Ultra-Widely Tunable VCSELs

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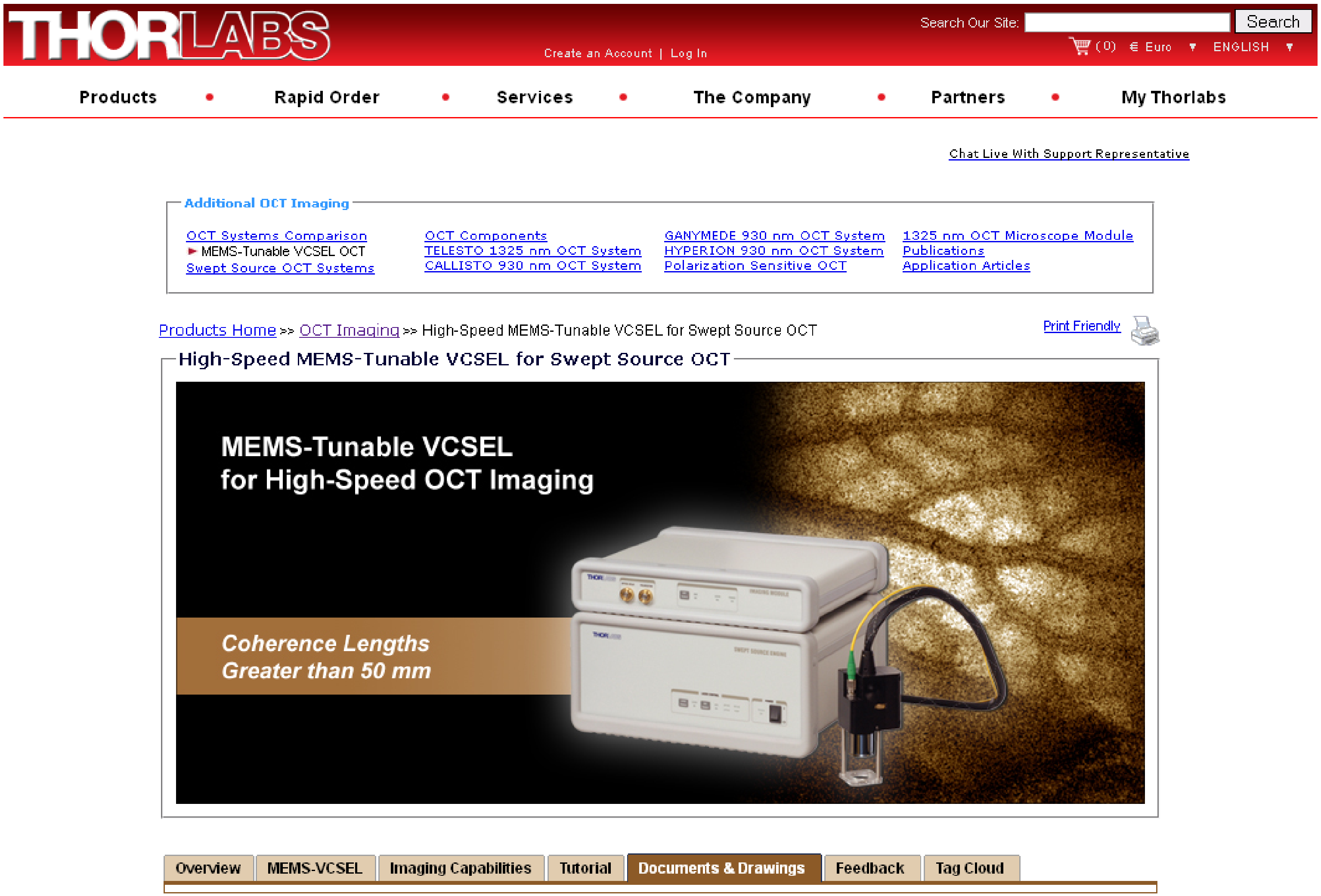
Outline

- Description of collaboration and foundational work
- Tunable laser technologies and MEMS-VCSEL details
- Introduction to optical coherence tomography (OCT)
- 1310 nm MEMS-VCSELs with a 150 nm tuning range
- 1060 nm devices with a 100 nm tuning range
- Summary of results and path forward

Collaborative Partners

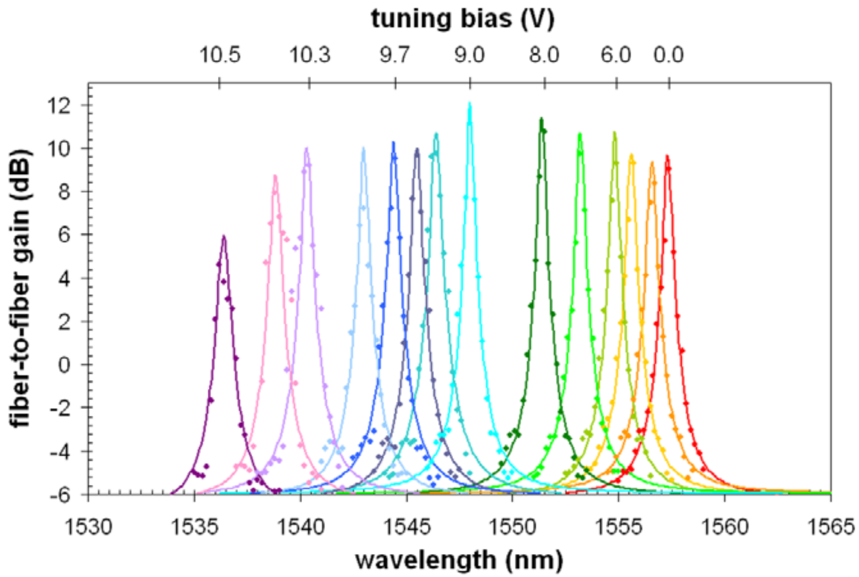
- Praevium Research
  - commercializing high functionality, miniaturized opto-electronic devices including broadband sources for OCT
- Advanced Optical Microsystems
  - optical microsystems design and fabrication consulting services (day job: Universitätsassistent, VCQ, Uni. Vienna)
- MIT, Fujimoto Group
  - original inventors and pioneers of OCT, validating device performance for medical imaging applications
- Thorlabs
  - responsible for investigating manufacturability and scalability of device designs; commercialization of final product

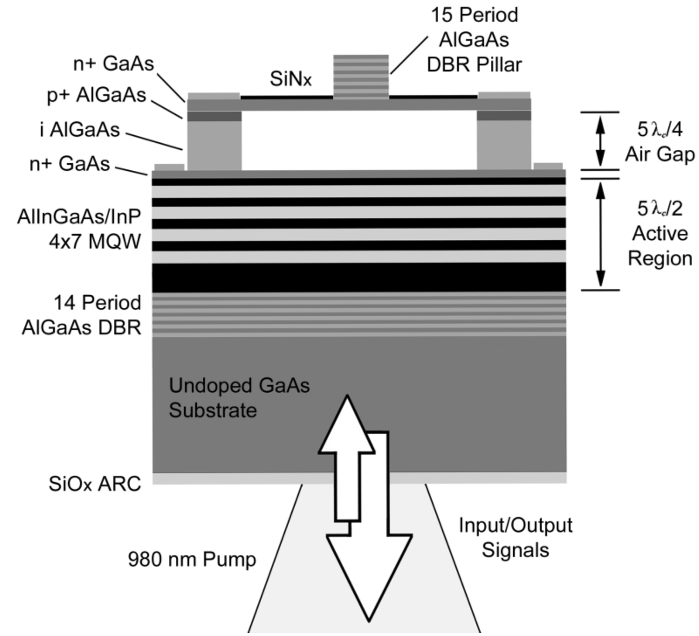
Commercial MEMS-VCSEL OCT System

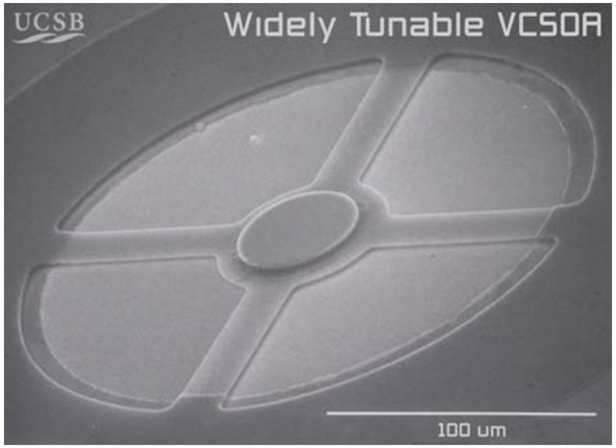


Commercial MEMS-VCSEL OCT System

Dissertation, UCSB: MEMS-Tunable VCSOAs





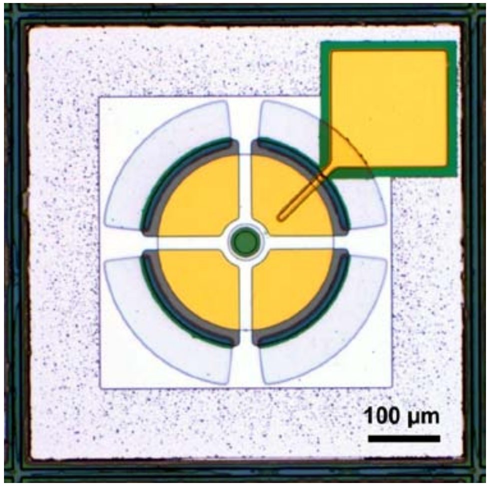


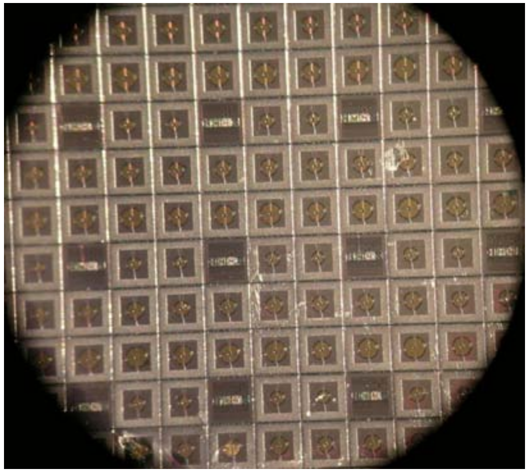
Tunable Vertical-Cavity Amplifiers:

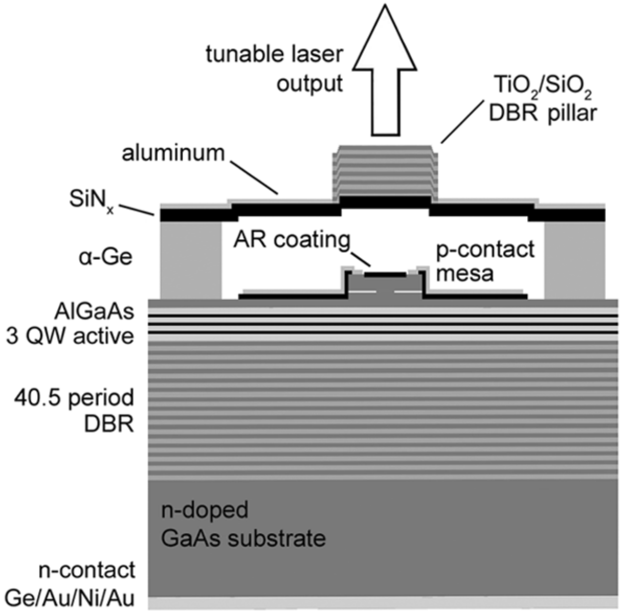
- Resonant Cavity optical preamplifiers
- Wafer-bonded GaAs/InP/GaAs cavity structure
- 28 AlInGaAs QWs with epitaxial MEMS DBR
- ~10 dB fiber-to-fiber gain over 21 nm
- Fiber-coupled gain of 11.2 dB (18.2 dB on chip)

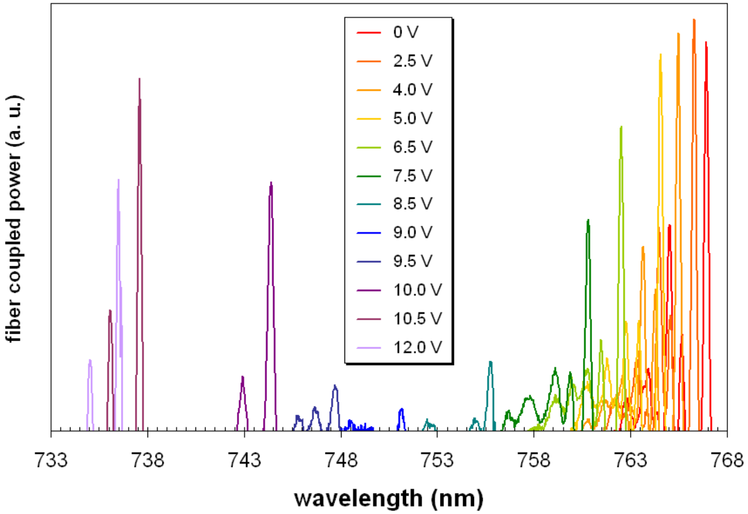
G. D. Cole, et al., Photonics Technology Letters **17**, 2526 (2005)

