






Cavity-Enhanced Frequency Upconversion of 2 μm Light for Quantum Efficient Detection

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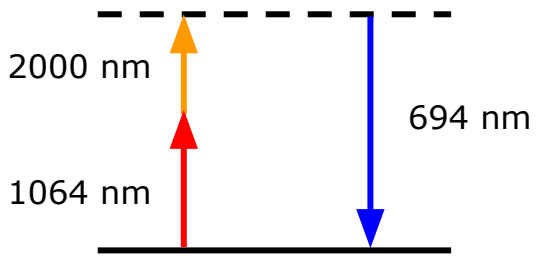
Mentors: Radhika Bhatt, Rana Adhikari - Caltech

Cryogenic Upgrade to LIGO to Reduce Thermal Noise

- LIGO Voyager upgrade uses crystalline silicon test masses at 123 K
  - Thermoelastic noise is minimized for Si at 123 K (thermal expansion coefficient zero crossing)
- 2 μm light has low absorption in silicon compared to 1064 nm
- At 2 μm PDs have low quantum efficiencies vs shorter wavelengths
  - Si PDs have QEs >99% at 700 nm
- SFG of 2 μm to 700 nm enables use of efficient Si PDs

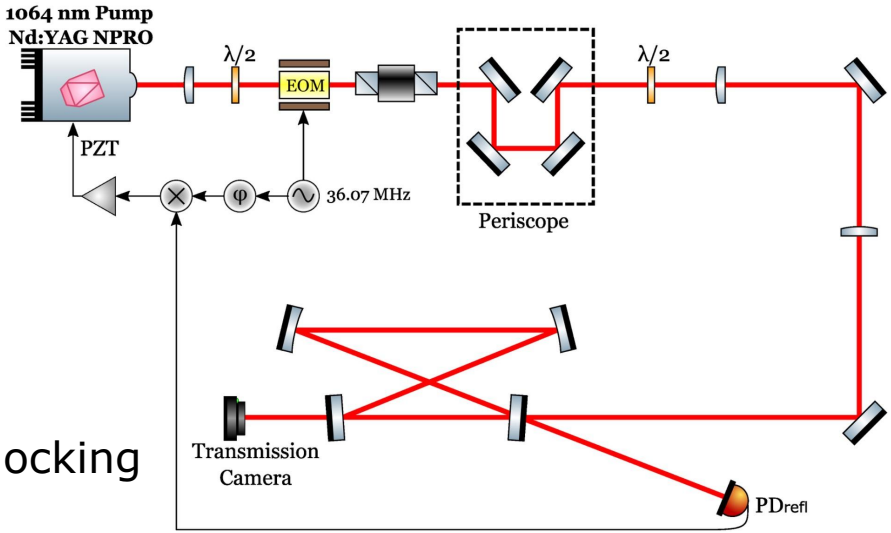
Cavity-Enhanced Sum-Frequency Generation

- PPLN has a large 2nd order nonlinear coefficient, facilitating SFG
- Conversion efficiency scales with pump intensity
- Resonant intracavity pump power is much greater than single pass
    - Higher conversion efficiency at the expense of cavity noise coupling into signal



Initial Cavity Setup and Design

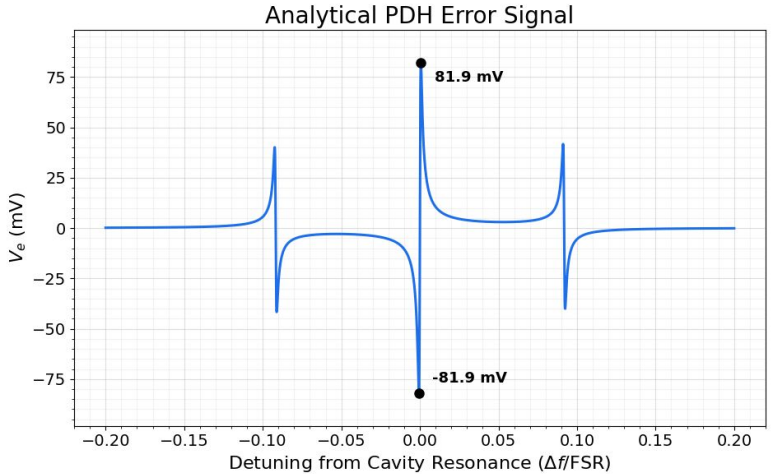
- Under-coupled bowtie cavity
  - Flat mirror: 1000 ppm transmittance
  - Curved mirror: 3000 ppm transmittance
- FSR: 393 MHz
- Finesse: 785*
- FWHM: 500 kHz*
- Modulated EOM at 36.07 MHz for PDH locking



