Applications of Broadly Tunable MEMS-VCSELS

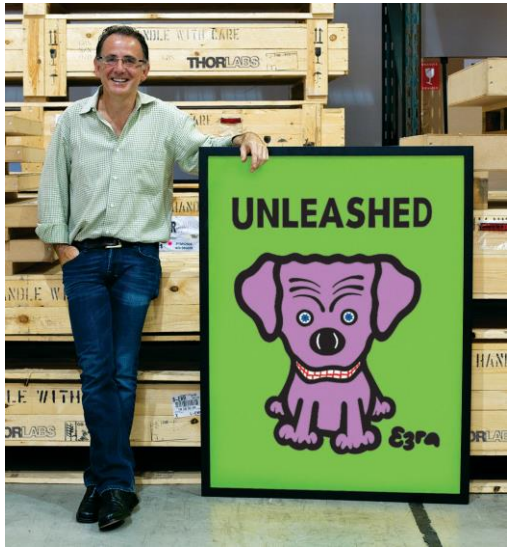
Peter J.S. Heim

October 18, 2019

Serving the Intellectually Curious

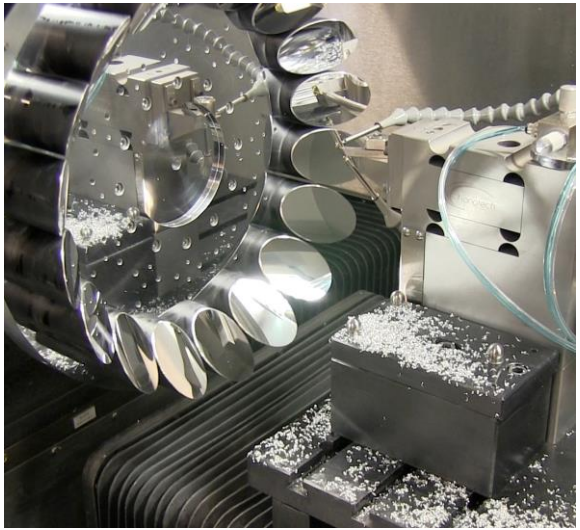
Thorlabs

- Corporate Headquarters: Newton, NJ
- ~ 2000 employees globally
- Company type: Private



Alex Cable - President & Founder

Thorlabs - Manufacturing



Thorlabs Sites Worldwide

Serving customers globally from 13 locations in 9 countries

Thorlabs Quantum Electronics

Thorlabs Quantum Electronics

Guilford Road 40,000 sqft
- 21,000 sq. ft of Clean Room

Stayton Drive 43,000 sqft
- 4,000 sq. ft of MOCVD Clean
- 14,000 sq. ft of Wafer Fab Clean Room planned

✓ State-of-the-art semiconductor manufacturing facilities dedicated to OEM and catalog customers.

✓ Staff of 160: 40% with PhDs or MS

✓ EPI thru Wafer FAB to full module production

✓ InP, GaAs, GaSb and $LiNbO_3$ device fabrication capability.

✓ ISO 9001:2015 certified

Semiconductor Lasers from 0.7 µm to 13 µm

Vertically Integrated Manufacturing

Capabilities that provide advanced supply-chain and manufacturing solutions for customers

Electro-optic Module

Module Production

Packaged Chip

Test & Reliability

Chip

Opto-electronic Packaging

Wafer

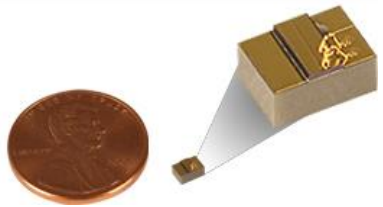
Wafer Fabrication

Wafer Growth

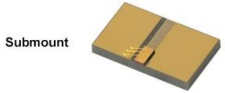
Epitaxial Wafer Growth

Products with increasing complexity and value-addition made in Jessup, MD

Broad Range of Semiconductor Products



Gain Chips for Tunable Lasers



Chip on Submount & C-Mount Laser Diode

Laser Diodes – TO Can Package

Hihg Power D-Mount Mount Packages

HHL Mid-IR Lasers

Gain Chip in Half Butterfly Package

Butterfly packaged Semiconductor Lasers and SLDs

Mid-IR Turnkey Laser

SOAs & Booster Optical Amplifiers (BOAs)

Serving Broad Range of Customers

TELECOM

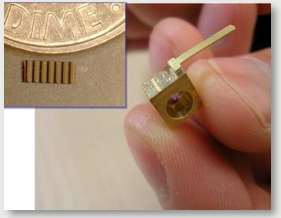
- Gain Chips
- Tunable lasers
- LiNbO3 Modulators
- Semiconductor Optical Amplifiers

MEDICAL

- MEMS VCSEL Tunable Laser for OCT
- Gain elements for tunable lasers
- Super Luminescent Diodes
- InP and GaAs Laser Diodes

DEFENSE

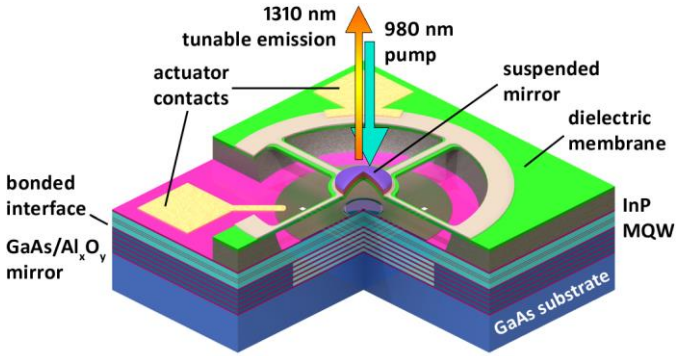
- QCL/ICLs
- LiNbO3 Modulators
- Laser Diodes
- Test Targets



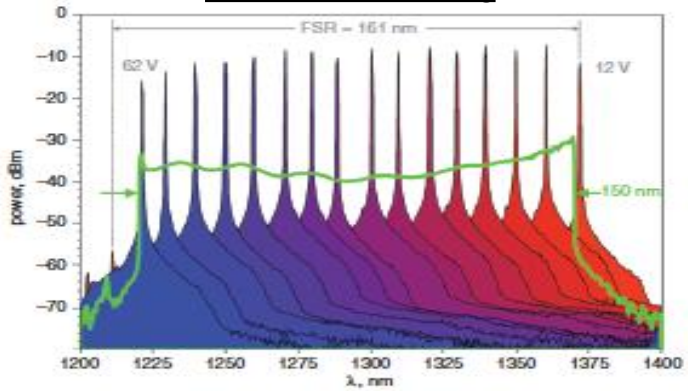
SENSING

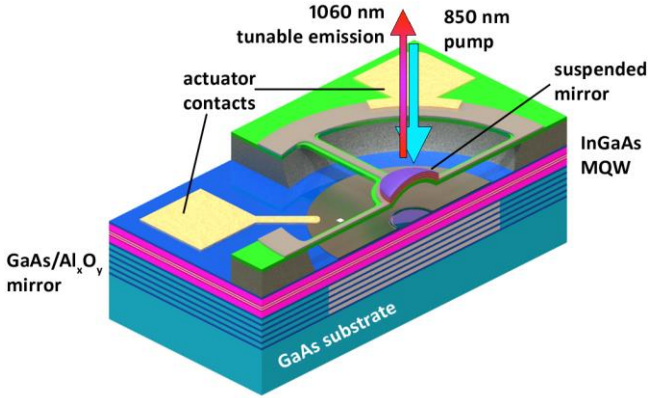
- High-speed Optical Amplifier Switches (NIR): Cavity ring-down sensors
- High Power laser diodes 780 nm: Raman spectroscopy or other remote sensing
- QCL/ICLs for trace gas sensing