Postdoc, LLNL: MEMS-Tunable VCSELs









Short Wavelength MEMS-VCSELs:

- Electrically injected ~760 nm tunable VCSEL
- Monolithic AlGaAs epi with graded n-DBR
- Oxide aperture for current/mode confinement
- Extended cavity design (intra-cavity ARC)
- All dielectric suspended mirror structure

G. D. Cole, et al., Optics Express **16**, 16093 (2008)

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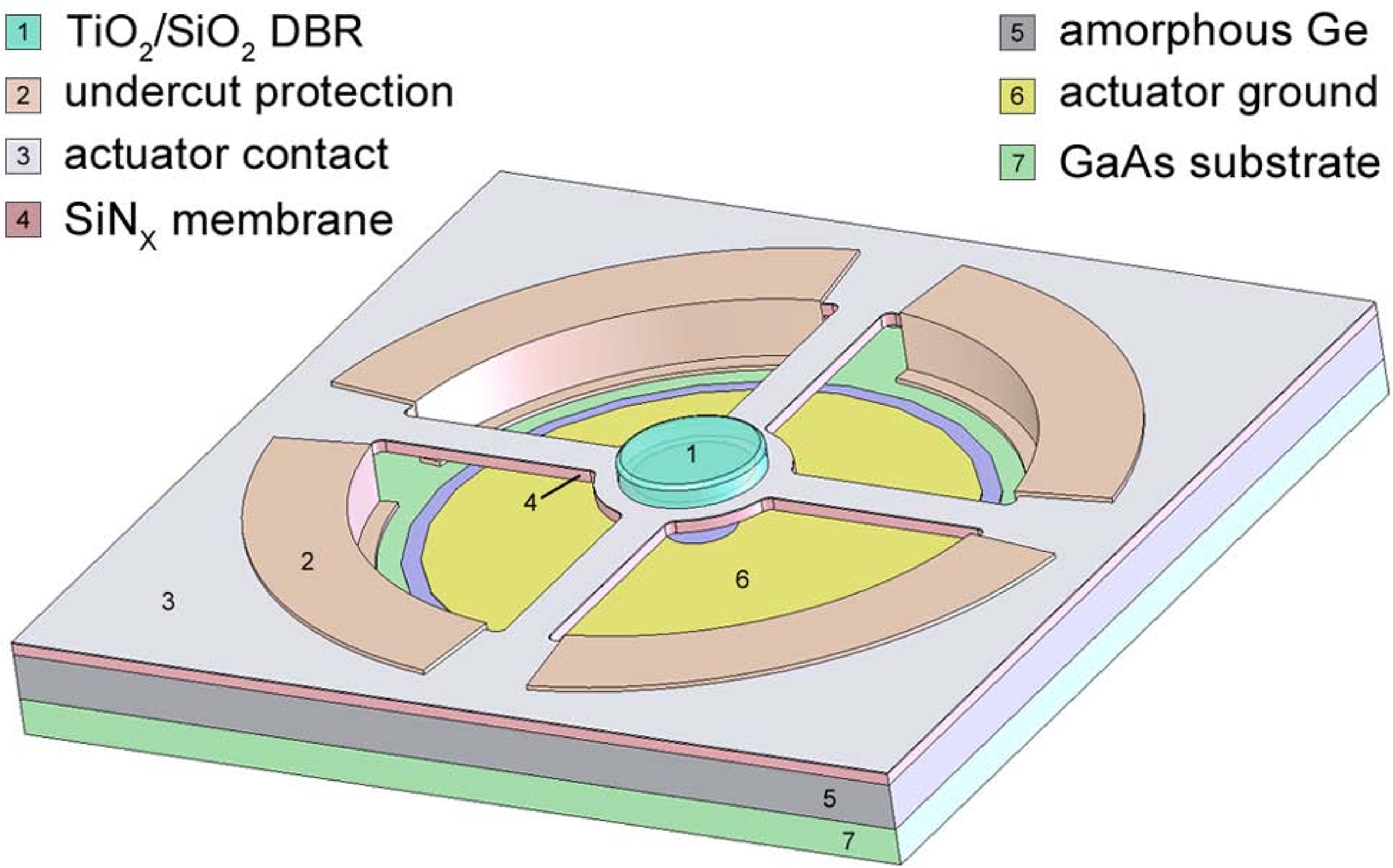

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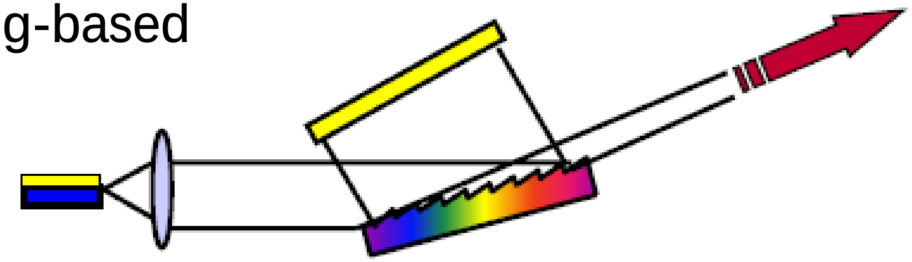
Select Tunable Laser Technologies

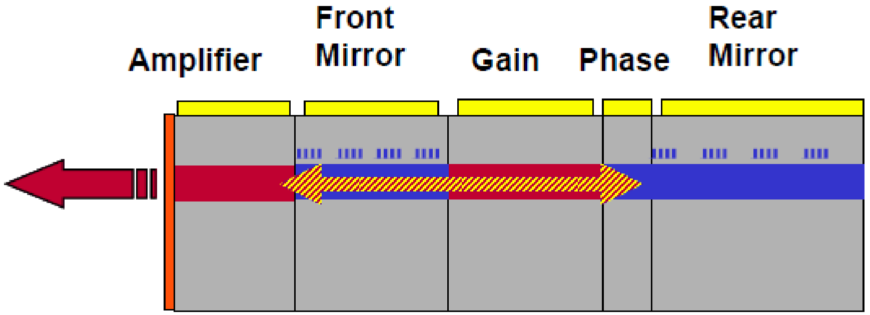
External Cavity Tunable Laser (ECTL)

- Diode gain medium with grating-based wavelength selective feedback
- Tuning range ≥ 100 nm
- Tuning speeds ≤ 100 kHz
- Wide tunability but slow tuning speed



Sampled-grating distributed Bragg reflector (SGDBR)

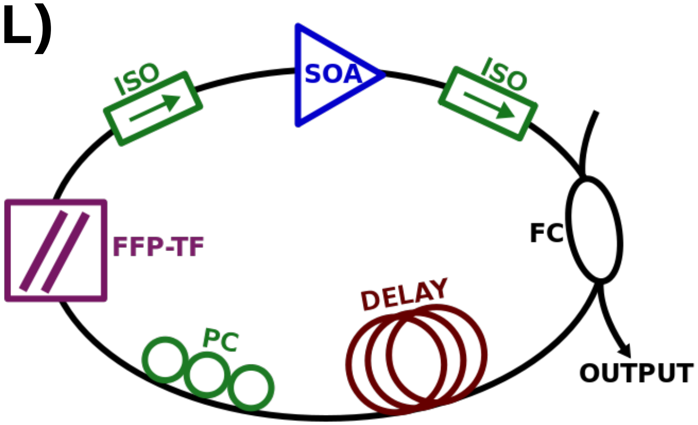
- Overlap of reflectance comb to select lasing wavelength
- Switching speeds in ns range
- Typical tuning range of ~50 nm
- Mode hops and complex control



Select Tunable Laser Technologies

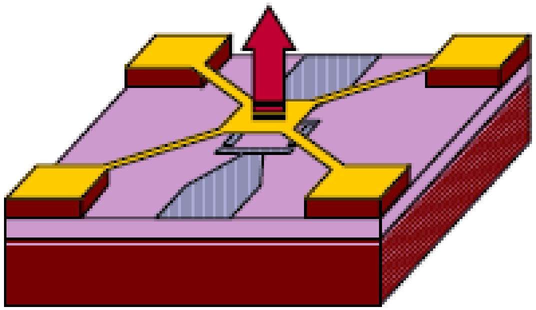
Fourier domain mode locked laser (FDML)

- Ring laser with intra-cavity tunable filter
- 160 nm tuning range demonstrated
- MHz sweep rates possible
- Wide tuning but with fixed sweep rate, limited wavelength accessibility

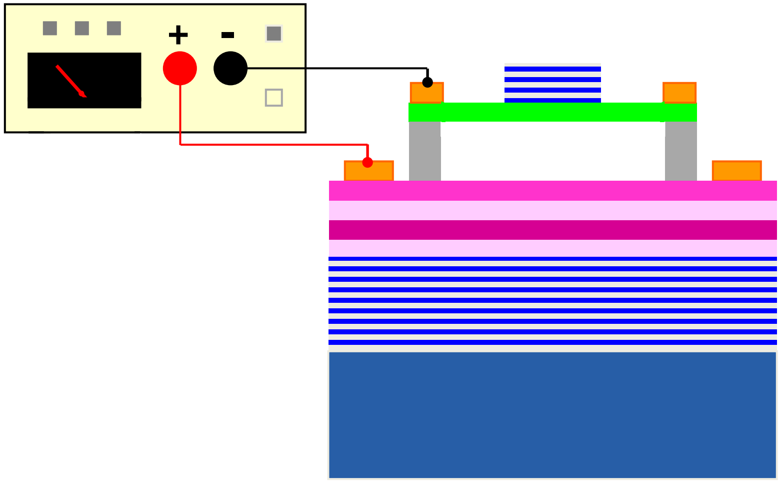


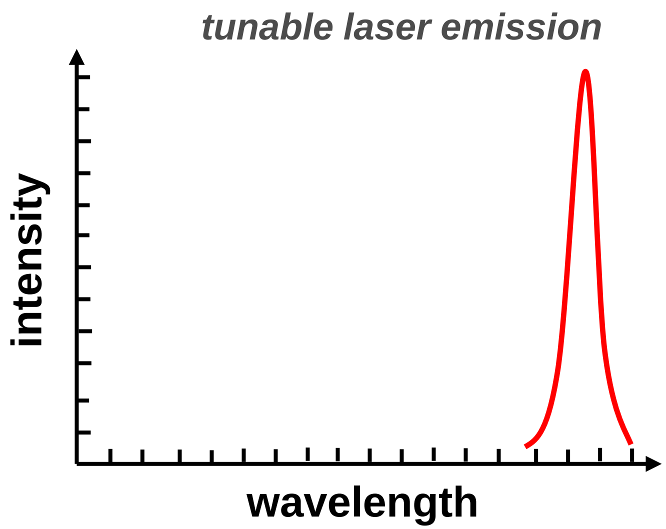
MEMS-tunable VCSEL

- Microcavity laser with suspended mirror
- >100 nm tuning recently demonstrated
- Sweep rates ~1 MHz (MEMS-limited)
- Compact devices requiring a simple control scheme; potentially low cost fabrication



