

Cavity-Enhanced Sum Frequency Generation For 2 μm Interferometer Readout

Project Presentation
LIGO SURF 2026

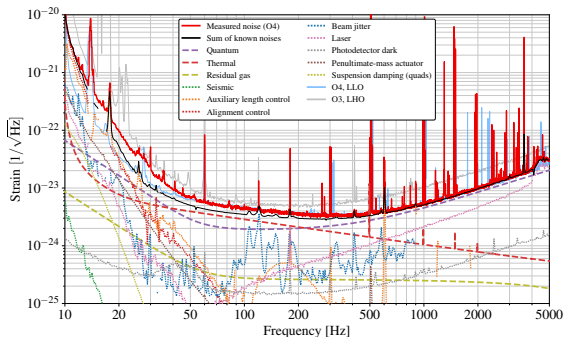
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Supervisor: Prof. Rana Adhikari

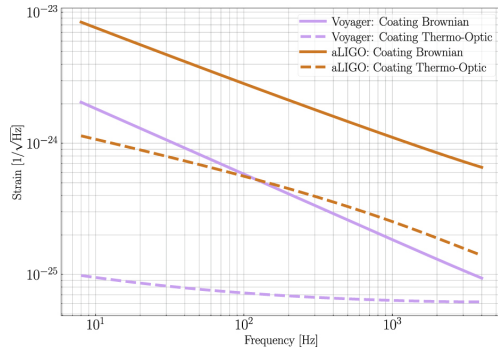
Caltech



What are we trying to solve?



Thermal noise limits detector sensitivity
in the most sensitive band



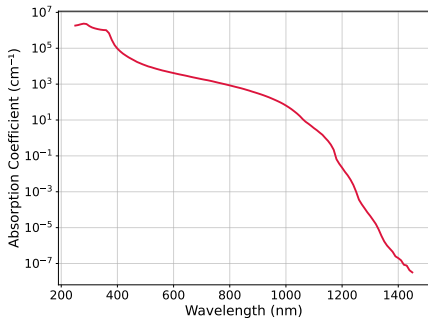
Crystalline Silicon at cryogenic operation
reduces thermal noise

Thermal Noise Reduction → Cryogenic Silicon Optics

Source: [1] Capote *et al.*, Phys. Rev. D **111**, 062002 (2025) [2] Adhikari *et al.*, Class. Quantum Grav. **37**, 165003 (2020)

What are we trying to solve?

LIGO uses 1064 nm as its main laser



However, Silicon is opaque to 1064 nm.

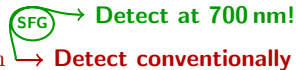
→ **But transparent to 2 μm**

Thermal Noise → Cryogenic Silicon Optics → Switch to 2 μm → Detect conventionally

At 2 μm , detectors are not as good!

Detector	QE at 2 μm (%)
HgCdTe	~ 94%
InGaAs	~ 87%
Ext. InGaAs	~ 75%

Using the techniques of non-linear optics, we can upconvert 2 μm → 700 nm, then detect the signal using > 99% QE photodetectors.



Sum Frequency Generation

In nonlinear optics, the optical response can be described by expressing the polarization as a power series in electric field:

$$\vec{P}(t) = \epsilon_0 \chi \vec{E}(t)$$

$$\vec{P}(t) = \epsilon_0 [\chi^{(1)} \vec{E} + \chi^{(2)} \vec{E}^2 + \chi^{(3)} \vec{E}^3]$$

Laser Beam:

$$\vec{E} = E_1 e^{i\omega_1 t} + E_2^* e^{-i\omega_2 t}$$

$$\Rightarrow 2\omega_1 \quad 2\omega_2 \quad \boxed{\omega_1 + \omega_2} \quad \omega_1 - \omega_2$$