Tunable MEMS-VCSEL: Optically Pumped

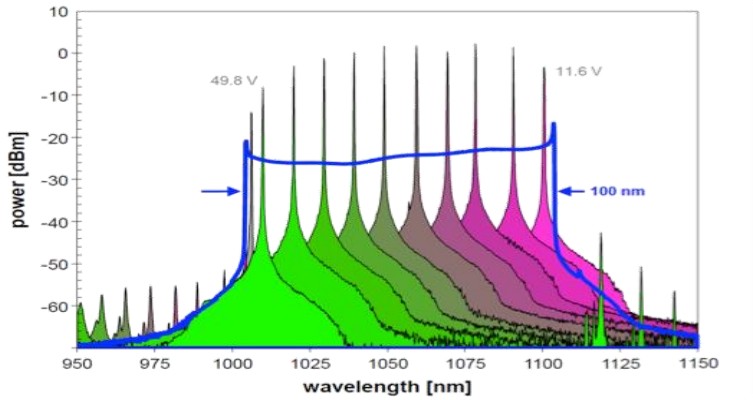


150nm/11.4% tuning

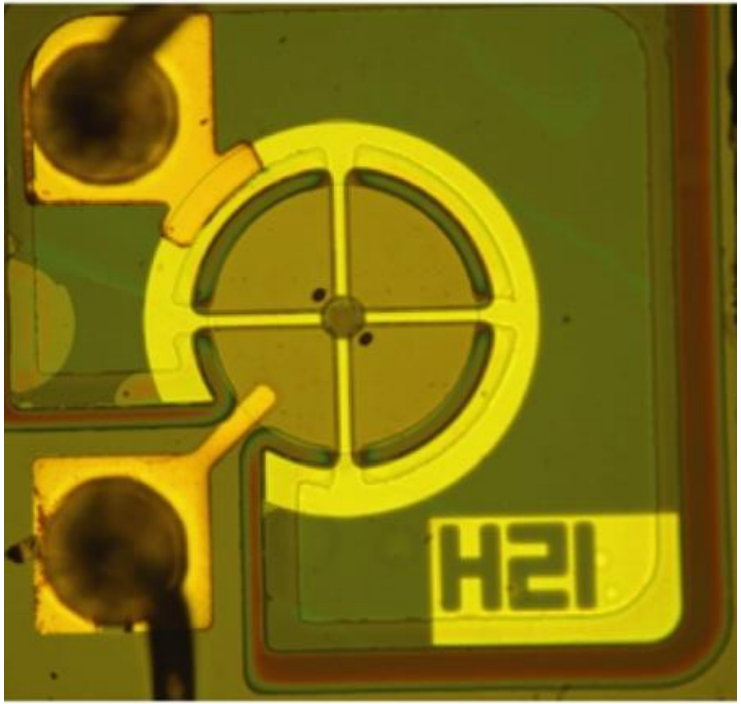


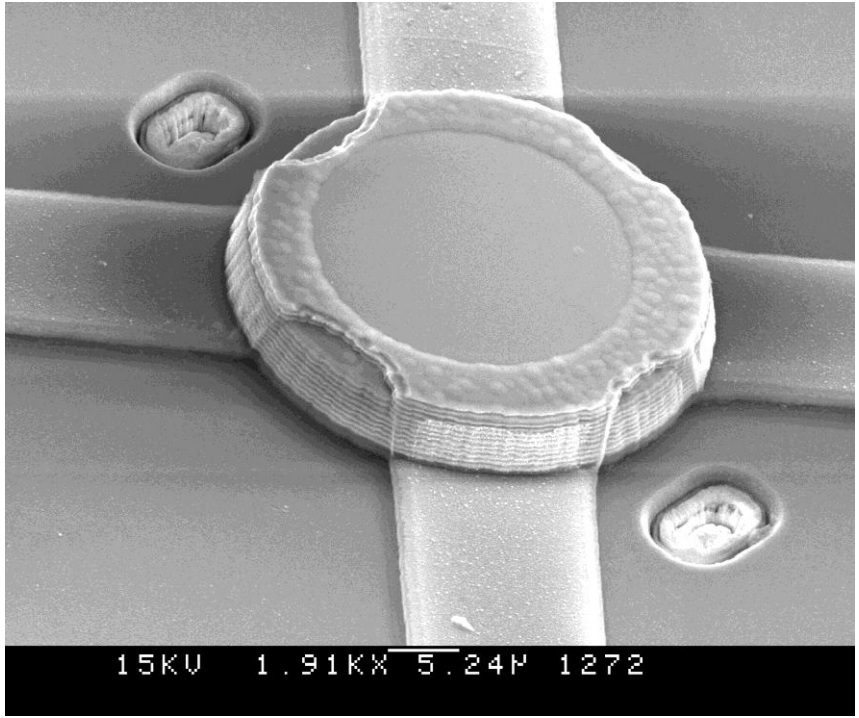


100nm/9.4% tuning



MEMS-VCSEL





Product Test Data Sheet

THORLABS

1300 nm Swept Wavelength VCSEL Sub-Module

OEM-100-0140

S/N: 002
Test Time: 05/17/2012 Tested By: Phong

QA: Passed

Summary of Test Conditions (T_{VCSEL}, T_{PUMP} = 25°C)

Parameter	*Symbol*	*Value*	*Unit*
Pump Current	I_{op}	160	mA
DC Bias	V_{DC}	8	V
Modulation Amplitude (sine wave)	V_{PP}	22.8	V
Drive Frequency	f_{op}	200	kHz

Absolute Maximum Ratings[1]

Parameter	*Ratings*	*Unit*
Bandwidth	115	nm
Pump Current**	200	mA
DC Bias[2]	70	V
Modulation Amplitude	70	V
Case Temperature	15~+30	°C
Drive Frequency	500	kHz

** Submodule 002 Uses a Higher Current Pump Laser

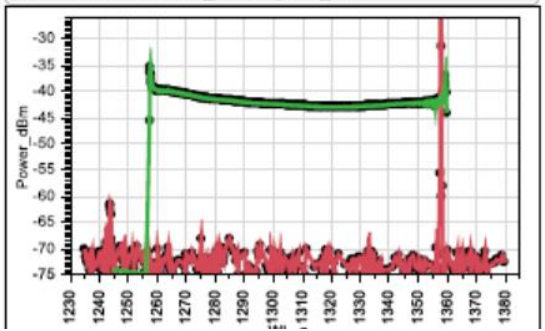
Summary of Test Results

Parameter	*Symbol*	*Value*	*Unit*
Optical Bandwidth	BW	101	nm
Optical Power (Average)#	Pop	140	µW
Power Ripple +	δP	0.9	%
Polarization Switching*	PS	PASS	P/F
Resonance Frequency	F_{RES}	325	kHz
Free Spectral Range	FSR	1244-1359	nm
Static Measurements			
Min Static Power[x]	P_{DC}	80	µW
Min Static SMSR[x]	$SMSR_{DC}$	52	dB

Optical Power Increase ~ 1%/°C for T_{VCSEL} at I_{op}

[x] Static Tests: 1340 – 1360 nm

Bivariate Fit of Power_dBm By WL_nm



MEMS-VCSEL Swept Source Module

	Symbol	Min	Typical	Max
Center Wavelength	λ_c	1280 nm	1300 nm	1320 nm
Tuning Range (-10 dB)	$\Delta\lambda$	95 nm	100 nm	
Average Output Power	P_o	20 mW	30 mW	
Duty Cycle (Unidirectional Sweep)	D	40	70	
Coherence Length	L_{Coh}		> 100 mm	
Scan Linearization Ratio (max/avg)	SLR			1.5
Side Peak Suppression Ratio	SPSR	50 dB		
Relative Intensity Noise (RIN) – Ortho-RIN	RIN_{ORTHO}			2%
Sweep Rate (examples)	R_{sweep}			
P/N SVM130-XXXX			50 kHz	
P/N SVM131-XXXX			100 kHz	
P/N SVM132-XXXX			200 kHz	
P/N SVM134-XXXX			400 kHz	

MEMS-VCSEL Swept Source Module

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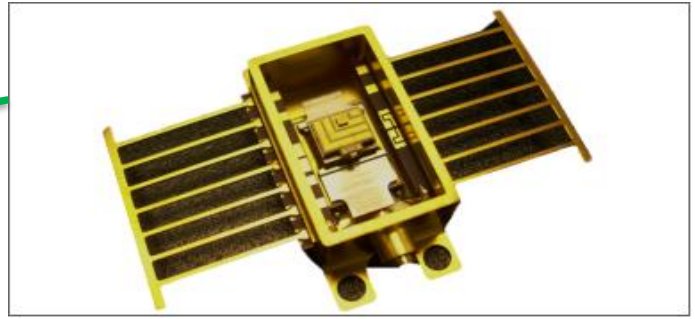
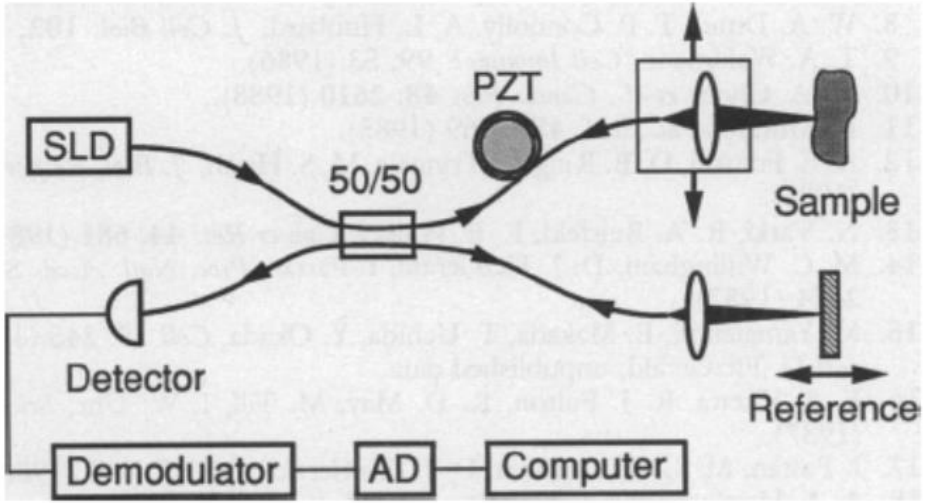
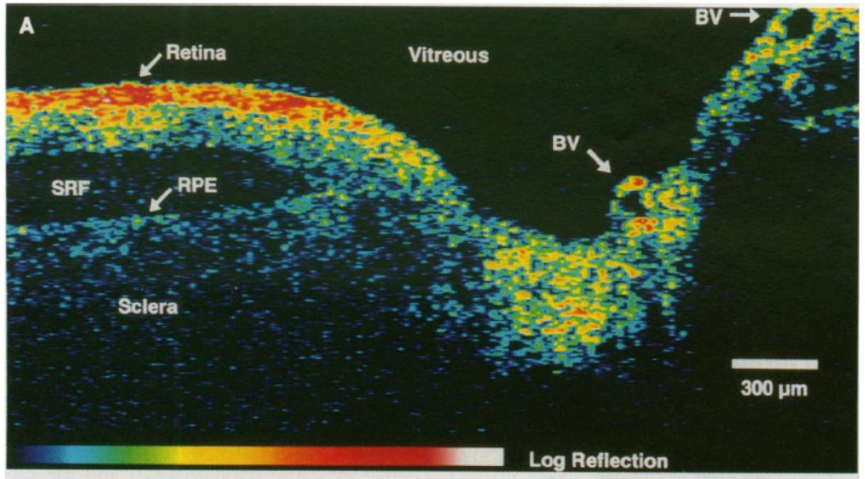


