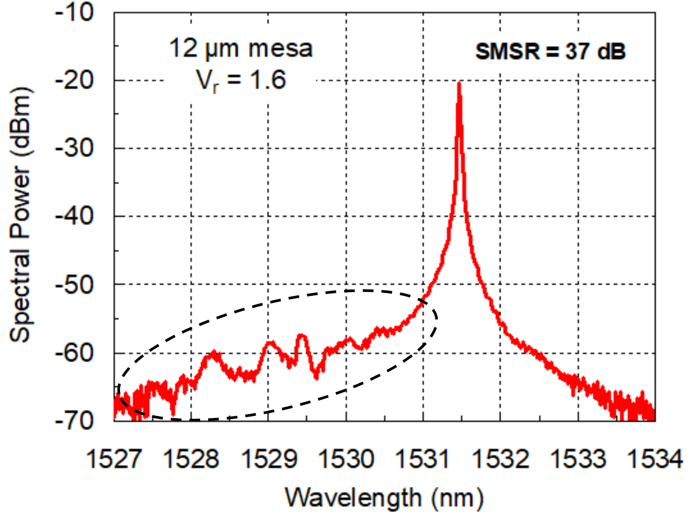


- Flat-curved mirror cavity
- λ = 1550 nm
- Cavity length = 23 μm
- As the mirror gets smaller, the optical cavity V-parameter gets smaller and the resonator supports fewer and fewer transverse modes

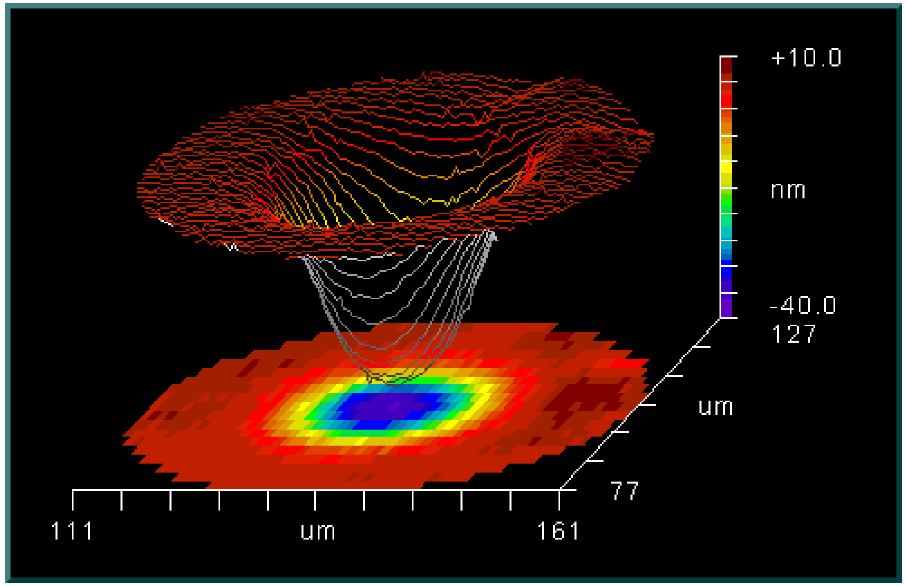
Vr = 2.5, 2 modes



Vr = 1.6, 1 mode

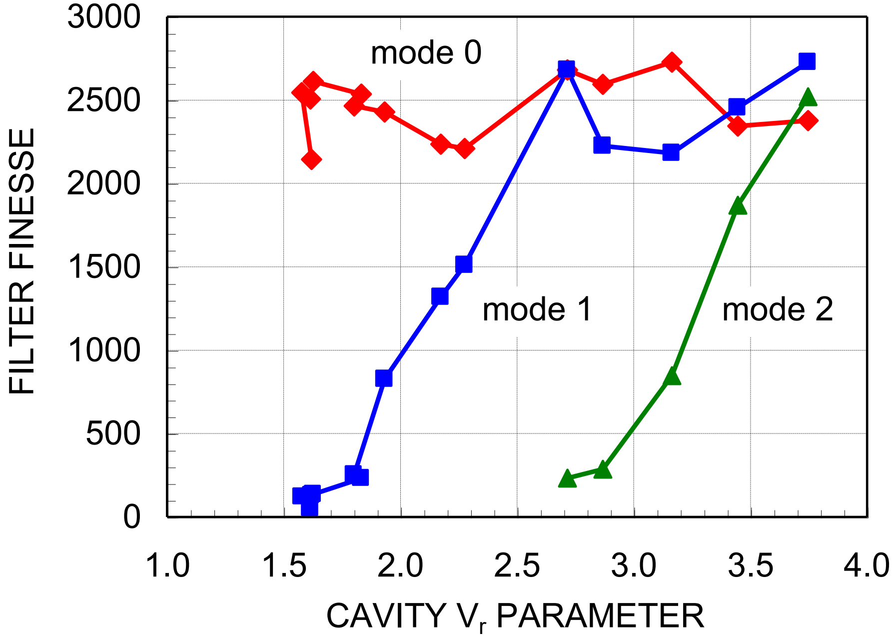


Measured Micro-Optical Mirror Profile

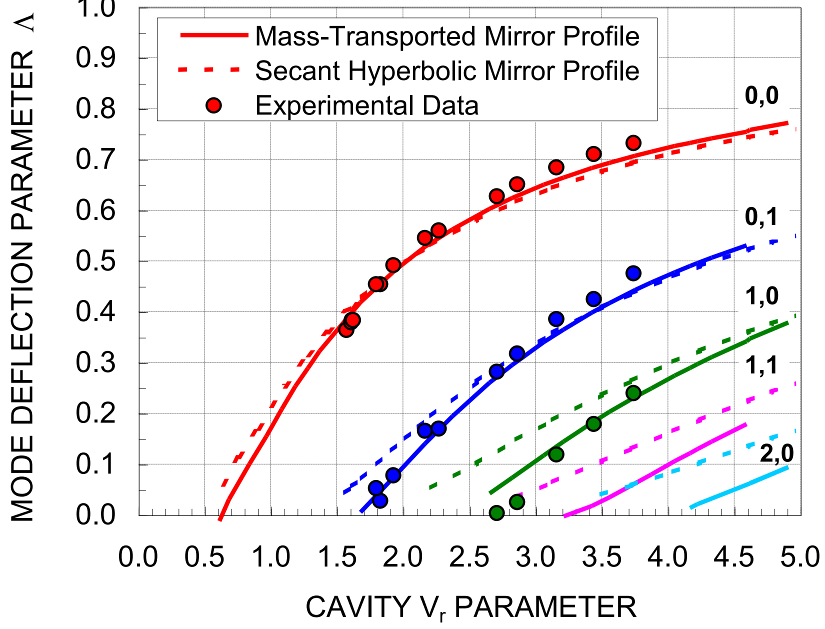


- Mirror fabrication technique:
  - Mass transport
  - Chemical-mechanical polishing
  - Grayscale etching is also applicable
- Wafer scale fabrication
- Mirror apex radius of curvature Rc ~ 1.0 mm

Measured Micro-Optical Filter Finesse and Mode Frequencies for Different Mirror Sizes



Measured Filter Finesse for Different Mirror Sizes

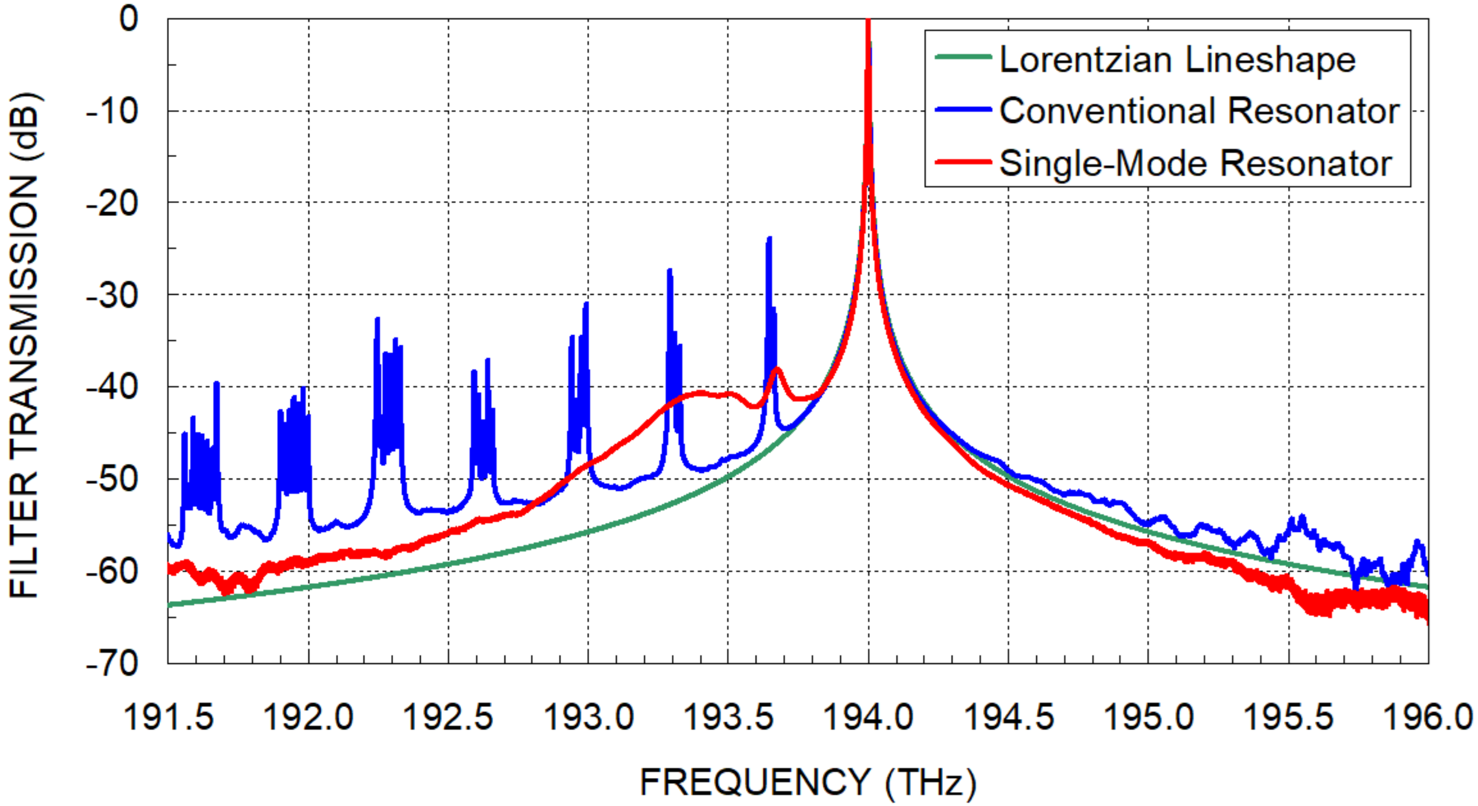


Measured and Calculated Λ-V Mode Diagram

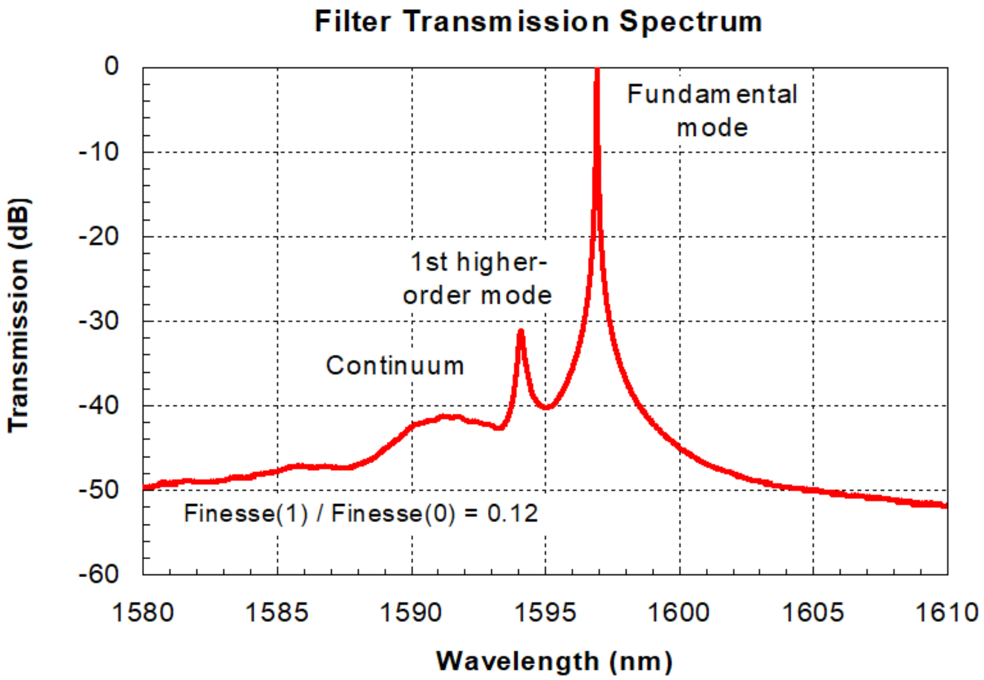
- Flat-curved mirror cavity; $\lambda = 1550$ nm, Cavity length = 23 µm; Design finesse ~ 3000
- As the cavity V-parameter gets smaller, higher order transverse modes get cut off one by one
- As the higher order modes approach their cutoff, their finesse is rapidly dropping to zero, i.e. linewidth broadens (diffraction loss)
- The fundamental mode finesse is limited only by the mirror reflectivities, this finesse is preserved as the V-parameter gets smaller
- Good agreement between the measured and calculated Λ-V modal diagrams

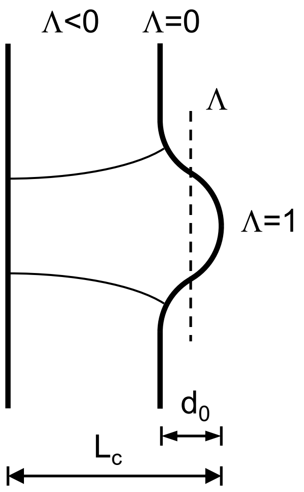
Compare Conventional and Single-Mode Resonator Spectral Transmission Lineshapes

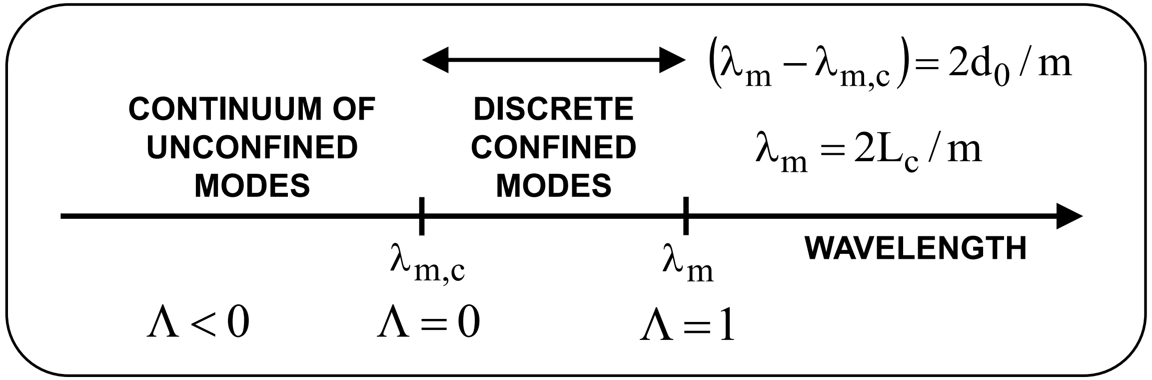
- Tunable filter scan through a laser line
- Input power not matched into the fundamental mode gets distributed between discrete or continuous higher order modes
  - Enhanced beam misalignment tolerance



Interpretation of the Resonator Transmission Spectrum


Filter Transmission Spectrum




$$(\lambda_m - \lambda_{m,c}) = 2d_0 / m$$

$$\lambda_m = 2L_c / m$$

CONTINUUM OF UNCONFINED MODES

DISCRETE CONFINED MODES

WAVELENGTH

$\lambda_{m,c}$ λ_m

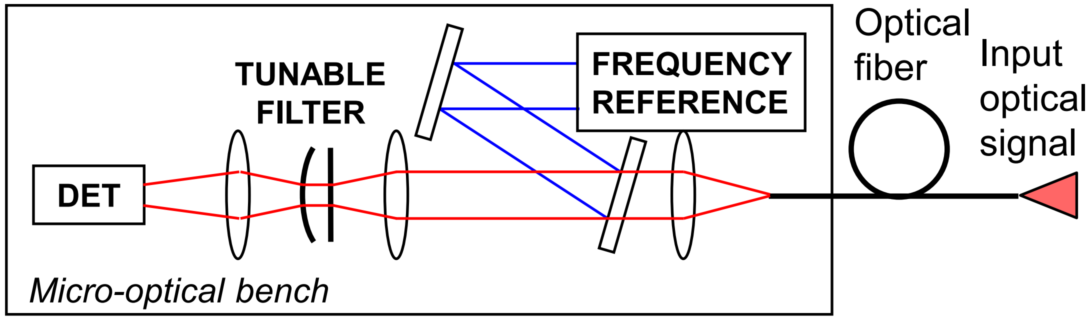
$\Lambda < 0$ $\Lambda = 0$ $\Lambda = 1$

The wavelength range of discrete modes is determined only by the mirror depth

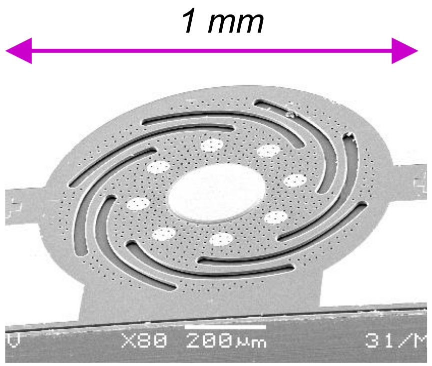
Applications:
Compact Micro-Optical Optical Spectrum Analyzer

