Interferometer Stabilization for CARS imaging

Esben Ravn Andresen
&
Vishnu Vardhan Krishnamachari

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Heterodyne coherent anti-Stokes Raman scattering (CARS) imaging

Eric O. Potma,* Conor L. Evans, and X. Sunney Xie

Department of Chemistry and Chemical Biology, Harvard University, 12 Oxford Street, Cambridge, Massachusetts 02138

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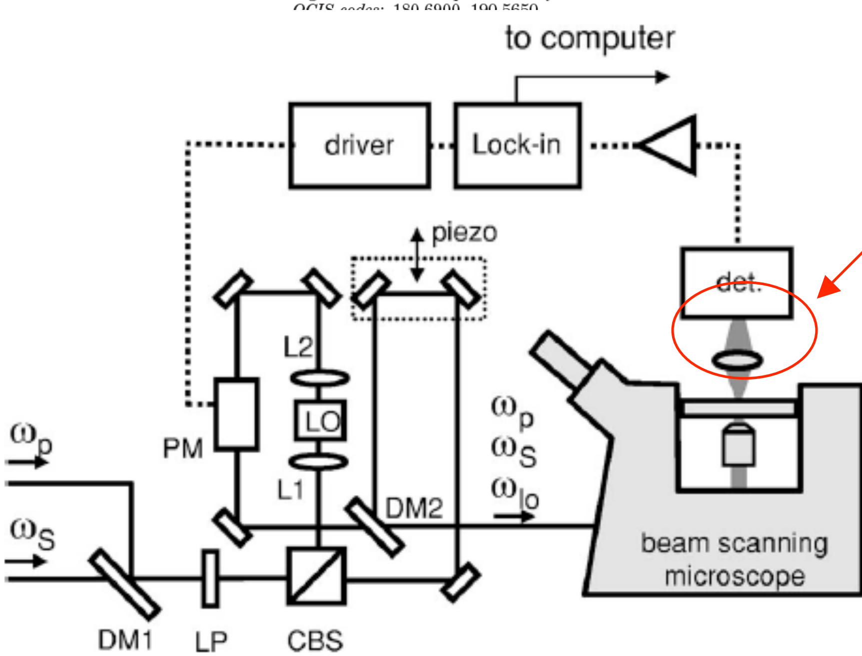
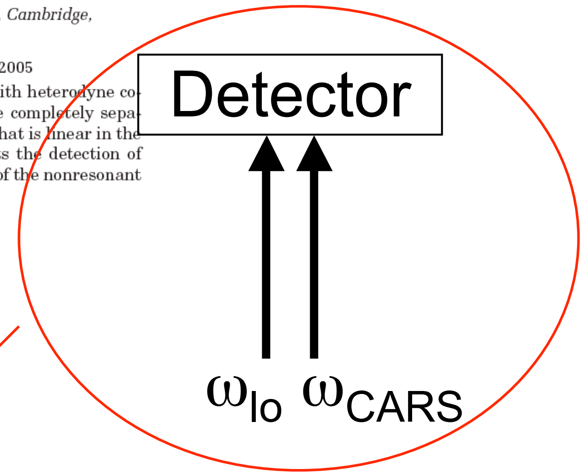
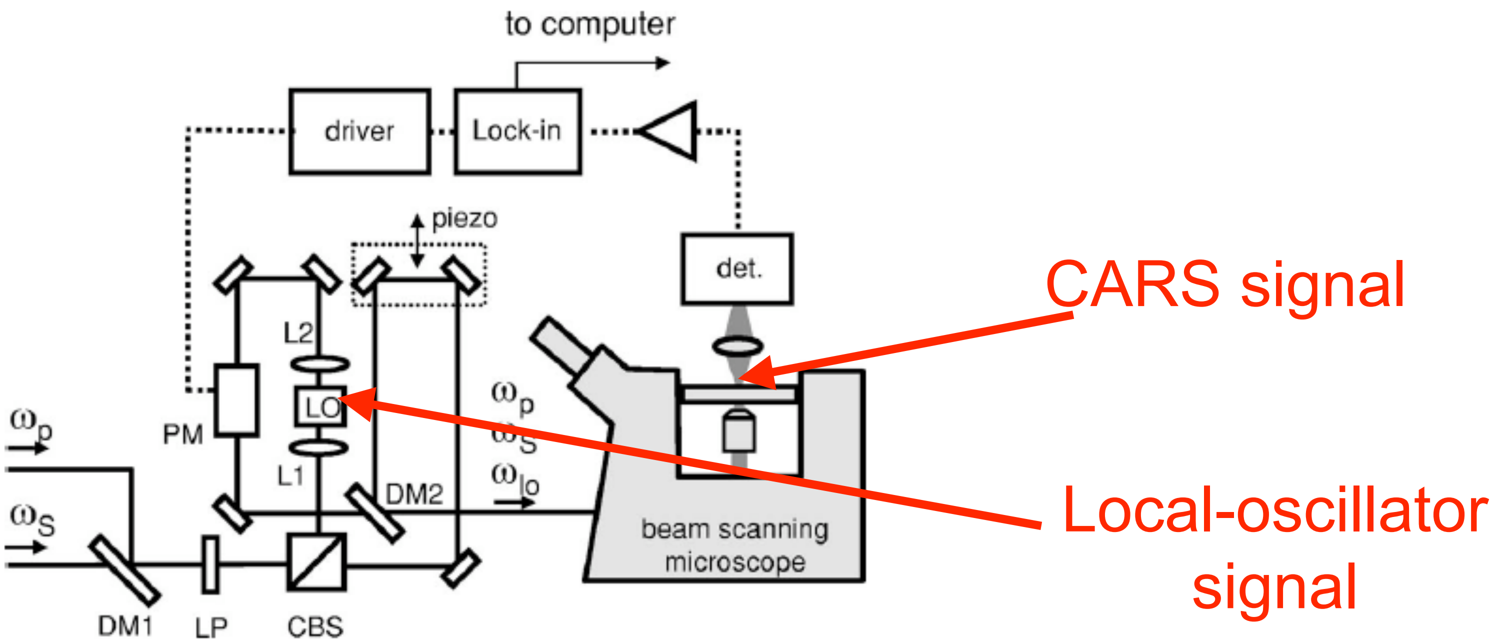
We have achieved rapid nonlinear vibrational imaging free of nonresonant background with heterodyne coherent anti-Stokes Raman scattering (CARS) interferometric microscopy. This technique completely separates the real and imaginary responses of nonlinear susceptibility $\chi^{(3)}$ and yields a signal that is linear in the concentration of vibrational modes. We show that heterodyne CARS microscopy permits the detection of weak vibrational resonances that are otherwise overshadowed by the strong interference of the nonresonant background.





- $\Delta\phi = \pi/2$
  $\Rightarrow I_{out} \propto \mathrm{Im}\{\chi^{(3)}\}$
  $\propto$ Conc
- $\Delta\phi = 0$
  $\Rightarrow I_{out} \propto \mathrm{Re}\{\chi^{(3)}\}$



Aim: To control the phase difference between the local-oscillator (ϕ_{lo}) and the CARS ($2\phi_p$-ϕ_s) signals

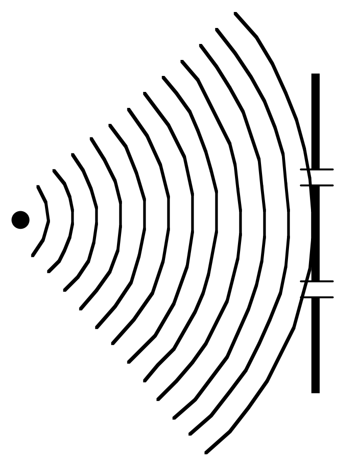
$\Rightarrow$ **Stabilize the interferometer**

Contents

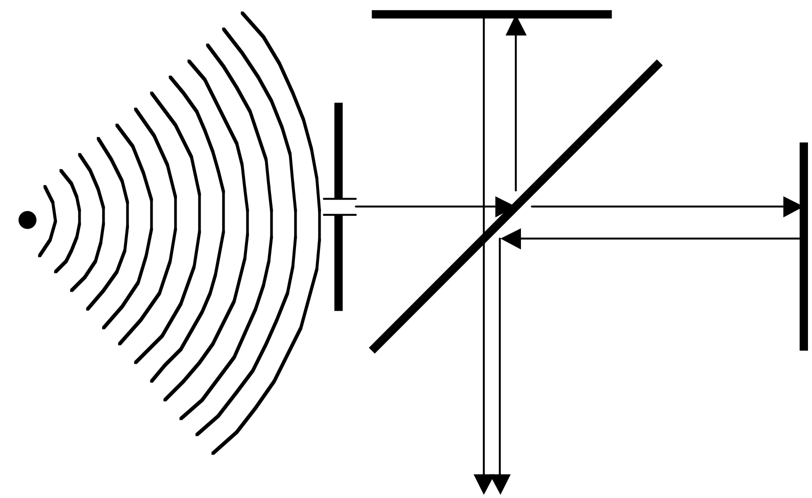
- A short review of interference
- Mach-Zehnder interferometer
- Stabilizing the interferometer
  - Data acquisition & Calibration
  - Generation of error signal
  - Feedback scheme
  - Stabilized output
- Looking ahead!