Optical Coherence Tomography





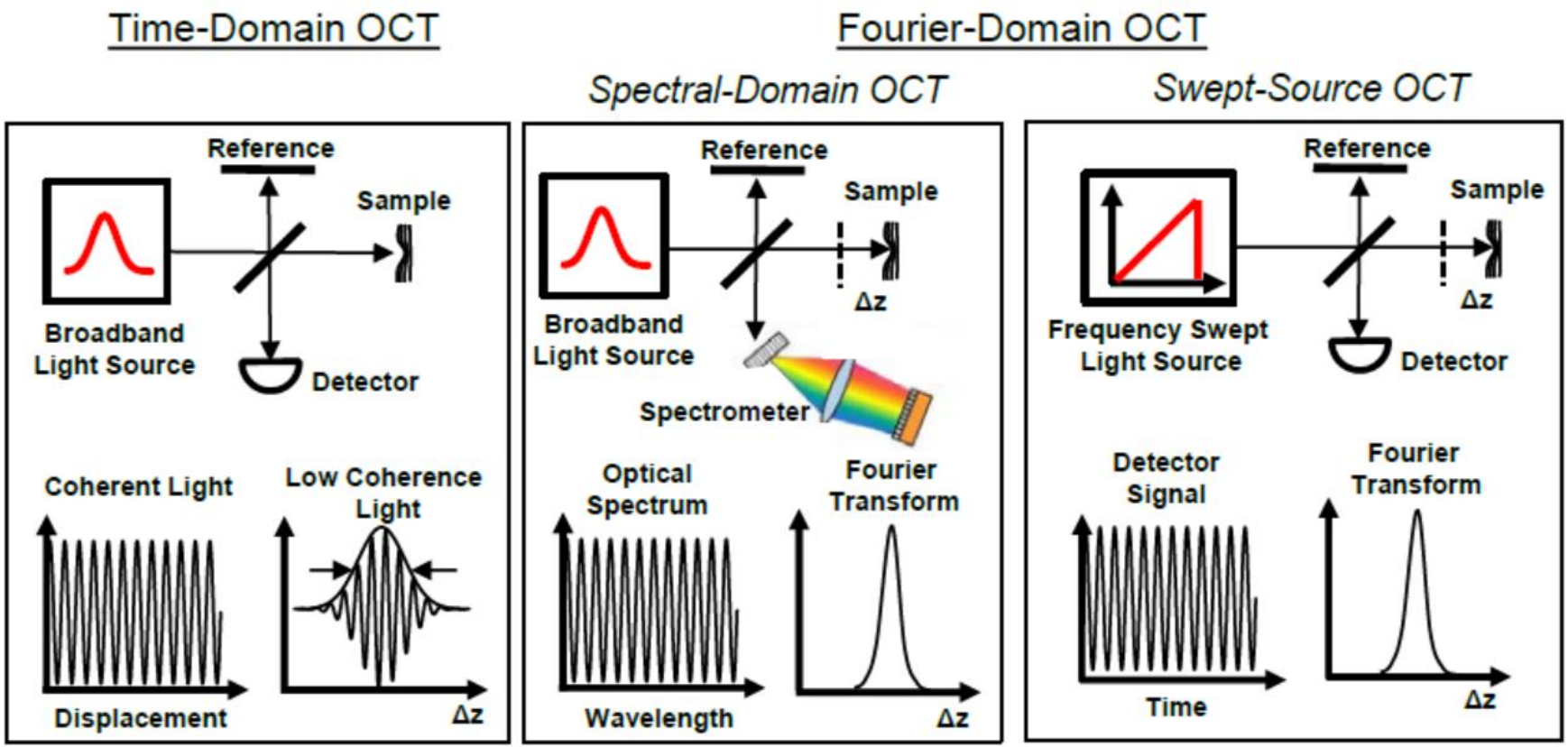
Huang, et al, Science, 1991

"A technique called optical coherence tomography (OCT) has been developed for non-invasive cross-sectional imaging in biological systems. OCT uses low-coherence interferometry to produce two-dimensional images of optical scattering from internal tissue microstructures"

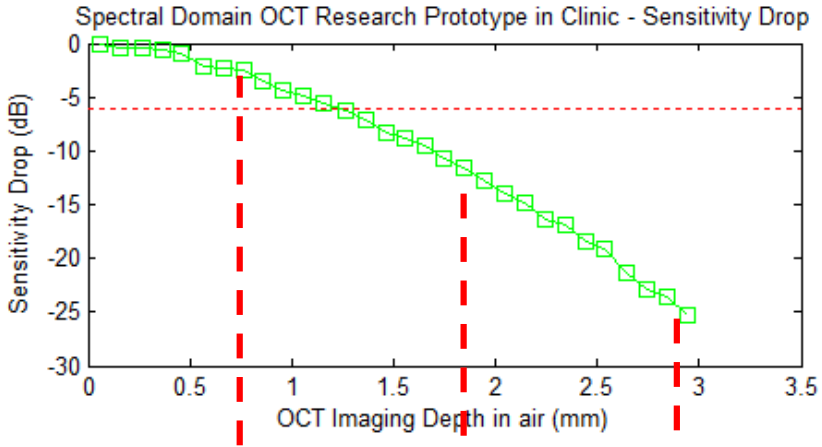
- ~ 30 Million OCT imaging procedures annually
- OCT system market approaching $1B per year

Swanson and Fujimoto, Biomedical Optics Expr., 2017

Evolution of OCT



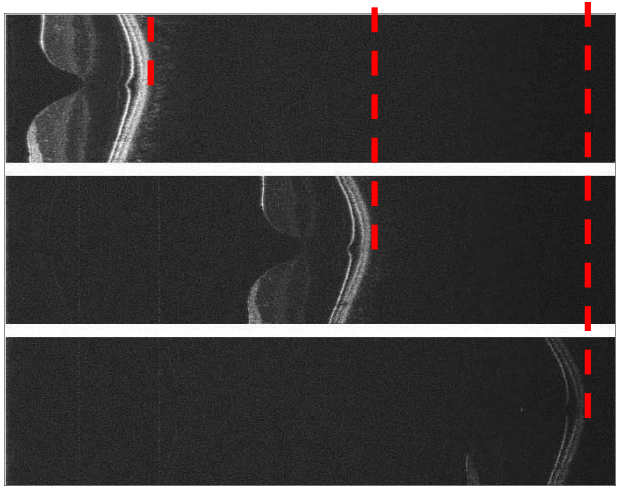
Sensitivity Roll-off in Spectral Domain OCT



-2dB (0.7mm)

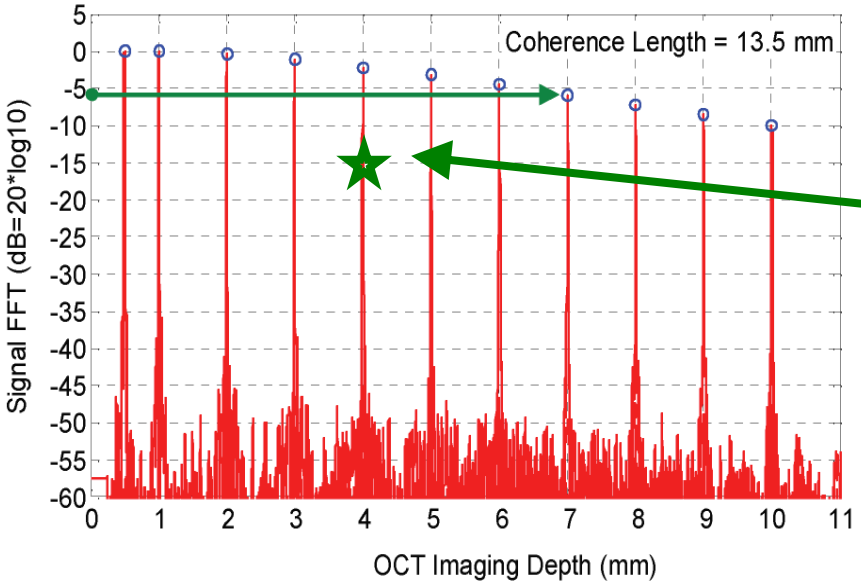
-10dB (1.8mm)

-25dB (3.0mm)

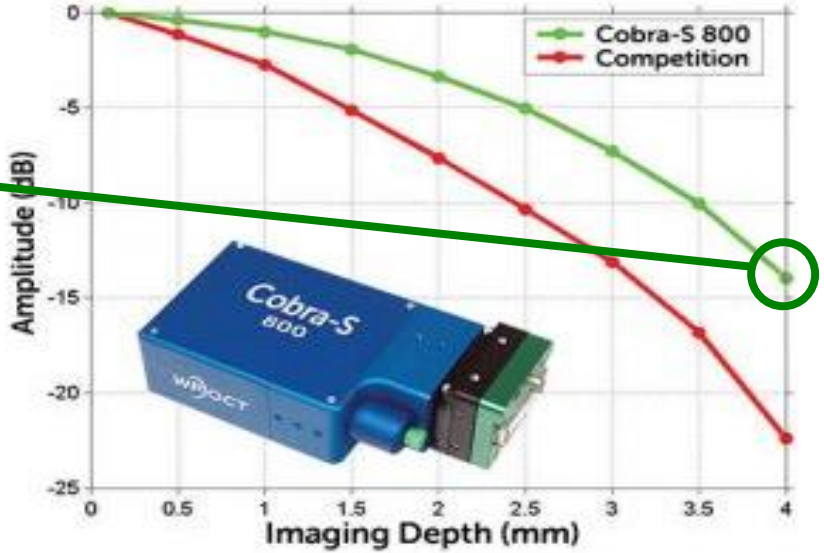


Increased Imaging Depth with SS-OCT

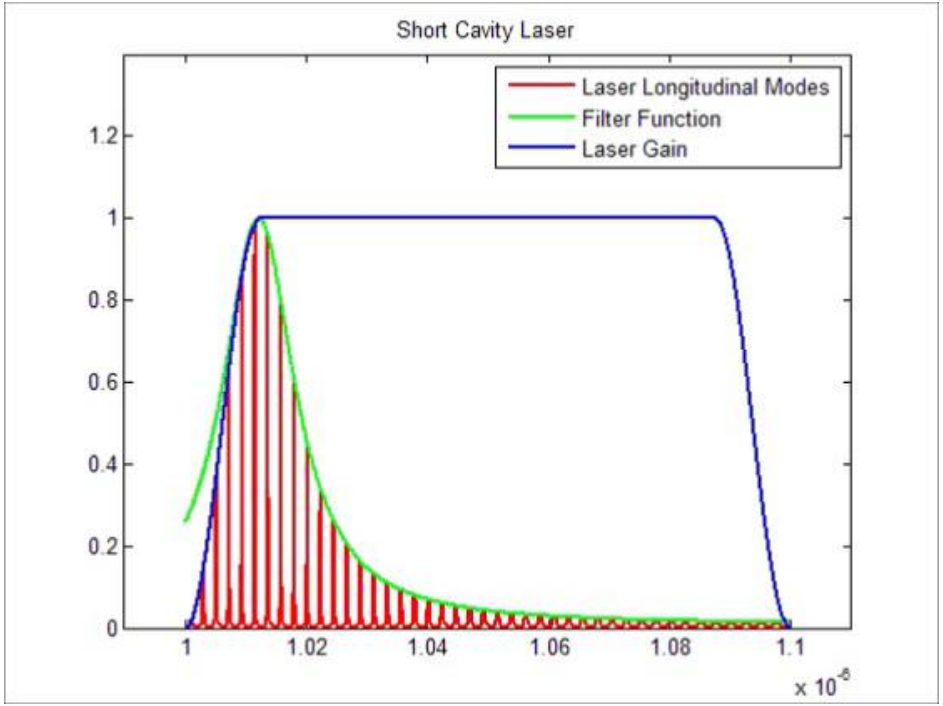
Swept-Source OCT (Short-Cavity Laser)