Axsun’s Optical Channel Monitor (OCM): Optical Spectrum Analyzer OSA for WDM Fiber Telecom

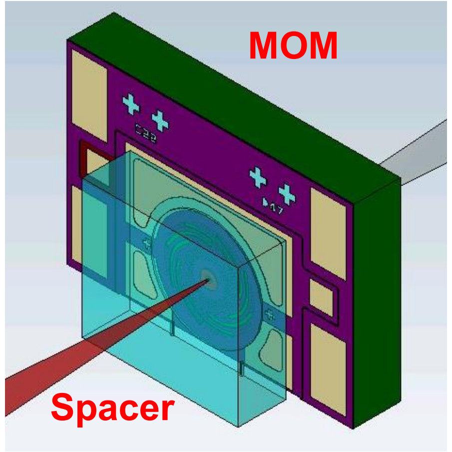
- Power / wavelength monitoring in wavelength division multiplexed optical networks
- Approach performance of a large grating-based OSA in a small package



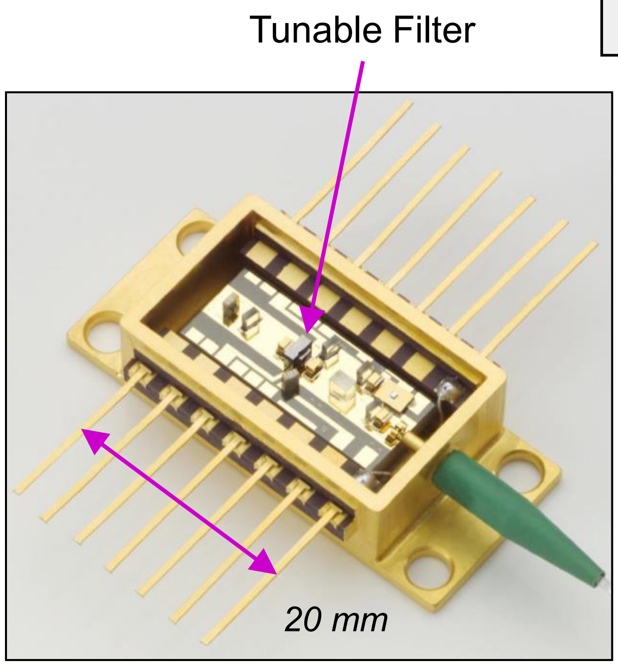
- Spectral Range:
  - C-band: 1525 – 1565 nm, 5.0 THz
  - L-band: 1570 – 1610 nm, 4.8 THz
- Channel Power: –45 to –5 dBm
- Frequency Resolution: 3 GHz
- Power / Frequency Accuracy: ±1 dB / ±8 GHz
- Optical Signal-to-Noise Ratio: up to 30 dB
- Tens of thousands such OCM’s had been deployed in WDM optical networks



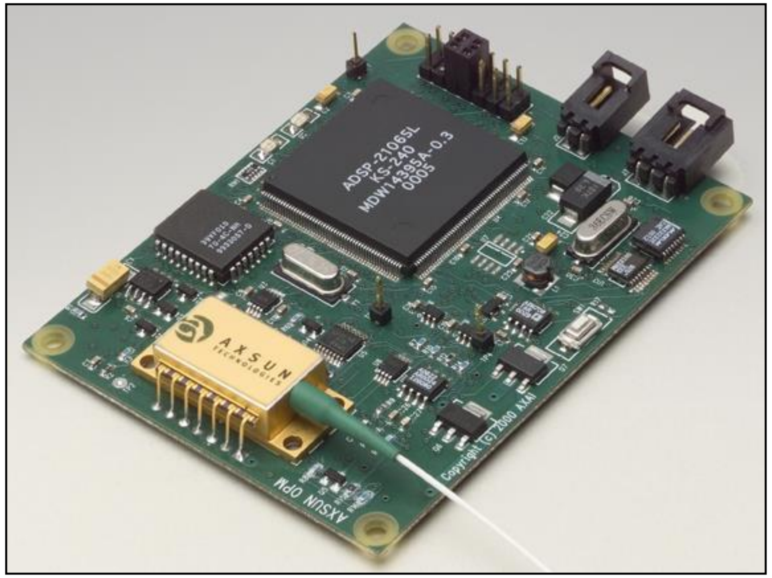
Filter: tethered membrane



Tunable filter assembly

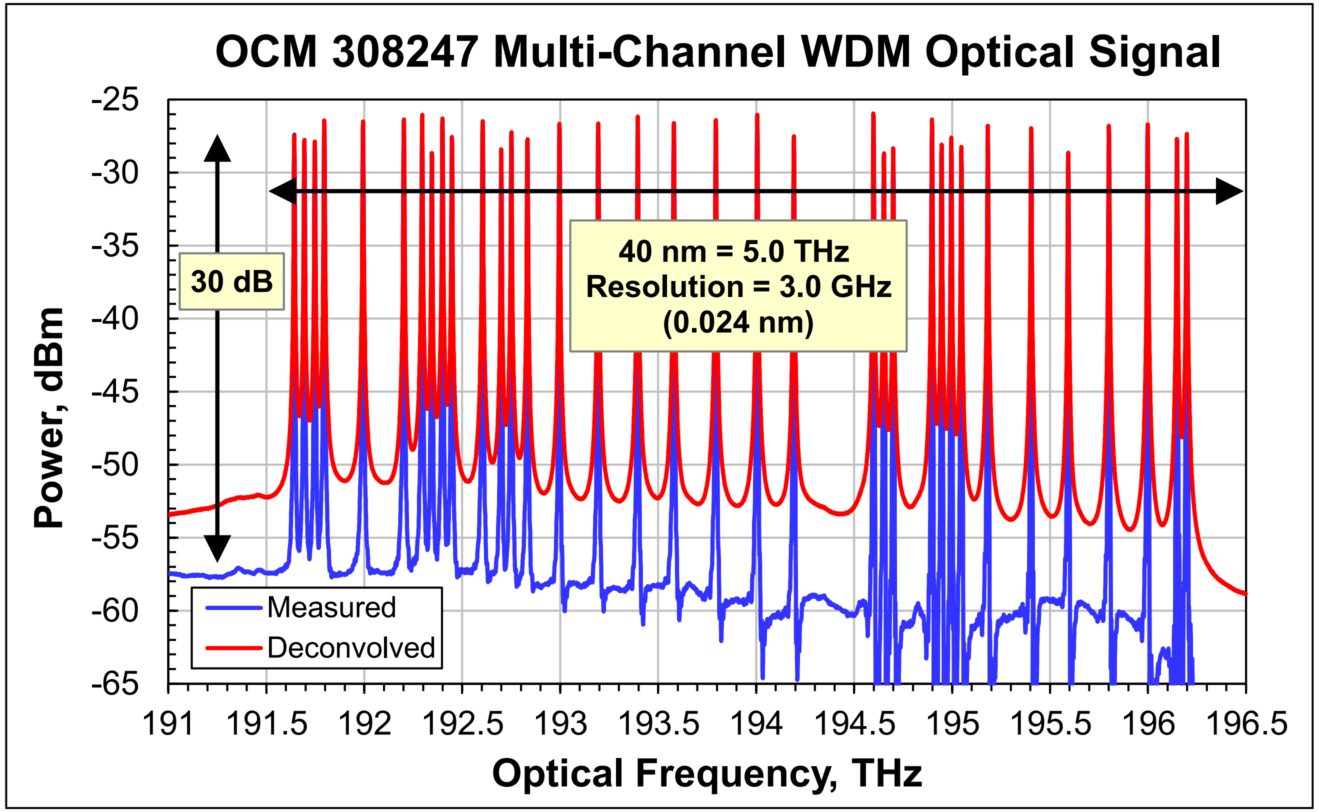


Micro-optical bench in hermetic package



Circuit board assembly

Axsun's Optical Channel Monitor (OCM): Measurement of a Wavelength-Division Multiplexed Multi-Channel Optical Signal



- Spectral range = 40 nm (5.0 THz) (1525 – 1565 nm)
- Spectral resolution = 0.024 nm (3.0 GHz)
- Optical channel spacing = 50 GHz
- Number of Channels: > 100
- Optical Signal-to-Noise Ratio, OSNR = 30 dB
- Use numerical spectral deconvolution to reduce Lorentzian spectral wings of the Fabry-Perot filter
- This is not a hero result for a science paper
- Tens of thousands such optical channel monitors had been deployed, reliably, in WDM optical networks

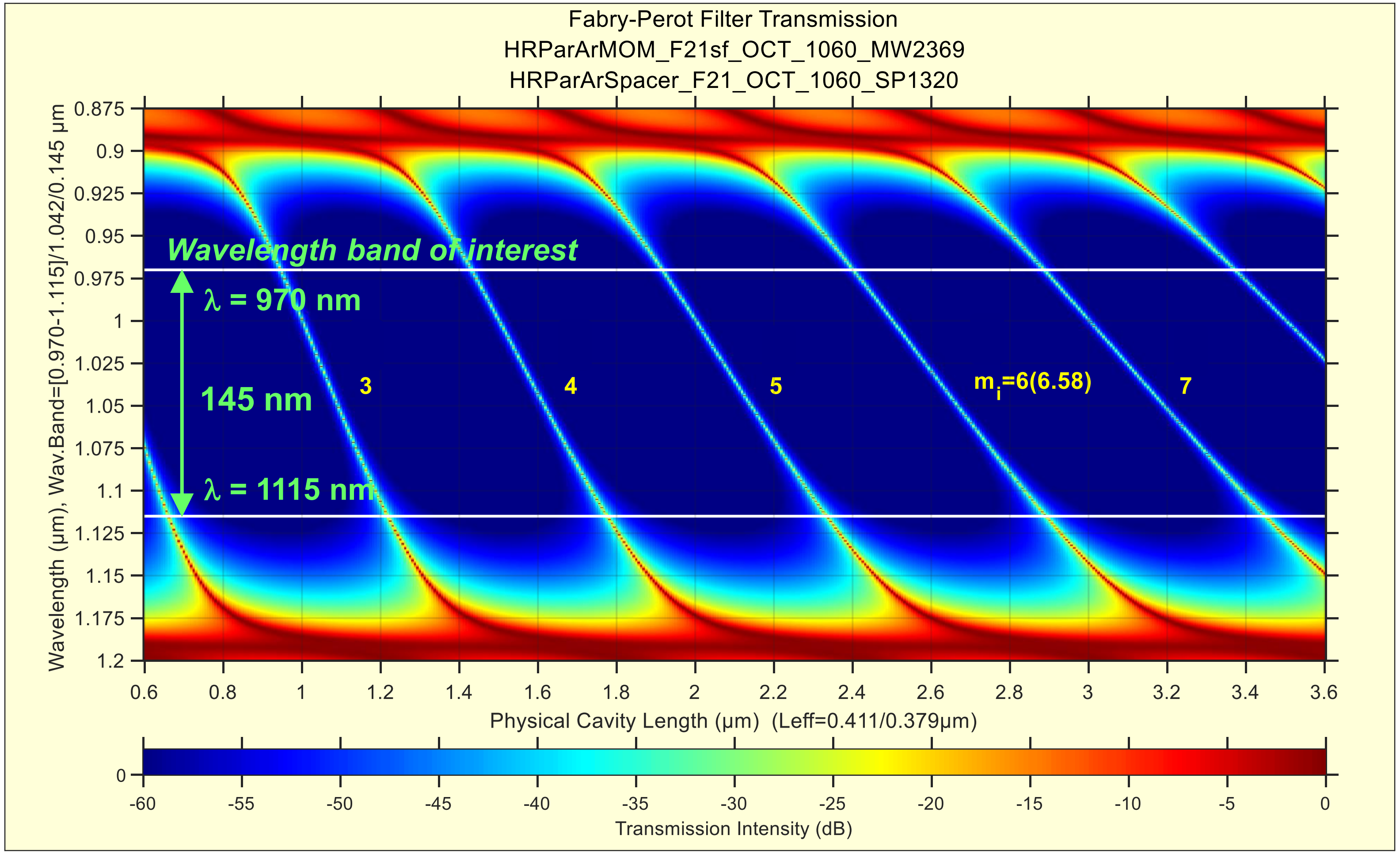
Reflective Spectral Selection Mode of Tunable Fabry-Perot Filters:

New, by Discovery

(This is also not in your Textbook)

Tunable Fabry-Perot Filter Transmission: With Dielectric Multi-Layer High-Reflectivity Coatings

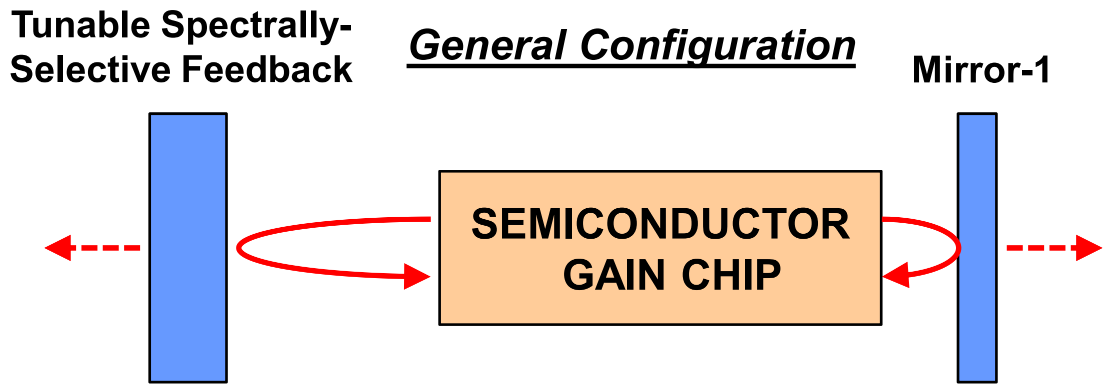
- Beautiful tunable filter:
  - compact, narrow linewidth (1-100GHz), widely tuning (>100nm), fast tuning (MEMS > 400kHz sweep repetition rate across the full tuning range)
- Can we use it to make a tunable external cavity semiconductor laser?



Dielectric coating reflection band
(Ta2O5/SiO2 on Si)

Tunable External Cavity Semiconductor Lasers

- Use a broadband semiconductor optical amplifier SOA gain chip with a narrow tunable spectrally-selective feedback
- Tunable Fabry-Perot filter configuration: **tilt filter optical axis** to send broadband reflected signal away from chip waveguide