Two types of inteference

- Interference due to **Division of Wavefront**
- Interference due to **Division of Amplitude**

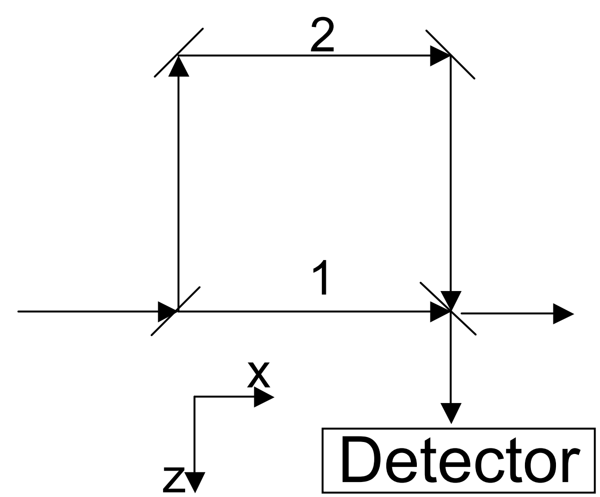


Young's Double-Slit Expt.
Division of wavefront



Michelson interferometer
Division of amplitude

Collinear Geometry



- Plane wave from arm 1:

  $E_1(x,y,z,t) = A\, e^{-ikz}\, e^{+i\omega t}$

- Plane wave from arm 2:

  $E_2(x,y,z,t) = A\, e^{-ik(z+2^*\Delta l)}\, e^{+i\omega t}$

  $= A\, e^{-ikz} e^{-i\Delta\phi}\, e^{+i\omega t}$

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

- Intensity at the detector:

  $$I_{out} \propto |E_1 + E_2|^2$$
  $$= |E_1|^2 + |E_2|^2 + 2|E_1||E_2|\cos(\Delta\phi)$$

Collinear Geometry

- Intensity at the detector:

$$I_{out}(\Delta\phi) \propto I_0 + I_{mod}\cos(\Delta\phi)$$

- If $\Delta\phi = 0$:

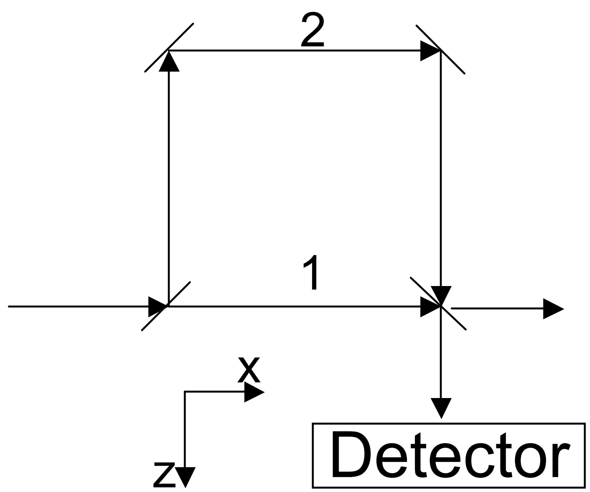
$$I_{out}(\Delta\phi) \propto I_0 + I_{mod}$$

- If $\Delta\phi = \pi/2$:

$$I_{out}(\Delta\phi) \propto I_0$$

- If $\Delta\phi = \pi$:

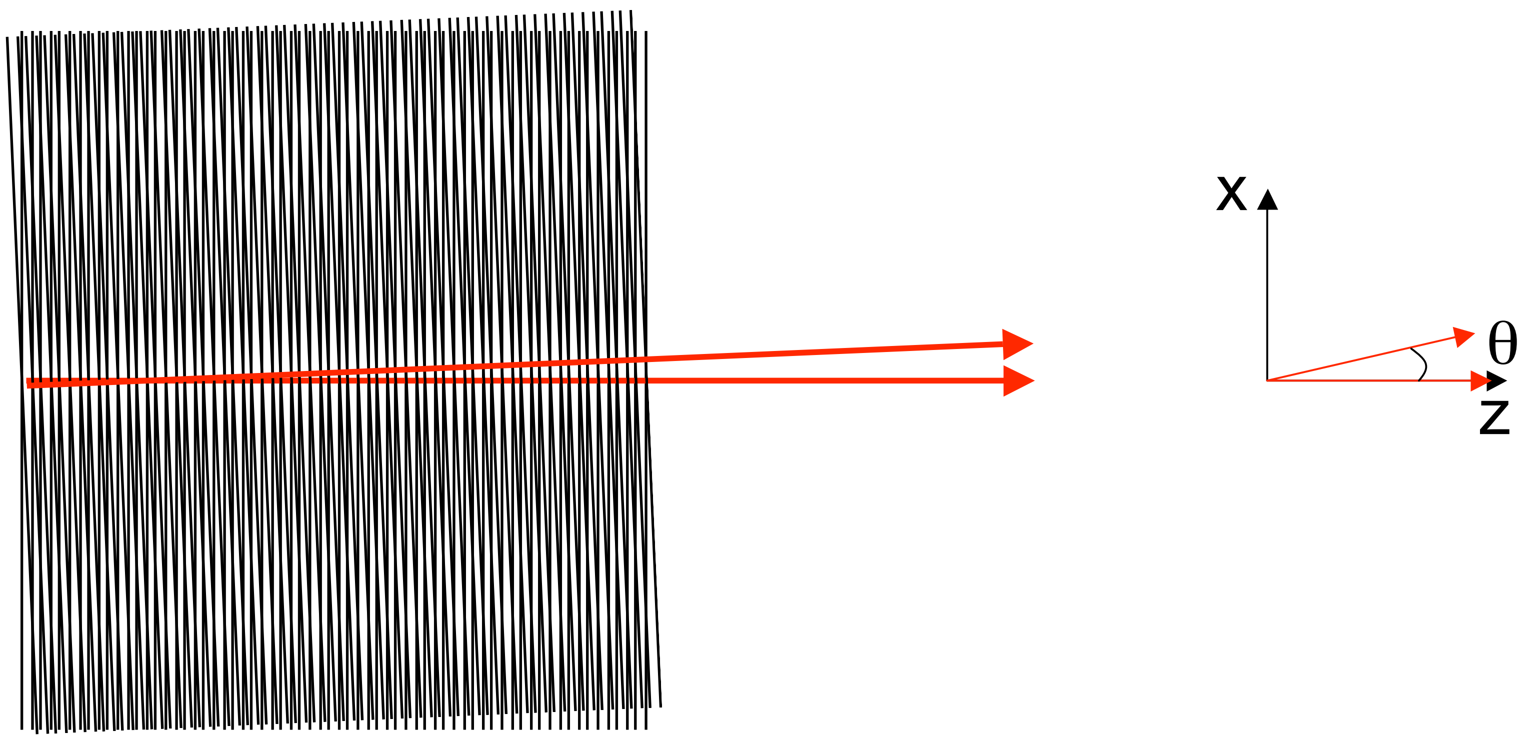
$$I_{out}(\Delta\phi) \propto I_0 - I_{mod}$$