MEMS-Tunable Surface-Emitting Lasers



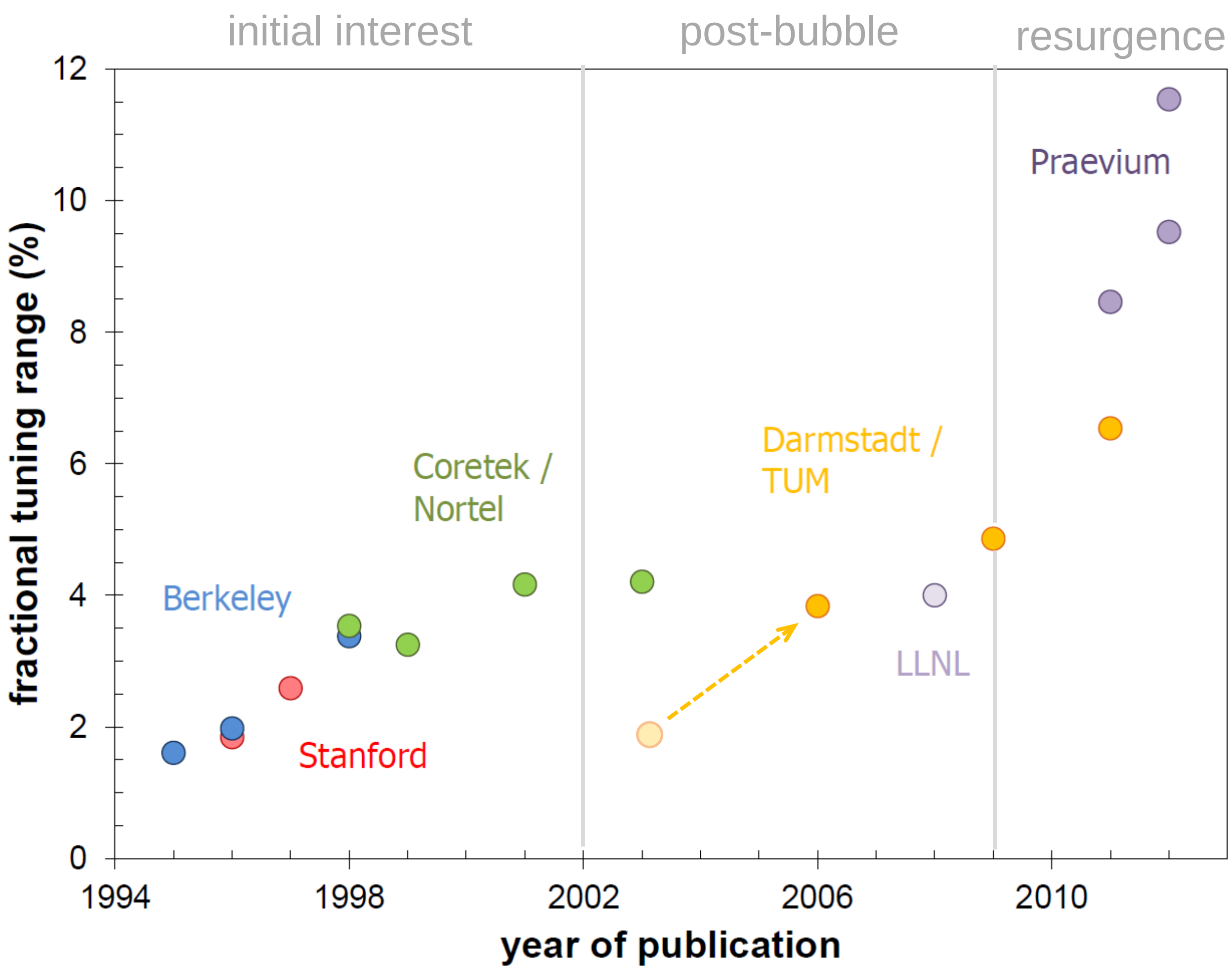


- Vertical orientation lends itself well to MEMS integration
- Bottom DBR and active region identical to fixed lasers (“half-VCSEL”)
- Top mirror is suspended, deflection alters axial cavity length
- Broad tunability enabled by wide gain spectrum & stopband, large FSR
- Rapid wavelength scanning possible with properly designed actuator

Historical Overview of MEMS-VCSELs

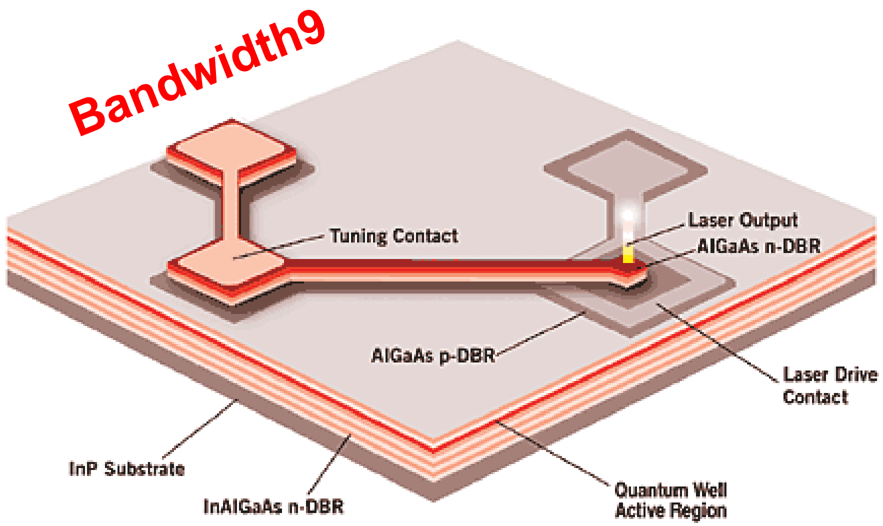
- First proposed by B. Pezeshki and J. S. Harris, Jr.
  - U.S. Patent 5,291,502 (filed on September 4, 1992)
- First devices demonstrated in 1995 (M.S. Wu, et al.)
  - key players: Stanford and Berkeley (Chang-Hasnain & Harris)
- Commercialization of telecom devices (BW9, Coretek)
  - Nortel purchases Coretek for $1.43 billion in stock (3/2000)
- Bubble bursts, MEMS-VCSEL dark ages (~2002-2009)
  - TUM/Darmstadt collaboration continues progress
- Recent resurgence: rapid increase in fractional tuning and revitalized commercialization efforts (BW10!)

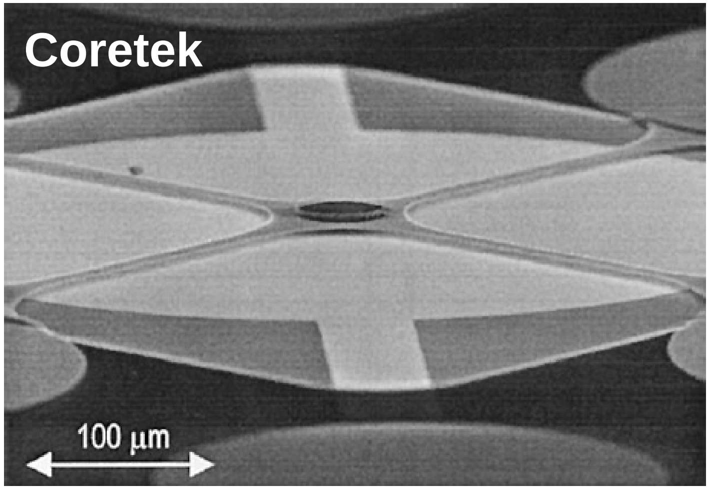
Fractional Tuning Range Versus Time



Applications of MEMS-VCSELs

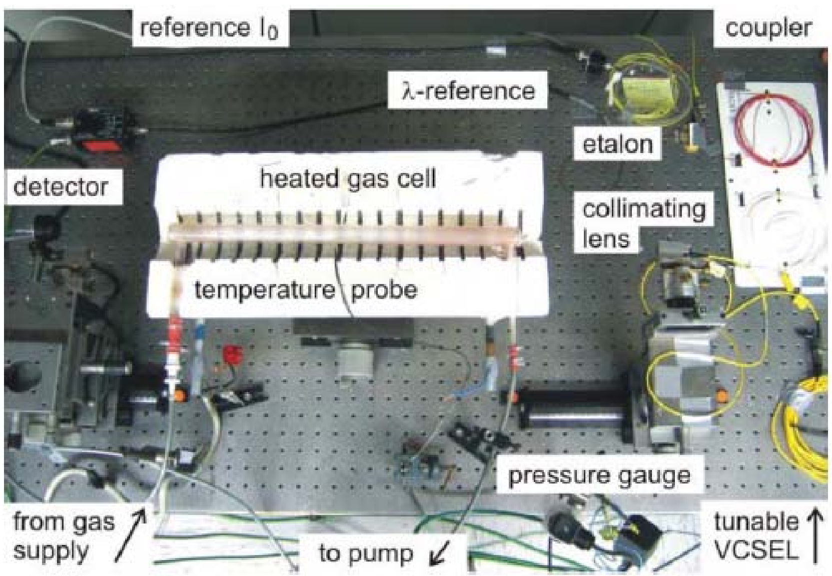
- Initial focus on telecommunications, particularly with the development of long-wavelength devices
  - potential uses: networks employing wavelength division multiplexing (WDM), laser spares, temperature drift compensation
  - “Tunable Long-Wavelength Vertical-Cavity Lasers: The Engine of Next Generation Optical Networks?” J.S. Harris, JSTQE Nov. 2000

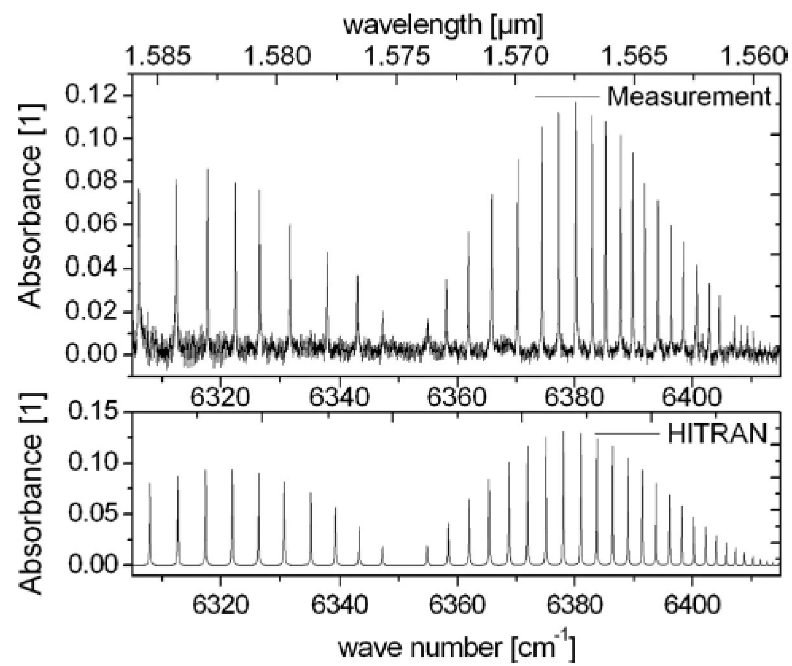




Applications of MEMS-VCSELs

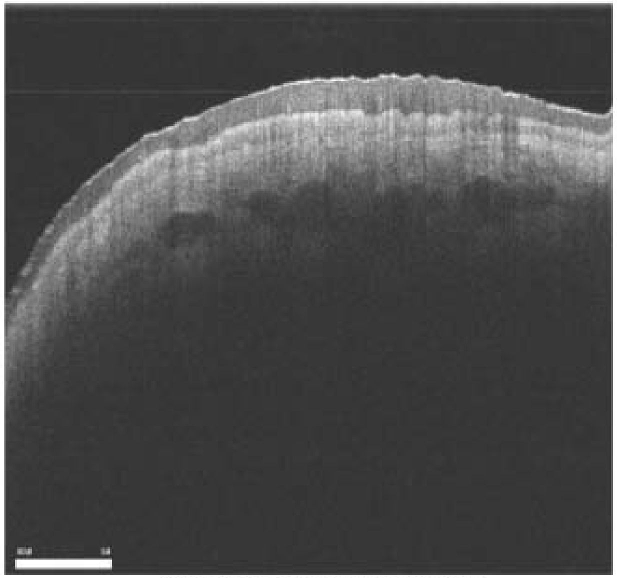
- Gas spectroscopy (CO, CO_2, NH_3, etc.)
  - tunable VCSELs enable broadband continuous single mode tuning with a narrow dynamic linewidth (~200 MHz) for trace gas detection
  - “Simultaneous spectroscopy of NH_3 and CO using a >50 nm continuously tunable MEMS-VCSEL” Kögel et al. IEEE Sensors 2007

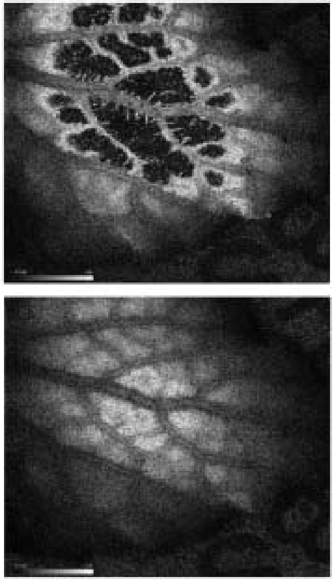


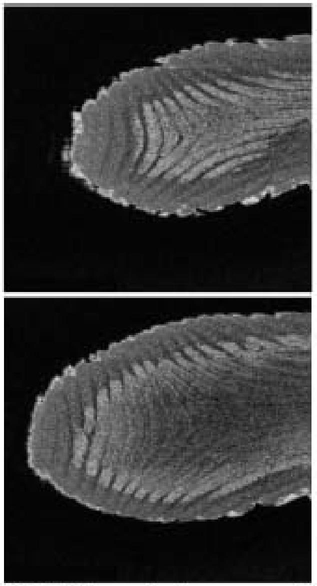


Applications of MEMS-VCSELs

- Optical Coherence Tomography (OCT)
  - optical medical imaging technique requiring broad and rapidly tunable laser systems; typical operating wavelengths 850-1310 nm
  - “OCT imaging up to 760 kHz using single-mode 1310 nm MEMS-tunable VCSELs with >100 nm tuning range” Jayaraman CLEO 2011