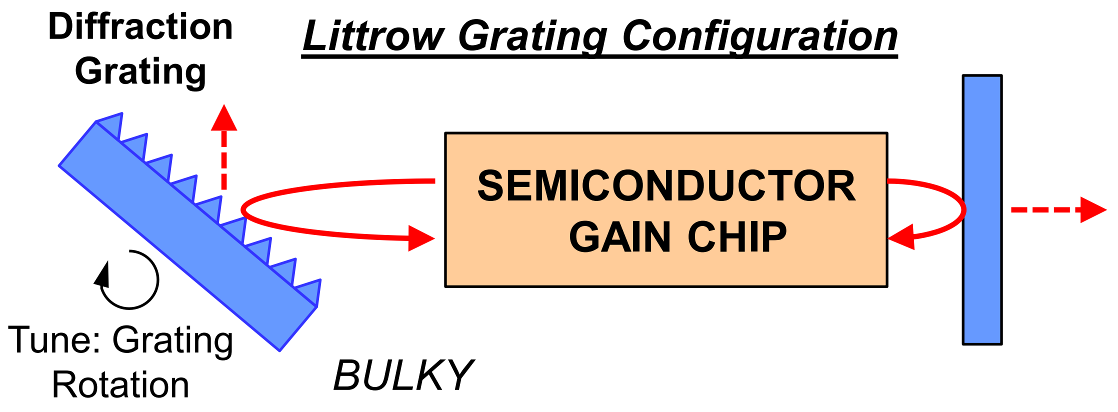


General Configuration

Tunable Spectrally-Selective Feedback

Mirror-1

SEMICONDUCTOR GAIN CHIP



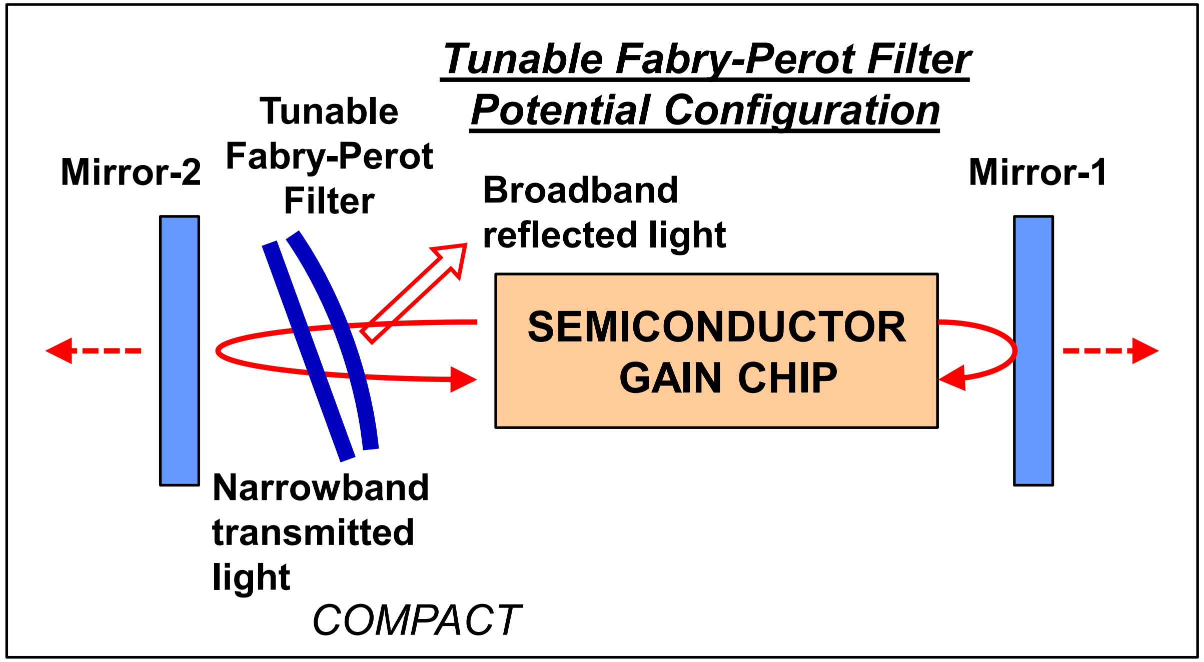
Littrow Grating Configuration

Diffraction Grating

SEMICONDUCTOR GAIN CHIP

Tune: Grating Rotation

BULKY



Tunable Fabry-Perot Filter Potential Configuration

Mirror-2

Tunable Fabry-Perot Filter

Broadband reflected light

Mirror-1

SEMICONDUCTOR GAIN CHIP

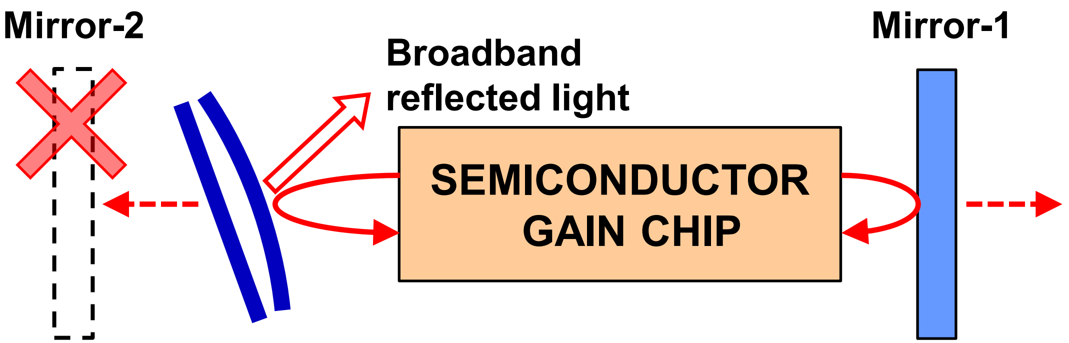
Narrowband transmitted light

COMPACT

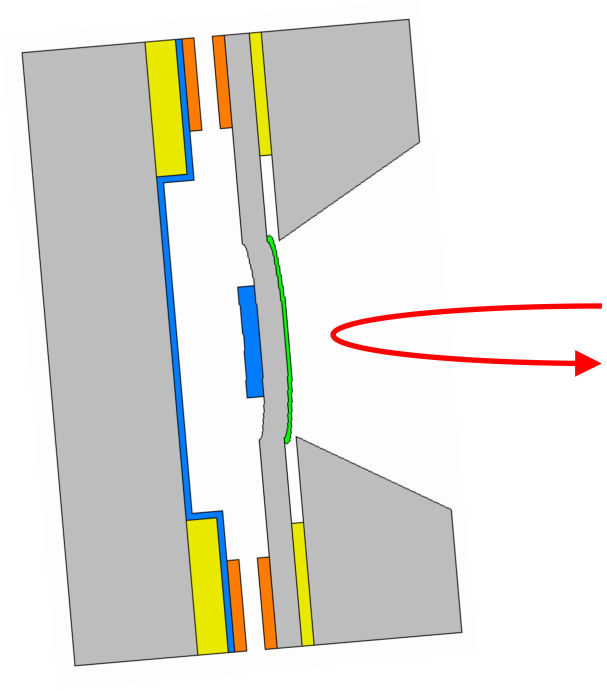
Discovering Reflective Fabry-Perot Tunable Filter

- Tunable laser with intracavity Fabry-Perot filter works well
- **Take away external mirror #2 → tunable laser still works!**
- Very simple tunable laser configuration
- How does it work ?????

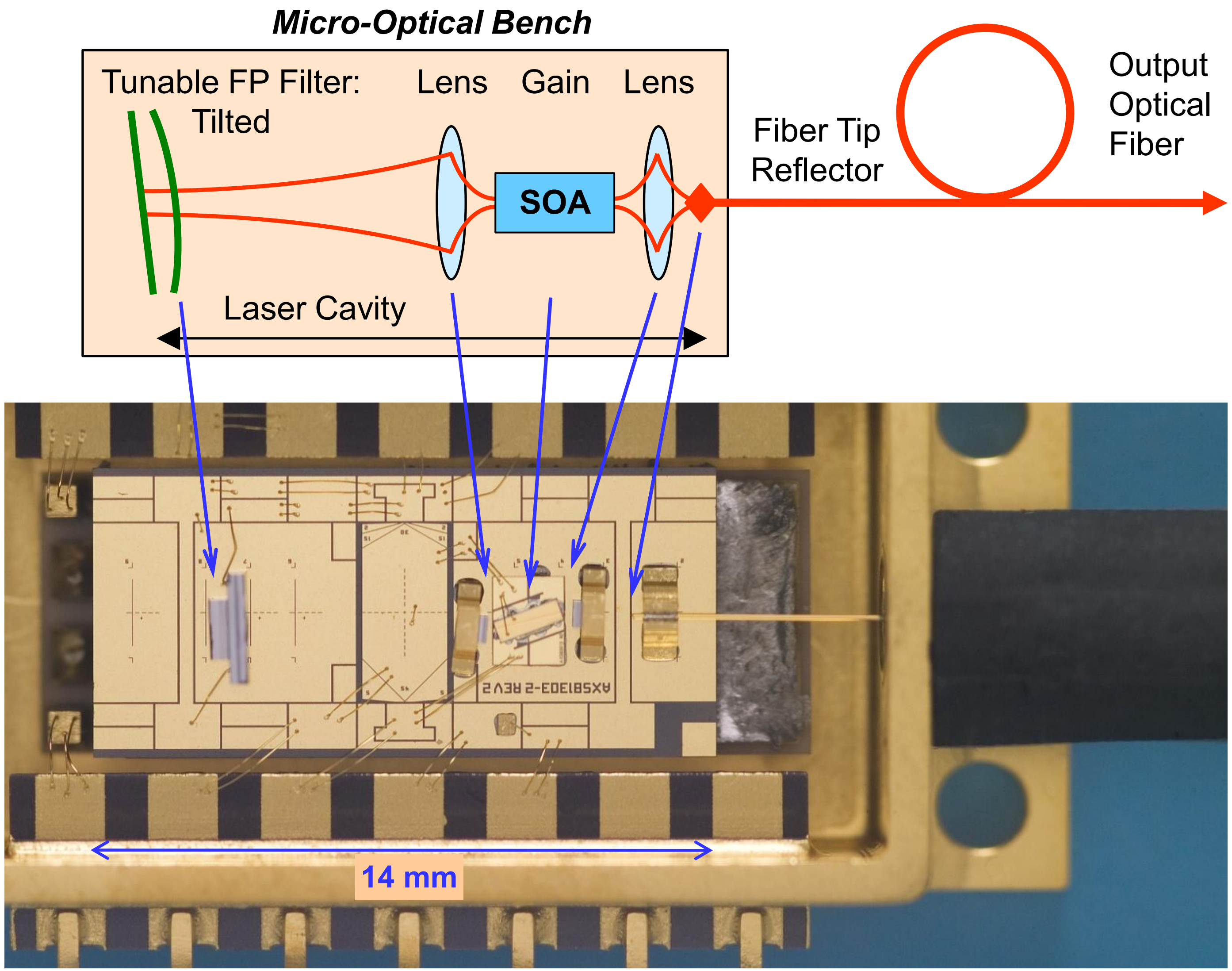
Reflective Fabry-Perot Tunable Laser



Tunable Reflective Fabry-Perot Filter:
MEMS Implementation



Reflective Fabry-Perot Tunable External Cavity Semiconductor Laser

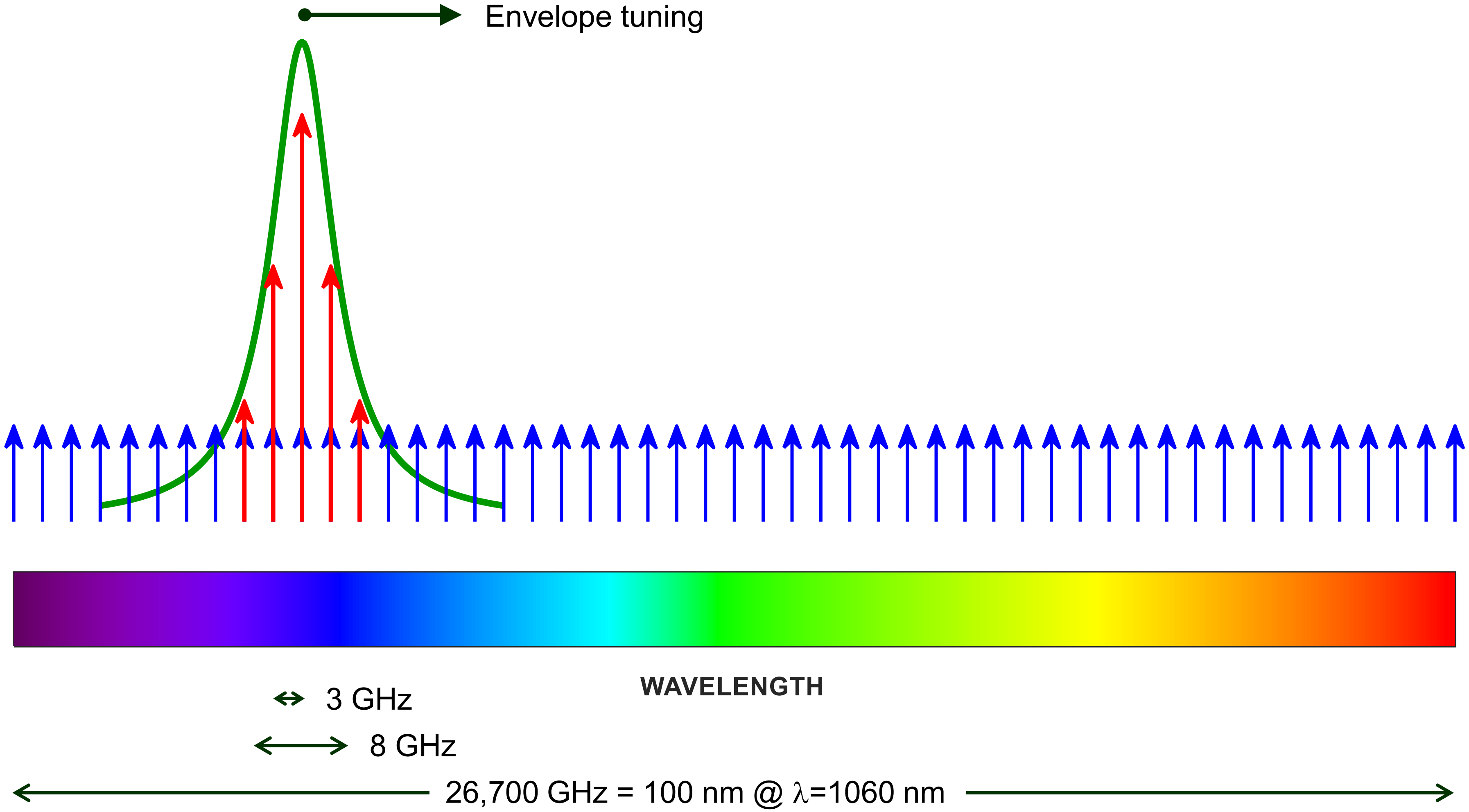


<u>Tilted Fabry-Perot Filter</u>:

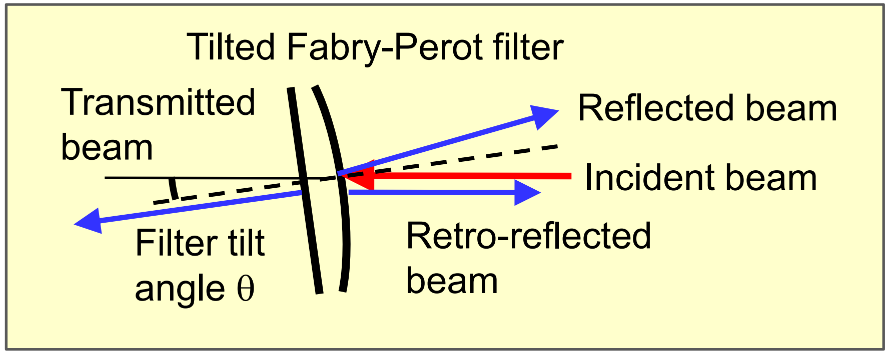
- Wide tuning range
- Narrow linewidth
- Fast tuning
- Compact
- **REFLECTIVE!**

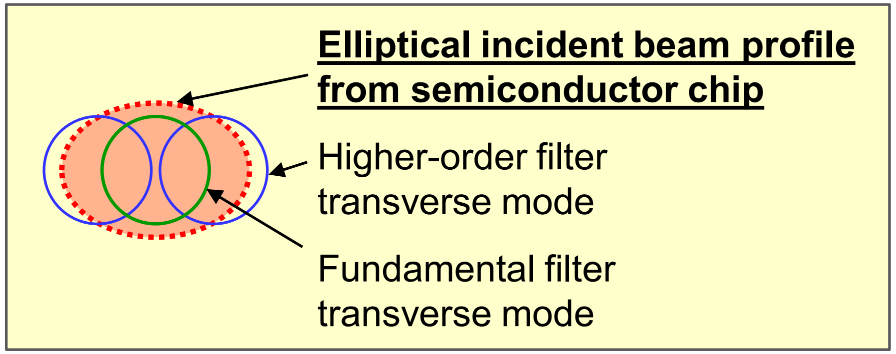
- *135 nm Wavelength Tuning Near 1060 nm*
- *<u>Mode envelope tuning</u>: tunable filter selects one or more modes to lase from the multitude of available laser cavity modes*

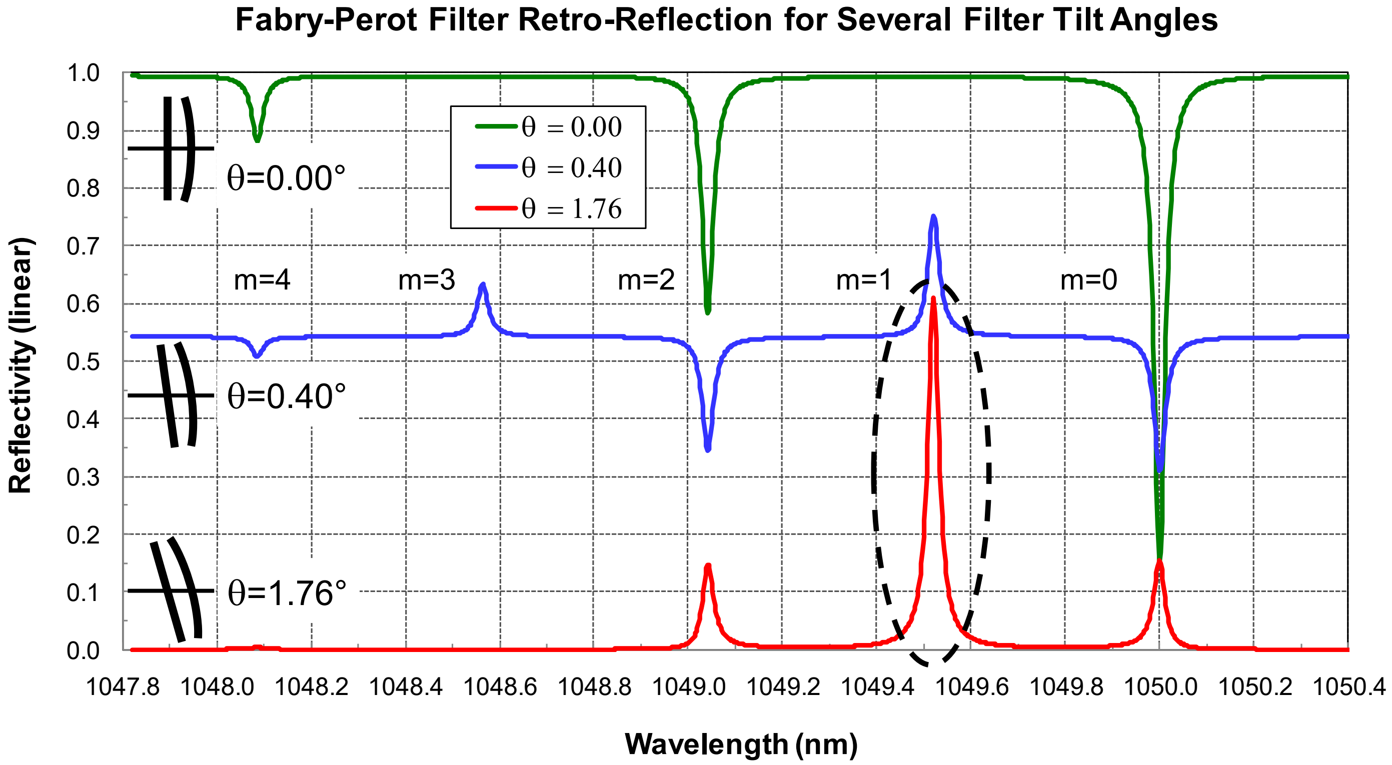
Envelope Tuning of Fixed Frequency Modes



Reflective Fabry-Perot Filter:
Ideal Tuning Element for Tunable Semiconductor Lasers