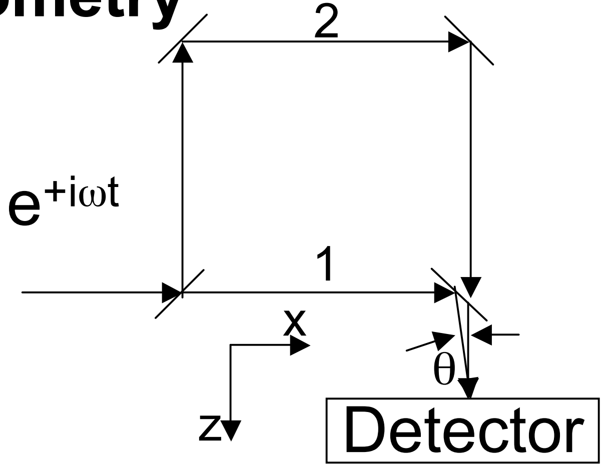
Non-Collinear Geometry

A plane wave:

$$E(x,y,z,t) = A\, e^{-ikz}\, e^{+i\omega t}$$



Non-Collinear Geometry



- Plane wave from arm 1:

  $$E_1(x,y,z,t) = A\, e^{-ikx\sin\theta}\, e^{-ikz\cos\theta}\, e^{+i\omega t}$$

- Plane wave from arm 2:

  $$E_2(x,y,z,t) = A\, e^{-ikz}\, e^{-i\Delta\phi} e^{+i\omega t}$$

Position of detection

- Intensity at the detector at the plane z =0:

  $$I_{out} \propto |E_1 + E_2|^2$$
  $$= |E_1|^2 + |E_2|^2 + 2|E_1||E_2|\cos(kx\sin\theta - \Delta\phi)$$

Path difference between the arms

Non-Collinear Geometry

- Intensity at the detector at the plane z =0:

$$I_{out}(x, \Delta\phi) \propto I_0 + I_{mod}\cos(kx\sin\theta - \Delta\phi)$$

- At x =0:

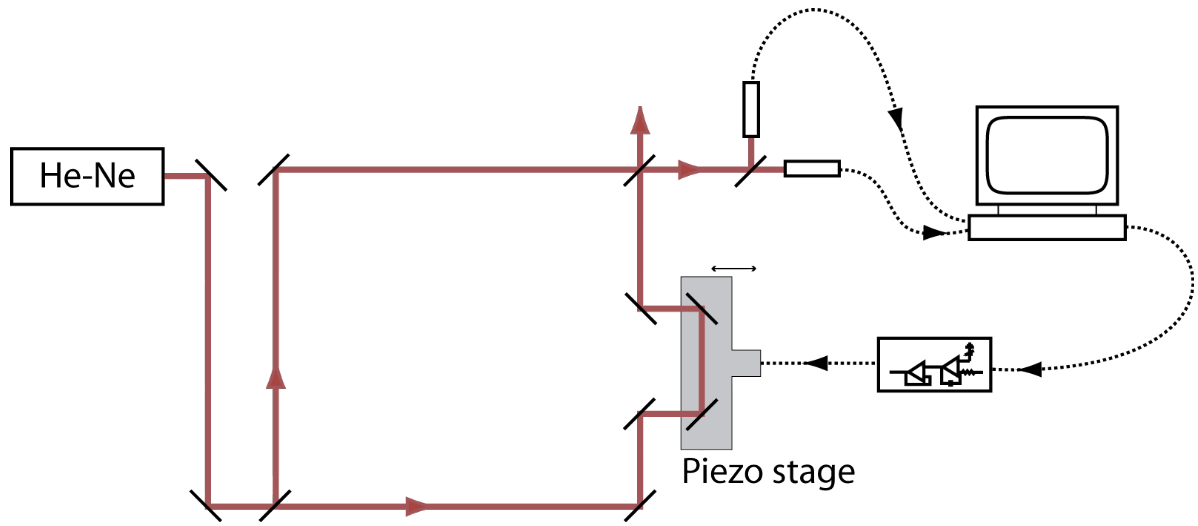
$$I_{out}(0, \Delta\phi) \propto I_0 + I_{mod}\cos(\Delta\phi)$$

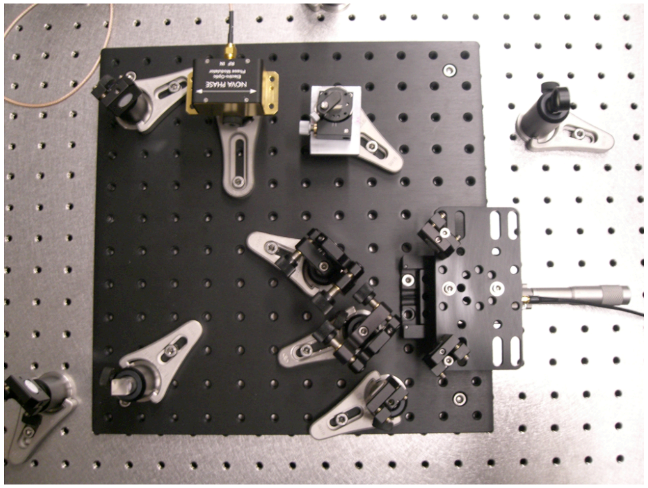
- At $x = x' = \pi/2k\sin\theta$:

$$I_{out}(x', \Delta\phi) \propto I_0 + I_{mod}\sin(\Delta\phi)$$

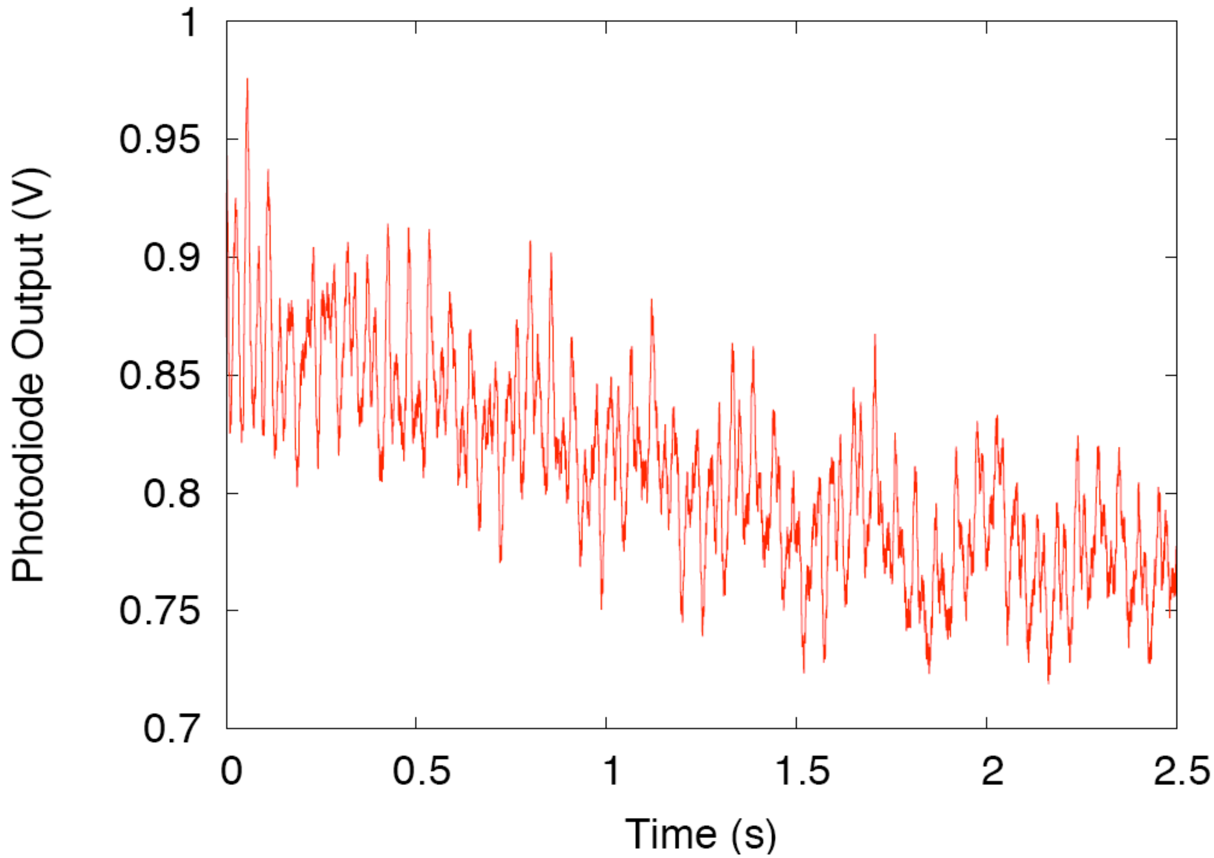
$$\boxed{\Delta\phi \propto \tan^{-1}\left(\frac{I_{out}(x', \Delta\phi)-I_0}{I_{out}(0, \Delta\phi)-I_0}\right)}$$

Mach-Zehnder Interferometer





Free-running output of one of the photo-diodes



How to Stabilize?