60kHz axial scan rate


200kHz axial scan rate


400kHz axial scan rate

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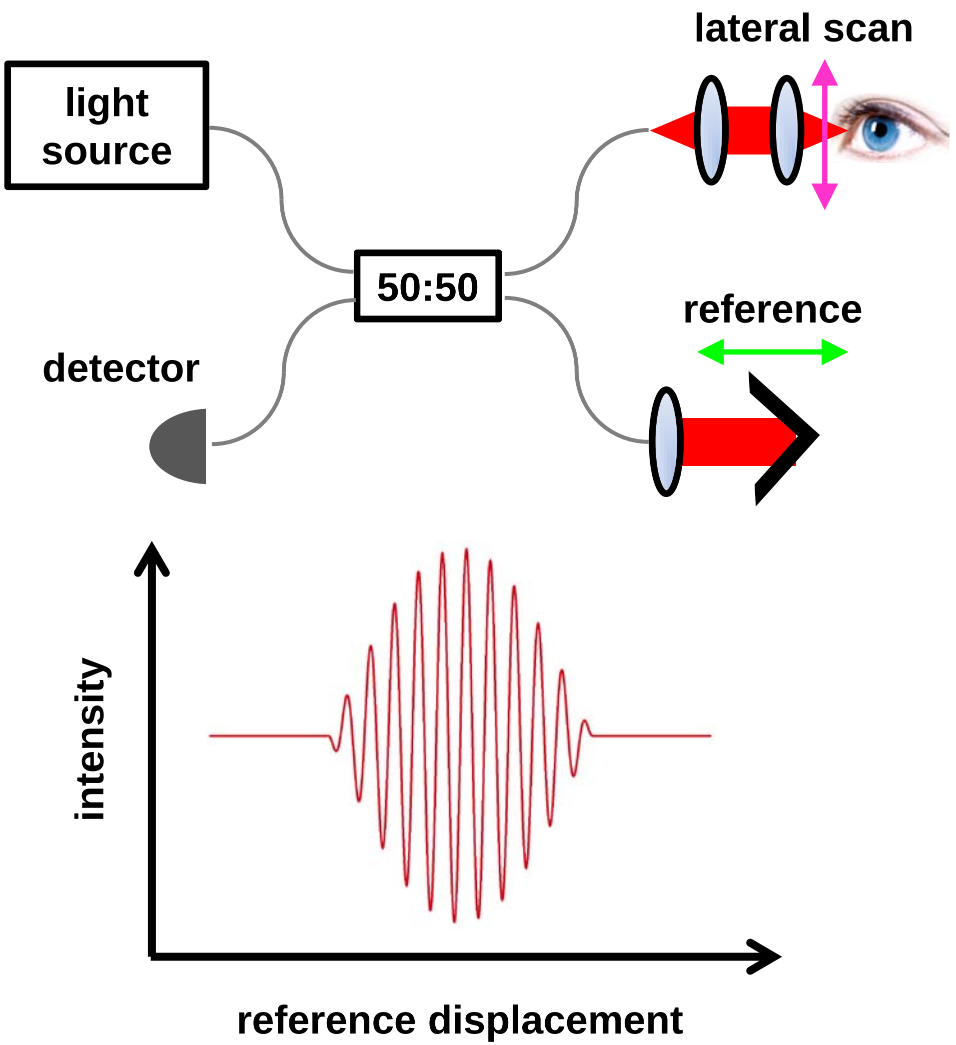
Optical Coherence Tomography (OCT)

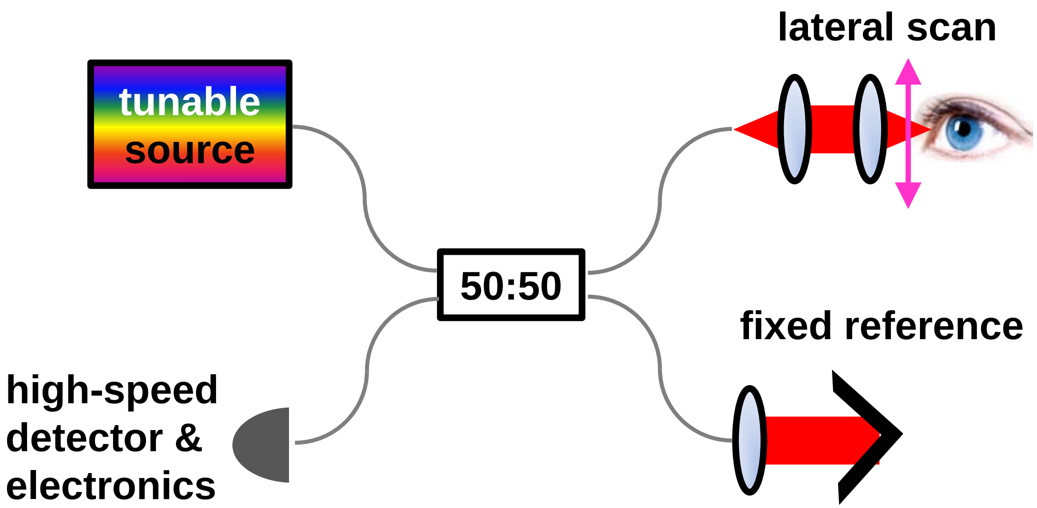
- “Optical Ultrasound” emerging medical imaging technology
- Enables real-time µm-scale subsurface and 3D imaging
- Imaging is performed by measuring the echo time delay and intensity of back-reflected/backscattered NIR light
- Typical imaging depths are from ~1 mm to >10 mm, depending on the scattering level of imaged tissue, the imaging mode, and light source coherence length
- Spatial resolution is 10-100× better than magnetic resonant imaging (MRI), computed tomography (CT), and ultrasound
- Applications include ophthalmic and vascular imaging, with trials underway for dentistry, dermatology, and cancer detection

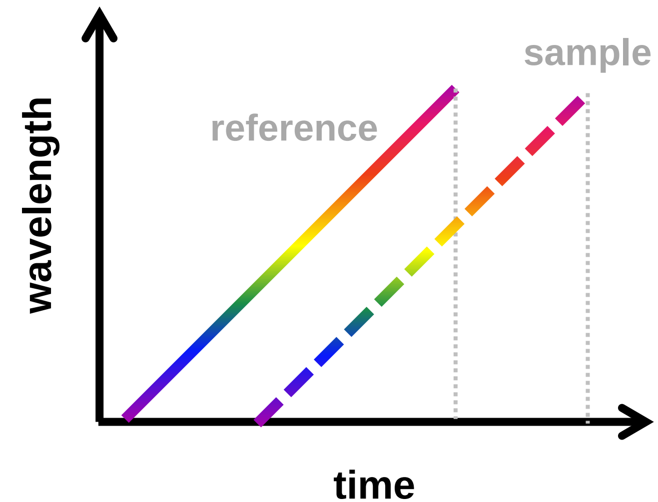
Basic OCT Operating Principles (Time Domain)

- Broadband (low coherence) light source yields high-contrast interference fringes when path lengths match
- Peak fringe intensity yields reflectivity for a given depth, scanning an optical delay line (pathlength ranging) yields tissue characteristics as a function of depth
- Lateral scanning of the probe creates a 3D map of sample



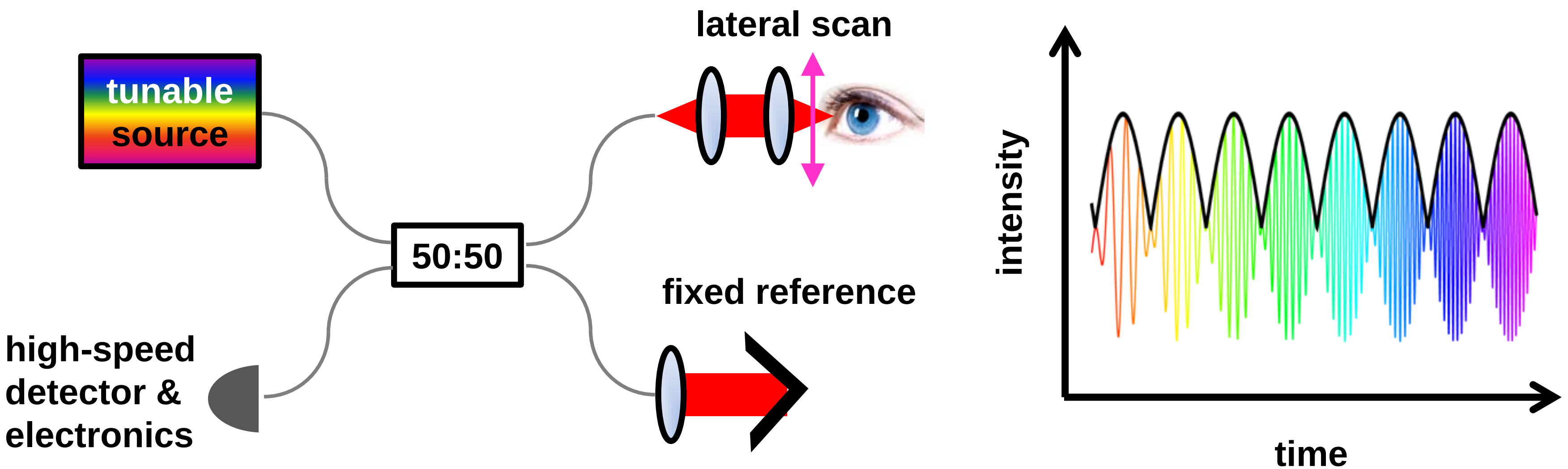
Improved Imaging Rates: SS-OCT





- Beat frequencies correspond to different delays, thus depths, in sample
- Fourier transform yields profile of reflection as a function of depth
- Ideal SS-OCT source requirements:
  - widely tunable (>100 nm) with narrow instantaneous linewidth
  - rapid (MHz) sweep rate with well behaved dynamics (critically damped)
  - output power levels from 30-50 mW (external amplification required)

Improved Imaging Rates: SS-OCT



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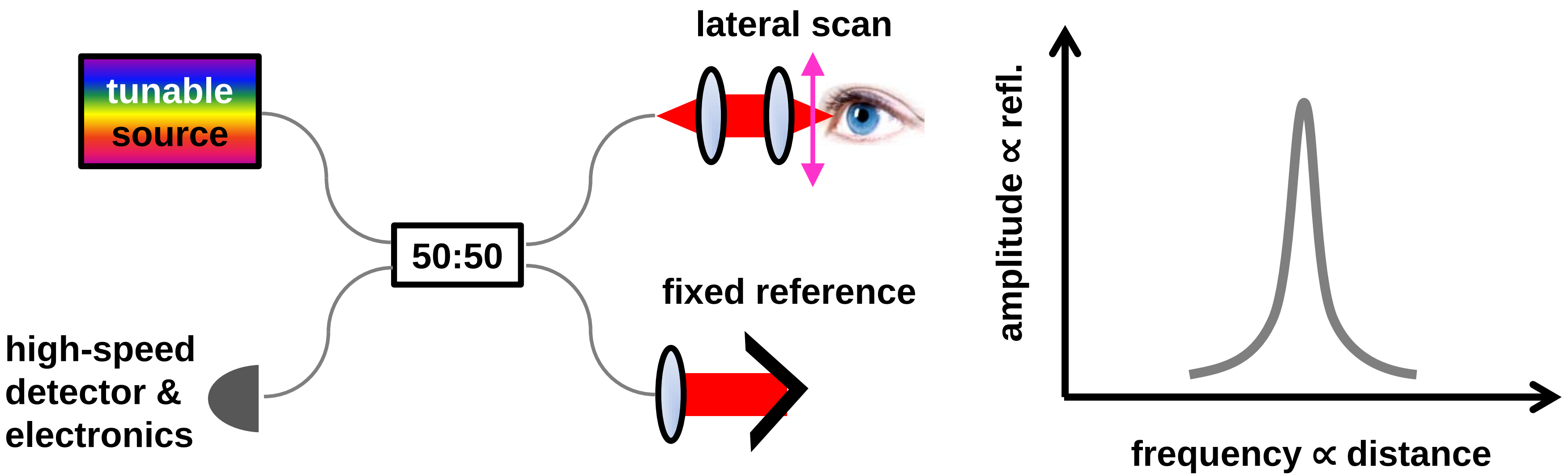