- Tilt filter optical axis relative to the incident beam direction: spectral reflection notch becomes retro-reflection peak
- **Retro-reflection: power coupled back into the incoming beam mode**
- Peak retro-reflection >60% for an elliptical incident beam
- Filter side mode suppression sufficient for lasing only in the main filter reflection peak
- **Enhanced retro-reflection with asymmetric reflectivity mirror coatings**
- **Gires-Tournois interferometer** = 100% reflector on the far side from the incident beam
- Modeling in good agreement with measurements

Modeling Reflective Operation of Tilted Fabry-Perot Filters

Modeling Reflective Operation of Tilted Fabry-Perot Filters

1. Two operating regime controlling parameters: incident beam angle relative to filter optical axis and beam wavelength
2. Expand angled incident beam spatial profile into spatial transverse modes of the Fabry-Perot resonator, at the incident beam wavelength (consider amplitude and phase)
3. For each resonator mode, using incident wavelength and modal resonant wavelengths, calculate modal reflection and transmission coefficients
   - Multiple transverse modes can be transmitted at a given wavelength because of the wide Lorentzian wings of spectral resonances
4. On both the incident and transmitted beam sides, reassemble the corresponding reflected and transmitted modes, with their relevant modal profiles and complex modal amplitudes, into the reflected and transmitted beams
5. Retro-reflection: calculate spatial overlap, and thus coupling retro-reflection coefficient, between the reflected beam profile and the incident beam profile.
   - This is relevant for calculating Fabry-Perot reflection coefficient back into the gain-chip waveguide mode.
6. Transmitted beam profile can be overlapped and coupled to the output fiber beam profile.
7. This reflective filter operating regime explicitly requires multiple transverse modes of the optical resonator
   - Use spherical mirror curvature obtained by stress-controlled optical coatings on thin Si mirror membrane
   - Radius of curvature Rc ~ 25 – 50 mm
   - This is a very different Fabry-Perot resonator geometry regime compared to the single-transverse mode resonator geometry

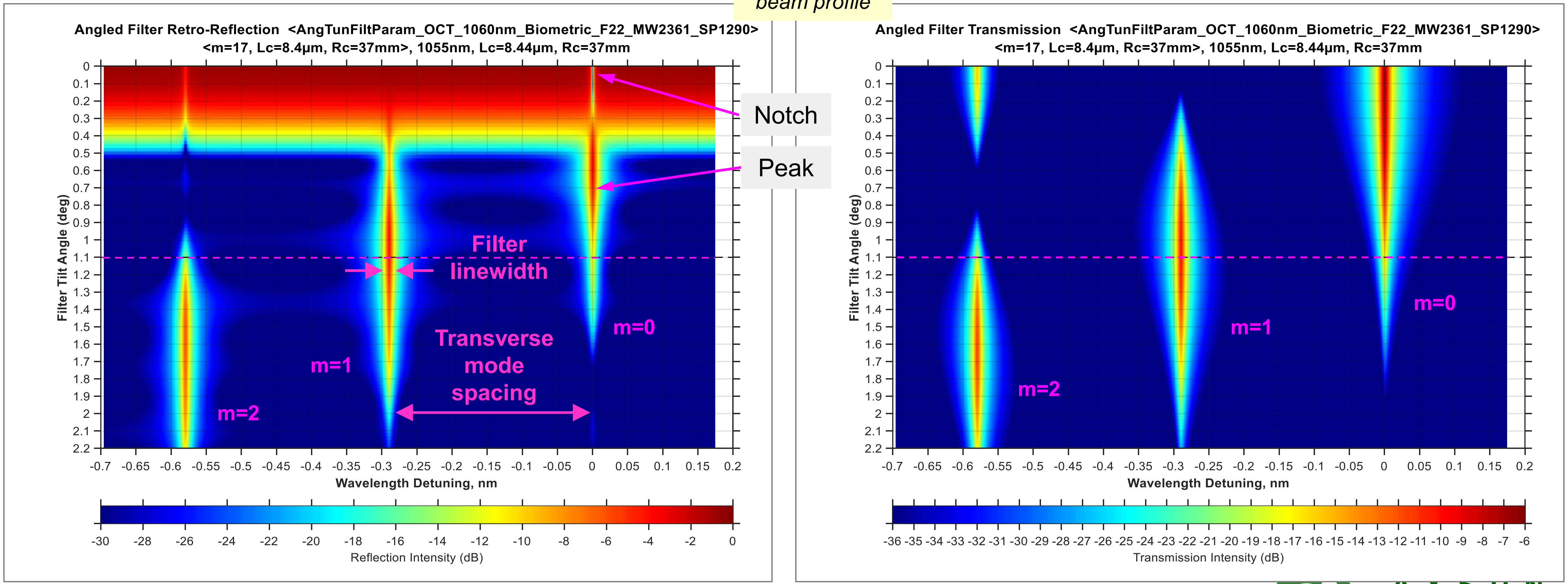
Tilted Fabry-Perot Filter: Retro-Reflection and Transmission Spectra vs. Tilt Angle → Narrow Linewidth (1.9 GHz/ 7 pm) Filter for Optical Coherence Tomography (λ=1055nm)

- Narrow linewidth, for deep imaging, filter for fast swept-source OCT
- Filter linewidth,1.9 GHz/7pm, smaller than transverse mode spacing, 78 GHz: multiple spectral reflection peaks, make one dominant
- Filter linewidth = Mirror.Coating.Reflectivities + Cavity.Length. Transverse mode spacing = Cavity.Length + Mirror.Curvatures

Retro-Reflection

Elliptical input beam profile

Transmission

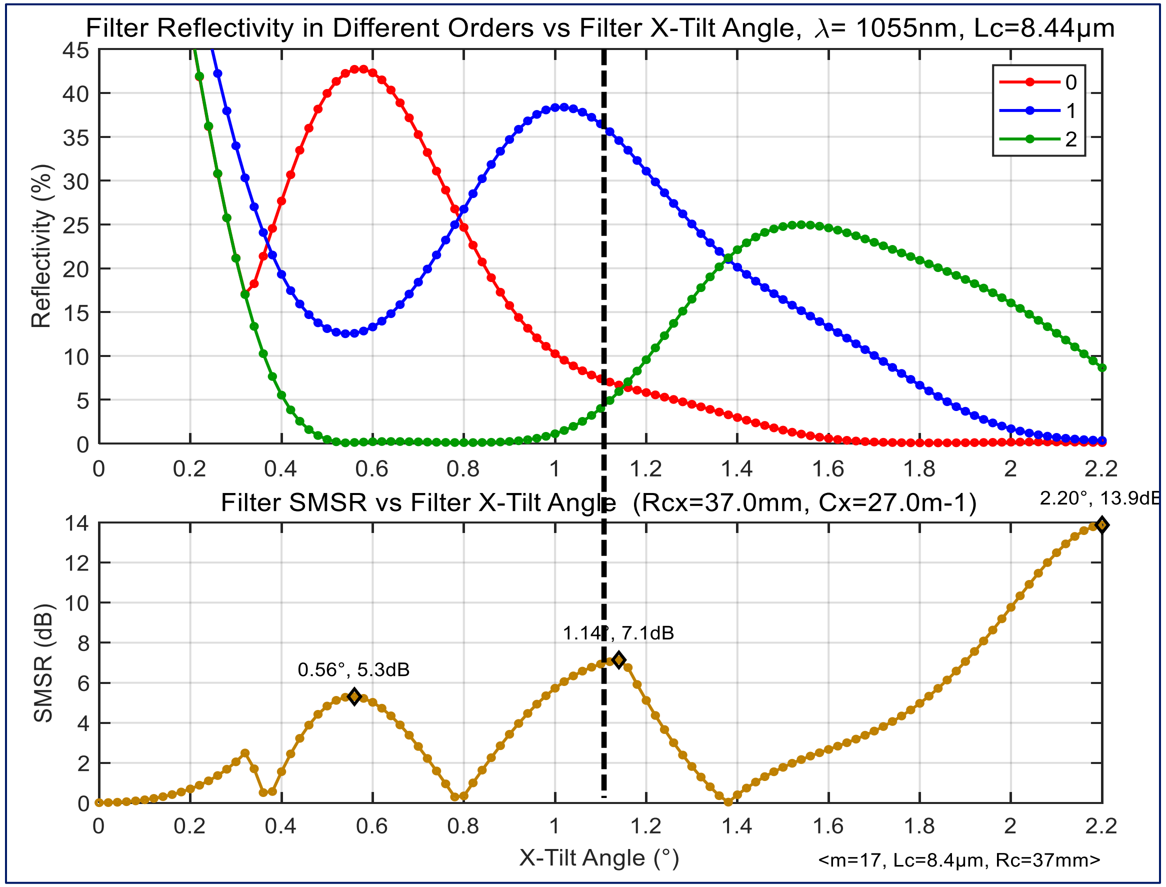


Tilted Fabry-Perot Filter (Narrow 1.9 GHz Linewidth): Modal Reflectivity vs. Tilt Angle and Retro-Reflection Spectrum at θ = 1.10°

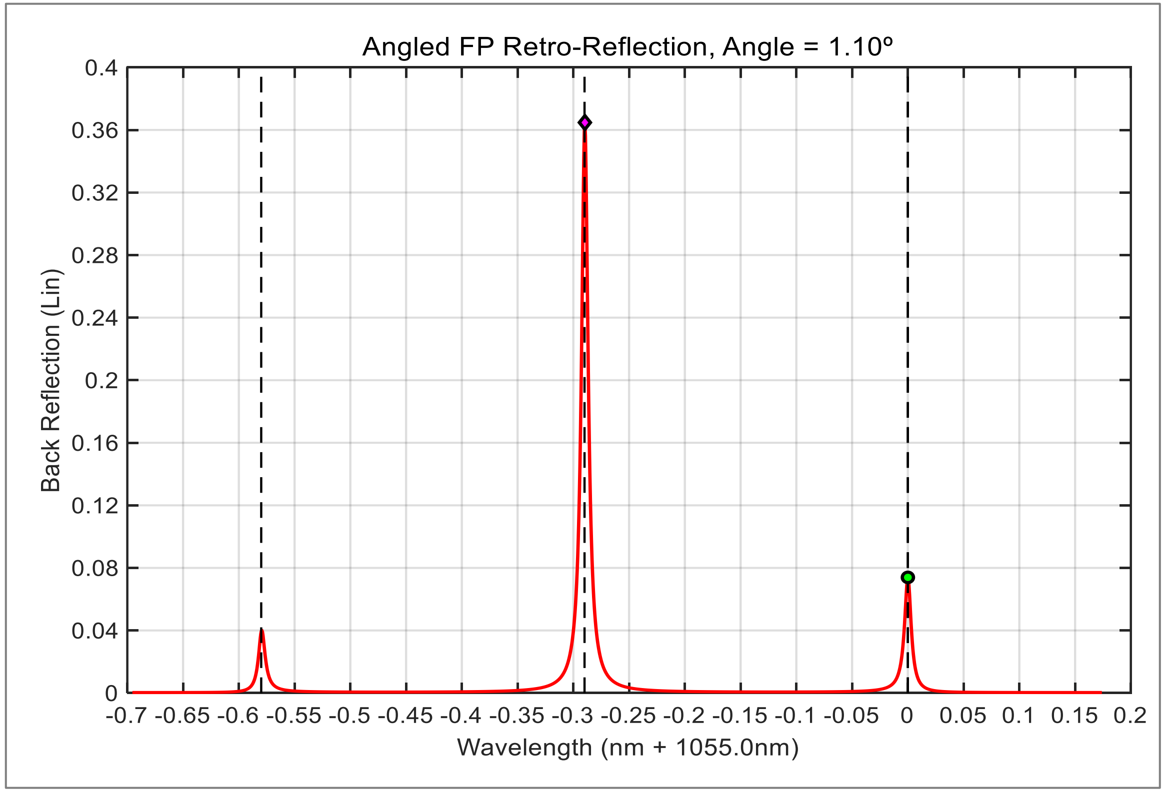
- For optimal tilt angle, single reflection peak is dominant with sufficient side-mode suppression
  - External-cavity semiconductor laser lases only at the main reflection peak
  - Filter retro-reflection into the chip waveguide mode is ~ 36%

Narrow 1.9 GHz filter @ **λ=1055 nm**
for Optical Coherence Tomography (OCT)

Modal Reflectivity



Reflection Spectrum

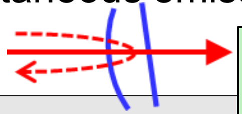


Tilted Fabry-Perot Filter: Retro-Reflection and Transmission Spectra vs. Tilt Angle → Wide Linewidth (88 GHz/ 0.81 nm) Filter for <u>Spectroscopy</u> (λ=1680 nm)

- On resonance, filter reflection and transmission both spectrally filter the incident signal
- Tunable laser for spectroscopy: reflection provides spectral slice feedback to the laser gain chip, transmission filters out amplified spontaneous emission coming from the gain chip

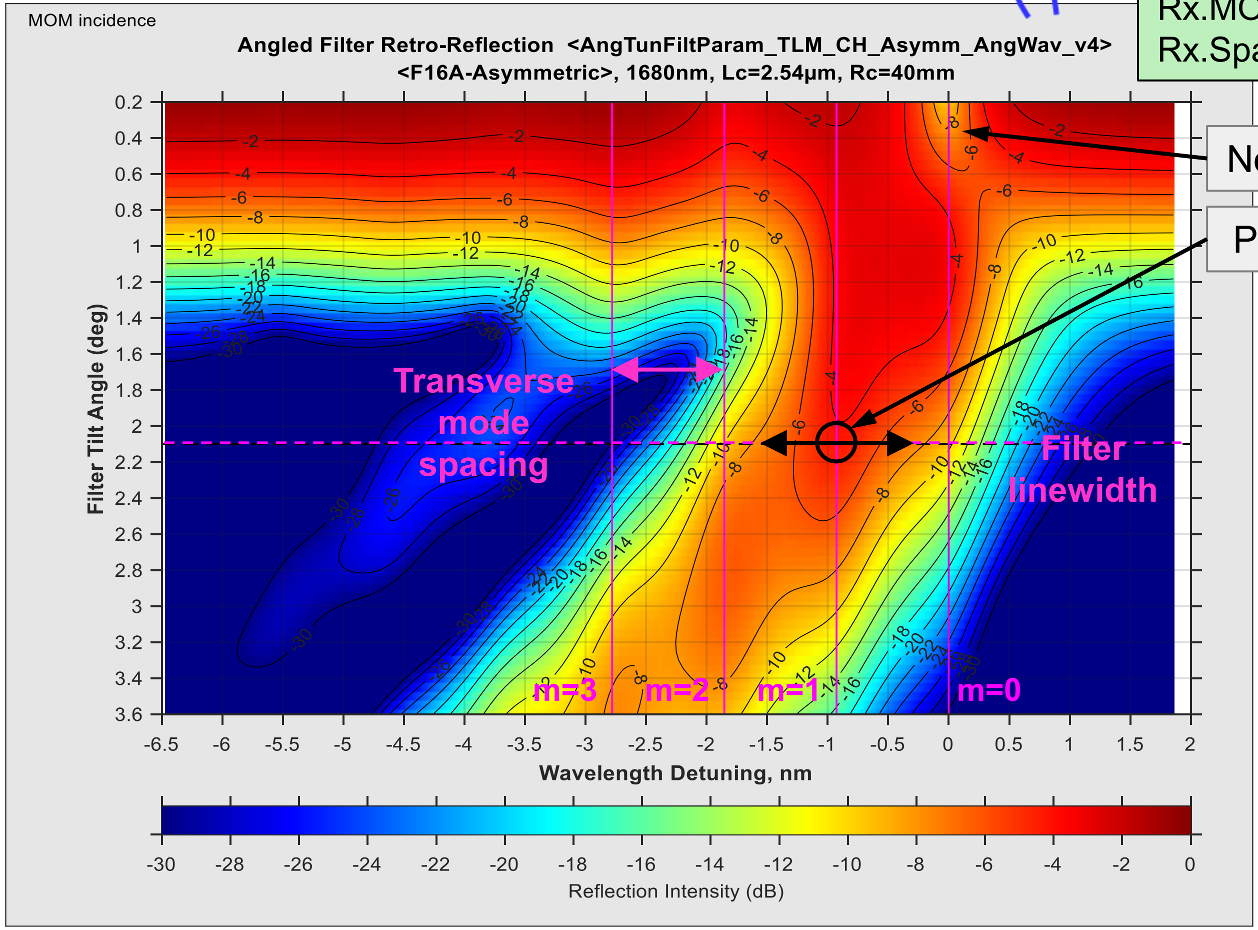
- Filter linewidth = **0.95 nm**
- Transverse mode spacing = **0.93 nm**
- Filter linewidth comparable to transverse mode spacing – transverse modes merge into a **<u>single spectral peak on reflection</u>**

