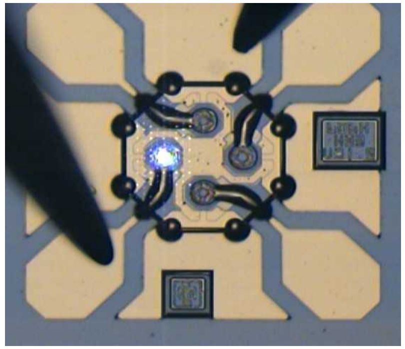
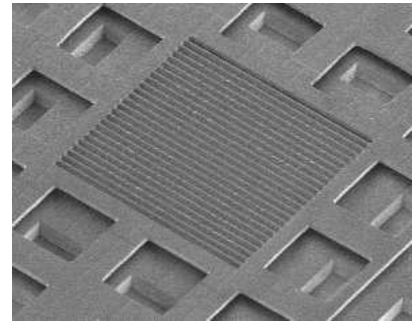
SAND2016-1480C

Single-Frequency VCSEL



MEMS Grating Interferometer



VCSELs for Interferometric Readout of MEMS Sensors

SPIE Photonics West 2016, San Francisco, CA
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Sandia National Laboratories

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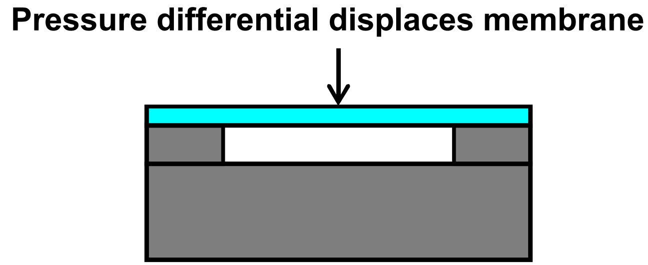
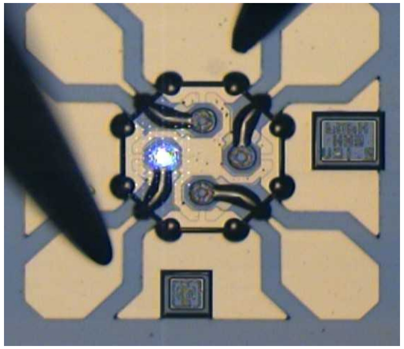
Outline

- MEMS sensors
  - Raw signal is position of moving mass
- Capacitive Readout Options
  - Vary gap
  - Vary overlap
- Optical Interferometer Options
  - Two-mirror Michelson
  - Grating Interferometer
- VCSEL requirements
  - Single mode
  - Stable wavelength
  - Low amplitude and phase noise
- Summary