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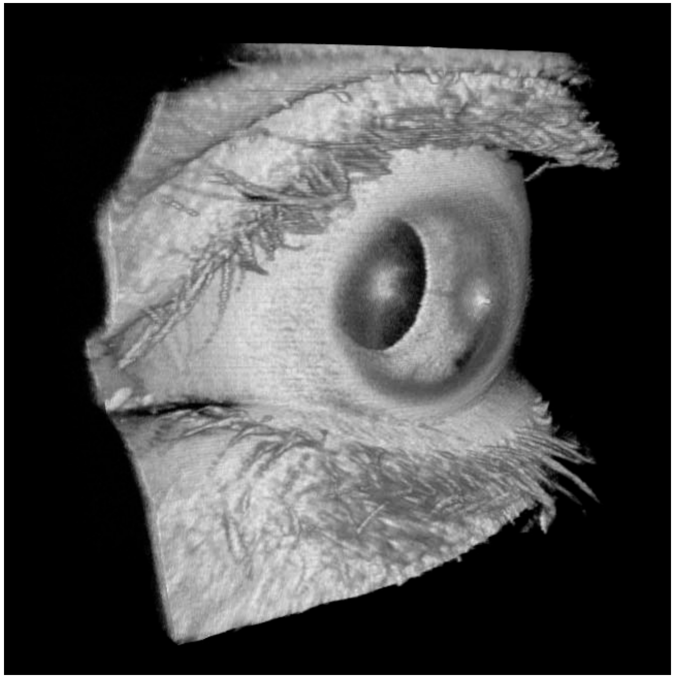
Example Imaging Results



- Volumetric OCT imaging of the anterior eye and retina
- Arbitrary cross-sections can be extracted from 3D dataset
- More details to follow in discussion of MEMS-VCSEL performance

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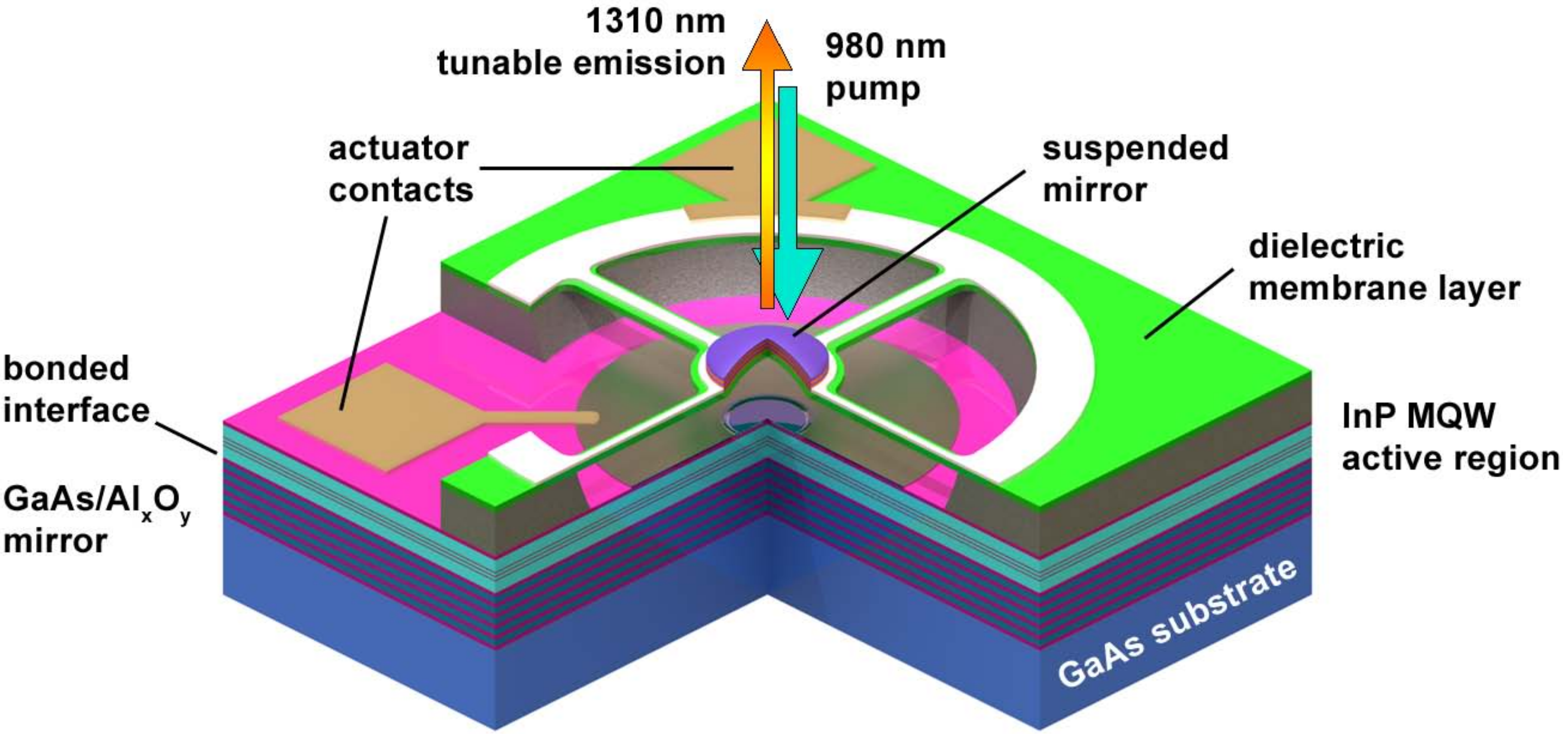
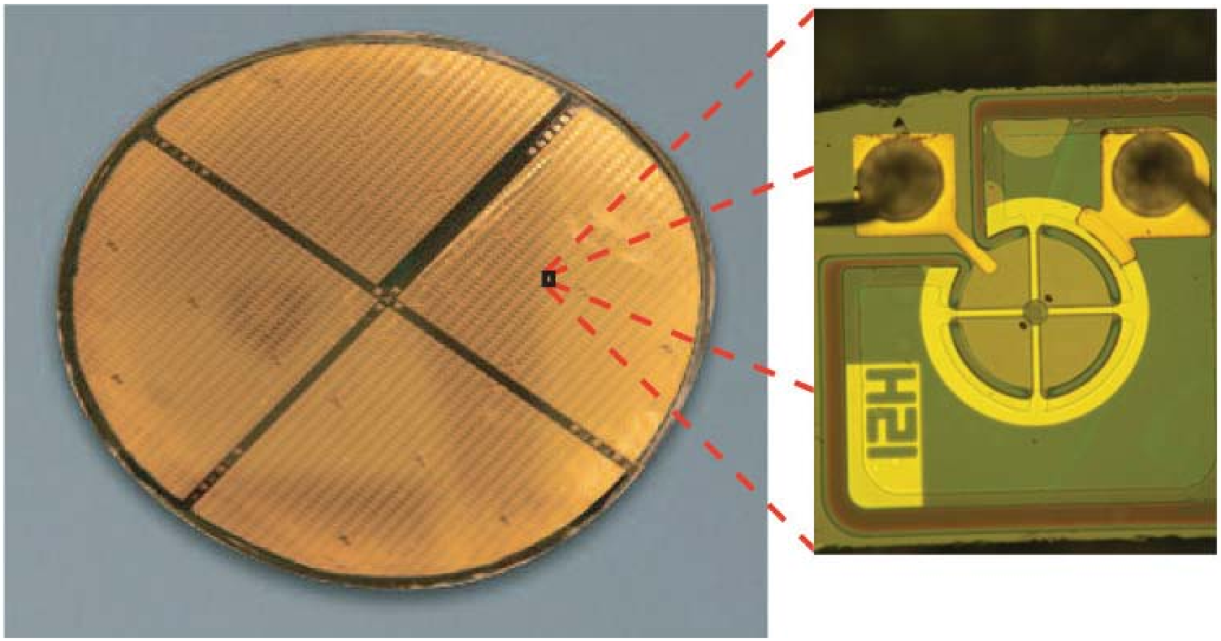
Ultra-Widely Tunable 1310 nm MEMS-VCSEL



- AlInGaAs MQW active and GaAs/Al_xO_y DBR combined by wafer bonding
- Optimized for optical pumping at 980 nm, short cavity for large FSR
- Dielectric suspended top mirror with integrated electrostatic actuator

Jayaraman, et al., Electronics Letters **48**, 867 (2012)

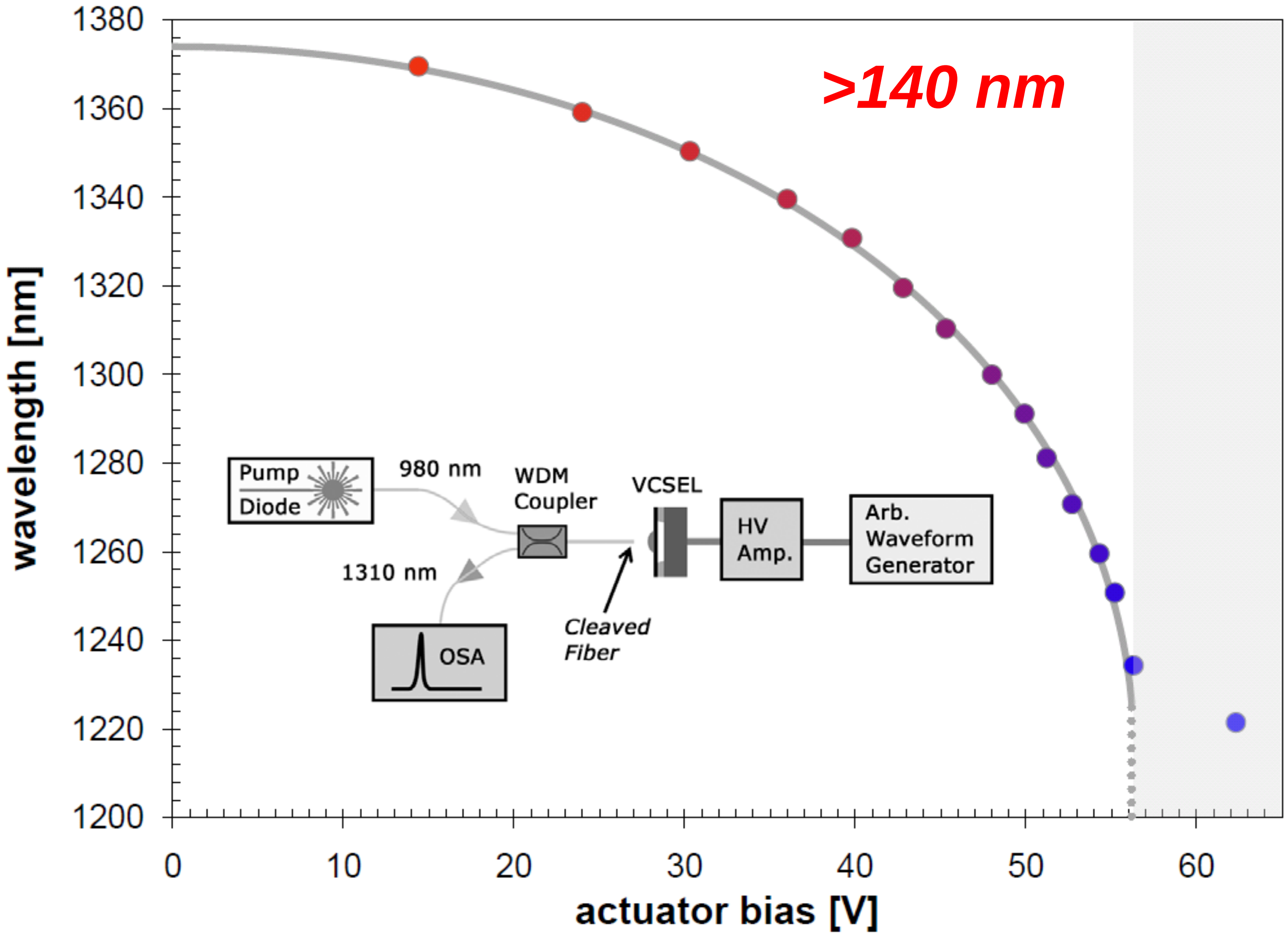
Wafer-Scale MEMS-VCSEL Manufacturing



- Robust fabrication procedure developed for suspended mirror structure
  - dry release, no polymer sacrificial films or need for critical point drying
- All-dielectric process employing low temperature (<300 °C) deposition
  - enables development of lasers at a variety of emission wavelengths