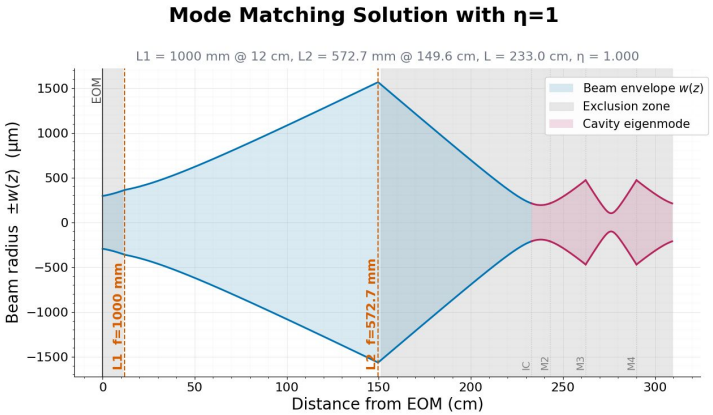
** The cavity mirror transmittances were later measured to be much lower than the listed values. The finesse was much higher and the FWHM was much lower.*

Measured PDH error signal was ~3 orders of magnitude below analytical value

- Measured 200 uV error signal amplitude
  - ~3 orders of magnitude below analytical value
- Suspected from cavity misalignment
- Moved and redesigned experiment in new lab



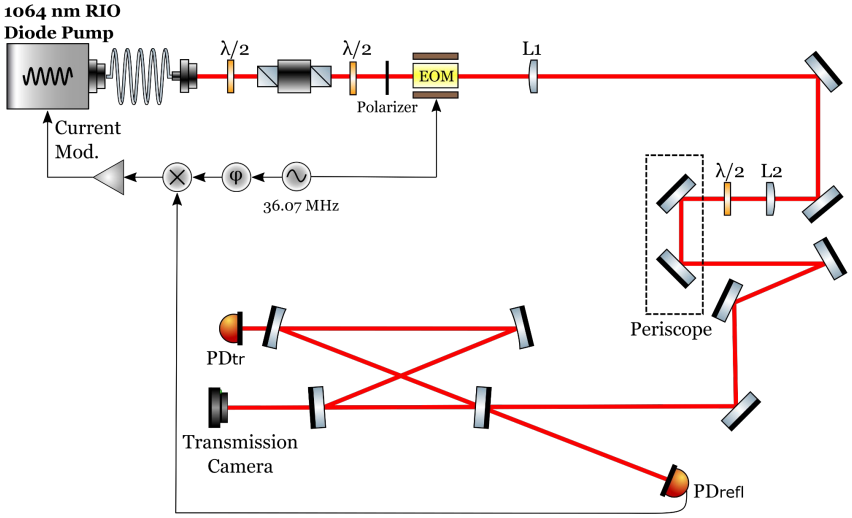
Optimal Mode Matching Solution for Positioning Sensitivity



- Mode matching: find a lens pair to match beam to the cavity eigenmode
- Vectorized grid search to find candidate solutions with perfect mode matching
- Rank candidates by tolerance to displacements from design position
- Solution can tolerate a 17 cm/5 cm displacement in L1/L2 until a 5% decrease in mode matching efficiency