MEMS Pressure Sensor



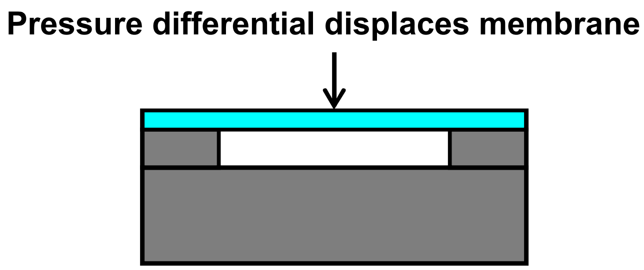
Single-Frequency VCSEL



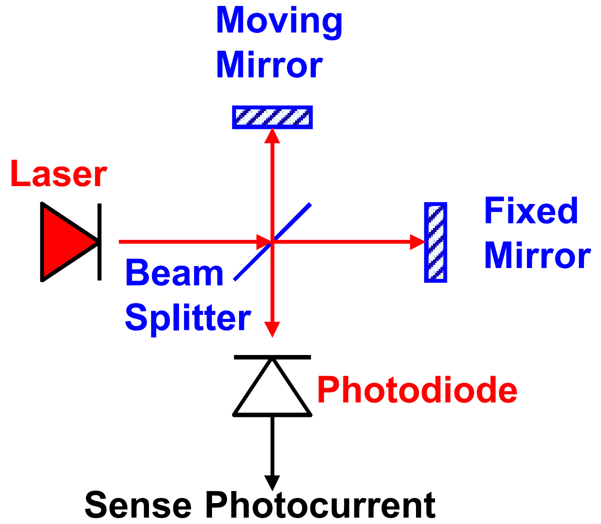
MEMS Sensors

- MEMS sensors offer low-cost due to batch fabrication
  - Pressure sensors, microphones, accelerometers, gyroscopes
- Raw signal is position of moving mass (proof mass)
- Traditionally MEMS position readout is capacitive
- Optical interferometric readout can improve resolution and dynamic range
  - But increases system complexity

MEMS Pressure Sensor

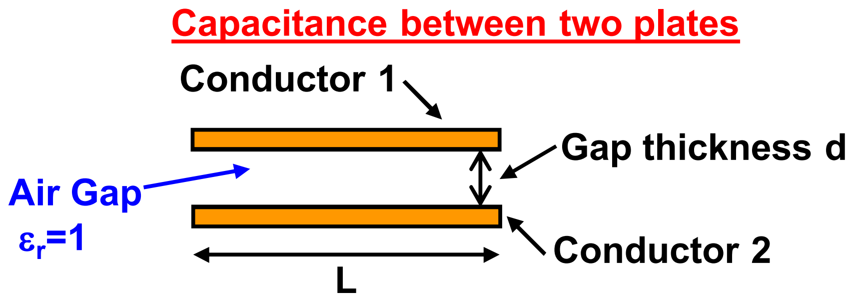


Michelson Interferometer



MEMS Sensors: Capacitive Readouts

- Parallel plate capacitance
  - Capacitance between two plates varies as $C = \varepsilon_0\varepsilon_r A/d$
  - Need C>10pF to measure with decent SNR
    - A=(1mm)^2,d=2um: C=5pF
    - Gap d must be small and fixed
- Option 1. Change gap between plates
  - Nonlinear sensitivity vs. position
  - Limited dynamic range
- Option 2. Change lateral overlap between plates
  - Periodic signal like interferometer
    - Period larger than 4 microns
    - Sensitivity 10x worse than interferometer



Capacitance $C = \varepsilon_0\varepsilon_r A/d$

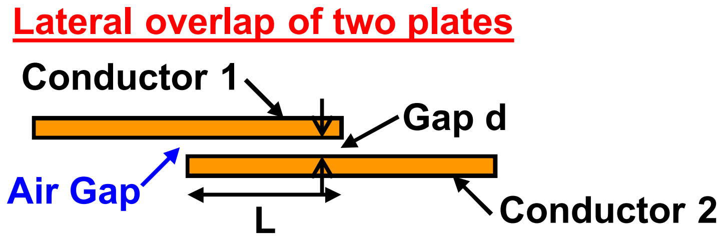


Plate overlap area A=L*W

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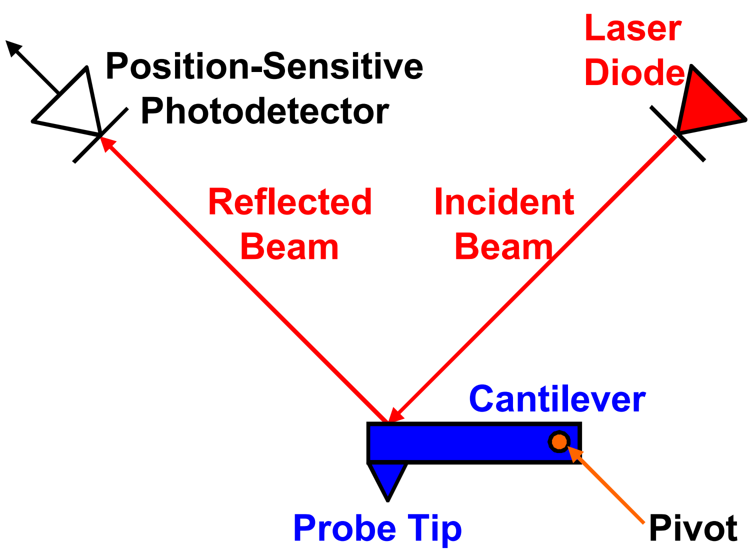
MEMS Sensors: Optical Readouts