Computer processing:

1. Acquire intensities and calibrate
2. Determine $\Delta\phi$ and generate an error signal

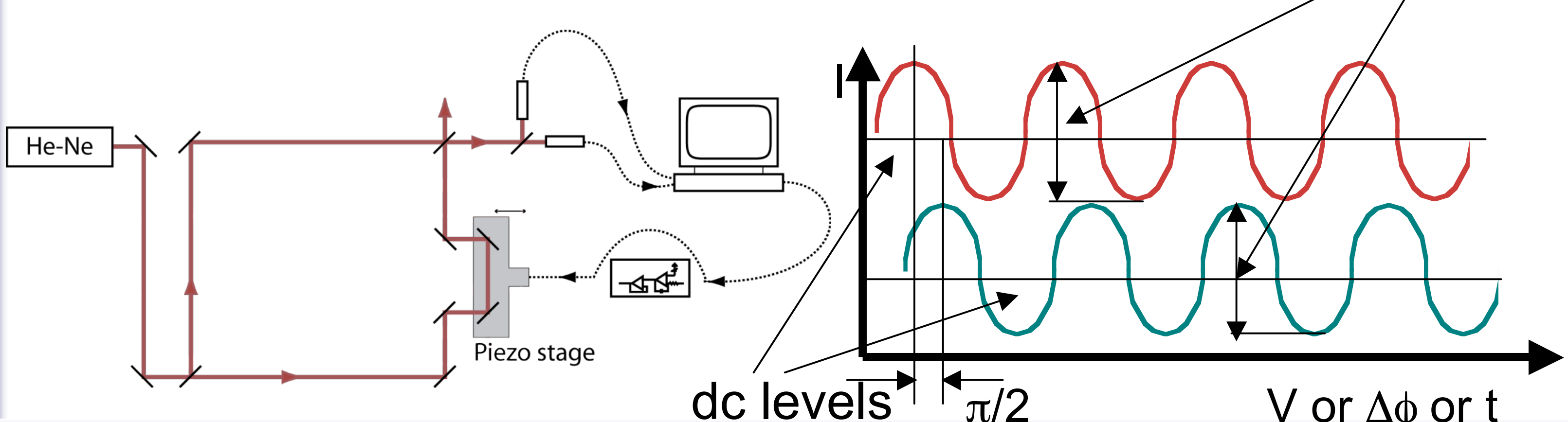
Electronic circuitry:

3a. Covert the error signal into a voltage signal for feedback
3b. Feed this signal to the piezo

Data Acquisition & Calibration

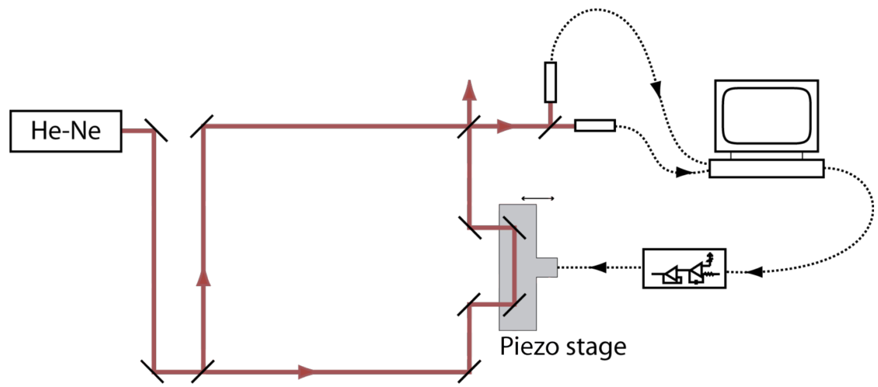
- Data Acquisition:
  - NI-DAQ board & C++/LabView
  - Acquisition speed - up to 9kHz (typical 4kHz)
- Calibration:
  - Set photo-diodes "π/2 out-of-phase"
  - Determine the
    - dc levels and amplitudes
  - Normalize the outputs to ±1

Done in 2 seconds!!