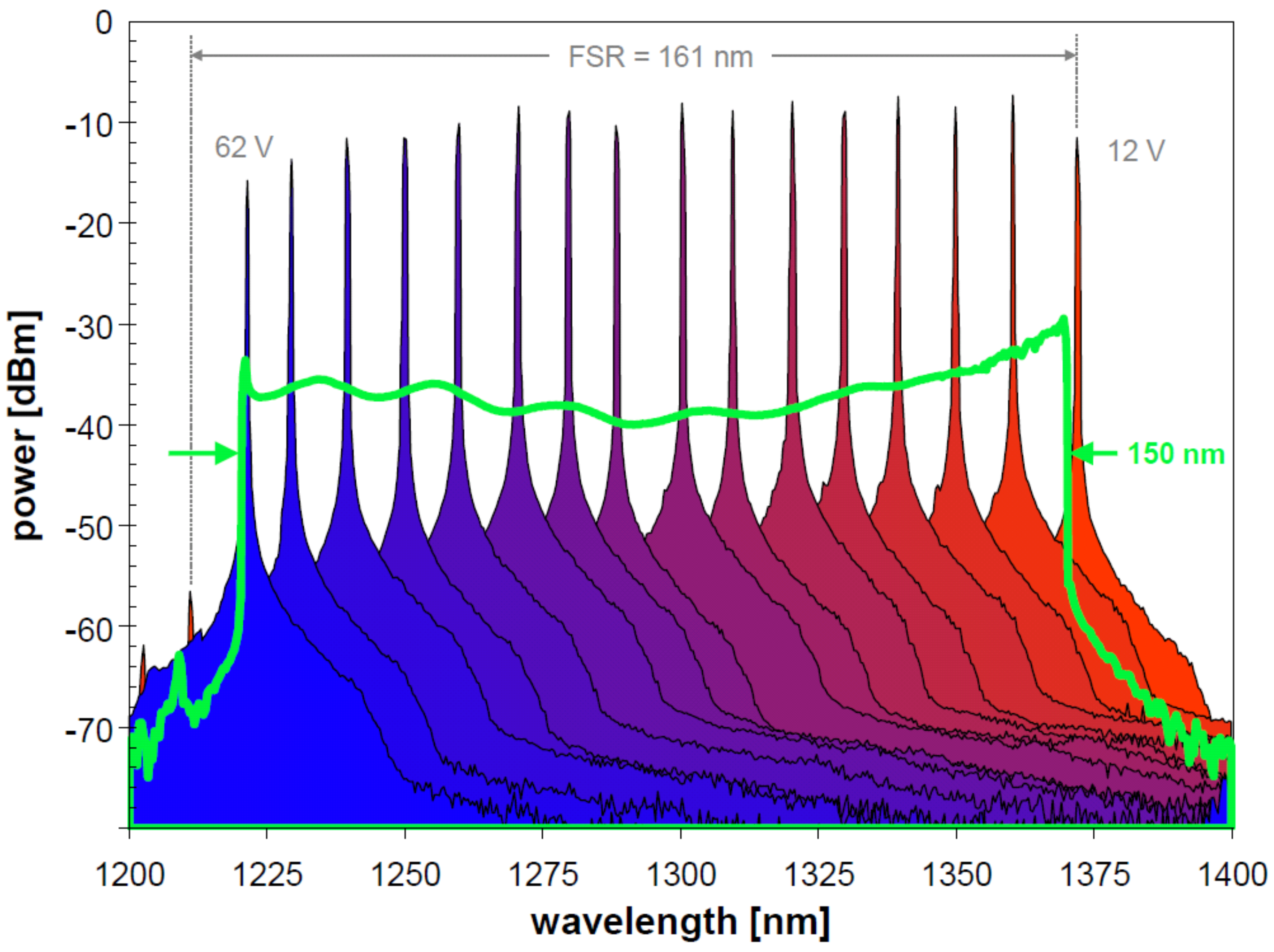
actuator fabrication based on: G. D. Cole, et al., JVST-B **26**, 593 (2008)

Ultra-Wide Static Tuning Response



Jayaraman, et al., Electronics Letters **48**, 867 (2012)

Overlaid Spectra & Dynamic Tuning



Jayaraman, et al., Electronics Letters **48**, 867 (2012)

MEMS-VCSEL-Based OCT Imaging

- Fiber-coupled VCSEL
  - 1310 nm: reduced scatter increased penetration
- WDM coupler and short-wavelength pump diode
- Arbitrary waveform generator and amp driver
- External amplification boosts power to 20 mW
- SOAs may be modulated for additional control knob on laser sweep rate

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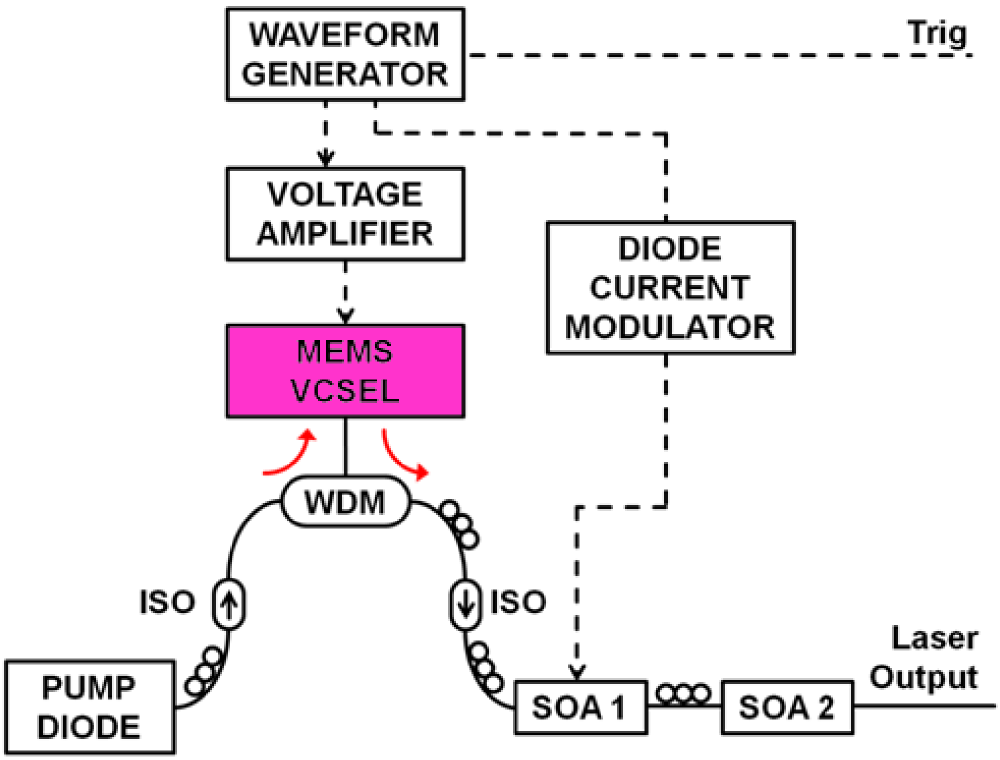
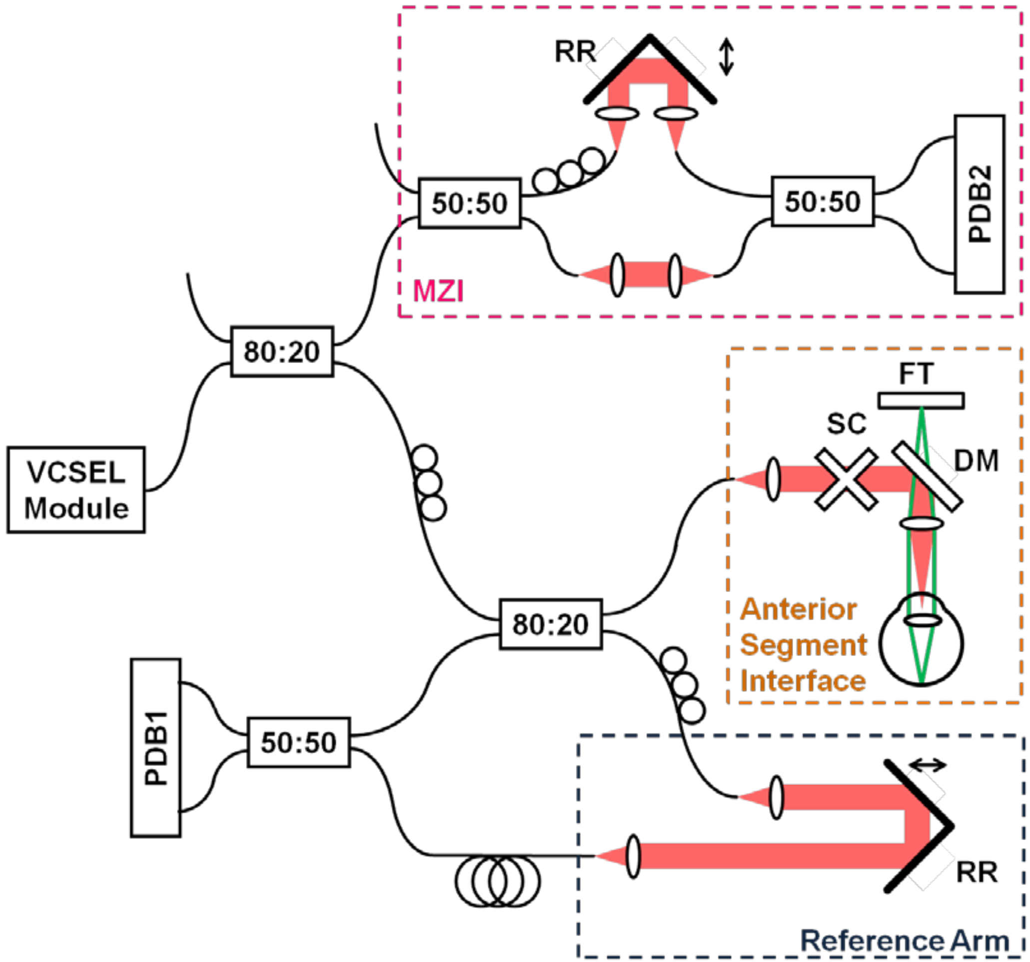
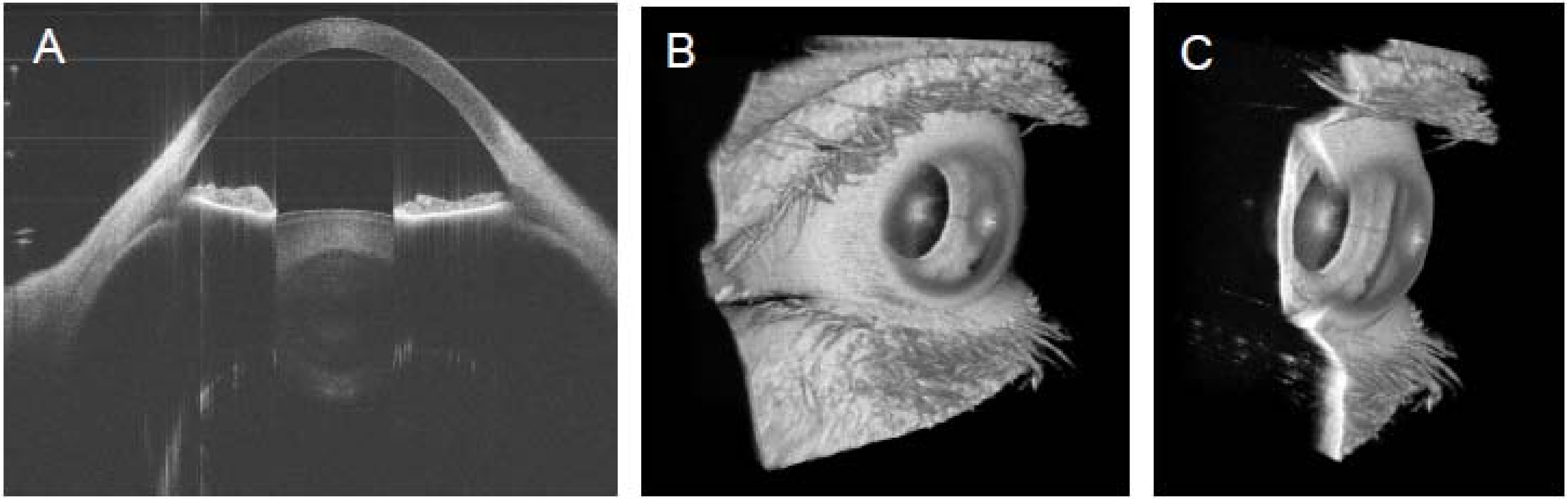


MEMS-VCSEL-Based SS-OCT Imaging

- Mach-Zehnder (MZI) for calibration fringe capture
  - interferometer records instantaneous laser frequency
- Lower path: interference between reflected probe and reference
  - beat note generated in frequency domain
  - Fourier-transform reconstructs reflectivity depth profile