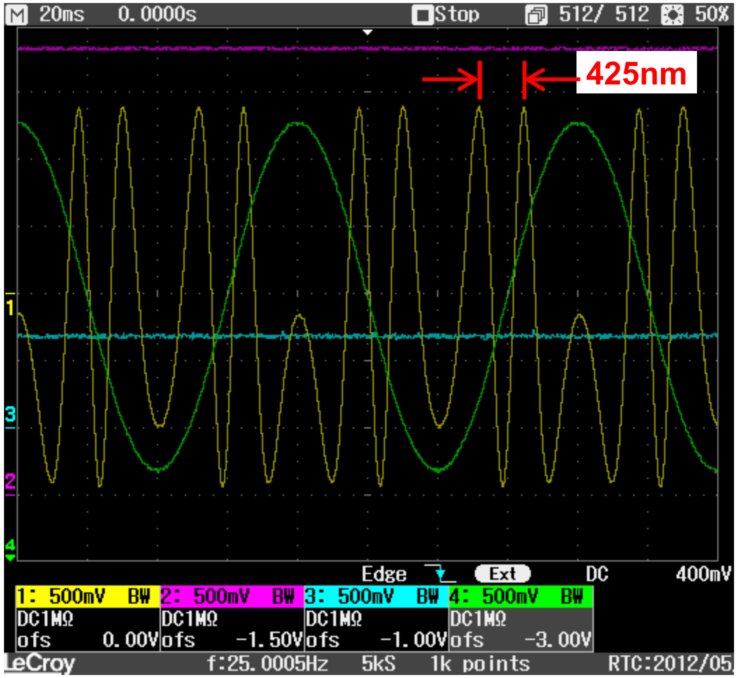
- Historically motivated by Atomic Force Microscope (AFM) usage of optical readouts
- Option 1. Change angle of beam
  - Requires a long "lever" arm

AFM Cantilever: Optical Sensor



- Option 2. Interferometer
  - Can sense position changes much smaller than 1 wavelength (850nm)
    - SNR=10^5 (100dB) yields 1pm (0.01A) resolution