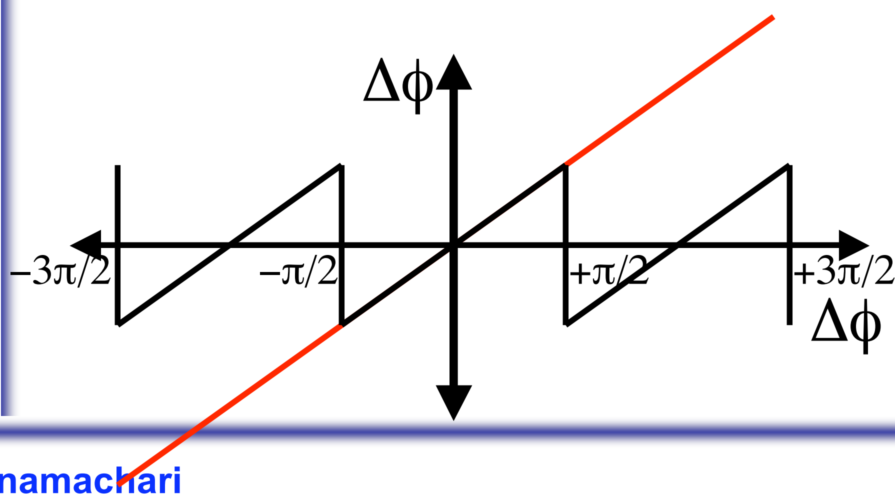


Phase Unwrapping & Error Signal

Contents
Interference
Mach-Zehnder
Stabilization
What's next

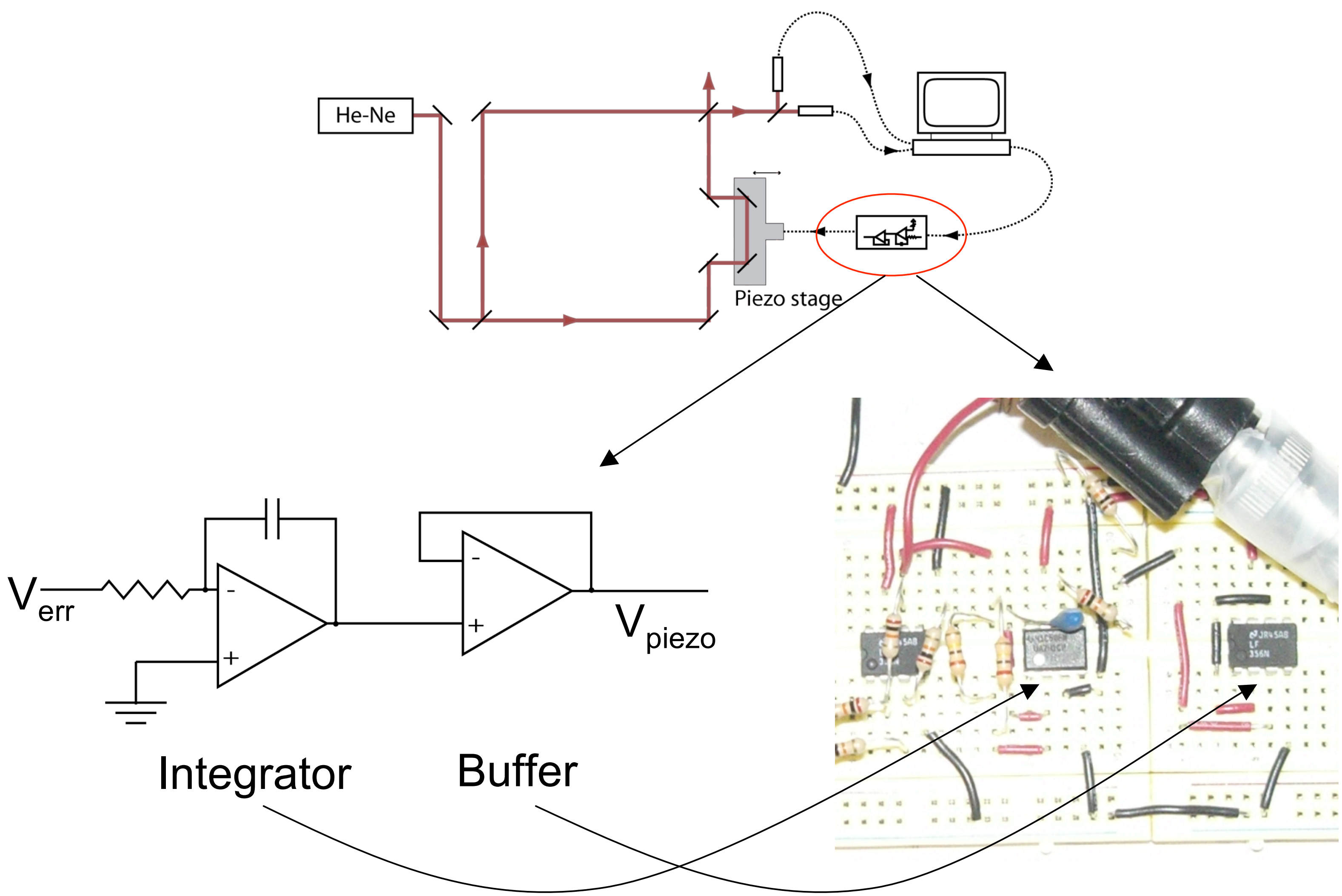


$$\Delta\phi = \tan^{-1}\left(\frac{(V_{pd1} - dc_{pd1})/amp_{pd1}}{(V_{pd2} - dc_{pd2})/amp_{pd2}}\right)$$

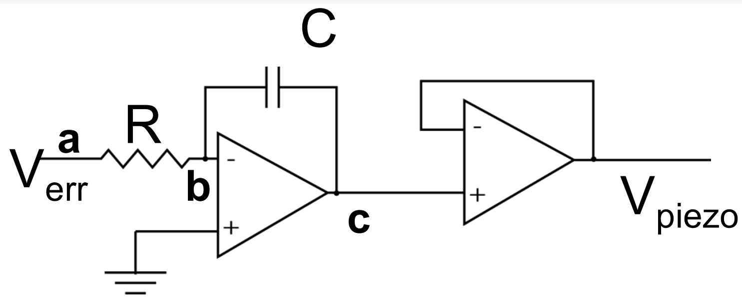


$$V_{err} = \alpha(\Delta\phi - \phi_{desired})$$

Electronic Feedback



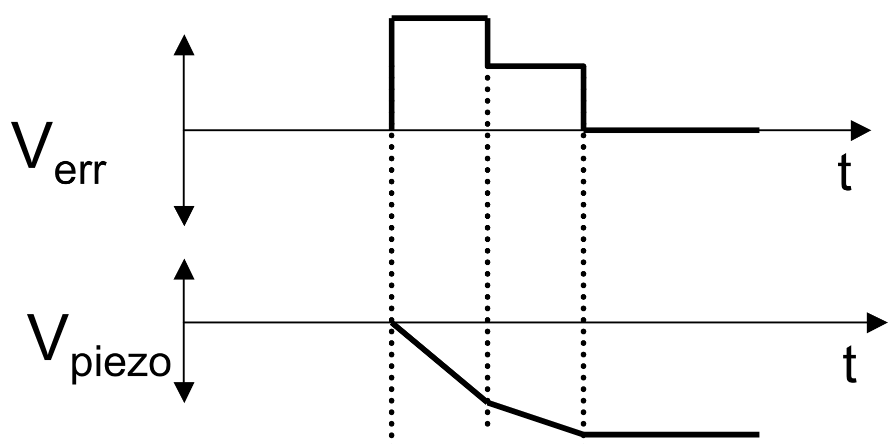
Electronic Feedback



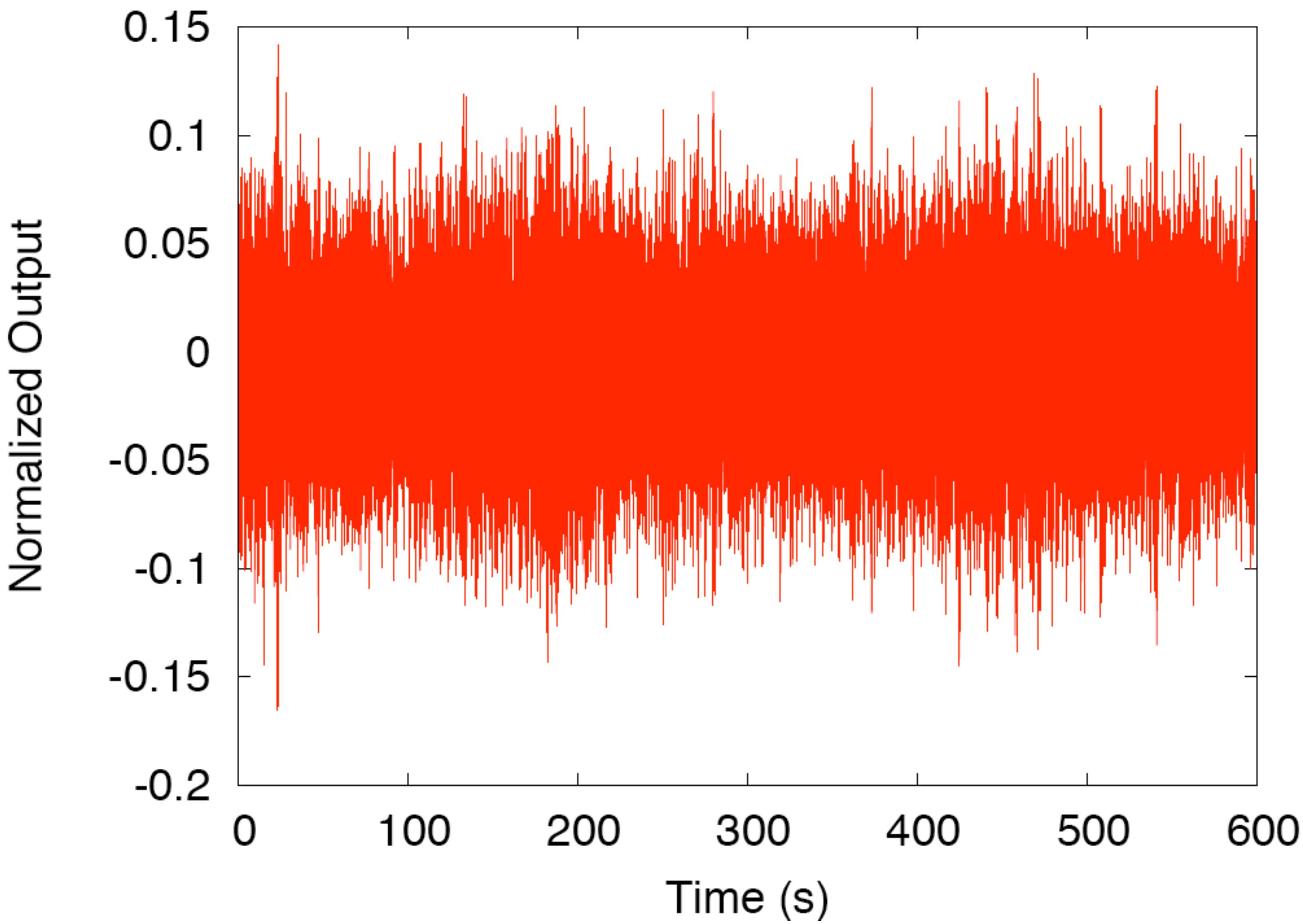
$$V_a = V_{err}$$
$$V_b = 0$$
$$V_c = V_{piezo}$$