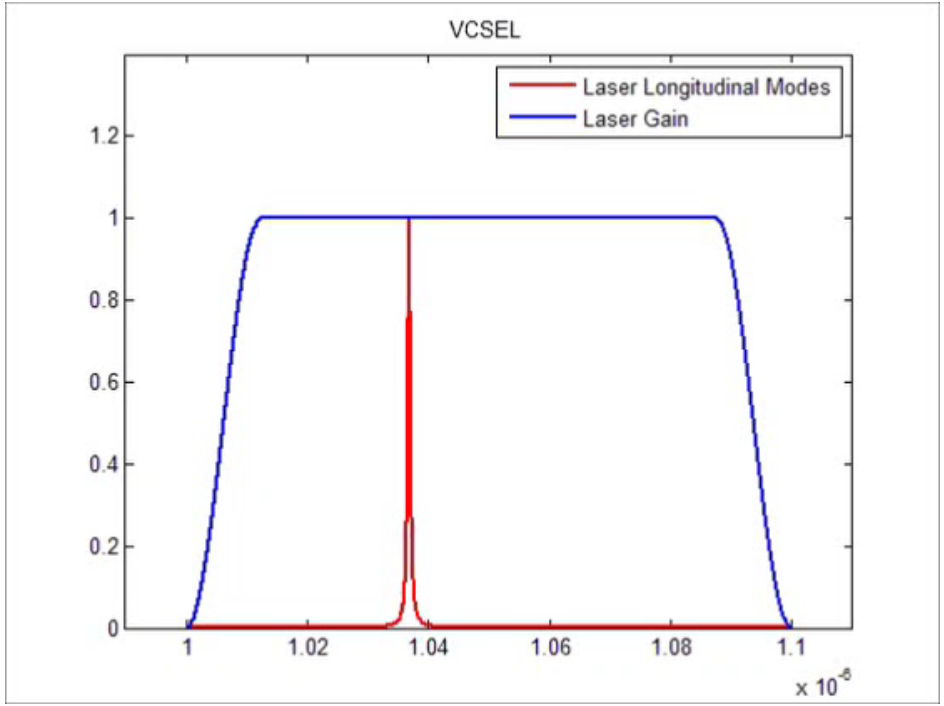


Spectral Domain OCT

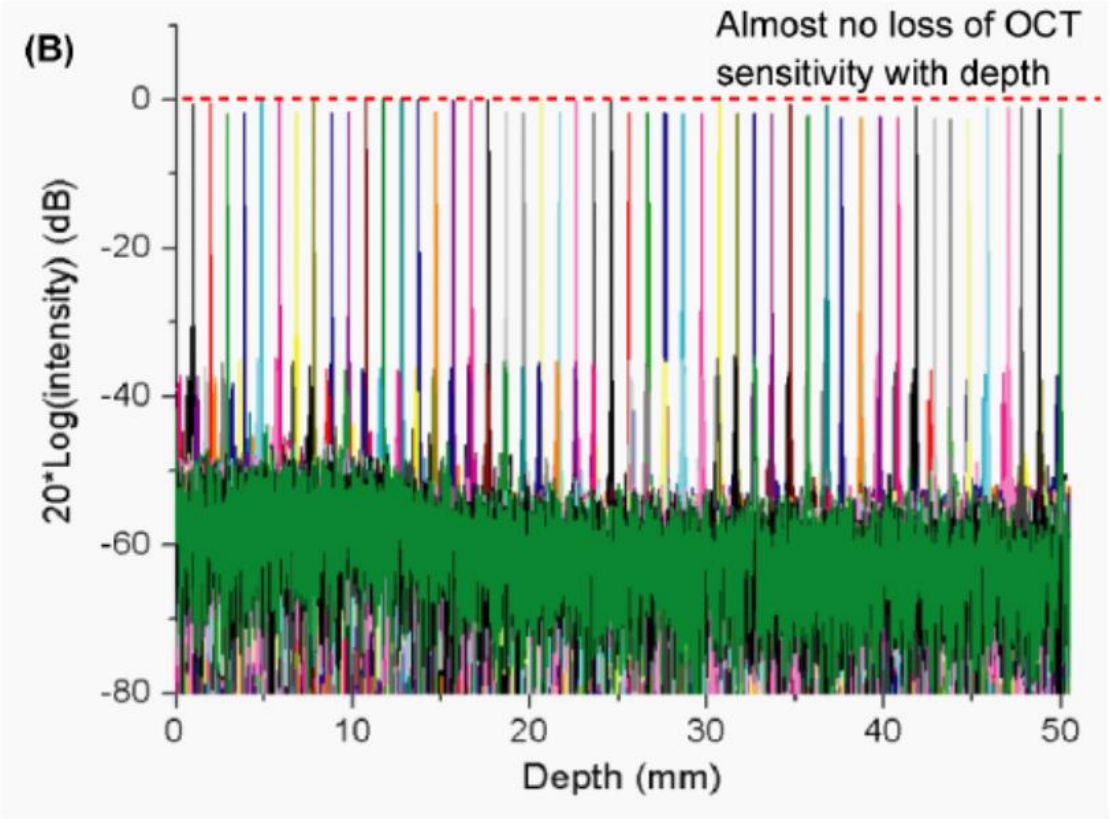


Short Cavity Laser vs Tunable VCSEL



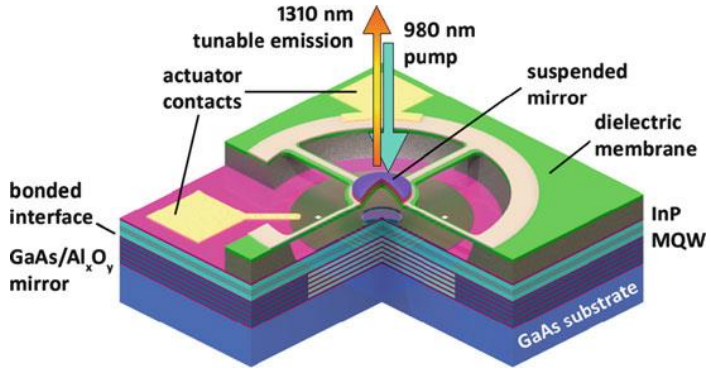


Drastic Increase in Imaging Depth with MEMS-VCSEL



Potsaid, et al, Proc. of SPIE, (2012)

MEMS-VCSEL Ideal Swept Source for OCT



History

- Wu et al 1995 (Berkeley).
- Larson et al 1996 (Stanford).
- Matsui et al 2003: 64nm tuning =4.1% (Coretek)
- Dudley et al 1994: wafer-fused InP/GaAs VCSELs (UCSB)
- MacDougal et al 1997: GaAs/AlxOy mirror (USC)

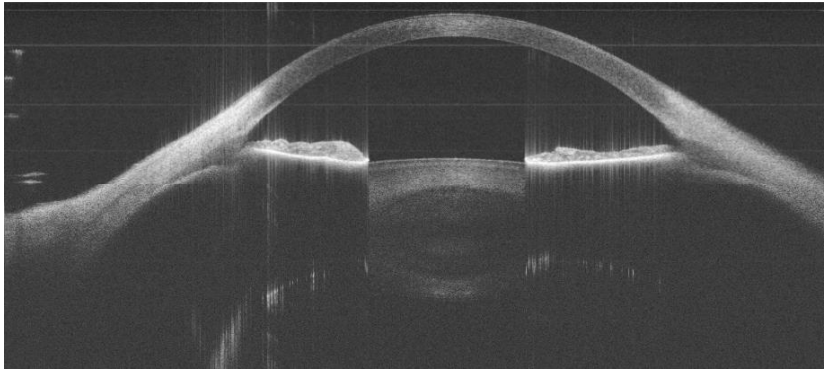
Fundamental Performance Advantages

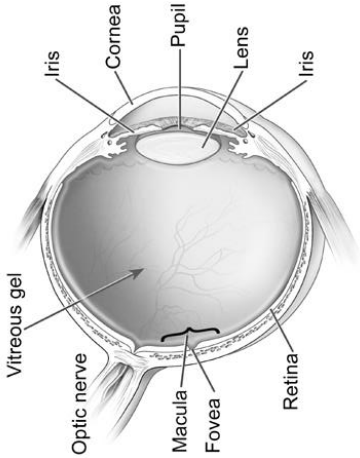
- Wide Tuning: Short micron scale cavity creates large mode spacing (FSR) and wide fractional continuous single-mode tuning range >10%.
- Fast Tuning: Small mirror mass and *adiabatic tuning* enable >2 MHz tuning speeds over full tuning range.
- Variable Speed: Engineered air damping provides flat mechanical frequency response.
- Narrow Linewidth: Short cavity produces single mode operation and >100 meter dynamic coherence length. Significant for anatomic imaging, metrology, and LIDAR.
- Wavelength Flexible technology from 650-5000 nm using InP, GaAs, GaSb based gain regions.
- Low-cost enabled by wafer-scale fabrication and test.

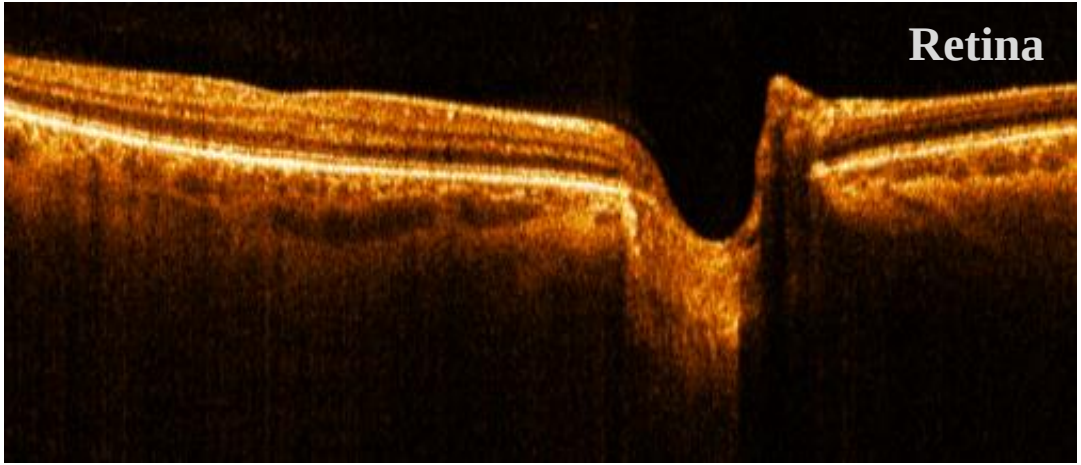
Application Area - Opthalmology

- Worldwide the largest market for OCT
  - 10,000‘s systems sold annually
  - 10,000,000‘s procedures annually

-- OCT can be particularly helpful in diagnosing **macular degeneration** (AMD), detachments of the neurosensory retina and retinal pigment epithelium, optic nerve disorders such as **glaucoma**.