Interferometer Readout: Period = $\lambda/2$



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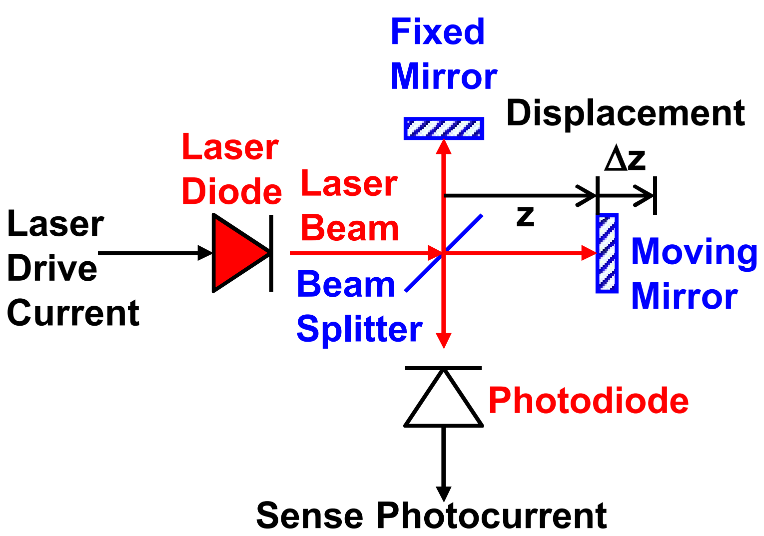
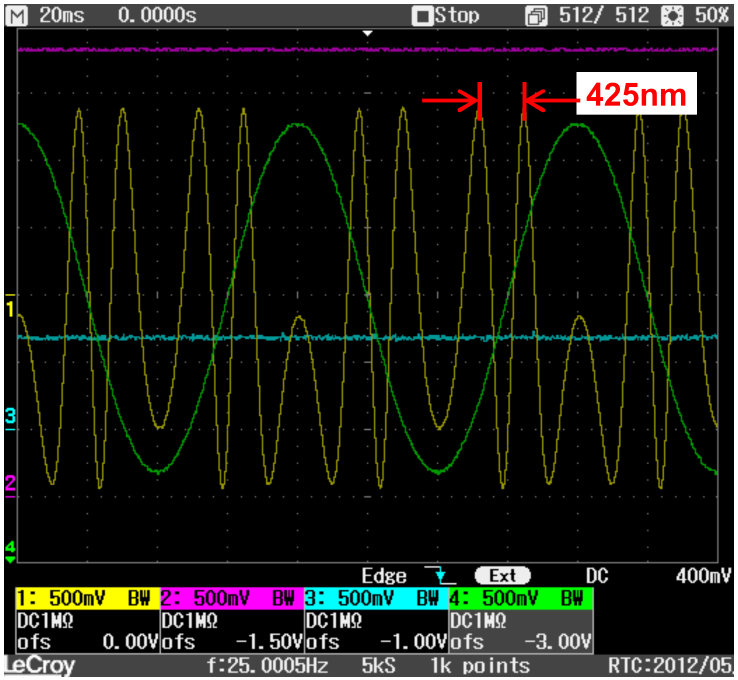
Interferometer Option 1: Two-Mirror Michelson

- Michelson topology
  - Advantage is large dynamic range
    - MEMS can move by >100λ
- Michelson data
  - Reference mirror driven with piezo over distance 900 nm
    - Noise is hardly visible: SNR>1,000, resolution<0.1nm

Michelson Schematic



Michelson Data



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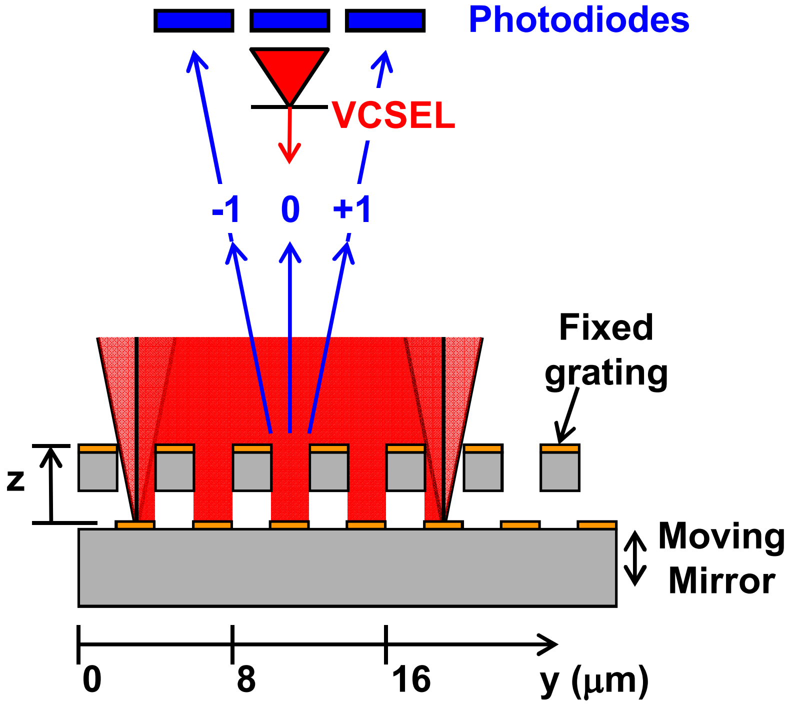
Interferometer Option 2: Grating Interferometer