$$I = -V_{err}/R = C\, d(V_c - V_b)/dt = C\, dV_{piezo}/dt$$

$$V_{piezo} = -1/RC \int V_{err}\, dt$$

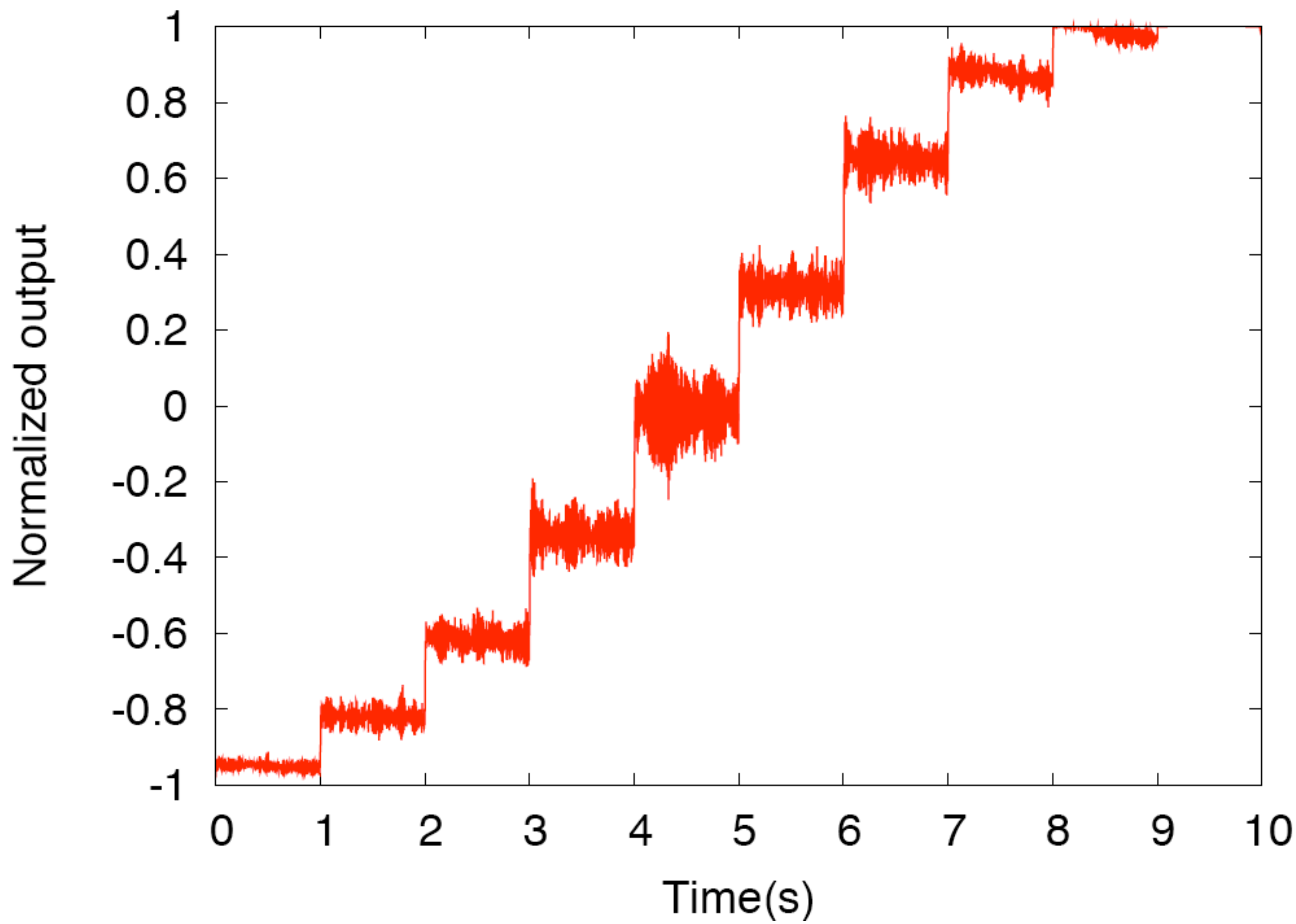


Stabilized Interferometer

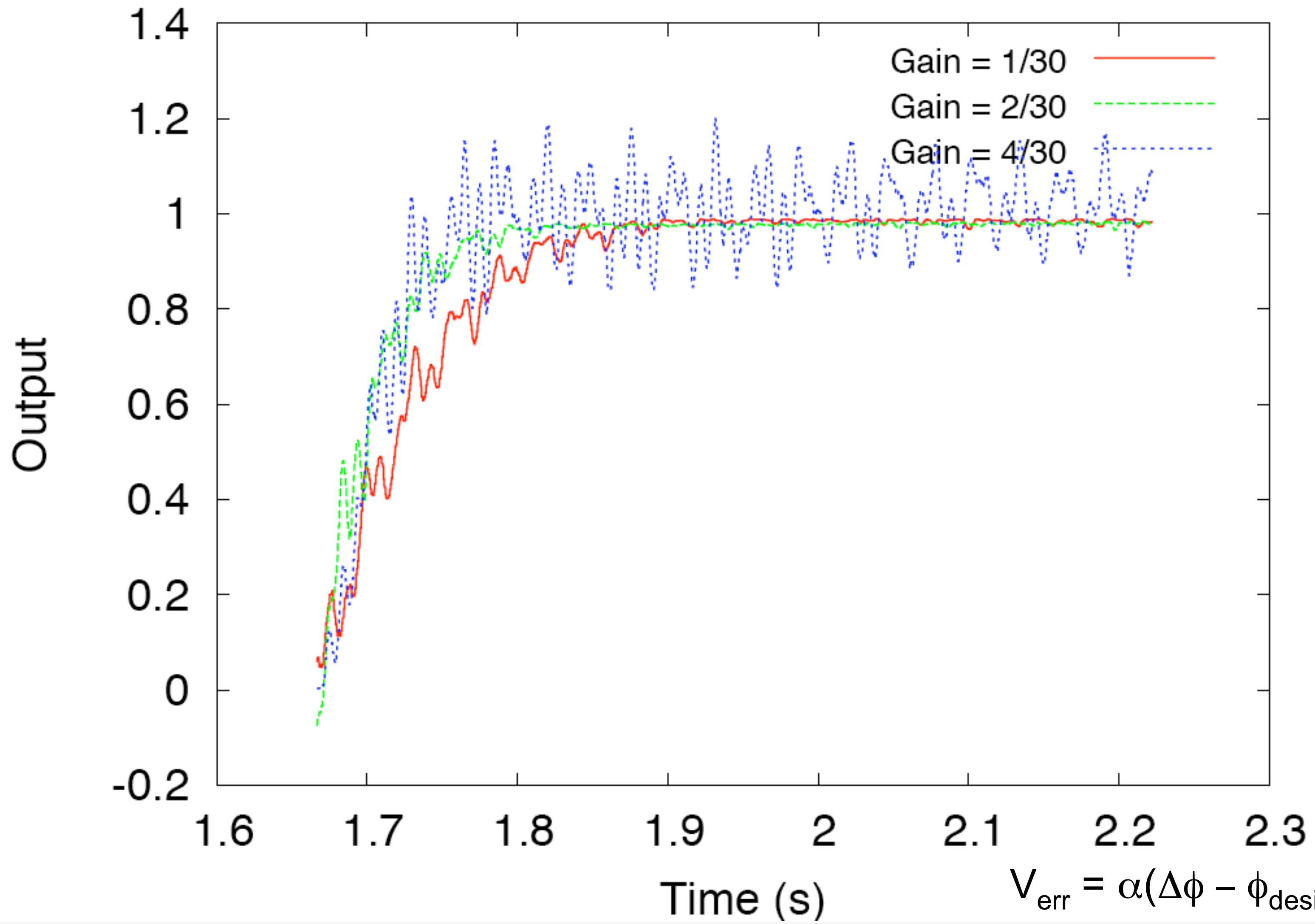


Department of Chemistry
UNIVERSITY OF CALIFORNIA, IRVINE
BERKELEY•DAVIS•IRVINE•LOS ANGELES•MERCED•RIVERSIDE•SAN DIEGO•SAN FRANCISCO•SANTA BARBARA•SANTA CRUZ