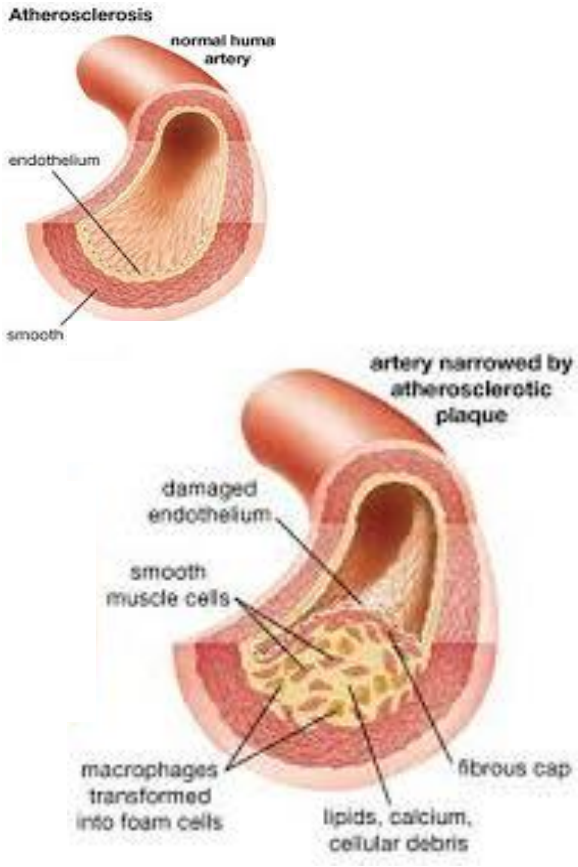


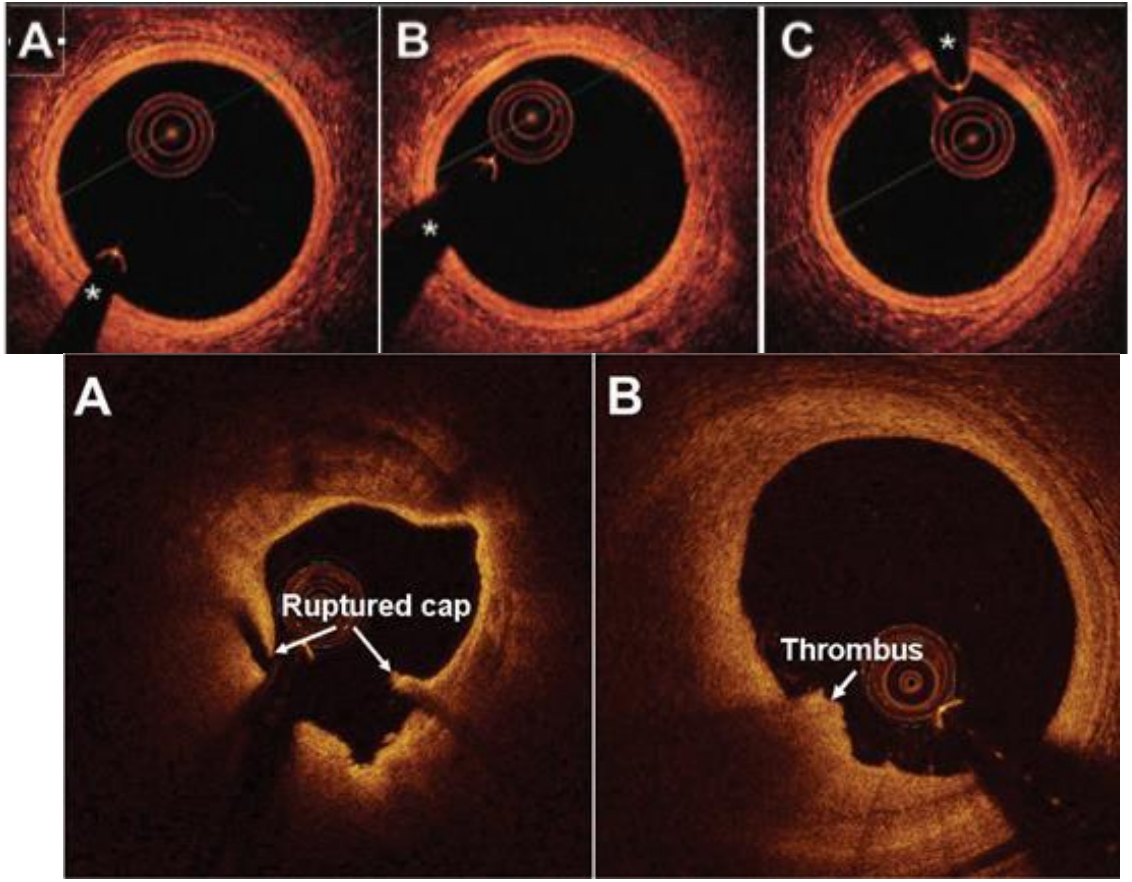




Courtesy of Thorlabs Lübeck

Application Area - Cardiovascular





www.brittanica.com

Alfonso et al. J. of Invasive Cardio. (2013)
Jia et al. J. of American Col. Of Cardiology, (2014)

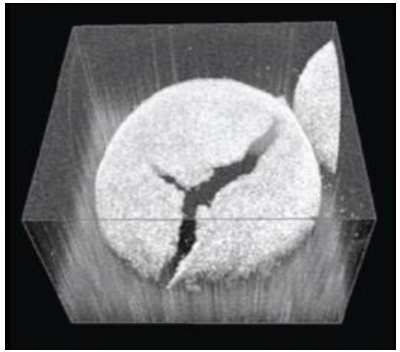
Other Developing Medical Application Areas

- Gastrointenstinal
- Dermatology
- Dental
- Brain Imaging
- Kidney Transplant Evaluation
- Bone Imaging

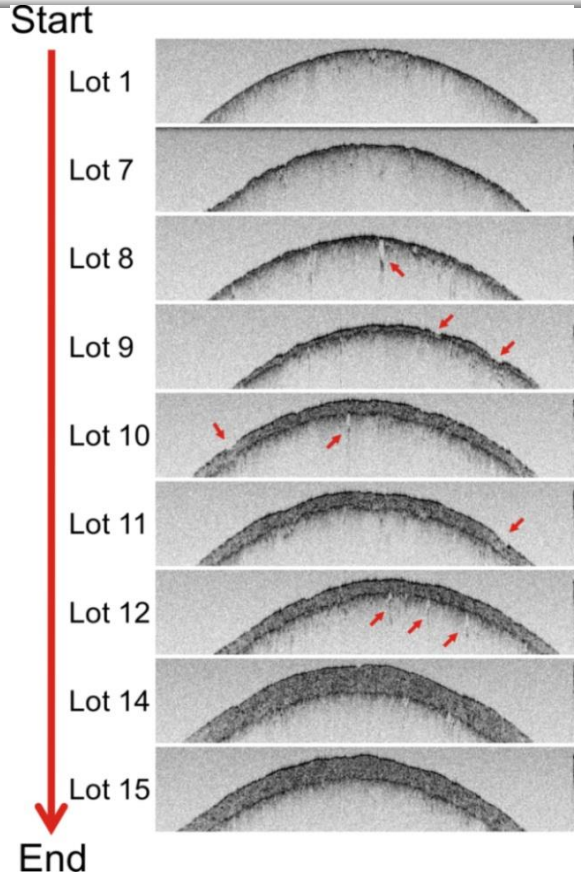
Non-Medical Applications - Pharmaceuticals

OCT can be useful to determine:

- coating thickness
- inter and intra-coating homogeneity
- defects in substrate and coating



cracked coating

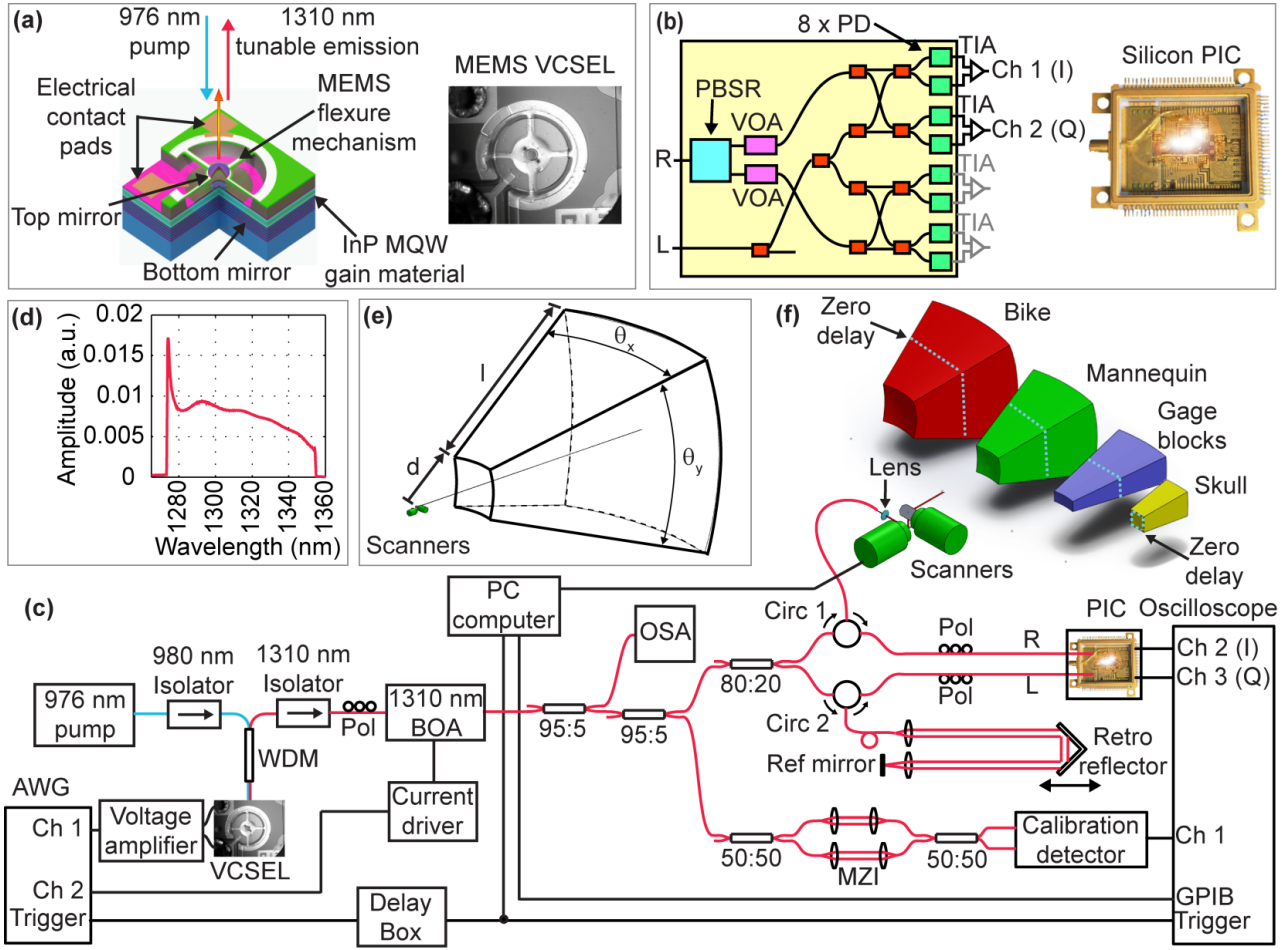


Thickness of tablet coating at different stages of the coating process;