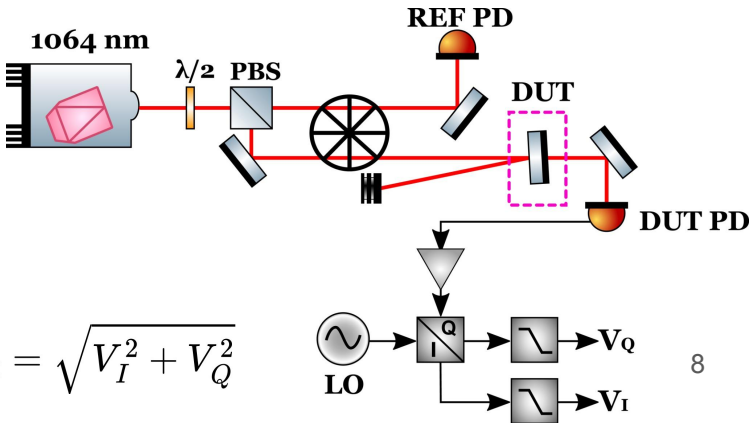
Revised Experimental Setup with Fiber Coupled Diode Laser

- Strong flashing of TEM00
- Unable to observe PDH error signal or reflection dips
- Flat mirrors had specified transmittance of 100 pm rather than 1000 ppm
    - Was unable to observe flashing with curved mirror as the input coupler



Characterizing Cavity Mirror Transmittance with Coherent Detection

- Chopper intensity modulates incident beam at 270 Hz
- LED & PD on chopper provides LO for square wave modulation
- Normalized with control (no DUT) to account for power division
- Measured for s/p polarization from 0 to 10 degree AOI
- Sensitive to 1 ppm with a SNR of 230

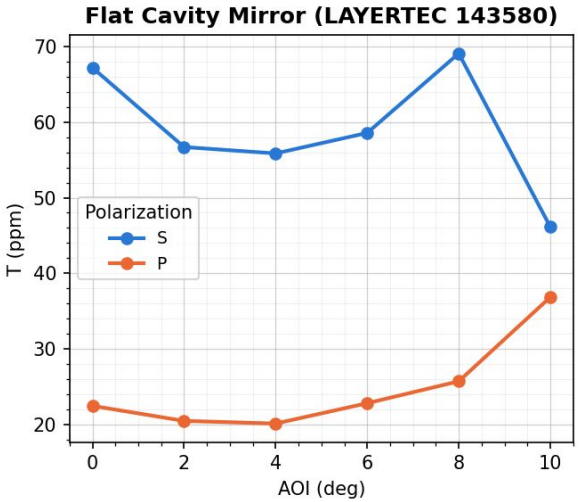


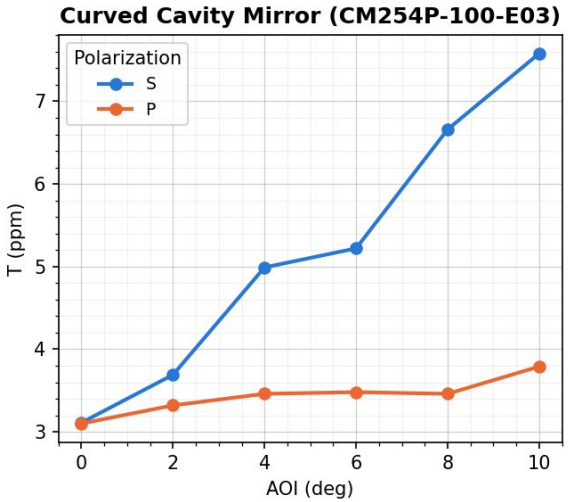
$$T = \frac{V_{DUT}^{DUT}/V_{REF}^{DUT}}{V_{DUT}^{CONTROL}/V_{REF}^{CONTROL}}$$