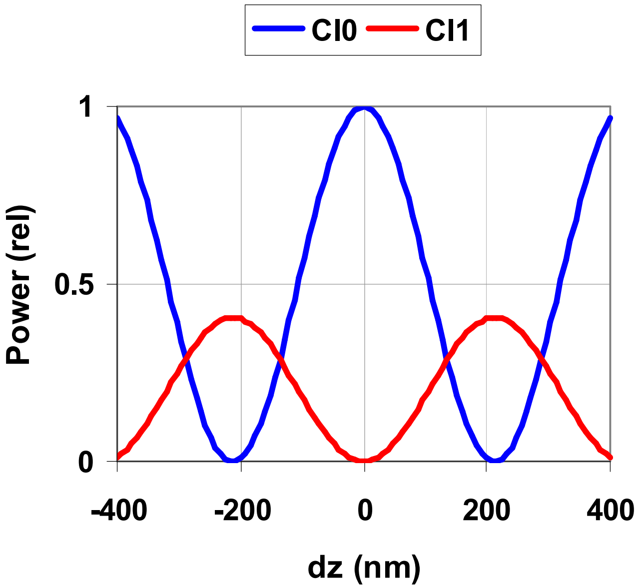
- Grating Interferometer Topology
  - Advantage is monolithic implementation

MEMS Cross-Section



- Grating Interferometer Theory
  - Grating is beam splitter (and one mirror)
  - Senses gap between grating and "moving mirror"

Photodiode Signals: 0th and 1st orders



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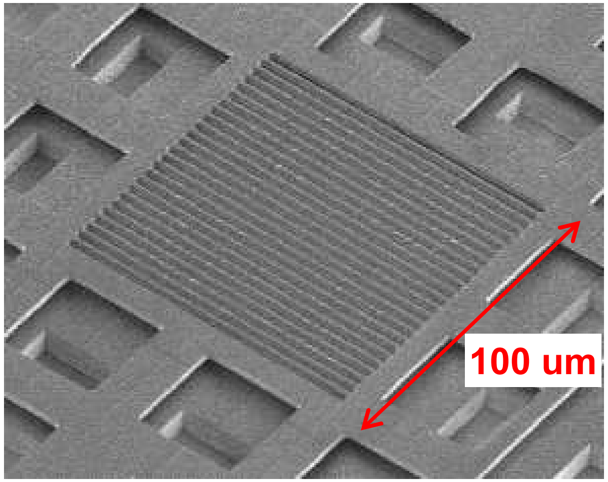
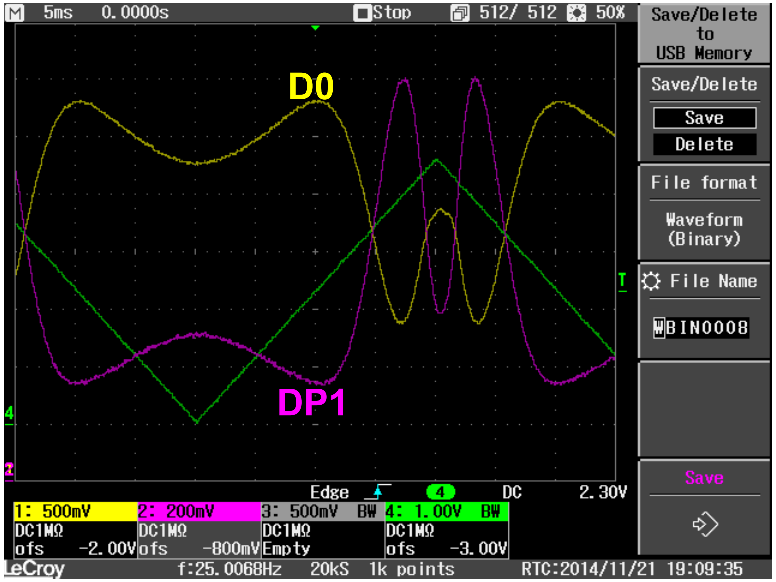
Grating Interferometer Data