Energy Conservation

$$\omega_1 + \omega_2 = \omega_3$$

Phase-Matching Condition

$$\vec{k}_1 + \vec{k}_2 = \vec{k}_3$$

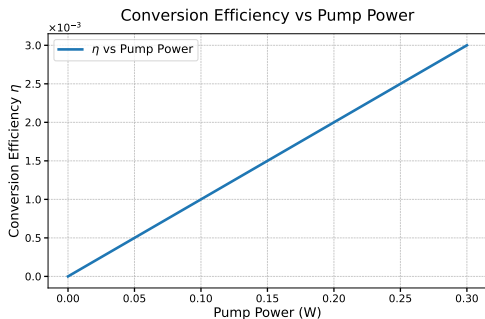


Bridging to the Experiment

Single-Pass SFG Limitation

Generated sum-frequency power depends on the pump intensity:

$$P_{\text{SFG}} \propto \eta_{\text{nl}} I_{\text{pump}} L^2$$



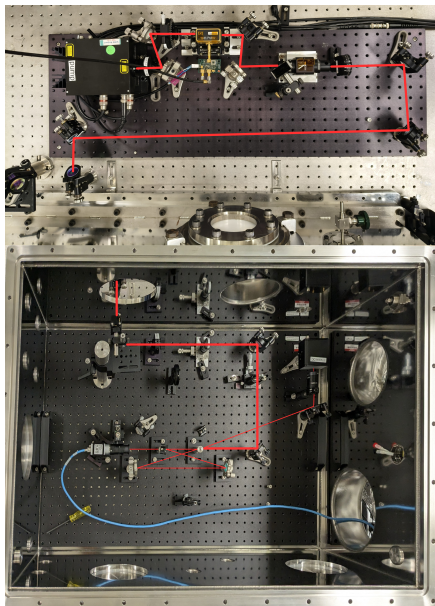
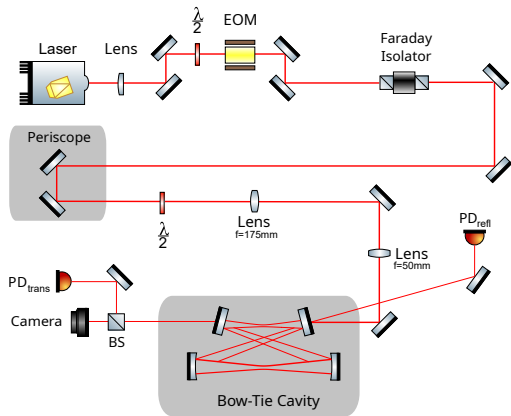
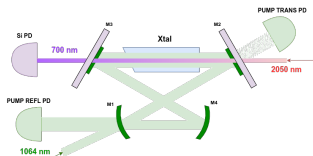
The Cavity-Enhanced Solution



A **resonant optical cavity** massively builds up circulating light intensity to drive high conversion efficiency.

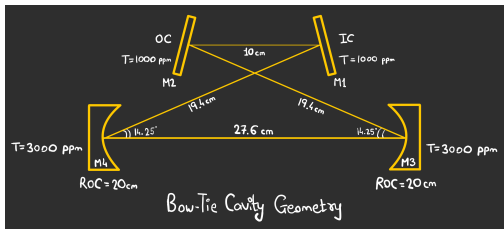
[1] D. Raghunathan, *Upconverted Light for GW Detector Control and Readout* LIGO-T2400259-v1

Experimental Setup

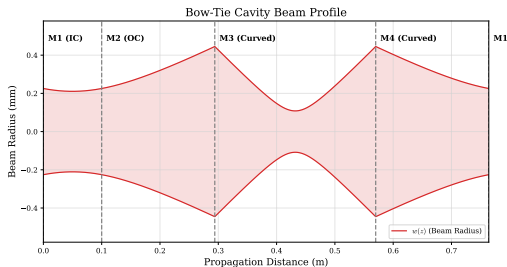


Graphic by: F. Salces Carcoba

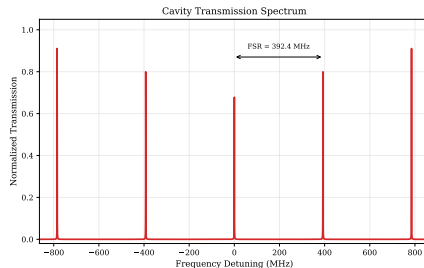
Bow-Tie Cavity Characterization



Cavity Geometry



Eigenmode Profile



Transmission Spectrum

Parameter	Value
Round-trip length	76.4 cm
Free Spectral Range	392.4 MHz
Finesse ($\mathcal{F}$)	783
Resonance Linewidth	0.5 MHz
Power enhancement	63
Beam waist	105 μm
Stability	0.094