Koller et al., European Journal of Pharmaceutical Sciences (2011)

Meter Range OCT

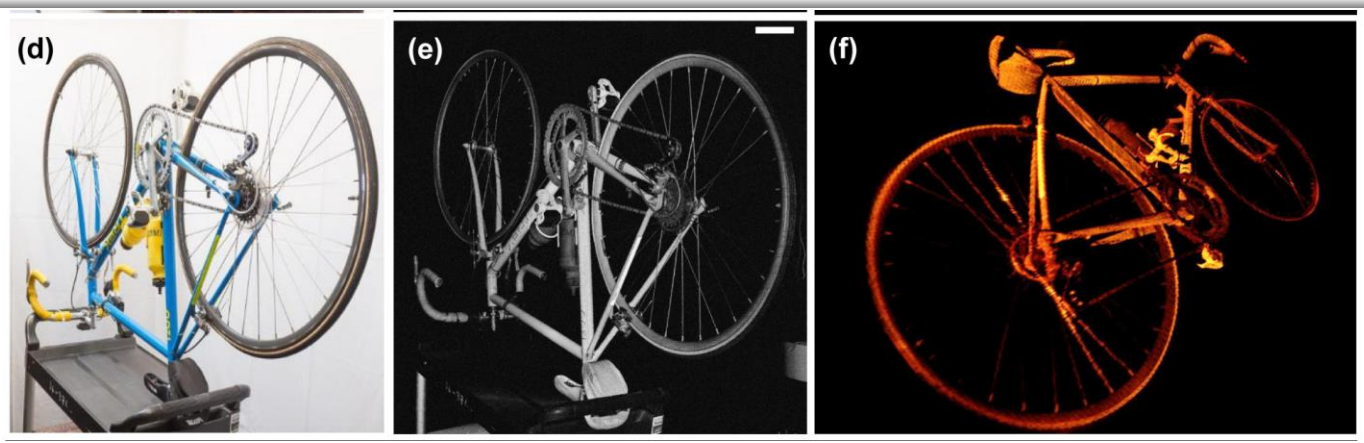
Detection



I & Q Detection

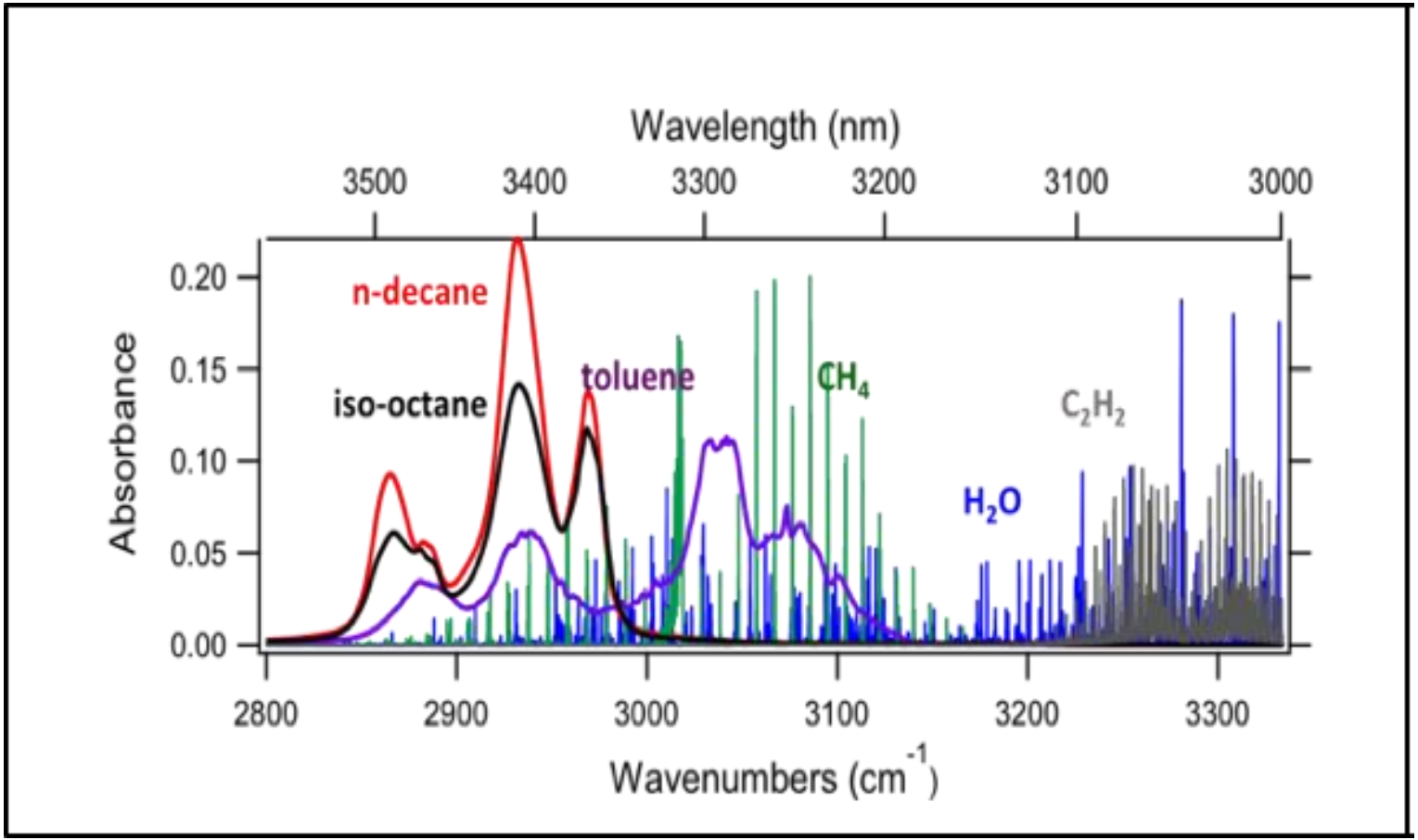
20GHz bandwidth
50GSPS Scope

Imaging Cubic Meter Volume with Micron Resolution

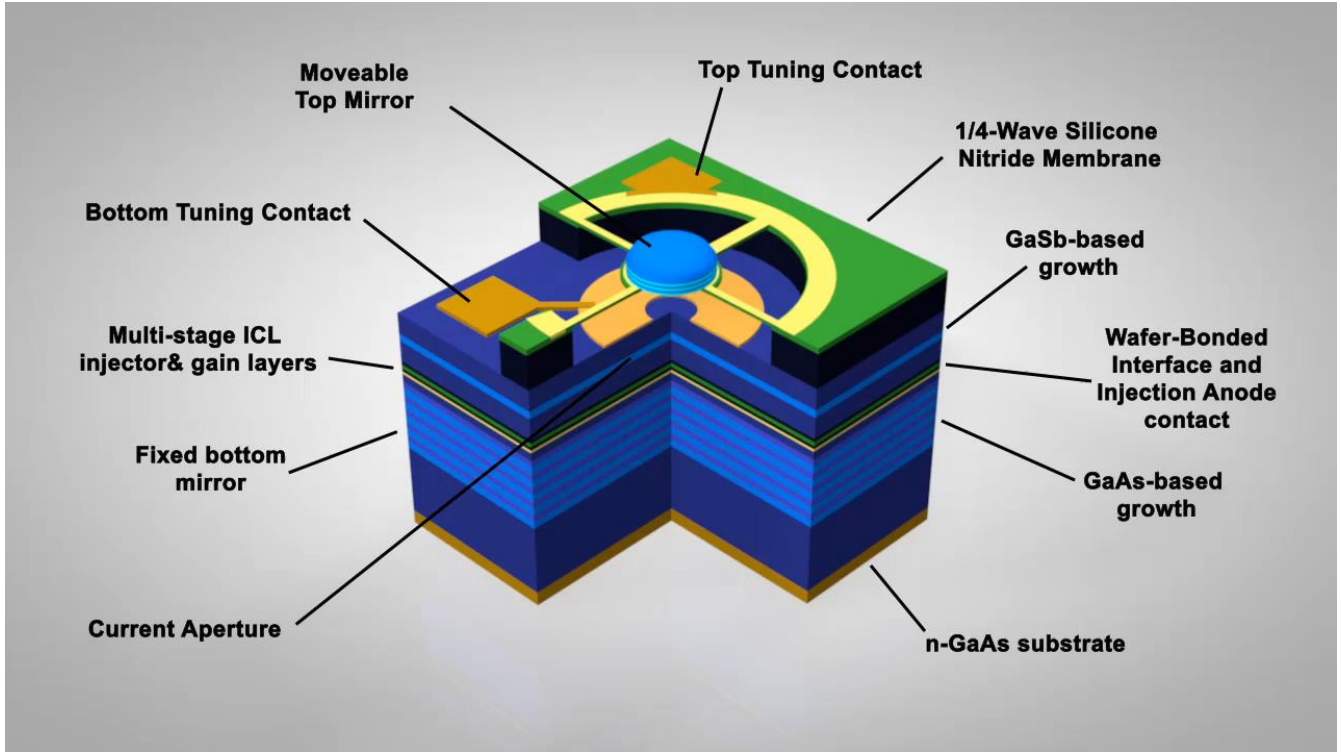


Zhao Wang, et al, Optica, (2016)