- Grating Interferometer Fabrication
  - Grating fabricated of 2.25-um thick polysilicon
  - SacOx thickness 3 um
- VCSEL + Interferometer Data
  - Drive proof mass electrically relative to grating
  - Detect 0 and +1 orders

Grating: 4-um Period



Photodiode Signals: 0^{th} and 1^{st} orders



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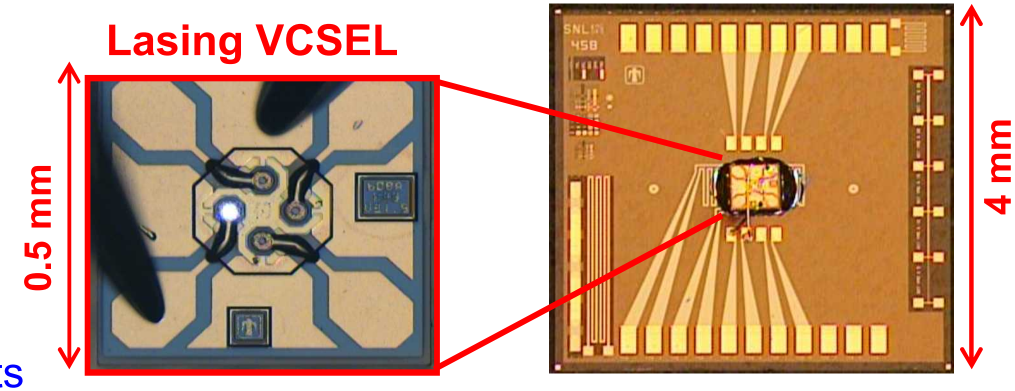
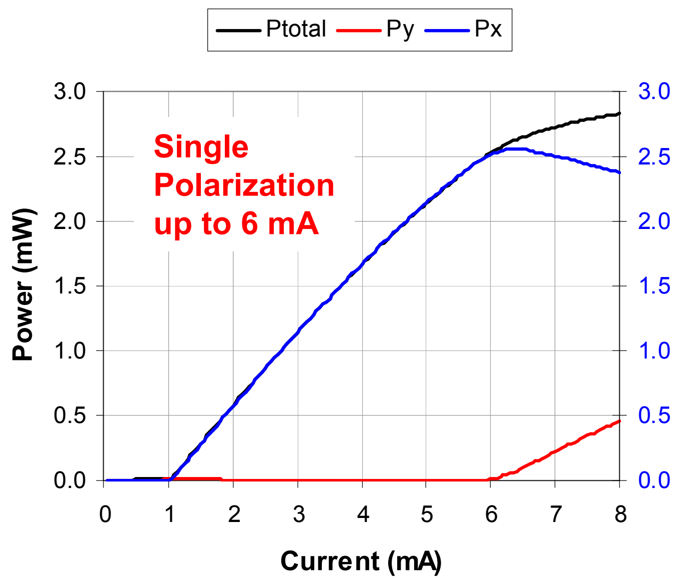
Single-frequency VCSEL Light Sources