Stabilized Interferometer

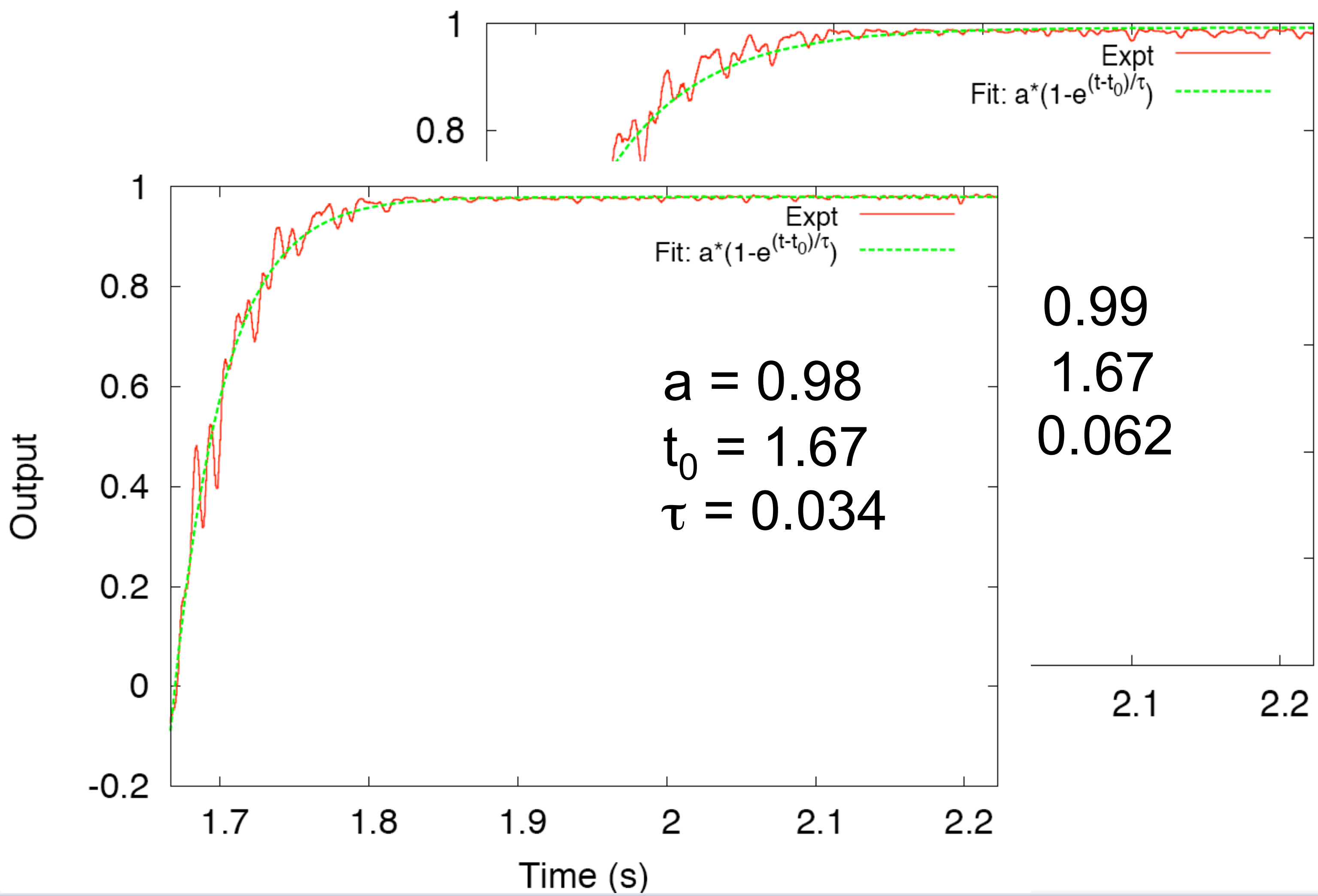


Characteristics - Time Response



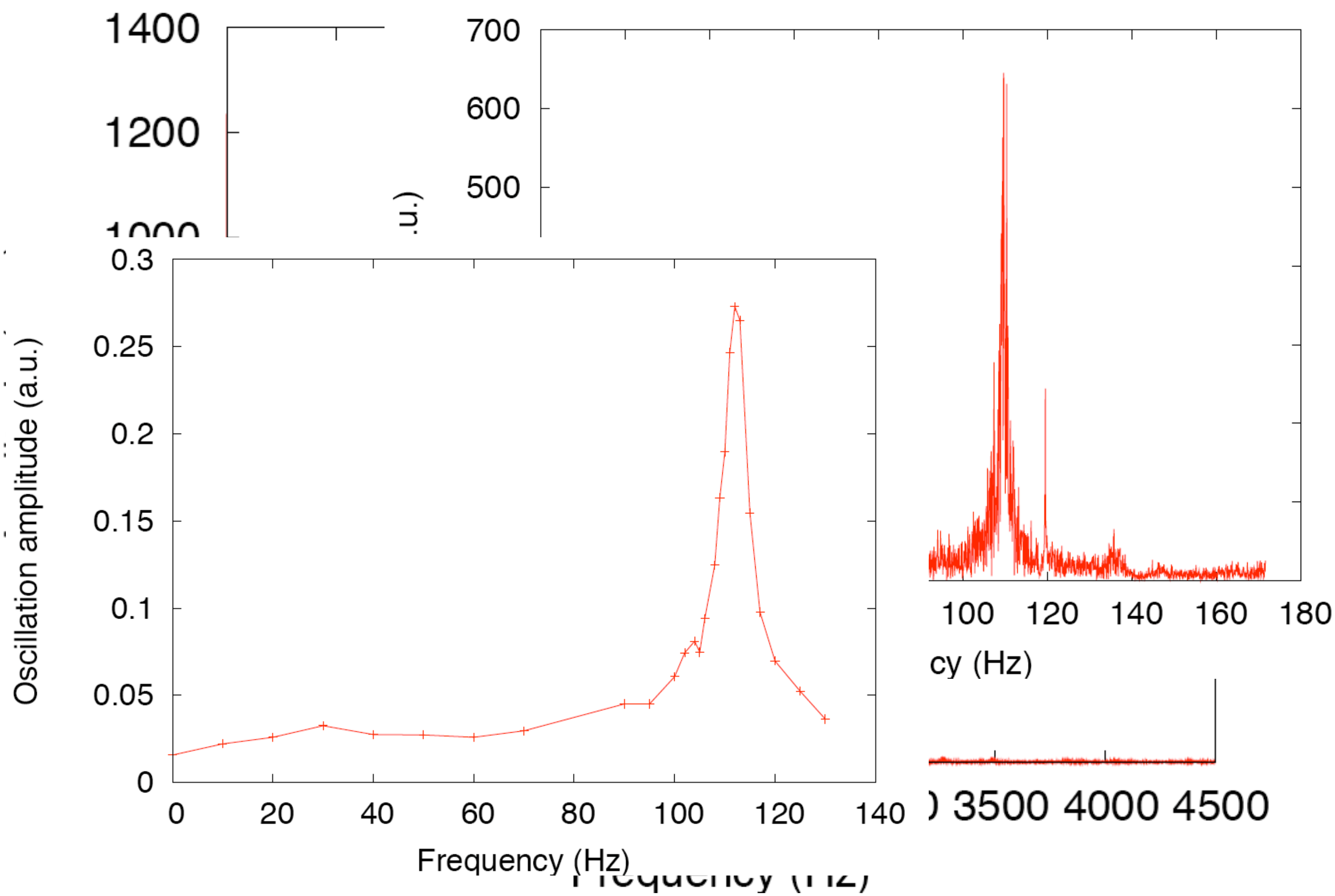
$V_{err} = \alpha(\Delta\phi - \phi_{desired})$