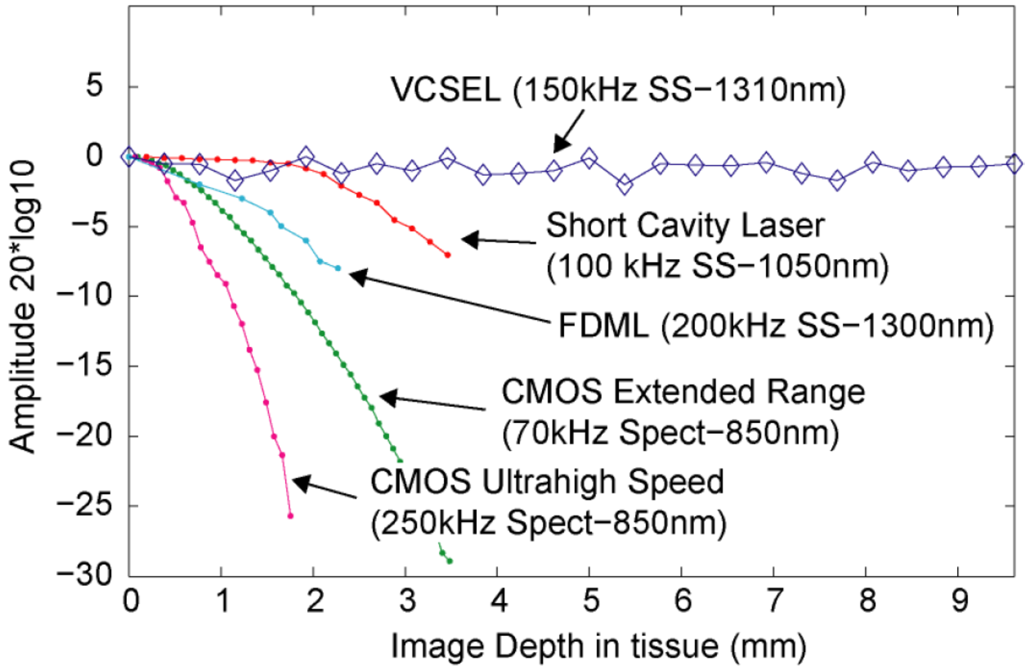


1310 nm Anterior Segment Imaging



- (A) High resolution cross-sectional image of the anterior eye
  - 10^3 axial scans over 21 mm obtained at 10^5 axial scans / second
- (B) Rendering of a 400 × 400 axial scan volume of the anterior eye
- (C) Cutaway of the volume in (B) showing interior features of the iris

State-of-the-Art Imaging Depth



- Narrow instantaneous linewidth enables deep (>>1 cm) imaging
  - enhanced spectral resolution → longer imaging depth in SS-OCT
- Competing laser sources suffer from multimode operation with tuning

Potsaid, et al. Proc. SPIE **8213** (2012)

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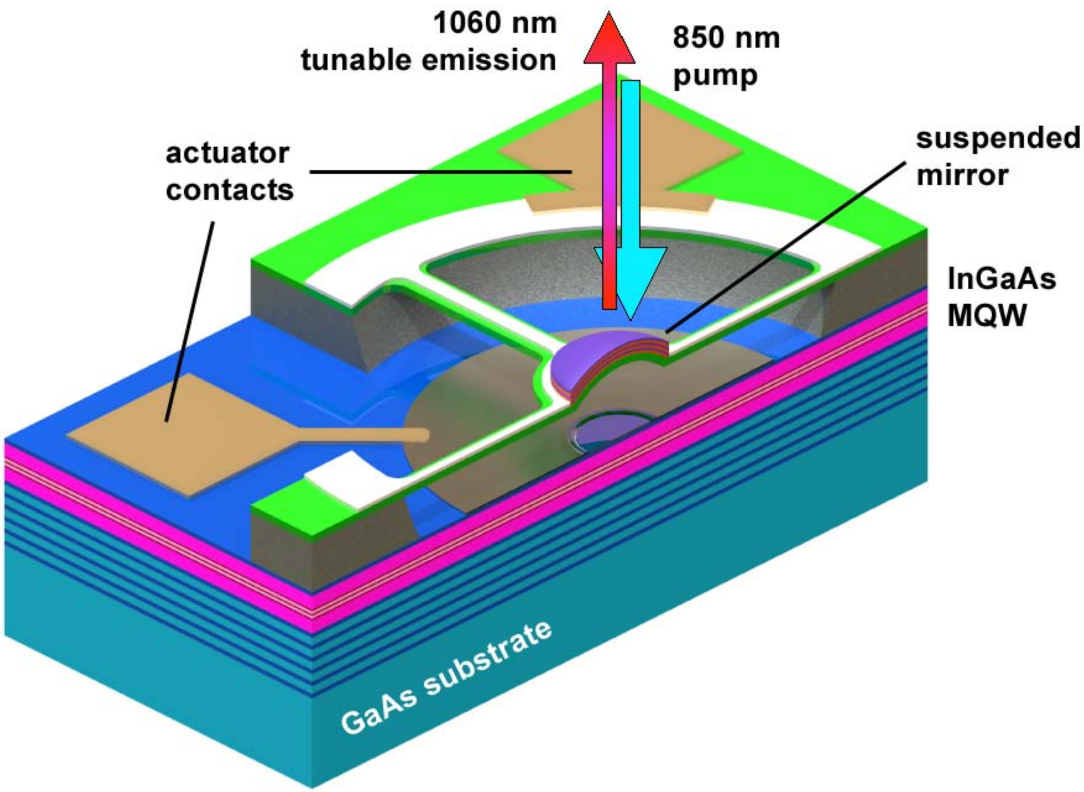
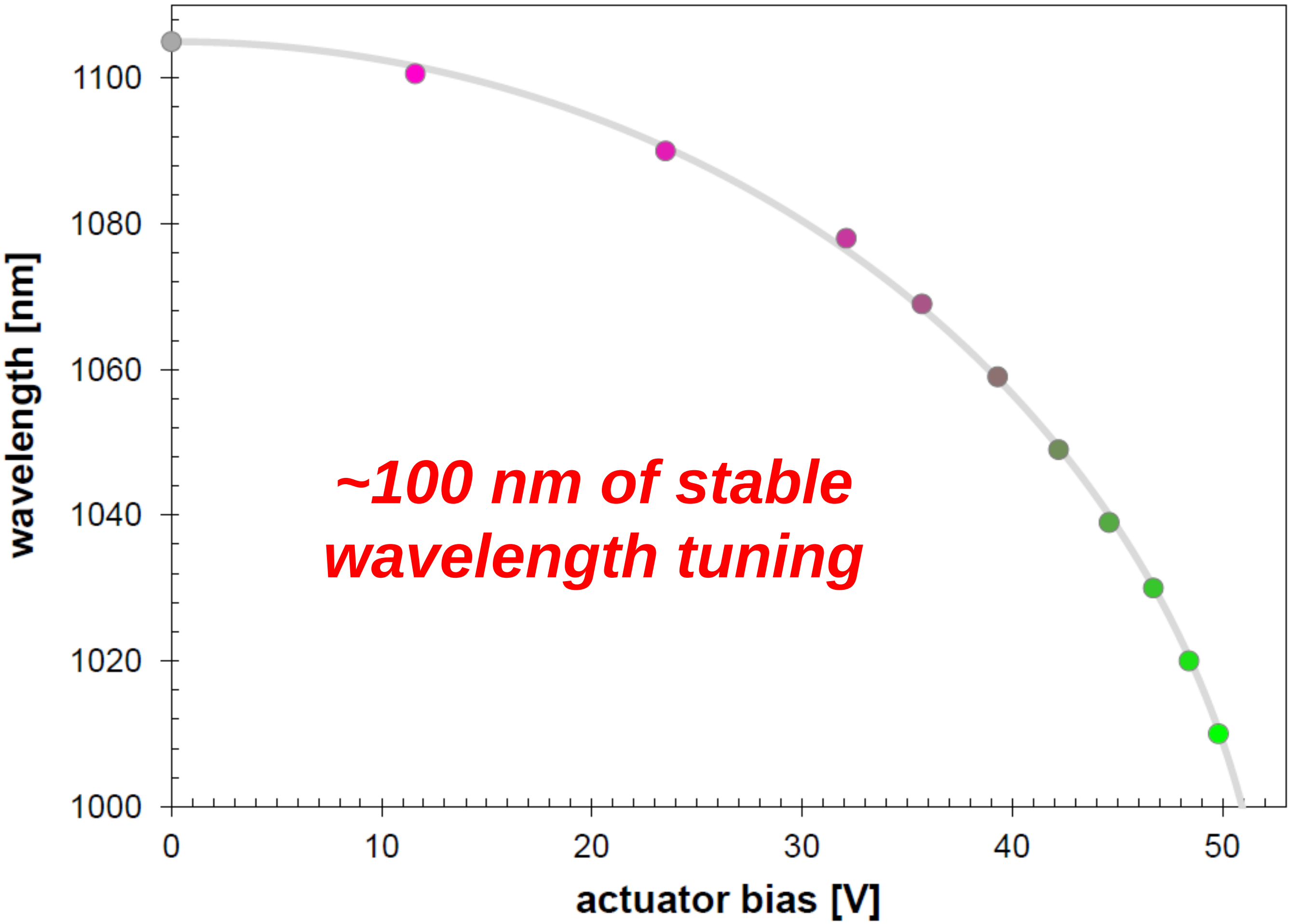
Ultra-Widely Tunable 1060 nm MEMS-VCSEL



- Monolithic “half VCSEL”
  - single epitaxial growth
- InGaAs MQW active
- Broadband reflectors
  - fully-oxidized bottom DBR (GaAs/Al_xO_y)
  - dielectric suspended mirror structure
- Integrated actuator optimized for critically damped freq. response
- Aim: retinal imaging

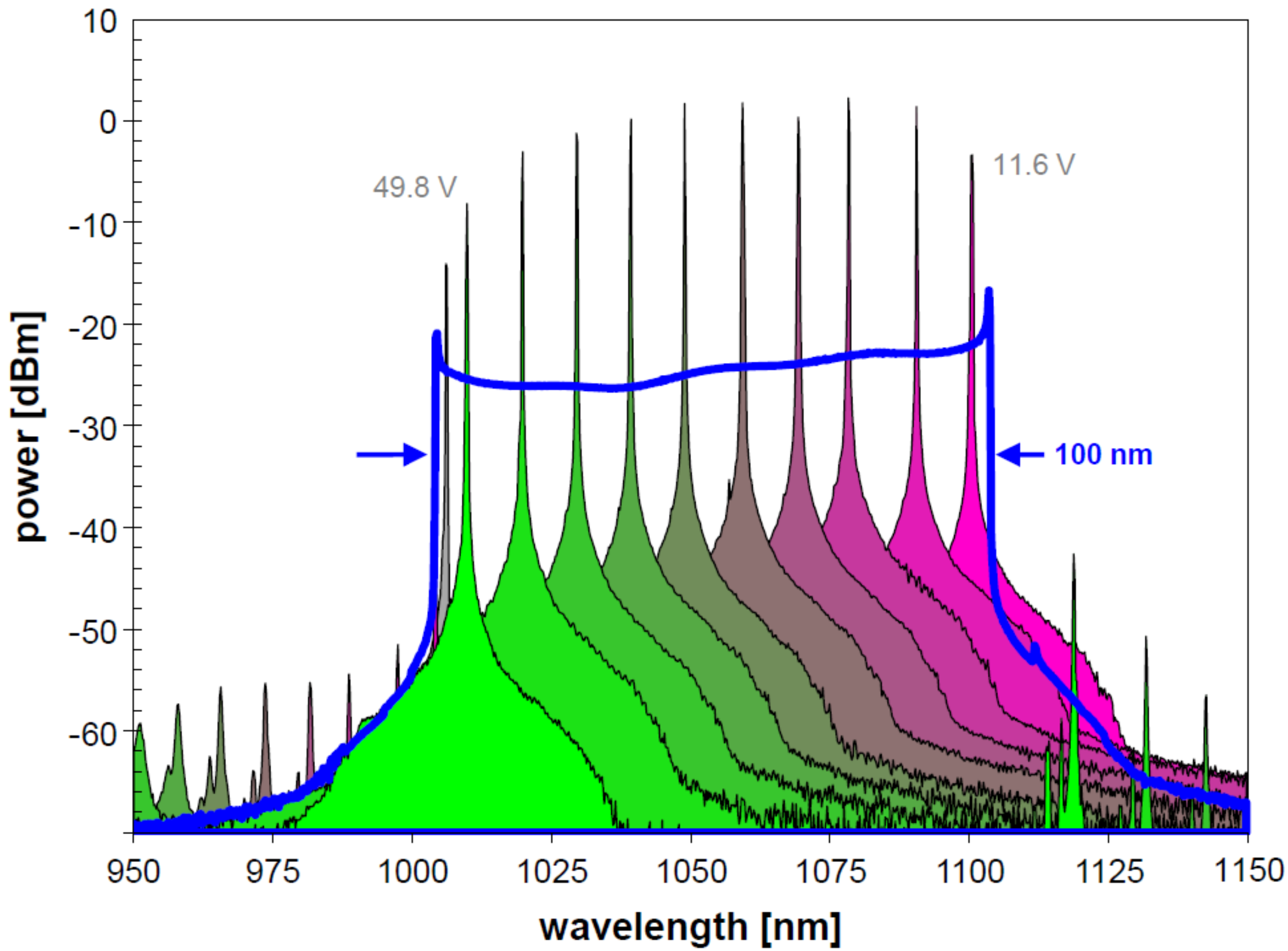
Jayaraman, et al., accepted for publication in Electronics Letters