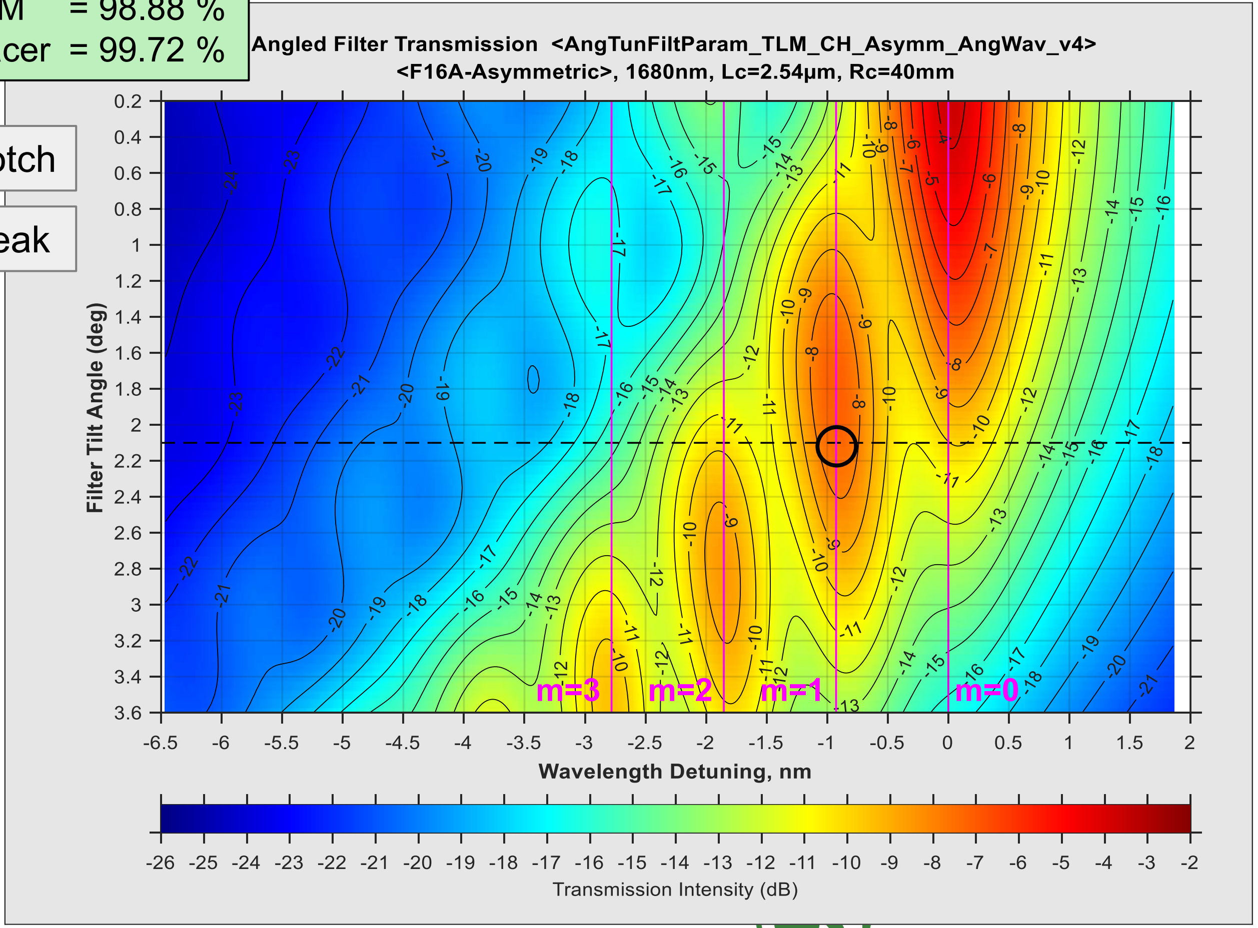
<u>Retro-Reflection</u>



<u>Asymmetry</u>:
Rx.MOM = 98.88 %
Rx.Spacer = 99.72 %

<u>Transmission</u>

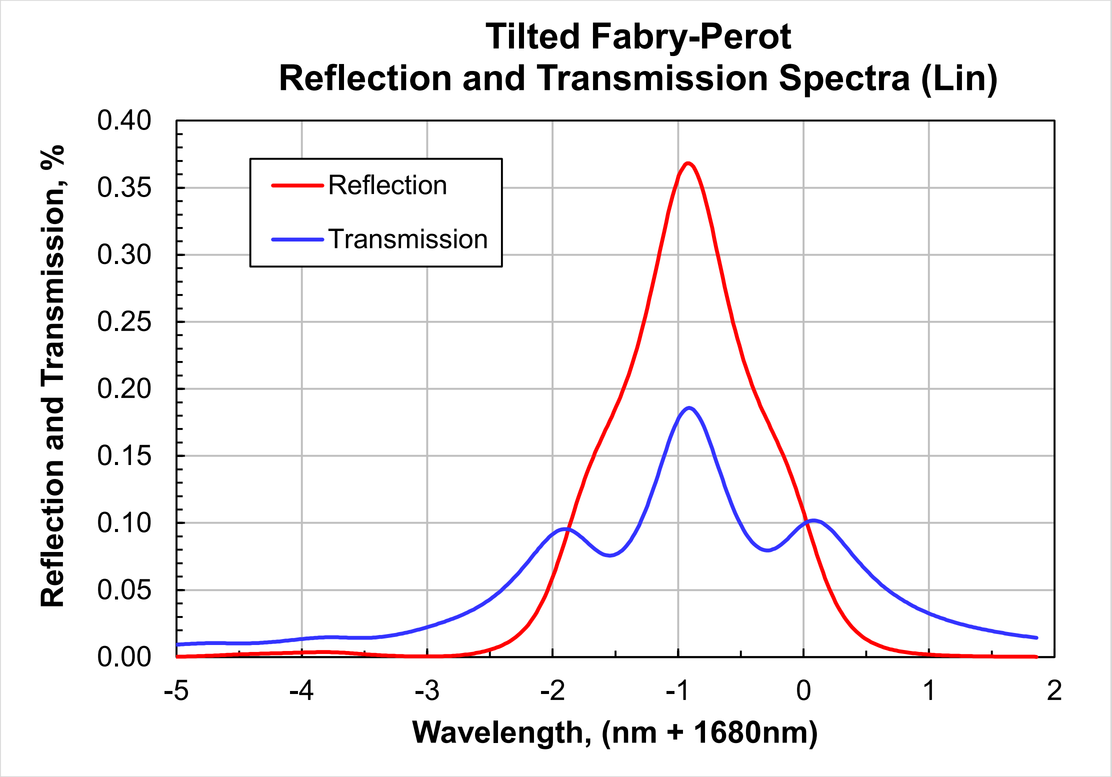


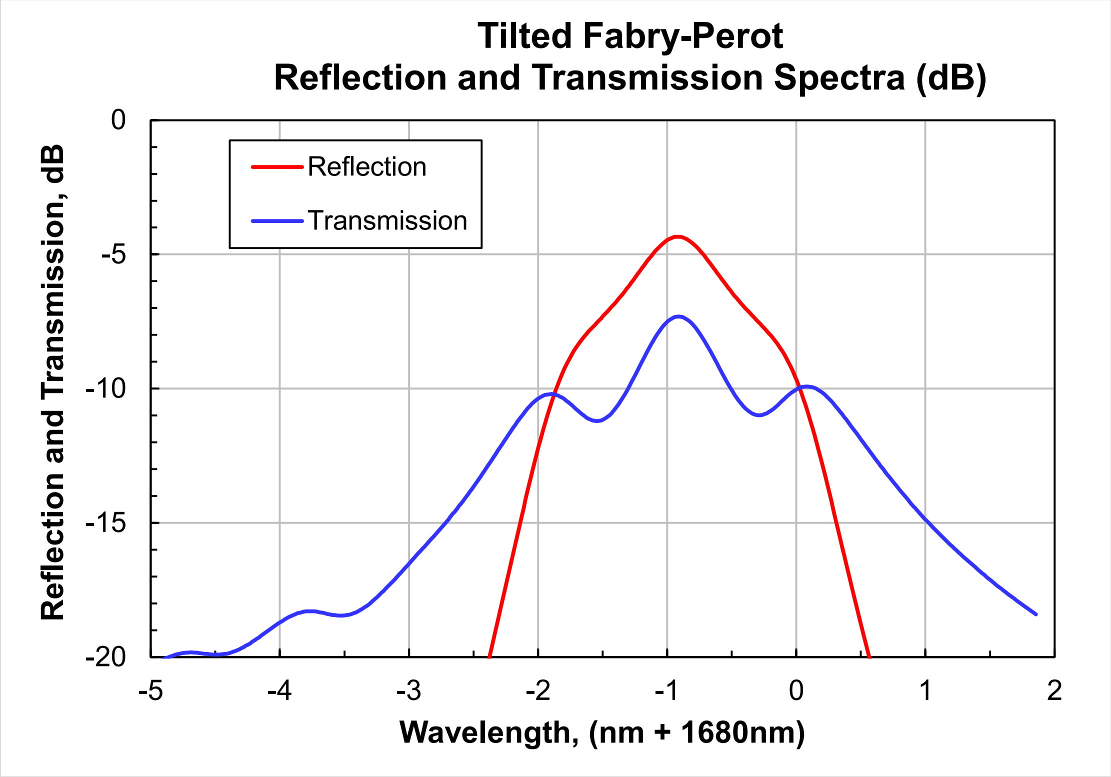


Tilted Fabry-Perot Filter (Wide 88.5 GHz Linewidth): Reflection and Transmission Spectra at θ = 2.1°

- Efficient spectral filtering in transmission – filters out gain chip broadband spontaneous emission, important for spectroscopy

Wide 88.5 GHz filter @ **λ=1680 nm**
for Tunable Laser Spectroscopy



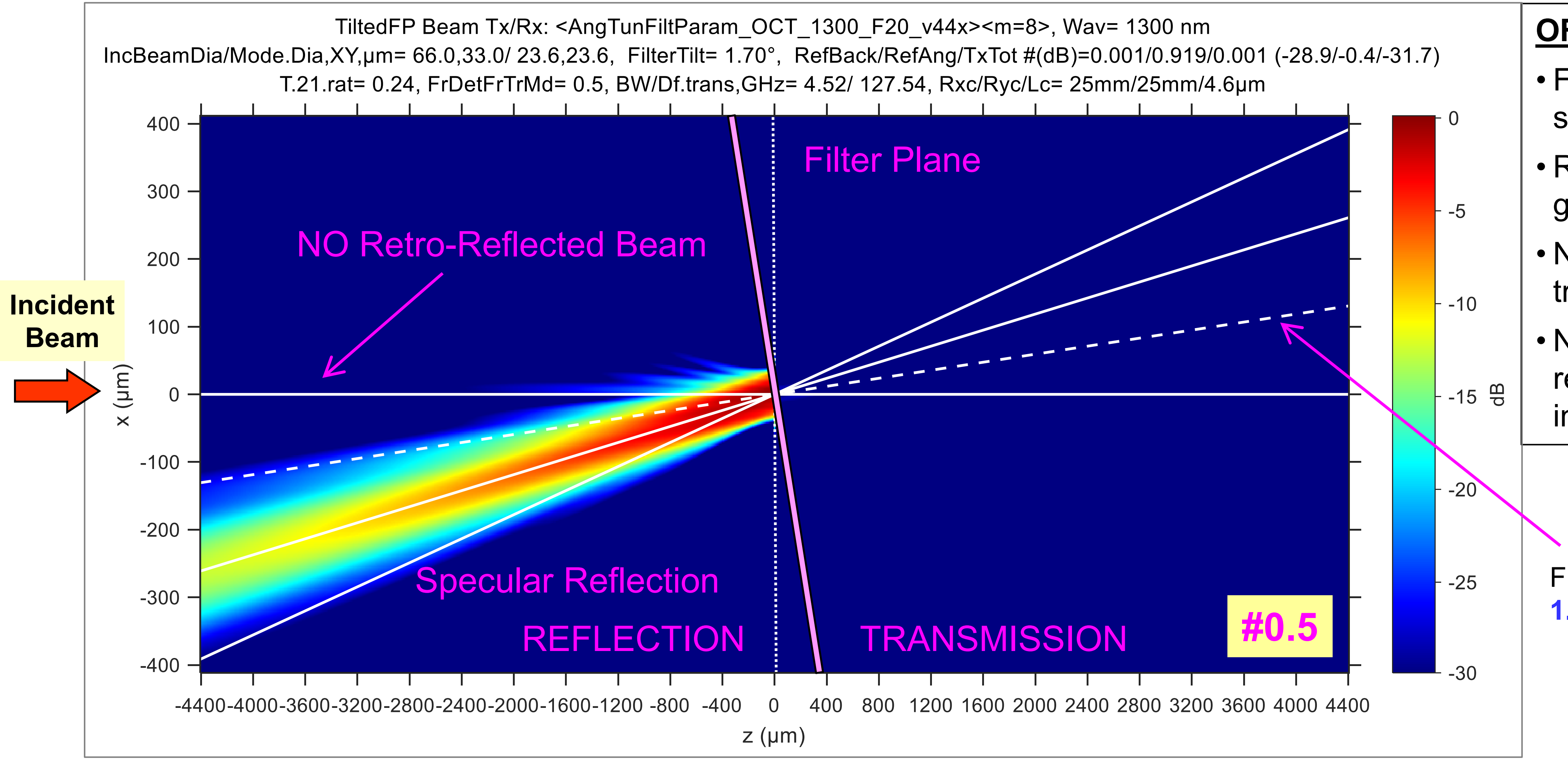


Reflective Fabry-Perot Operation: Beam Propagation Pictures

Off Resonance, Tune m = 0.5:
Tilt Angle = 1.7°, Retro-Reflection = -28.9 dB (0.1%)

OCT @1300 nm

REFLECTED AND TRANSMITTED BEAMS



Filter optical axis, **1.7 deg**

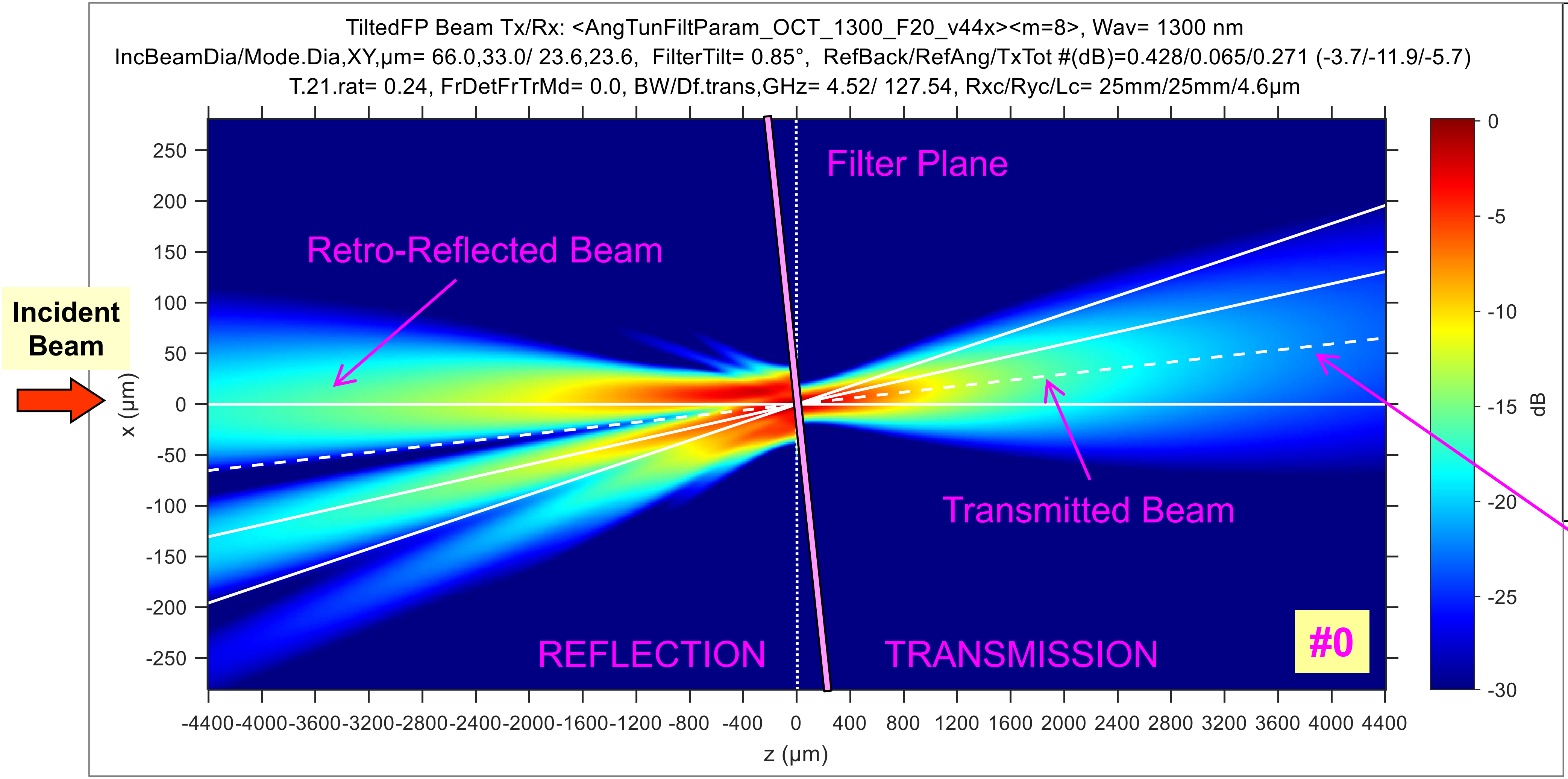
OFF RESONANCE

- Filter acts as a simple mirror
- Reflected power goes off at an angle
- No power is transmitted
- No power is retro-reflected into the incoming beam

On Resonance, Tune m = 0.0:
Tilt Angle = 0.85°, Retro-Reflection = -3.7 dB (43%)

OCT @1300 nm

REFLECTED AND TRANSMITTED BEAMS



TiltedFP Beam Tx/Rx: <AngTunFiltParam_OCT_1300_F20_v44x><m=8>, Wav= 1300 nm
IncBeamDia/Mode.Dia,XY,μm= 66.0,33.0/ 23.6,23.6, FilterTilt= 0.85°, RefBack/RefAng/TxTot #(dB)=0.428/0.065/0.271 (-3.7/-11.9/-5.7)
T.21.rat= 0.24, FrDetFrTrMd= 0.0, BW/Df.trans,GHz= 4.52/ 127.54, Rxc/Ryc/Lc= 25mm/25mm/4.6μm

ON RESONANCE

- Resonant mode **m=0** pattern is transmitted on resonance
- This unbalances the modal reflection interference pattern
- Significant power is now retro-reflected back into the incoming beam