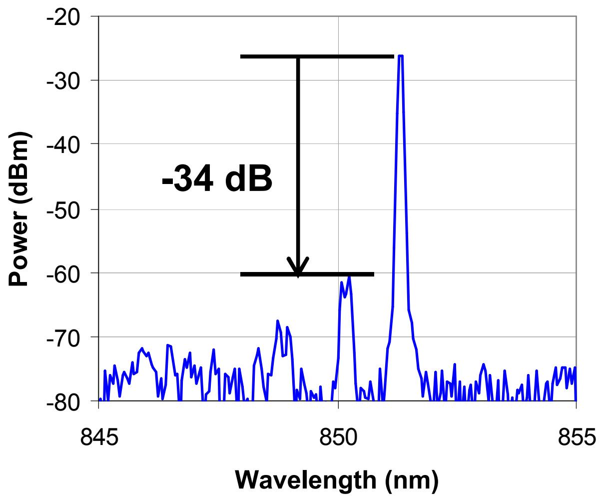
- A single-frequency laser is ideal for driving most interferometers
  - Large displacement range
  - Narrow collimated beams
- VCSEL
  - Compact form factor
  - Low-power consumption
  - Compatible with integrated circuits
    - Drive with 2mA current at 1.7V drop
  - Single frequency, single polarization



VCSEL Output Power vs. Current



Single-frequency VCSEL spectrum



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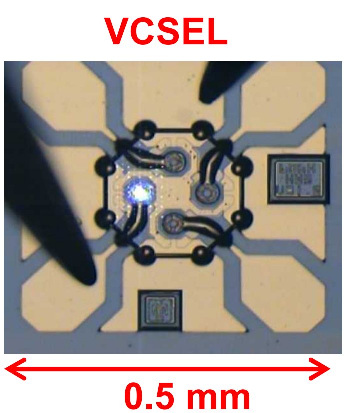
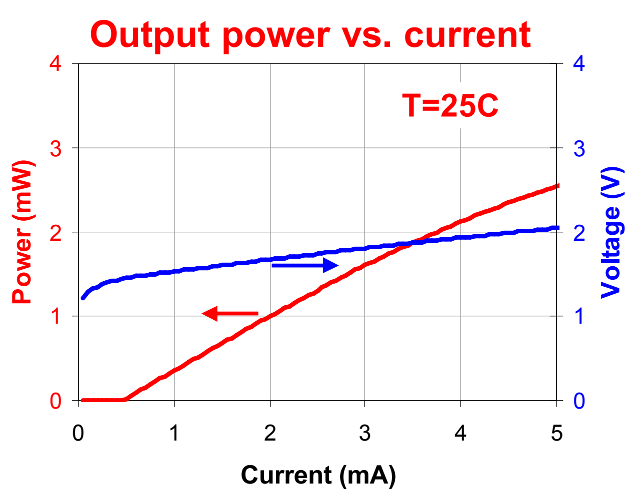
VCSEL frequency stability

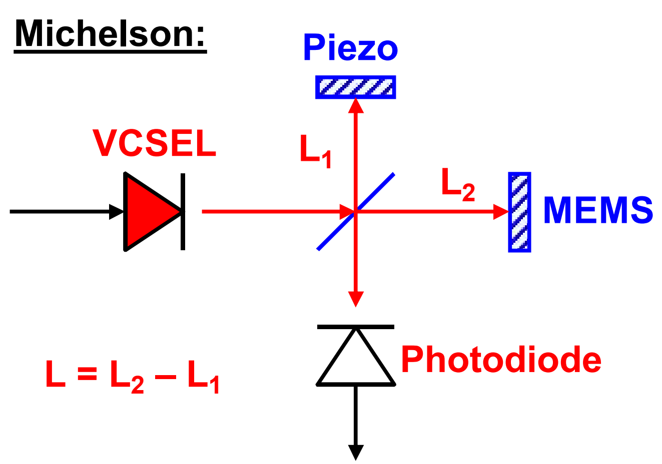
- Spectroscopy-grade VCSEL
  - Wavelength = 850 nm
    - Frequency = 353 THz
  - Current = 2 mA
    - Threshold Ith = 1 mA
  - Voltage = 1.7 V
  - Output power = 0.2 mW (at 100 C)
  - Linewidth = 50 MHz
  - Temperature tuning = -25 MHz/mK
  - Current tuning = -125 MHz/uA