Static Tuning Response



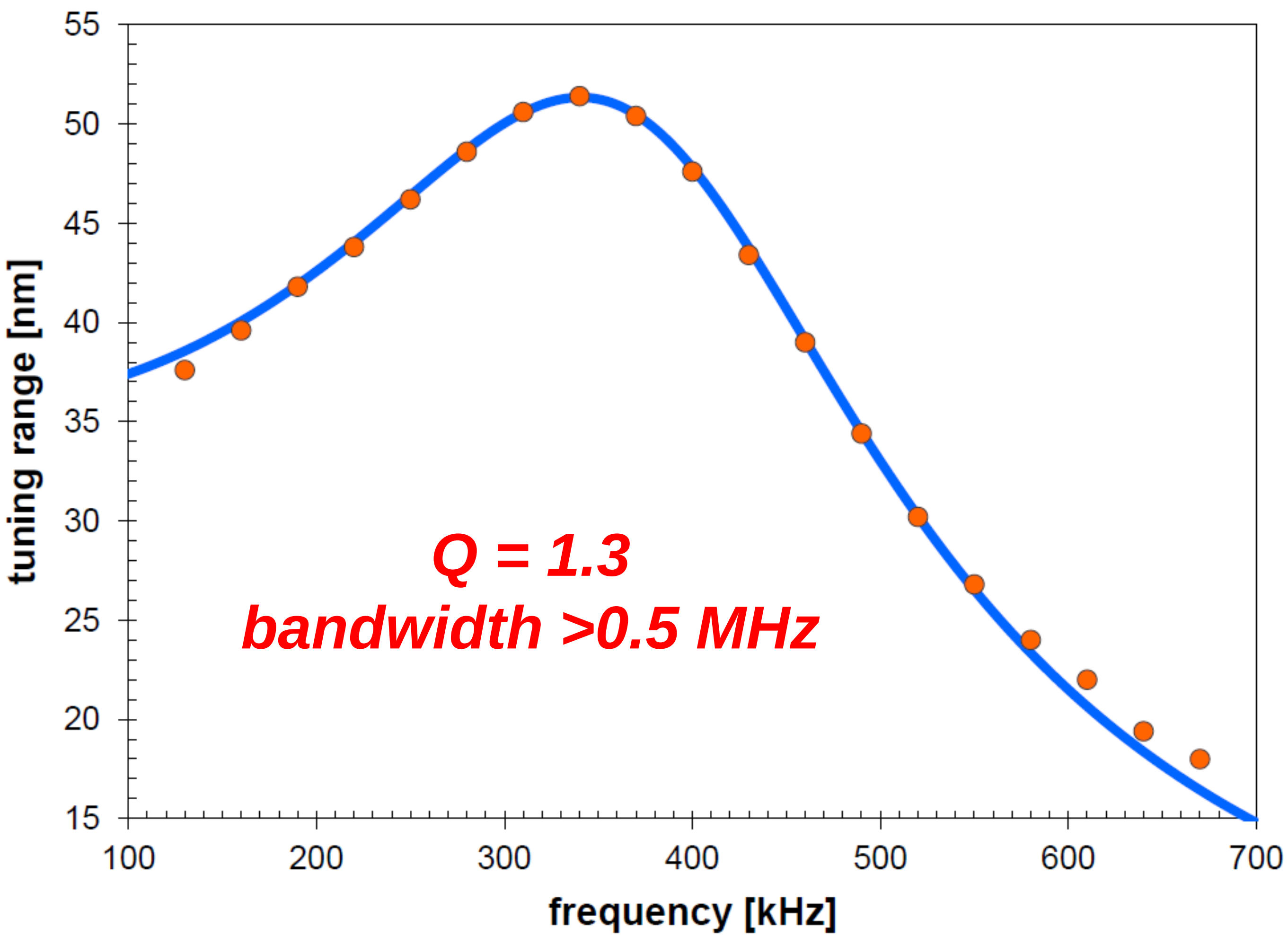
Jayaraman, et al., accepted for publication in Electronics Letters

100-nm Dynamic Tuning Response



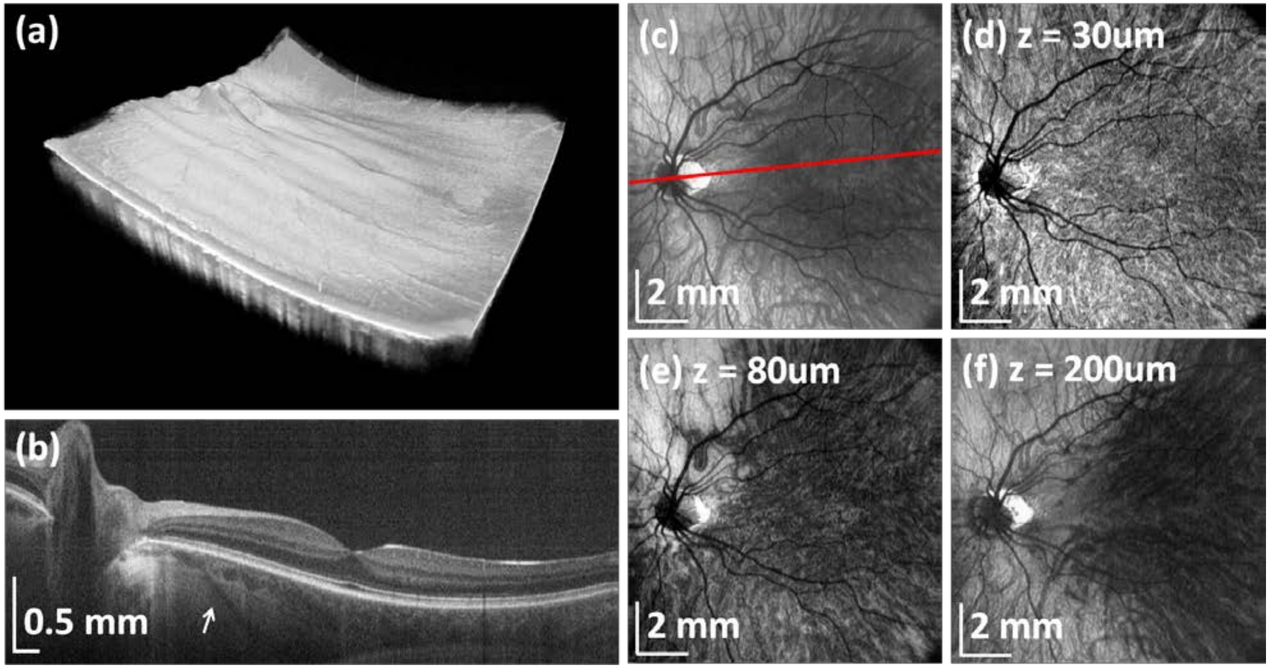
Jayaraman, et al., accepted for publication in Electronics Letters

Electrostatic Actuator Frequency Response



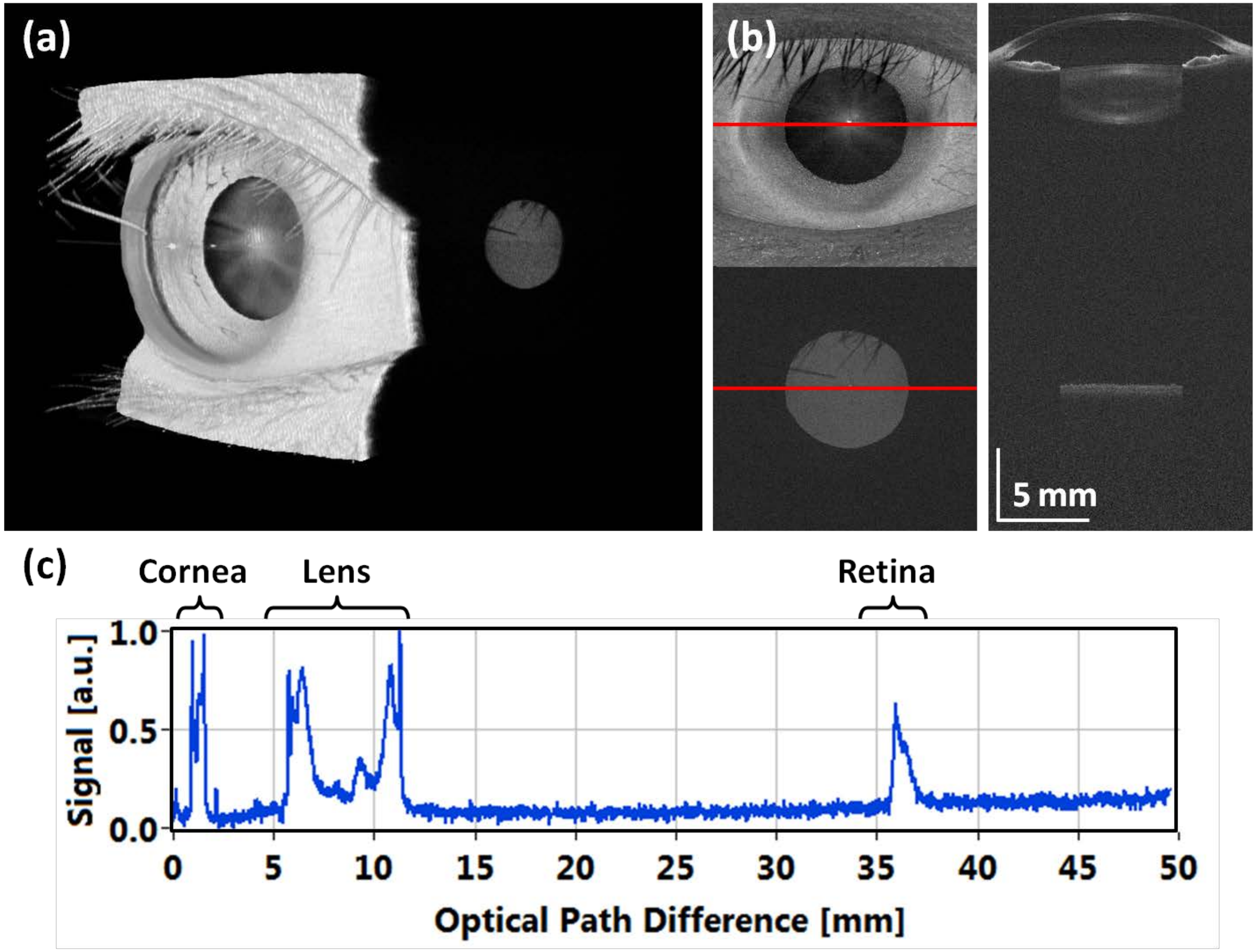
Jayaraman, et al., accepted for publication in Electronics Letters

Wide-Field Choroidal (Sub-Retinal) Imaging



- (a) Rendering of volumetric wide-field OCT imaging data set
- (b) Cross-sectional image of choroid and sclera [red section line in (c)]
- (c-f) Projection images at depths of (d) 30 μm, (e) 80 μm, (f) 200 μm

Full Eye Imaging at 1060 nm



Grulkowski, et al., accepted for publication in Optics Express

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Summary of Laser Properties

- Ultra-widely tunable optically pumped MEMS-VCSELs have been demonstrated for application in SS-OCT
  - 150 nm dynamic tuning range at 1310 nm
  - 100 nm dynamic tuning range at 1060 nm
- Actuator bandwidth in the 0.5 MHz range with well-behaved frequency response (near critically damped)
- Reasonable maximum tuning voltages (<60 V)
- Commercially viable wafer-scale fabrication procedure has been developed for dielectric electrostatic actuator
- Demonstration of state-of-the art SS-OCT performance

Path Forward

- Push FSR as wide as possible for maximum tuning
- Electrically injected devices for compact sources
- More operating wavelengths (850 nm and visible)
- Reliability studies on MEMS actuator structure
- Exploration of additional imaging applications
- High-speed transient spectroscopy demonstrations