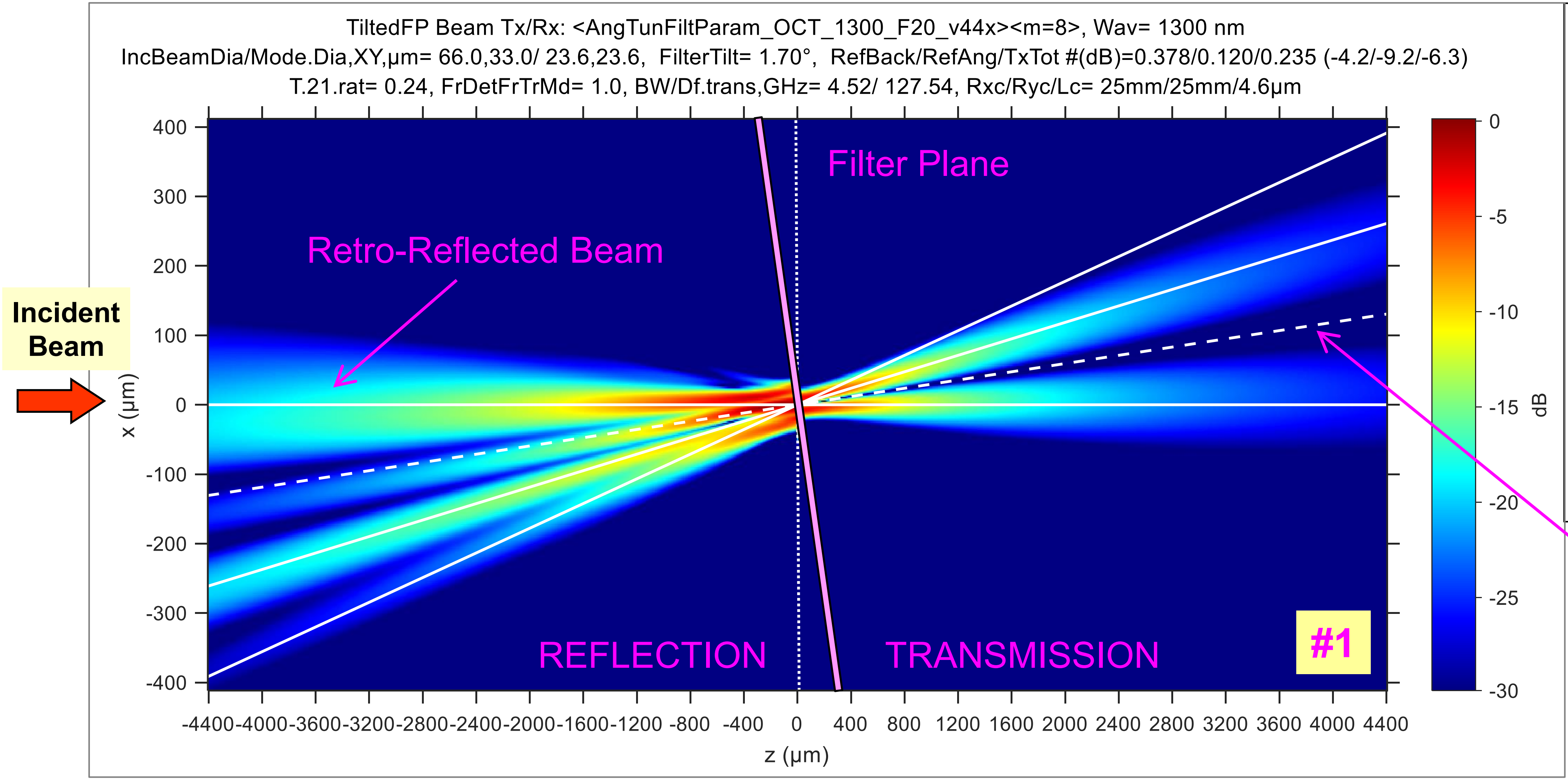
Filter optical axis, **0.85 deg**

Δf_{filter} = 4.5 GHz
Δf_{trans} = 128 GHz

On Resonance, Tune m = 1.0:
Tilt Angle = 1.70°, Retro-Reflection = -4.2 dB (38%)

OCT @1300 nm

REFLECTED AND TRANSMITTED BEAMS



ON RESONANCE

- Resonant mode **m=1** pattern is transmitted on resonance
- This unbalances the modal reflection interference pattern
- Significant power is now retro-reflected back into the incoming beam

Filter optical axis,
1.7 deg

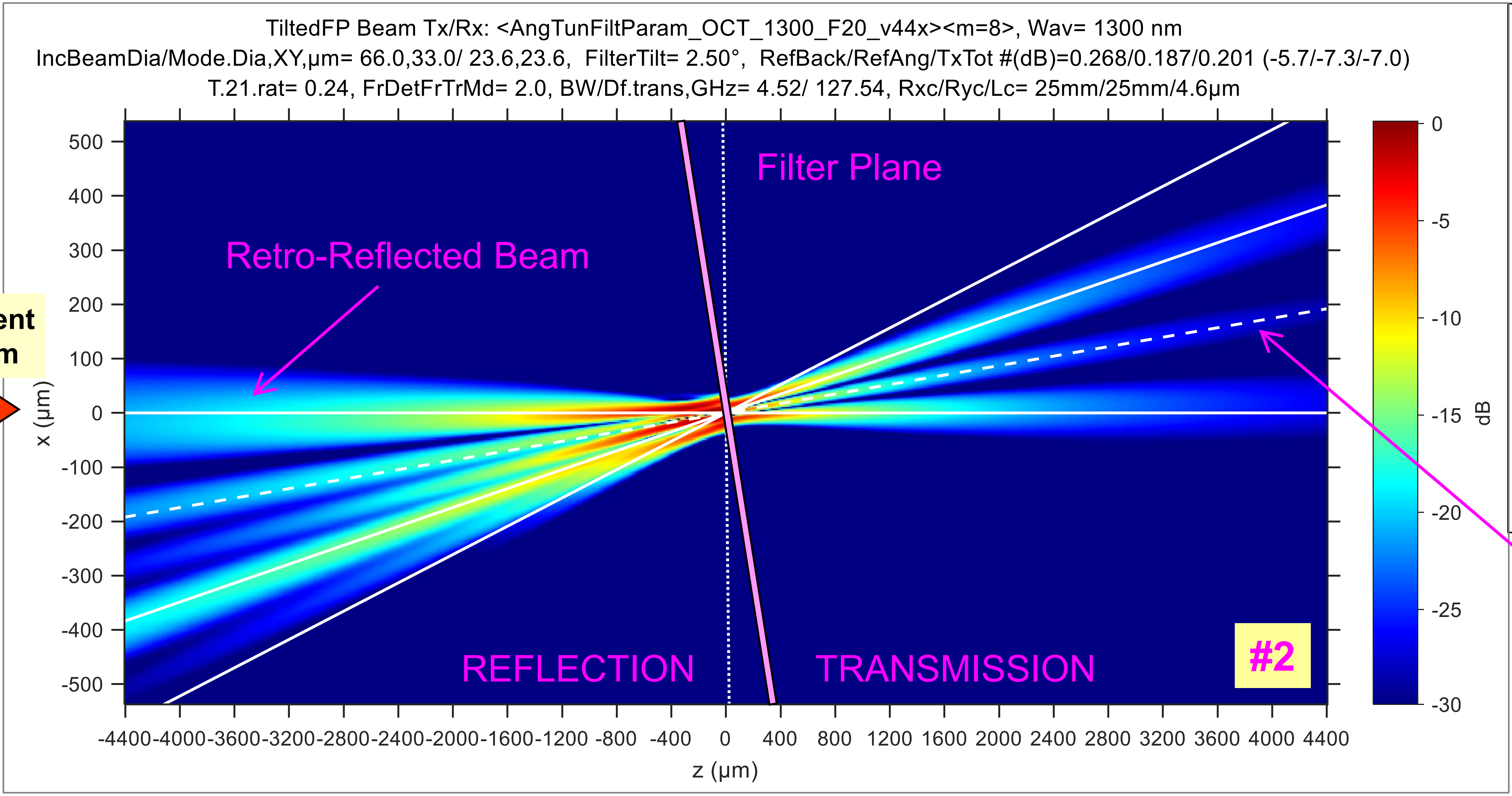
Δf_{filter} = 4.5 GHz
Δf_{trans} = 128 GHz

On Resonance, Tune m = 2.0: Tilt Angle = 2.50°, Retro-Reflection = -5.7 dB (27%)

OCT @1300 nm

REFLECTED AND TRANSMITTED BEAMS

Incident Beam



ON RESONANCE

- Resonant mode **m=2** pattern is transmitted on resonance
- This unbalances the modal reflection interference pattern
- Significant power is now retro-reflected back into the incoming beam

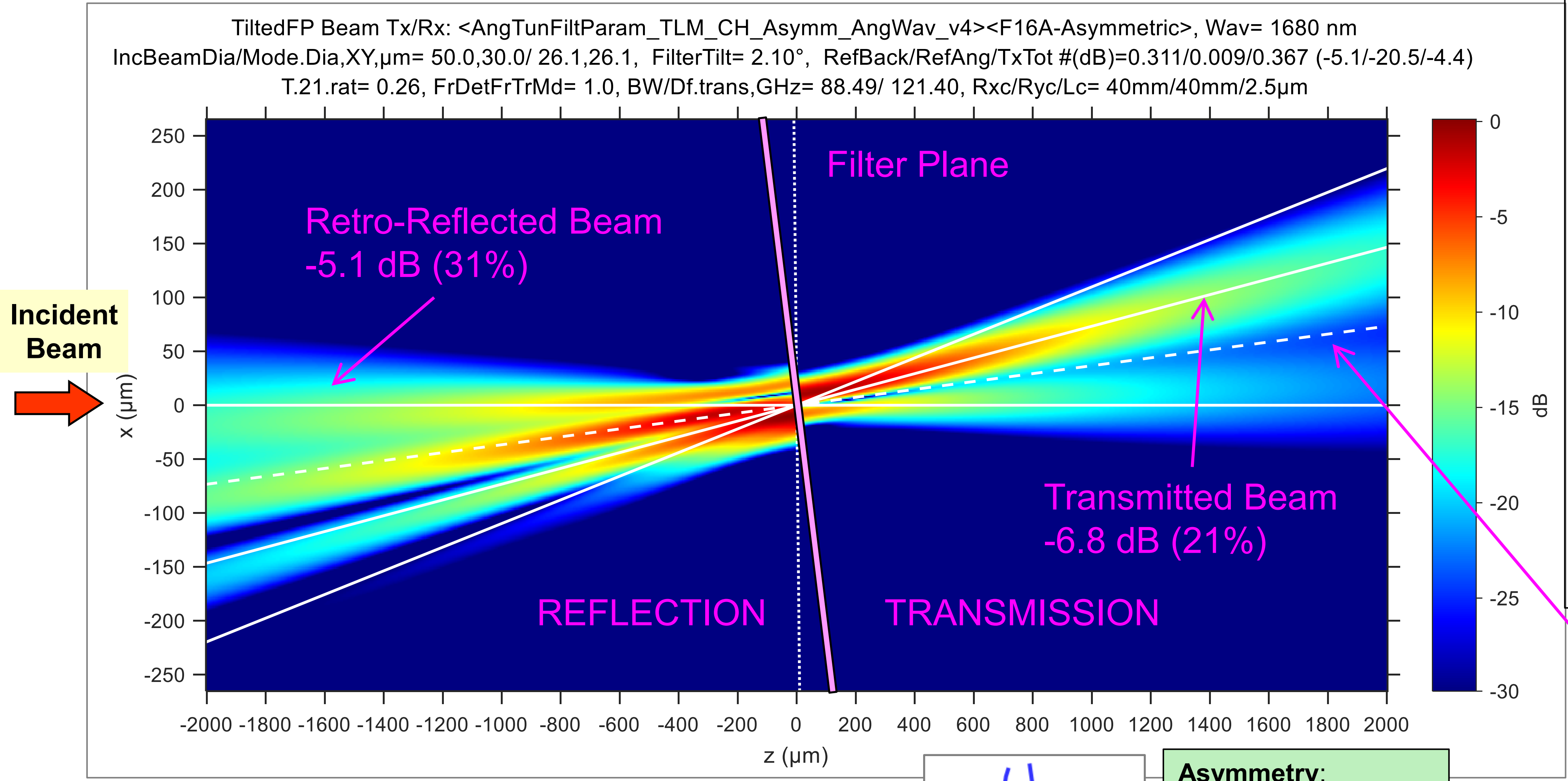
Filter optical axis, **2.5 deg**

Δf_{filter} = 4.5 GHz
Δf_{trans} = 128 GHz

On Resonance, Tune m = 1.0:
Tilt Angle = 2.10°, Retro-Reflection = -5.1 dB (31%)

Spectroscopy @1680 nm

REFLECTED AND TRANSMITTED BEAMS


TiltedFP Beam Tx/Rx: <AngTunFiltParam_TLM_CH_Asymm_AngWav_v4><F16A-Asymmetric>, Wav= 1680 nm
IncBeamDia/Mode.Dia,XY,µm= 50.0,30.0/ 26.1,26.1, FilterTilt= 2.10°, RefBack/RefAng/TxTot #(dB)=0.311/0.009/0.367 (-5.1/-20.5/-4.4)
T.21.rat= 0.26, FrDetFrTrMd= 1.0, BW/Df.trans,GHz= 88.49/ 121.40, Rxc/Ryc/Lc= 40mm/40mm/2.5µm

Incident Beam

Filter Plane

Retro-Reflected Beam
-5.1 dB (31%)

Transmitted Beam
-6.8 dB (21%)

REFLECTION

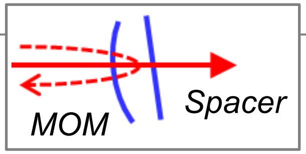
TRANSMISSION

ON RESONANCE

- Resonant mode **m=1+** pattern is transmitted on resonance
- Significant power is now retro-reflected back into the incoming beam
- Mirror reflectivity asymmetry controls reflected / transmitted power ratio
  - Highest filter reflectivity for 100% outer mirror

Filter optical axis,
2.1 deg

Δf_{filter} = 88 GHz
Δf_{trans} = 121 GHz



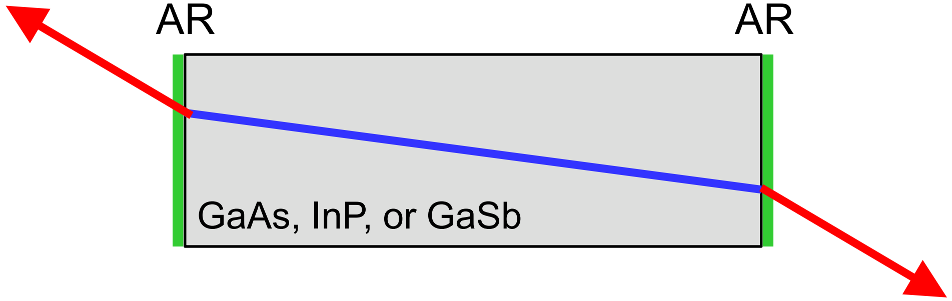
Asymmetry:
Rx.MOM = 98.88 %
Rx.Spacer = 99.72 %

Tunable Lasers Using Tilted Reflective Fabry-Perot Filter:

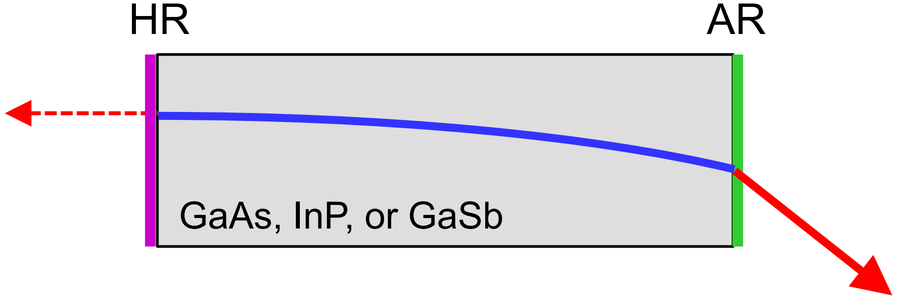
Compact Butterfly Packaging of Many Laser Configurations

Semiconductor Lasers: Tunable External Cavity Configurations

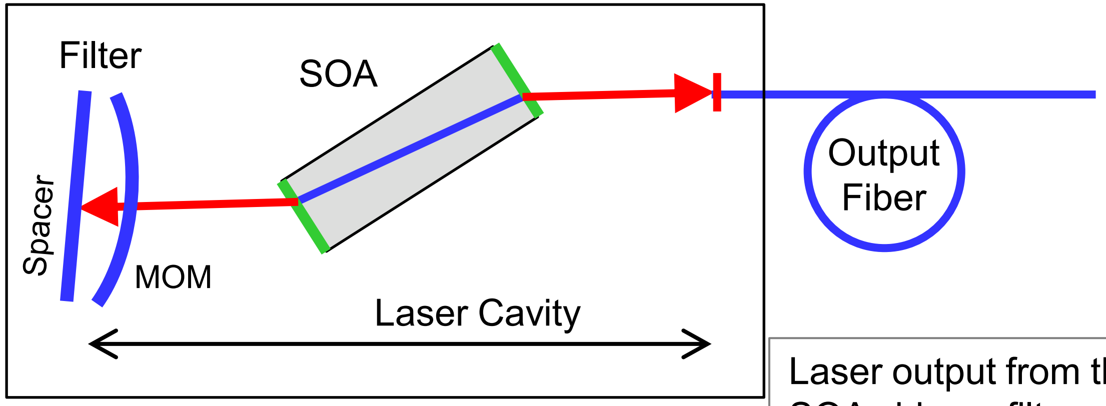
Semiconductor Optical Amplifier SOA Angled Facet Chip