Gas Sensing: 3.0 – 3.5 um

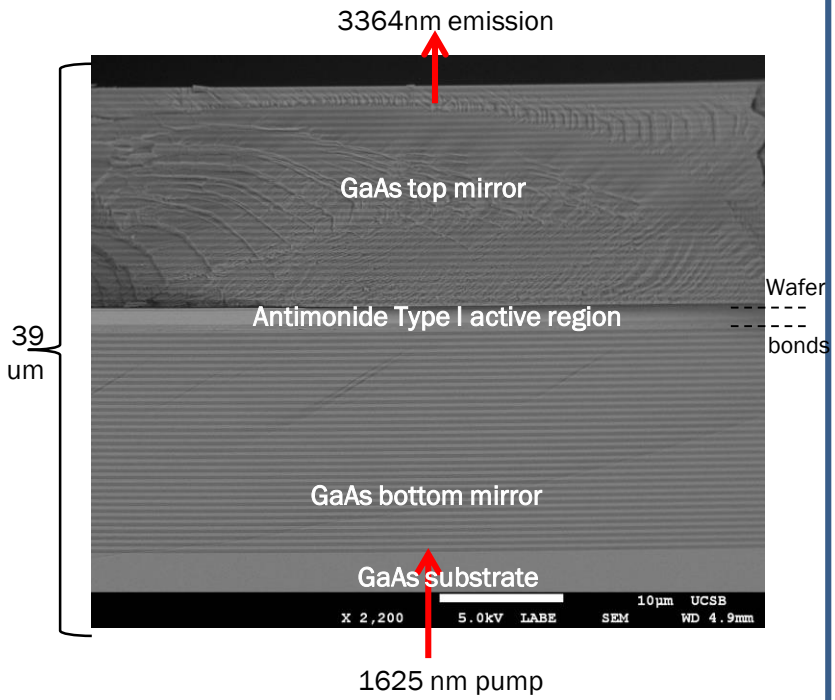


Moving to the Mid-IR: ARPA-E Monitor Program

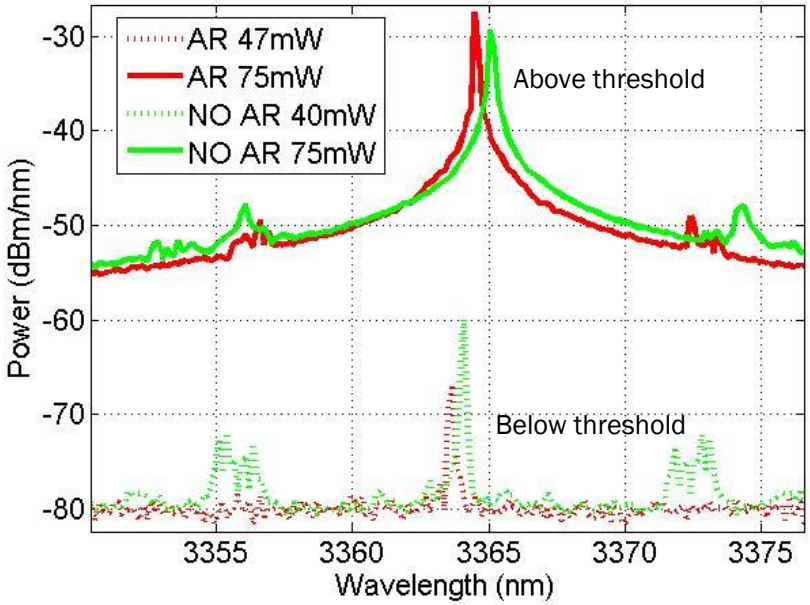


Room Temp CW Operation Demonstrated: Feb 2018

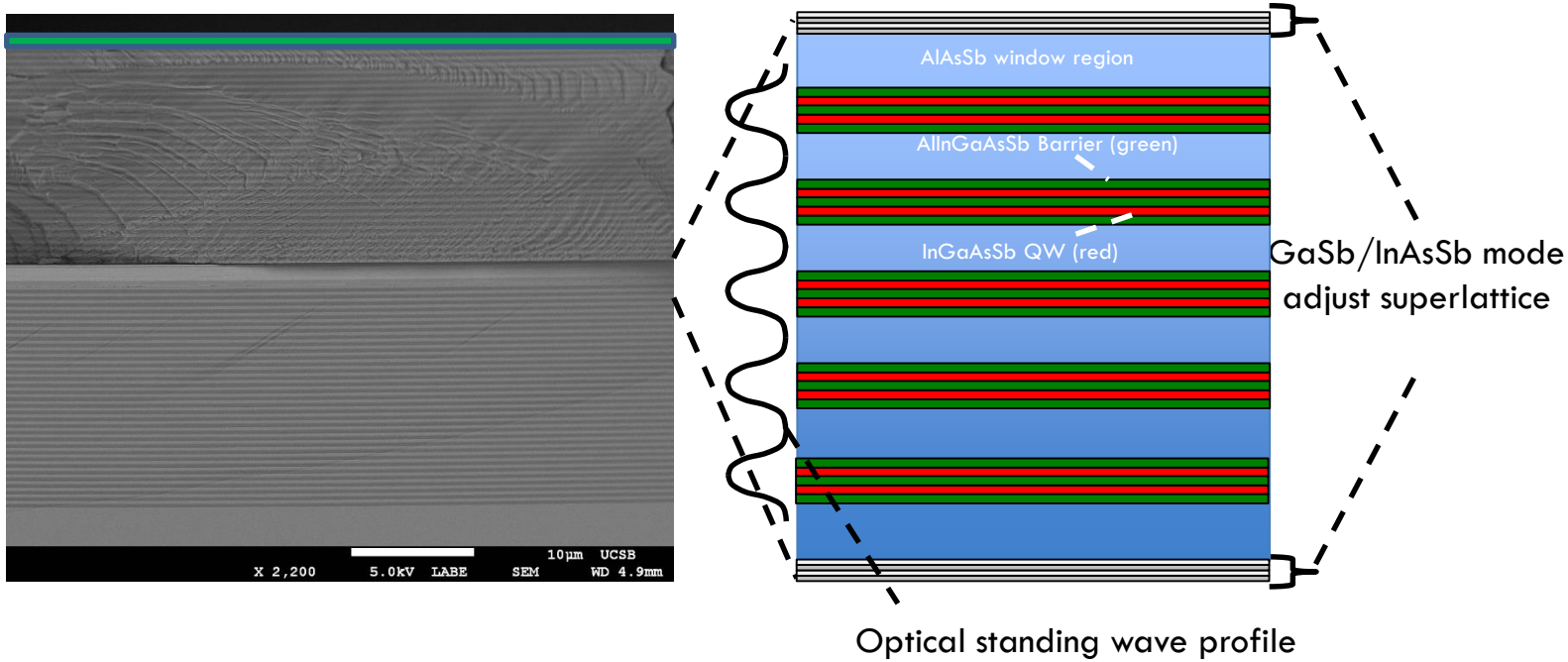
Double-bonded device cross section



Above and below threshold optical spectra



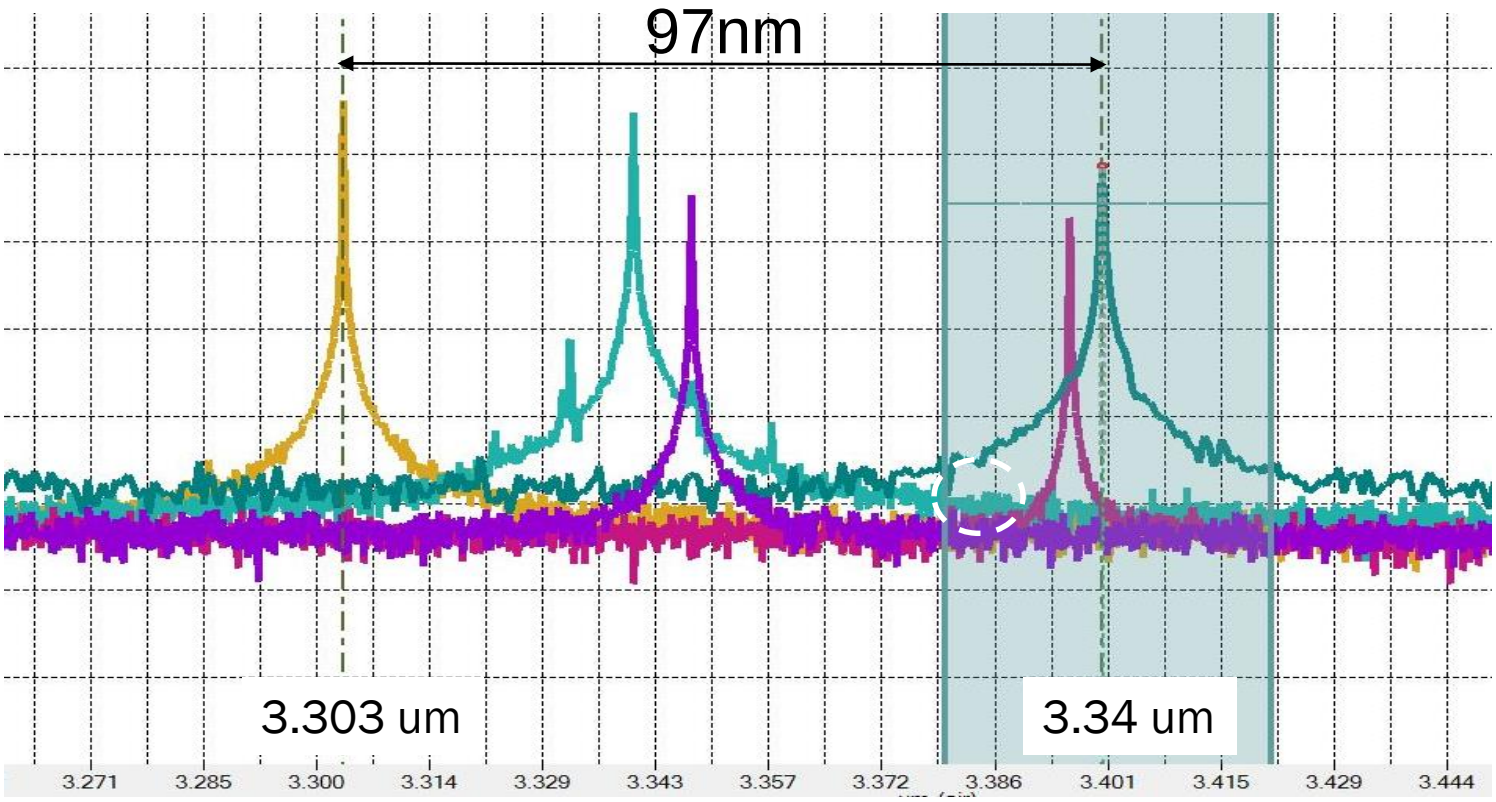
Optically-pumped VCSEL Device Structure



Key features:

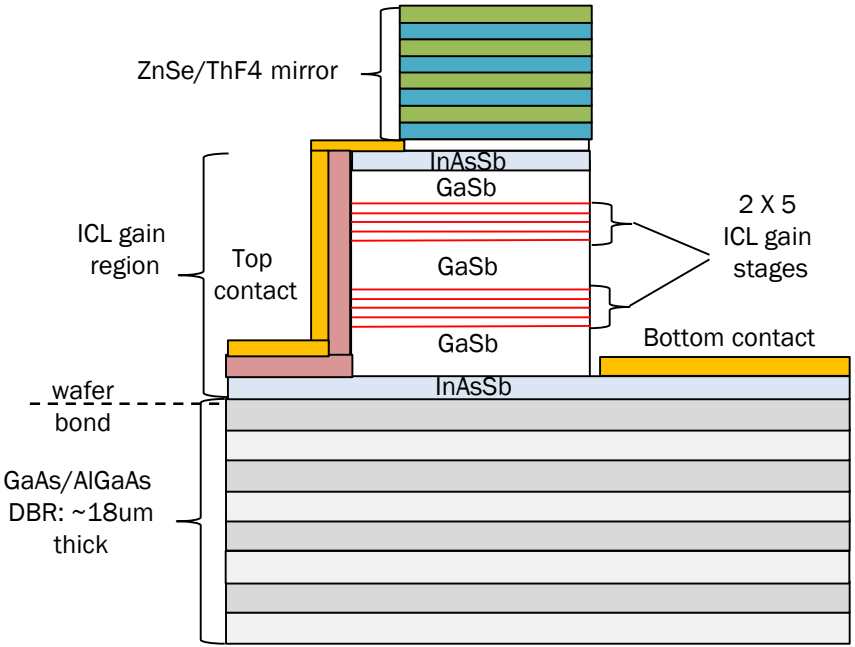
- GaSb-based core grown via MBE
- Superlattice at top and bottom of structure can be left intact, or sacrificially etched to adjust mode position for optimal overlap of standing wave peaks with QWs

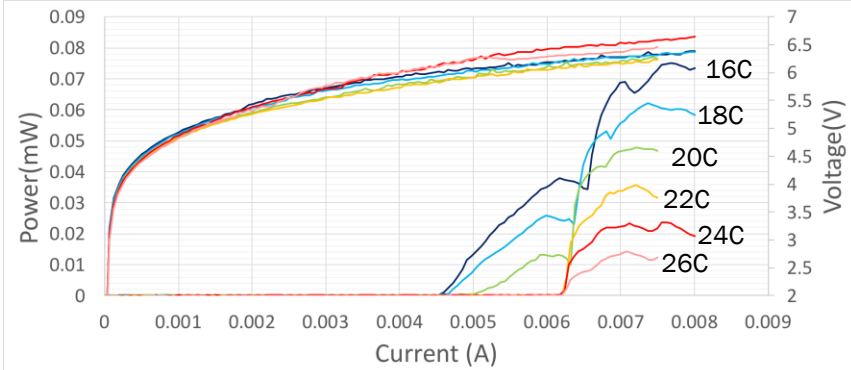
Wide Tuning Across Wafer Variation

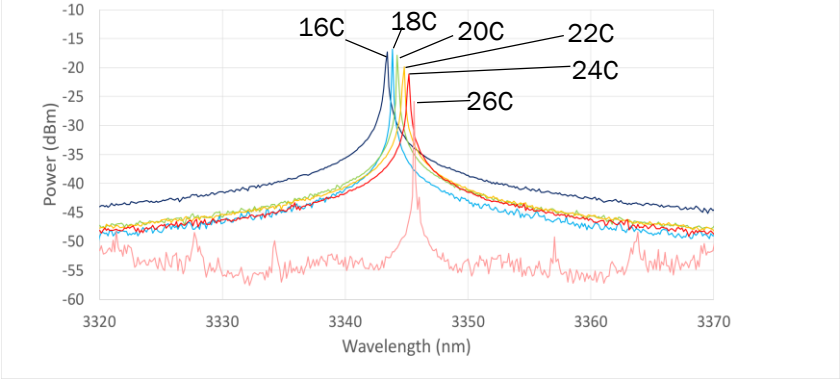


Room Temp CW Electrical Pumping: CLEO Europe 2019

Device Structure



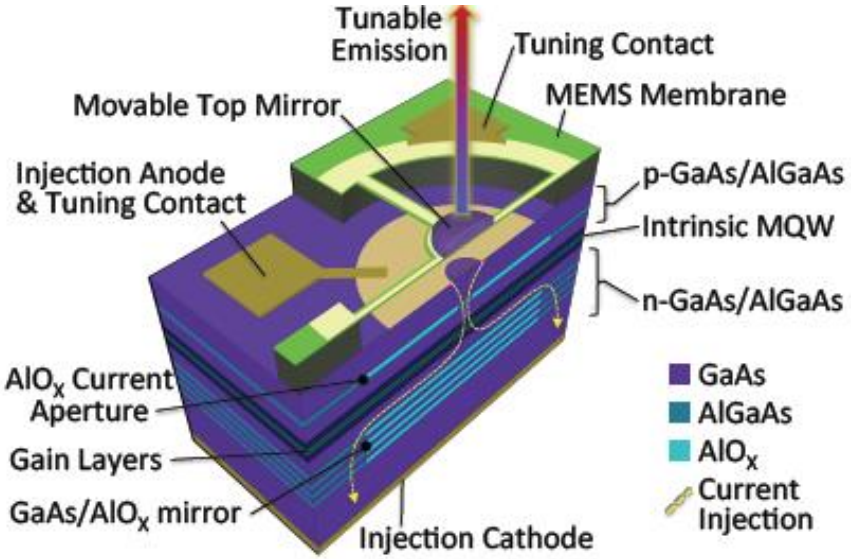


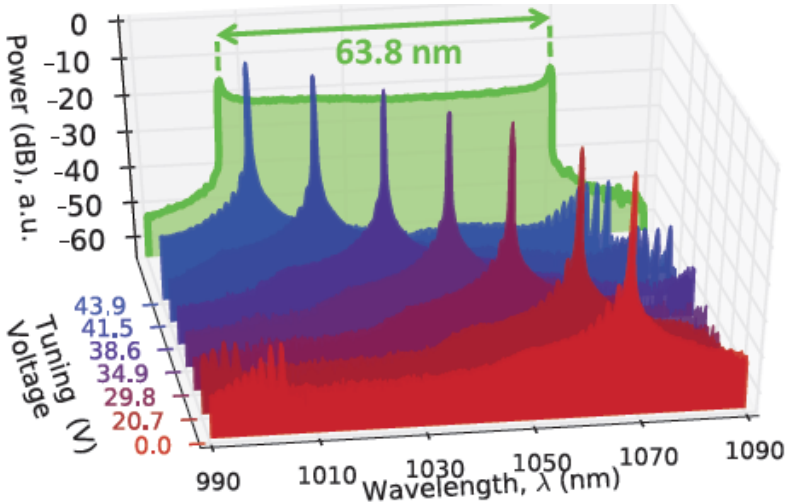


3.3 um eVCSEL

- Successfully demonstrated RTCW eVCSEL at 3.343 um with maximum CW lasing temperature of 26C.
- Employed wafer-bonded GaAs/AlGaAs bottom mirror, 10 ICL stages in GaSb-based active region, and top deposited ZnSe/ThF4 mirror.
- Optical spectra appear single mode with tens of microwatts output power.
- No current aperture was employed resulting in at least 2/3 of current being wasted outside optical mode.
- Thermal tuning of 1nm/mA via bias current injection could enable methane detection.
- Next steps are increasing output coupling for more power, reducing wasted current to drop threshold, and incorporating MEMS tuning.

Electrically Pumped MEMS-VCSEL (eVCSEL)

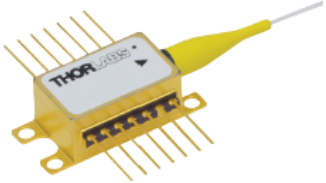




Initial eVCSEL Testing

Electrically-Pumped MEMS-VCSEL

- Wafer-Scale Monolithic MEMS-VCSEL Chip
- 1060 nm CWL with >60 nm Tuning Range
- Co-Packaged with Optical Amplifier
- Output Power: >15 mW
- 14-Pin Butterfly Package



Idea in the Works!
Hungry for Your Thoughts

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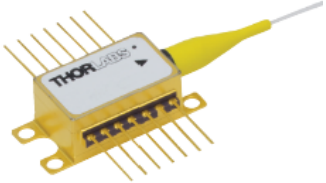

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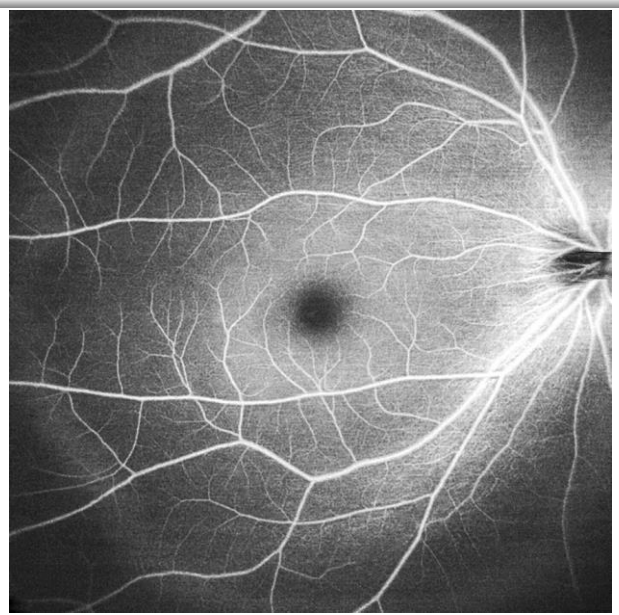

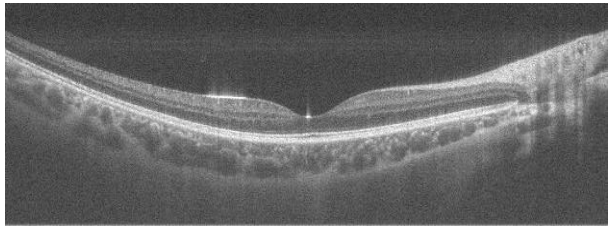

800 kHz A-scan rate

Additional MEMS-VCSEL Requirements

- Reproducible oxidation of fully-oxidized semiconductor mirror: needed for broad tuning
- Precise centering of broadband dielectric mirror: needed for broad tuning
- Precise control of MEMS release layer: control zero-voltage wavelength
- Heterogeneous integration of diverse materials (including wafer bonding)
- Complex processing (~15 mask levels)
- Assembly processes (e.g. die bonding) can change performance from wafer-level testing
- Optical pumping: increases complexity of all test steps, including burn-in

Future challenge → Cost Reduction

- Many OCT and spectroscopy applications can scale to much larger markets if laser costs can be significantly reduced (10x – 100x)
- Monolithic MEMS-VCSEL has inherent capability to scale to lowest cost through wafer-scale integration
- Electrically-Pumped MEMS-VCSEL with same performance as current oVCSEL
- Low-cost packing: integration with OCT and wavelength control elements

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