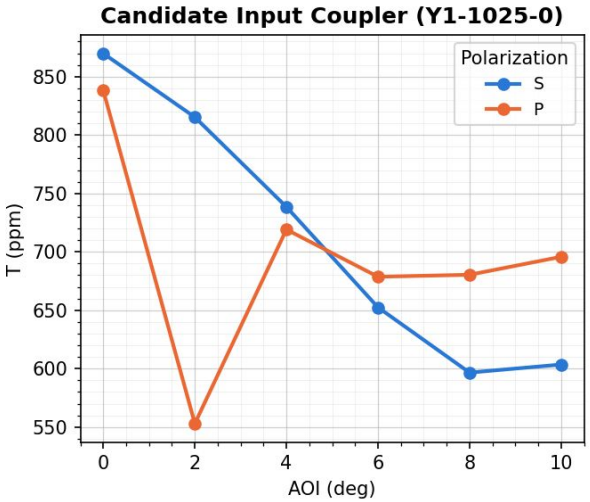
$$V_R = \sqrt{V_I^2 + V_Q^2}$$

Cavity Mirror Transmittance Measurements

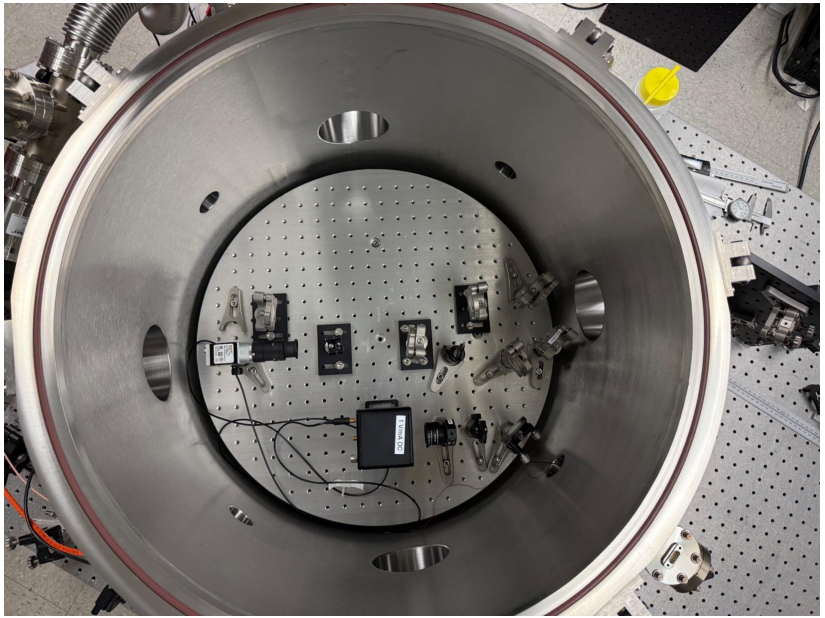
- Transmittance of curved mirror was much lower than spec
- A 597 ppm Y1 input coupler overcouples cavity — greater PDH error signal







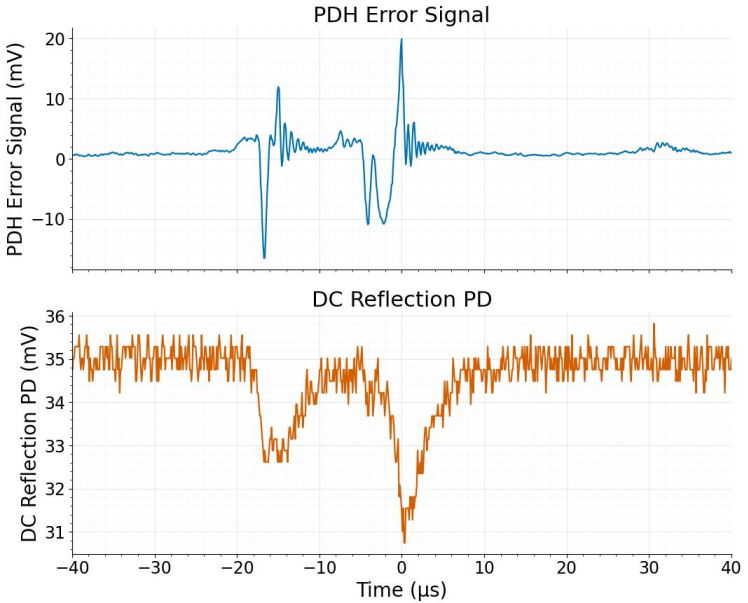
Reformed Cavity with 597 ppm Input Coupler





Observed PDH Error Signal and Reflection Dips

- Persistent TEM00 Flashing after alignment
- Measured PDH error signal: 36.42 mVpp
- Measured reflection dip: 12.1%
  - 43% expected from transmittances
- Attempted lock — laser noise contaminated error signal
  - Mitigated with improved laser stability





Acknowledgements

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