Single Angled Facet SAF Amplifier Chip

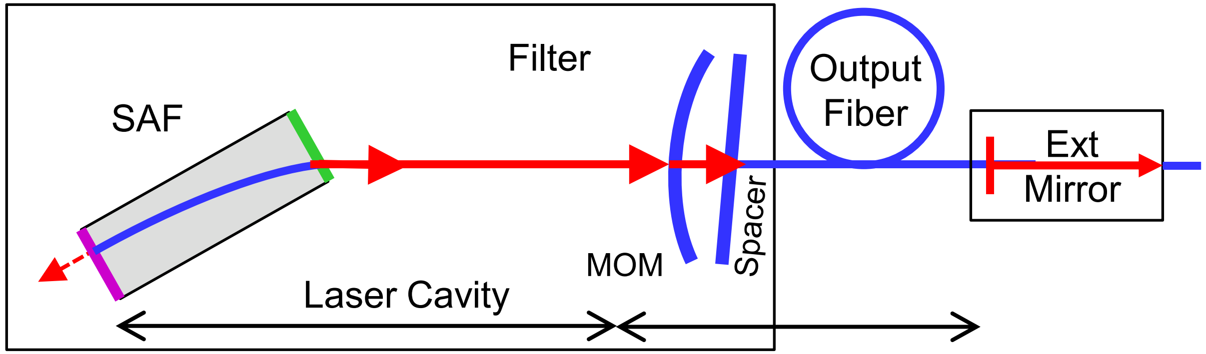


OCT Laser Module
for swept-frequency optical coherence tomography



Laser output from the SOA side, unfiltered spontaneous emission

TLM = Tunable Laser Module
for Spectroscopy



Center Wavelengths
GaAs: 1060 nm
InP: 1300, 1450, 1680 nm
GaSb: 2300 nm

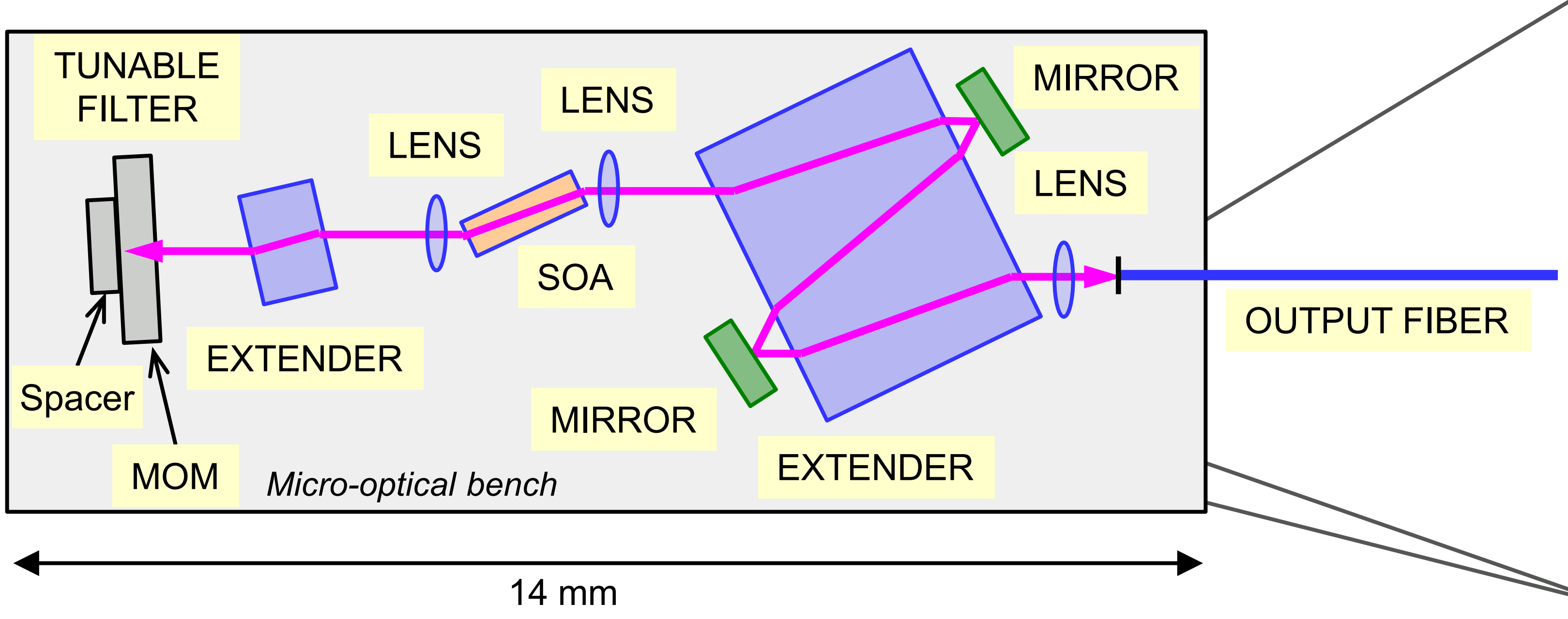
Laser output through the filter side for additional spectral filtering of amplified spontaneous emission ASE

AXSUN
Excelitas Technologies

Tunable Laser Package with a 50 mm Long Folded Laser Cavity with Dielectric Cavity Extenders

- Longer optical cavity folded on the micro-optical bench
- Optical Coherence Tomography – OCT (medical imaging)

1060 nm



SOA = Semiconductor Optical Amplifier

Laser output coupling cavity mirror is internal to the package on the fiber tip

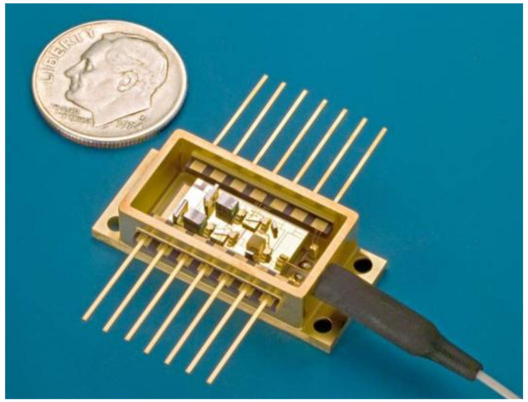
Optimize laser optical cavity length for dynamic laser tuning of swept-frequency lasers

Cavity extenders and lenses, transparent:

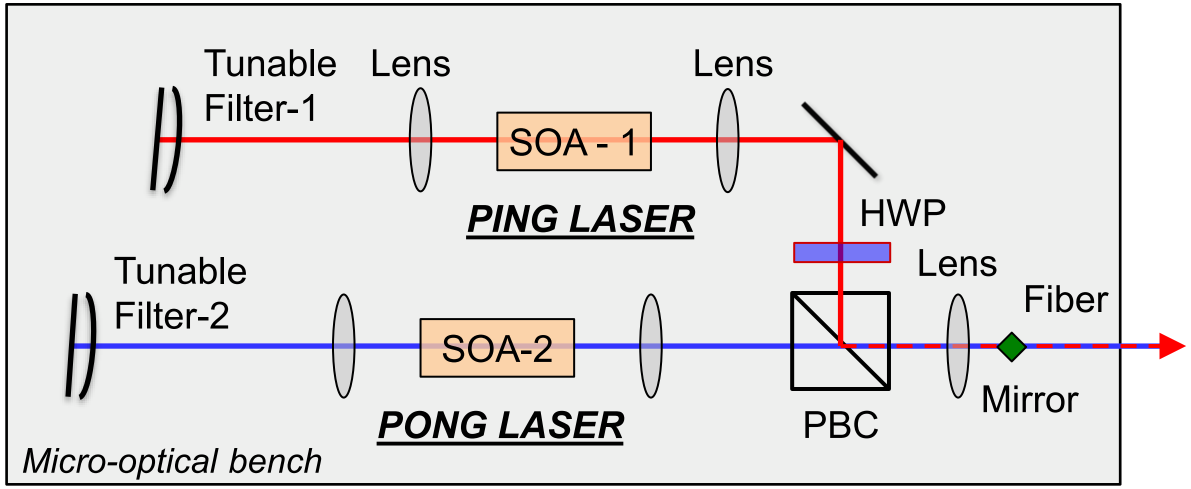
- **Si** for 1300 nm lasers
- **GaP** for 1060 nm lasers

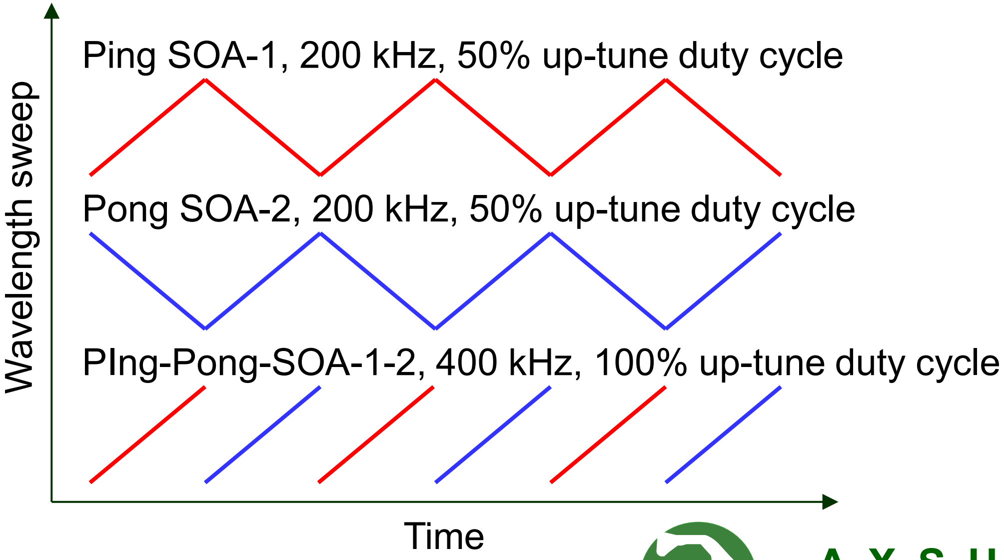
Dual Source Ping-Pong Swept-Frequency Laser: High Duty-Cycle Sweep
→ *Optical Coherence Tomography – OCT*

- For a MEMS tunable filter, it takes time to reverse tuning direction, high duty cycle sweep is difficult
- An approach for high-speed high duty cycle tunable laser: “ping-pong” laser
  - Combine two lasers in a single package
  - Each laser at 50 % up-tune duty cycle, polarization combine to 100 % up-tune duty cycle
  - Turn power of one laser off when the other one is tuning
  - Example: 400 kHz ping-pong laser at 1050 nm with 100 nm sweep
- Also: dual wavelength band laser

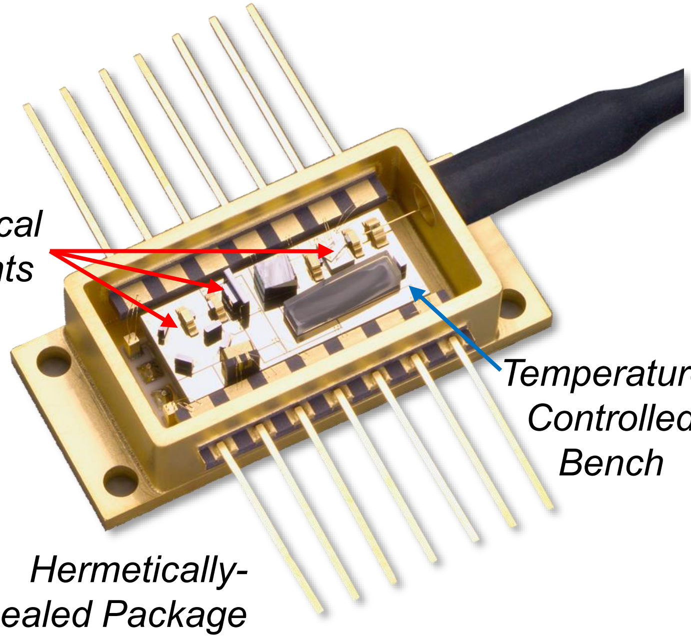


Ping-Pong Dual Laser Package





Axsun/Excelitas Fast Swept Frequency Lasers for Optical Coherence Tomography Medical Imaging

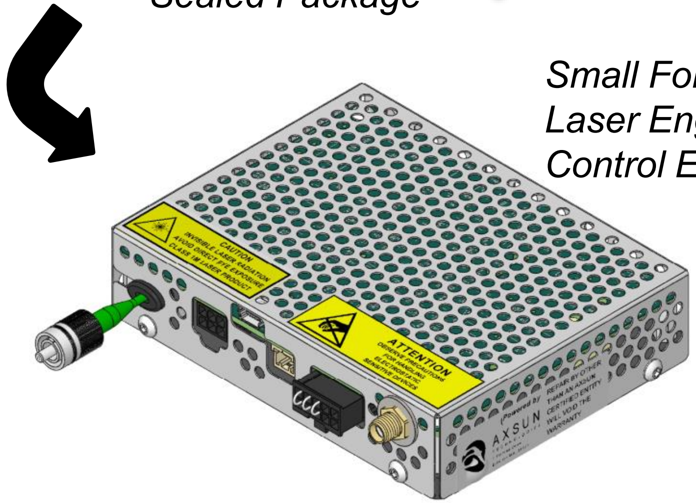


Fiber Output

Micro-Optical Components

Temperature-Controlled Bench

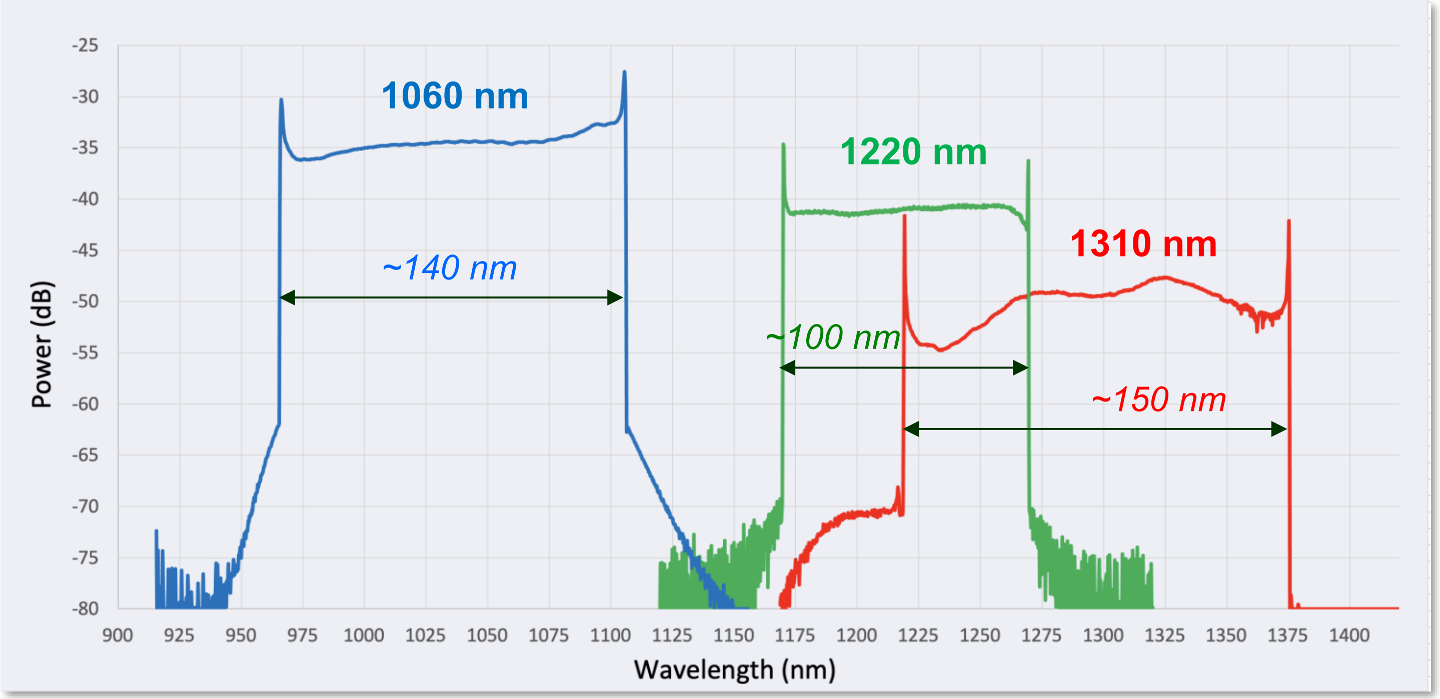
Hermetically-Sealed Package



Small Form Factor Laser Engine With Control Electronics

Sample Laser Tuning Ranges Covered

Average Spectrum, Dynamic Tuning



P.avg ~ 50 – 80 mW

Applications of
Fast Tunable External Cavity Semiconductor Lasers
Enabled by Reflective Fabry-Perot Tunable Filters

Eye Retinal Imaging and Angiography (Blood Flow): Topcon Healthcare, DRI Triton^{TM} Swept-Source OCT