Characteristics - Time Response

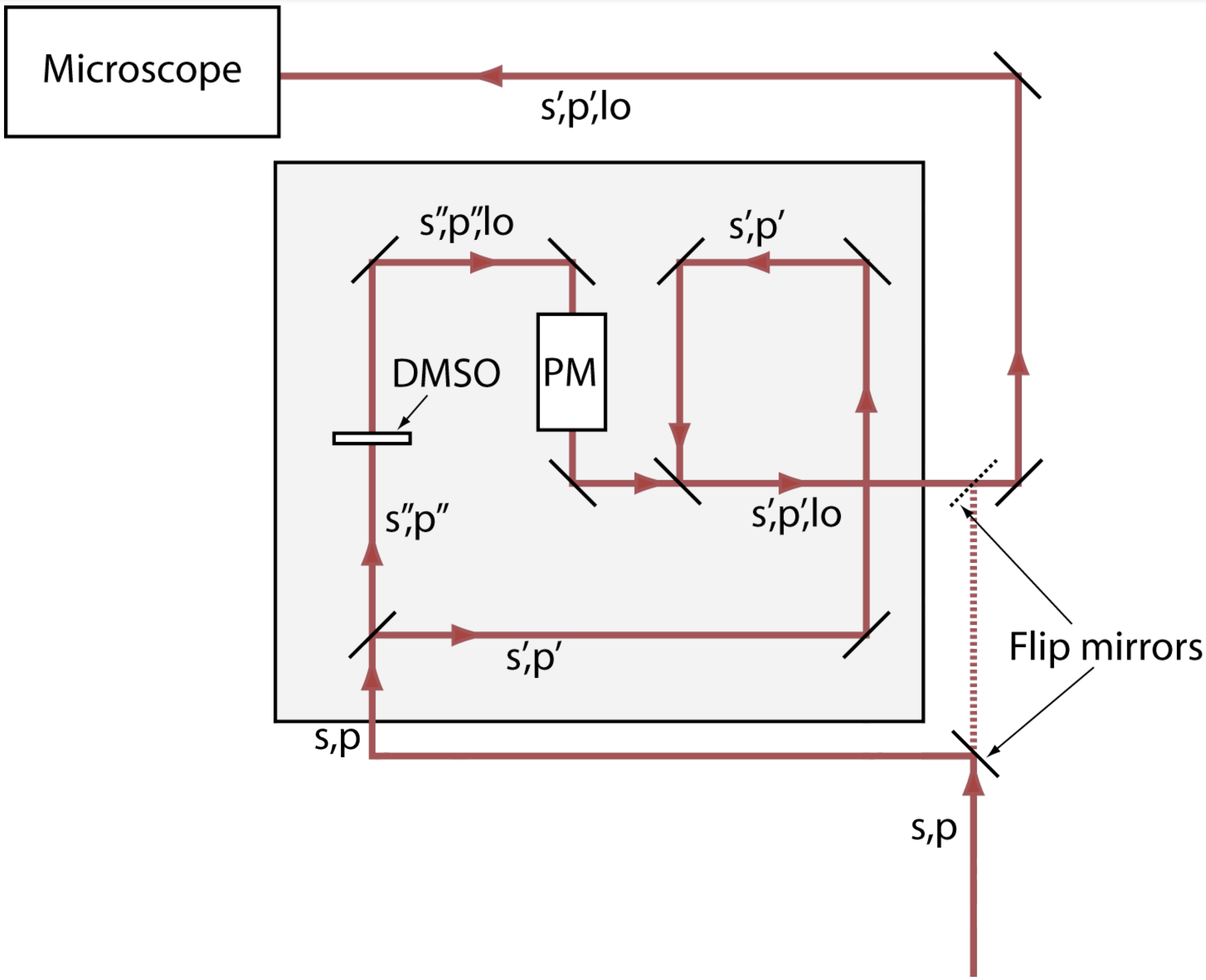


$a = 0.98$
$t_0 = 1.67$
$\tau = 0.034$

Characteristics - Noise



What’s Next?



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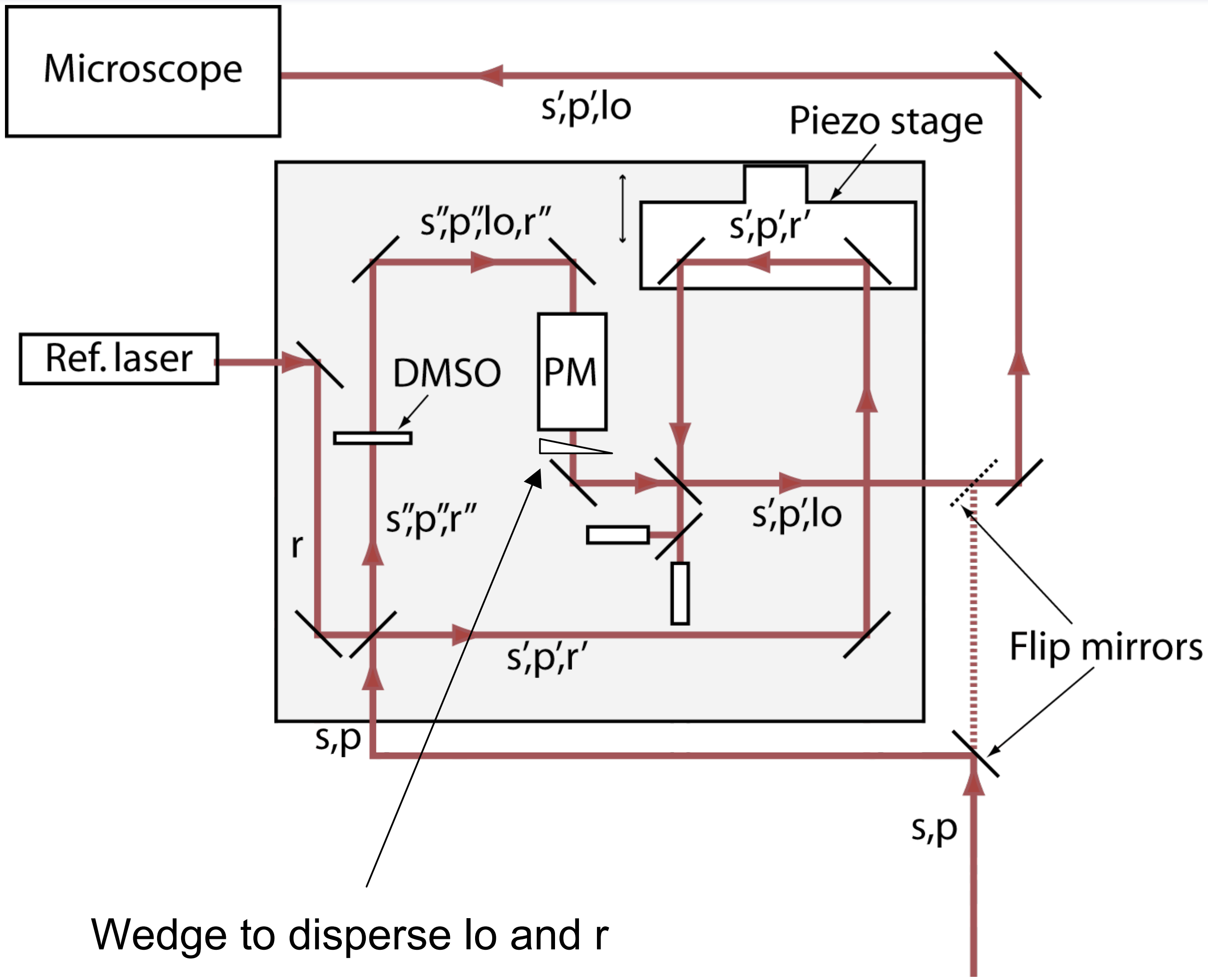
Microscope
s′,p′,lo
Piezo stage
s″,p″,lo,r″
s′,p′,r′
Ref. laser
DMSO
PM
s″,p″,r″
r
s′,p′,lo
s′,p′,r′
Flip mirrors
s,p
s,p
Wedge to disperse lo and r

Conclusion

- Mach-Zehnder interferometer
- Collinear and non-collinear interferometers
- Stabilization of the interferometer
  - Calibration and generation of error signal
  - Integrator as an electronic feedback element
- Low resonance frequency of piezo
  - Slower feedback response