- Interferometer converts FM to AM
  - Un-equal arm lengths yield sensitivity to laser frequency
    - Example:
      - Laser: λ=850nm, f=353THz
      - Interferometer: ΔL=10μm
      - Frequency change: df=50MHz
      - Differential phase change: dϕ=1E-5

$$d\phi = 2\pi \left(\frac{L}{\lambda}\right)\left(\frac{df}{f}\right)$$







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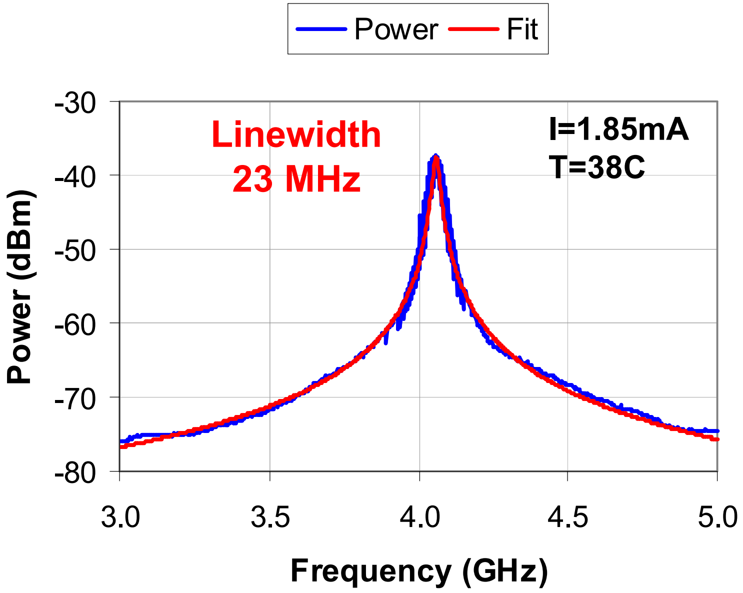
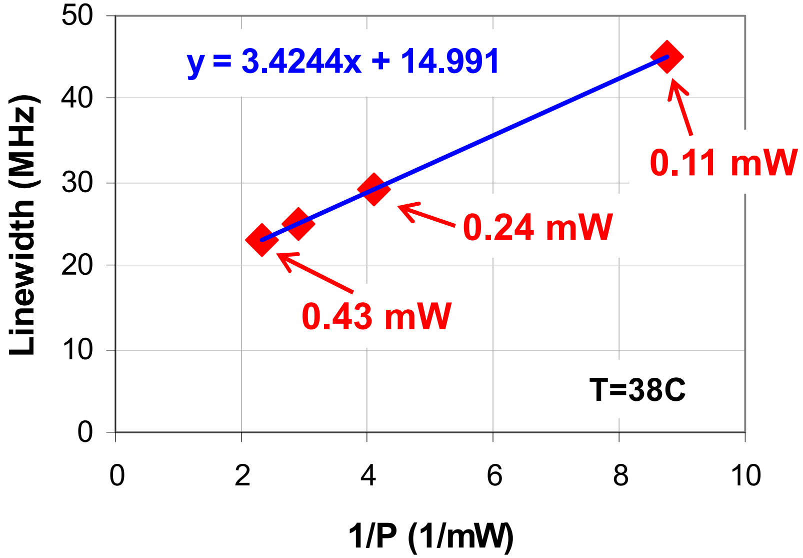
Narrow Linewidth VCSELs

- VCSEL linewidth measurement
  - 23 MHz measured
    - Some slow frequency drift observed during 5-second spectrum analyzer sweep



- Linewidth versus output power
  - Expect 1/P dependence



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Summary

- MEMS sensors offer high performance, small form factor, and low cost
  - COTS sensors use capacitive sensing of MEMS position
- Optical readouts can improve MEMS sensor performance
  - Higher Sensitivity
  - Large Dynamic Range
- Single-frequency VCSELs can meet the needs for MEMS readout
  - Low cost
  - Compact integration with MEMS
  - DC accuracy requires stable wavelength
  - High SNR requires low intensity noise and frequency noise