OPHTHALMOLOGY

1060 nm swept-frequency laser

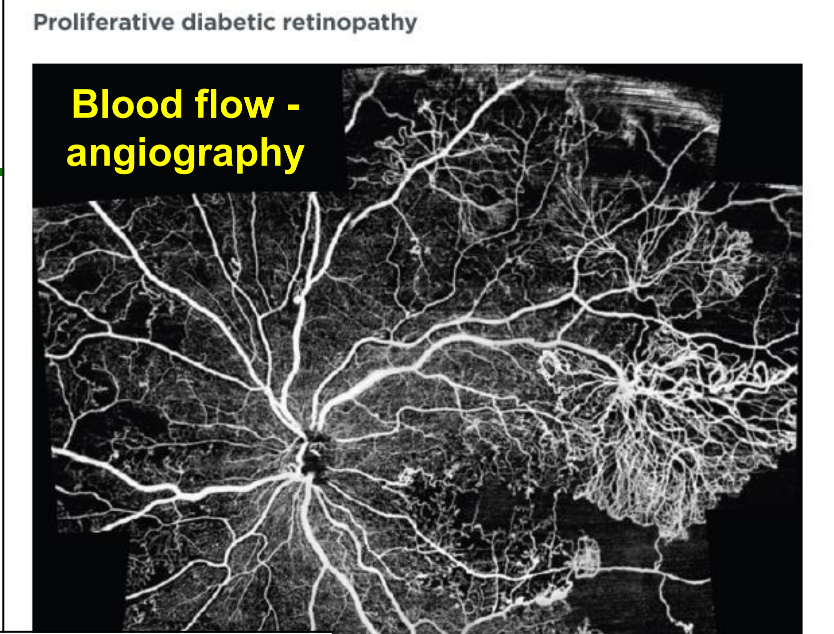
https://topconhealthcare.com/products/triton/

https://topconhealthcare.jp/wp-content/uploads/2020/08/Topcon_Triton_Brochure_Rev5_202105_E325-.pdf

Retinal and choroidal disease diagnostics:

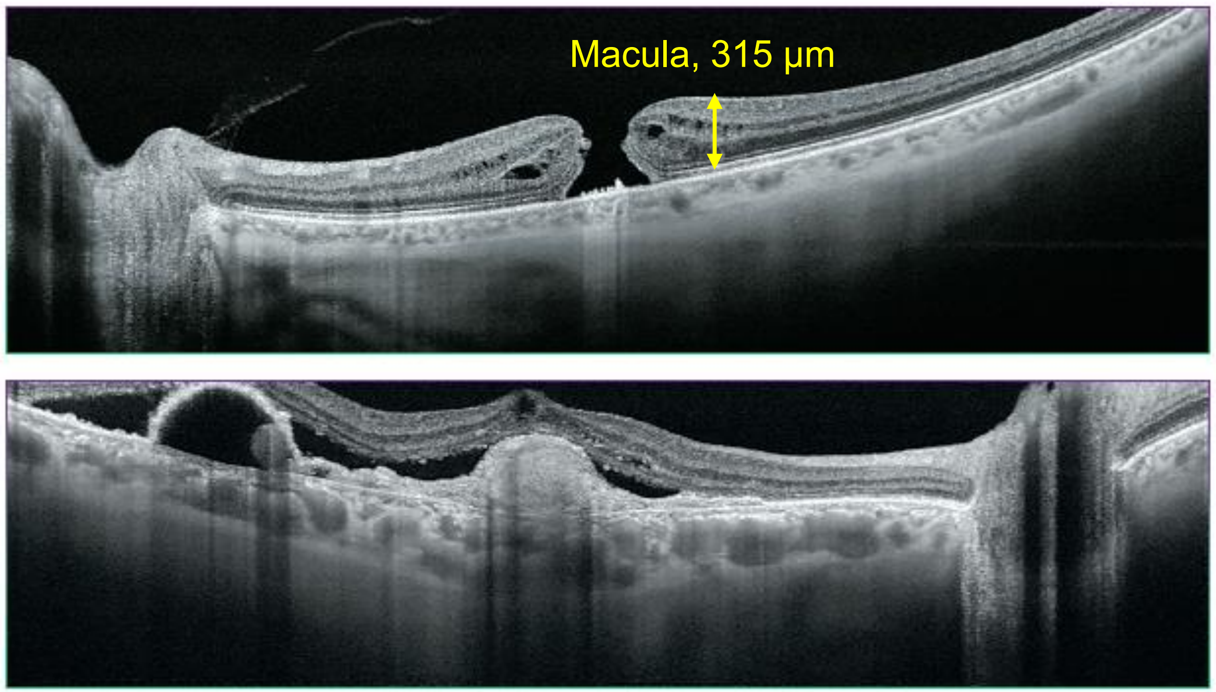
- Retinal detachment
- Diabetic retinopathy
- Glaucoma
- Macular degeneration
- Retinal and choroidal blood vasculature

Proliferative diabetic retinopathy



SS OCT Angio^{TM} Montage
Courtesy: Akihiro Ishibazawa, MD, PhD.
Asahikawa Medical University, Graduate School of Medical Sciences, Hokkaido, Japan

Retinal pathologies

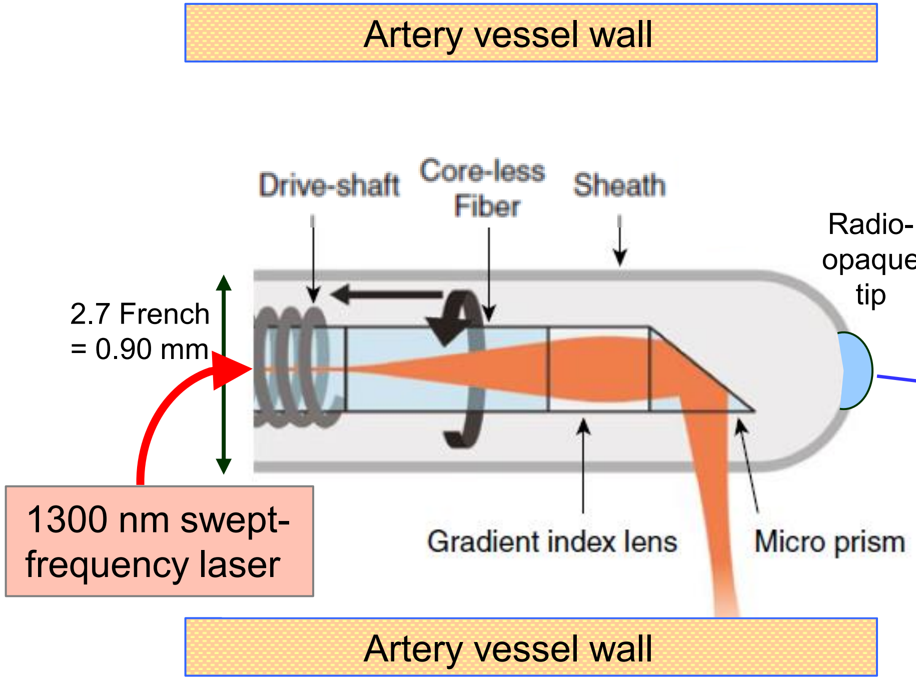


Courtesy: Professor Jose Maria Ruiz Moreno MD, University of Albacete, Spain

AXSUN
Excelitas Technologies

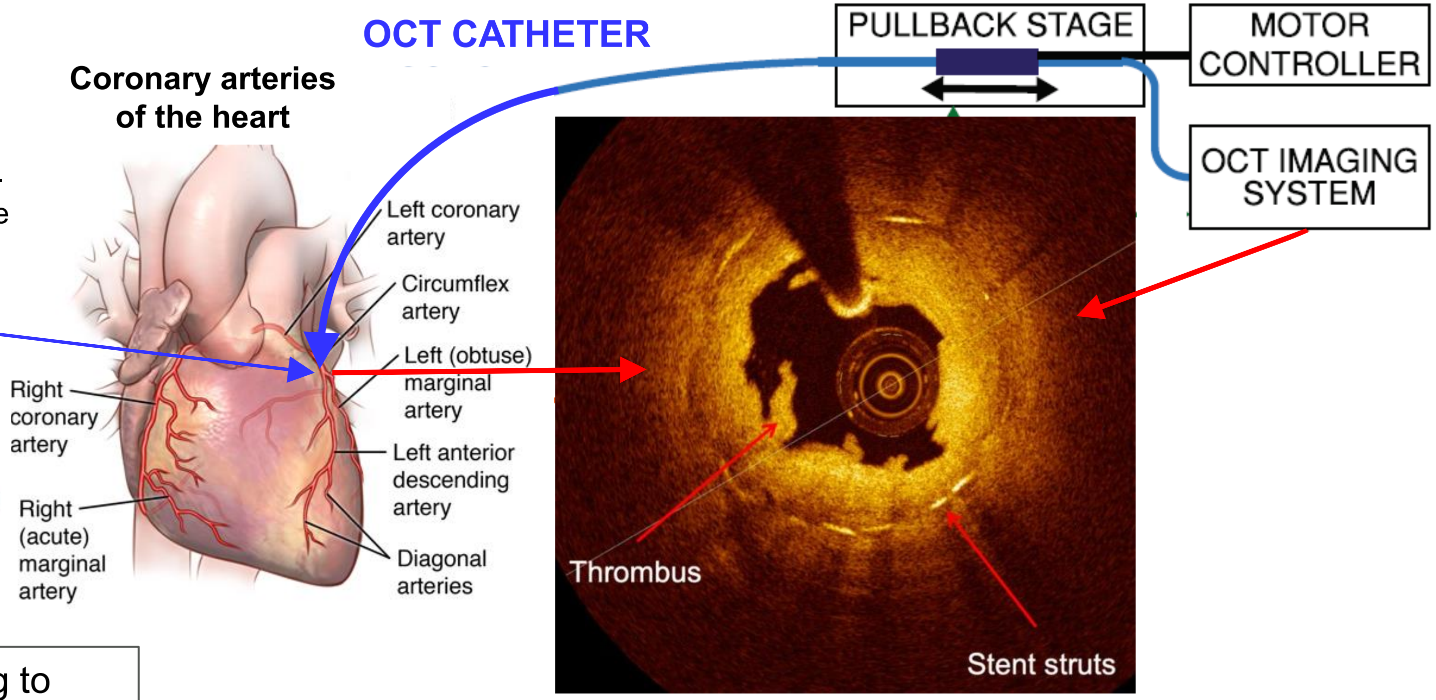
OCT: Intravascular Coronary Artery Imaging

OCT FIBER OPTIC CATHETER: SIDE IMAGING PROBE



- Saline or contrast agent flushing during imaging to clear blood cells and offer view onto the arterial wall
- Image a spiral scan on arterial walls by a combination of probe rotation and simultaneous pullback
- Radio-opaque probe tip for co-registration with low-resolution X-ray imaging to locate probe position in the heart

INTRAVASCULAR CORONARY OCT



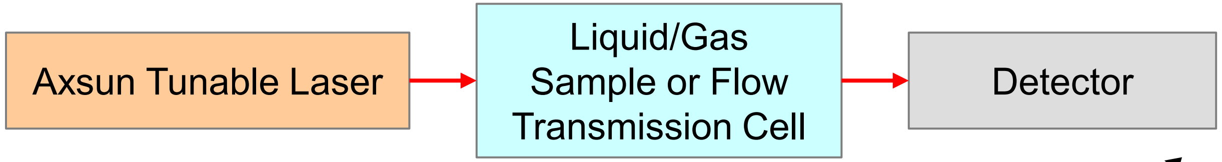
LightLab / Abbott

- Measure plaque thickness on coronary artery walls
- Measure stent apposition in coronary arteries

M.L. Villiger and B.E. Bouma, “*Physics of Cardiovascular OCT*”, in I.-K. Jang (ed.), *Cardiovascular OCT Imaging*, Springer 2015

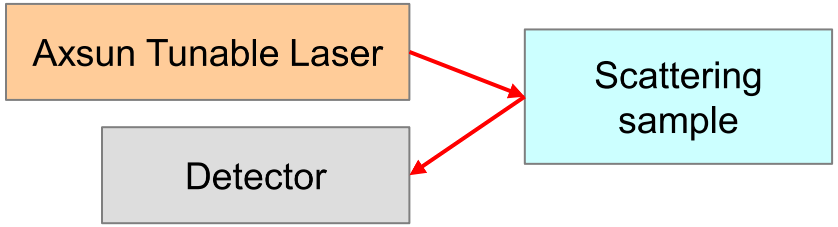
Tunable Laser Spectroscopy TLS – Industrial Applications

- Molecular spectroscopy signature bands
  - OH band = 1350–1550 nm, CH band = 1550–1800 nm, CH combination band = 2100–2350 nm
- Hydrocarbon gases, natural gas (transmission)
  - Methane, ethane, propane, butane, etc.
  - Real time measurement of natural gas constituent concentrations, gas energy content
- Plastic type identification from spectral signature (scattering)
  - Nylon, polypropylene, polyethylene
- Pharmaceutical industry (scattering)
  - Identifying and quantifying pharmaceutical ingredients in mixed powders; pill ID
- Liquids – bioprocess monitoring (transmission)
  - Real time monitoring concentration of process ingredients: glucose, glycerol etc.
- Tunable laser spectroscopy allows spectral measurements even in presence of high absorption, or high optical density


Axsun Tunable Laser

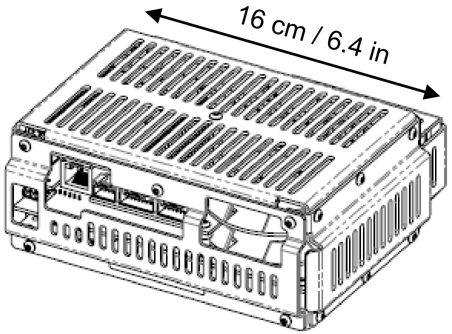
Liquid/Gas Sample or Flow Transmission Cell

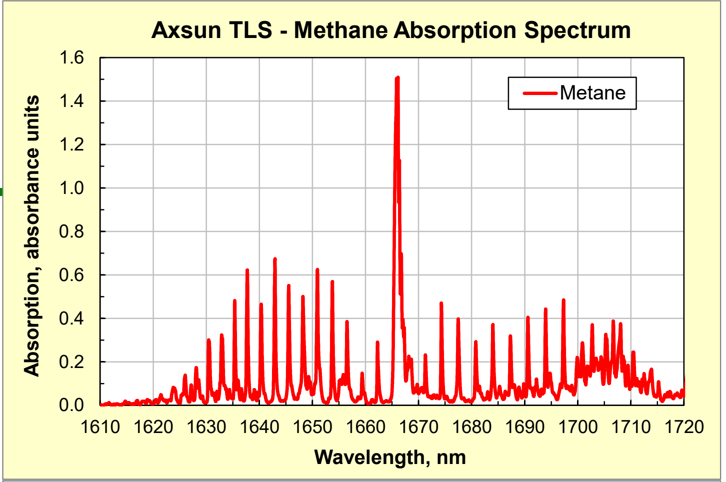
Detector

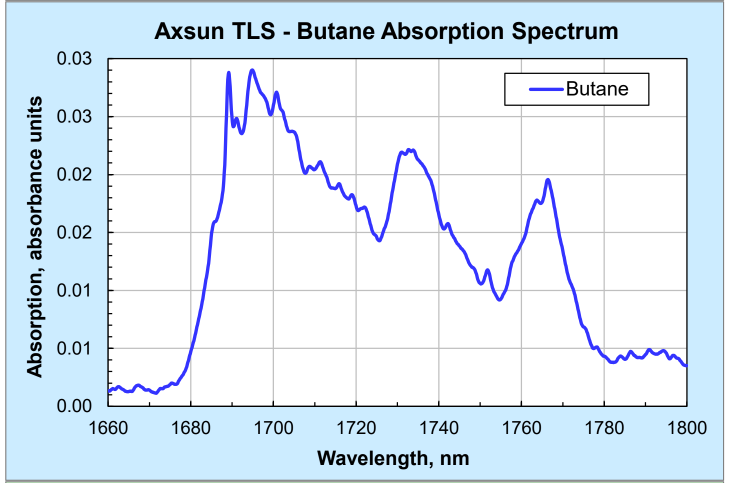

Axsun Tunable Laser

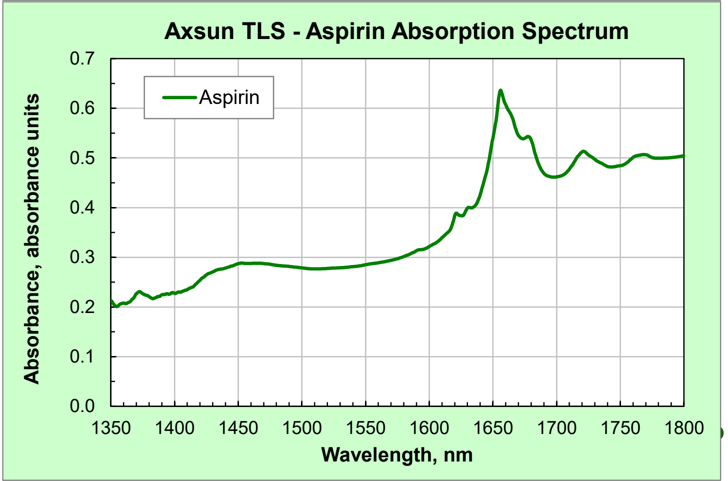
Scattering sample

Detector




Axsun TLS - Methane Absorption Spectrum


Axsun TLS - Butane Absorption Spectrum


Axsun TLS - Aspirin Absorption Spectrum

Conclusions

The ~~Humble~~ Mighty Fabry-Perot Interferometer

- The humble two-mirror Fabry-Perot optical interferometer is a very versatile device with many different operating regimes.
- More than 126 years after its introduction in an 1899 research paper, it still surprises us with discoveries of its new functionalities:
  - Single transverse mode Fabry-Perot optical resonator
  - Reflective spectral selection for tilted Fabry-Perot optical resonator
- Compact MEMS implementation of tunable Fabry-Perot filters enables a variety of modern technological applications
  - Optical spectrum analyzer
  - Tunable external cavity semiconductor laser
- Reflective mode Fabry-Perot filters enable tunable external cavity semiconductor lasers with a variety of applications:
  - Swept-Source Optical Coherence Tomography, fast SS-OCT, for medical and industrial imaging
    - Ophthalmology, cardiology, dermatology
  - Spectroscopy of gases, liquids and powders in petrochemical, pharmaceutical and bioprocessing industries
- The mighty Fabry-Perot interferometer is a technological enabler in the XXI century