Calculated Parameters

Pound-Drever-Hall (PDH) Locking

Phase Modulation (EOM)

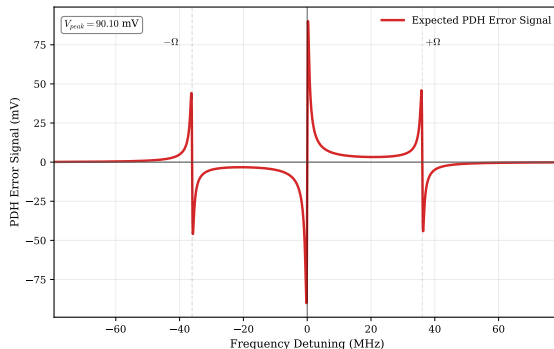
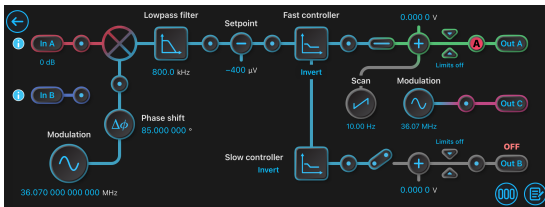
$$E_{\text{inc}} = E_0 e^{i(\omega t + \beta \sin \Omega t)}$$

Bessel functions expansion reveals the sidebands:

$$E_{\text{inc}} \approx E_0 [J_0 e^{i\omega t} + J_1 e^{i(\omega+\Omega)t} - J_1 e^{i(\omega-\Omega)t}]$$

- ▶ Anti-symm dispersion curve
- ▶ Lock frequency to cavity resonance

Expected PDH Error Signal

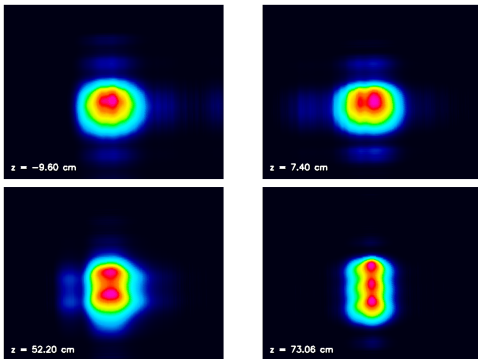
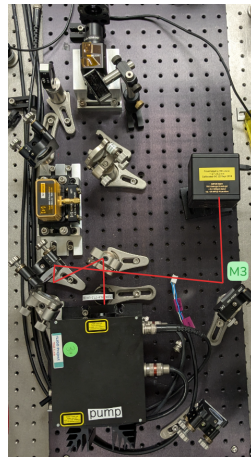


Central Challenge:
Weak PDH Error Signal

Investigation: Spatial Profile

Higher order spatial modes observed

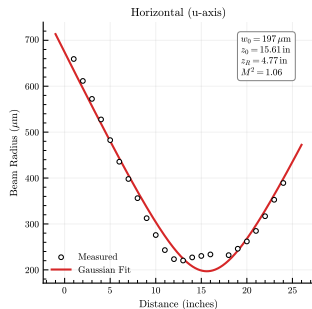
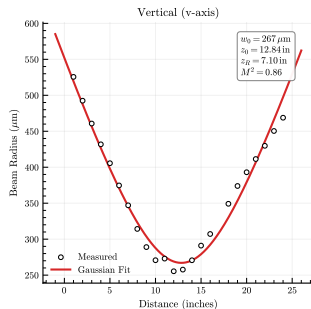
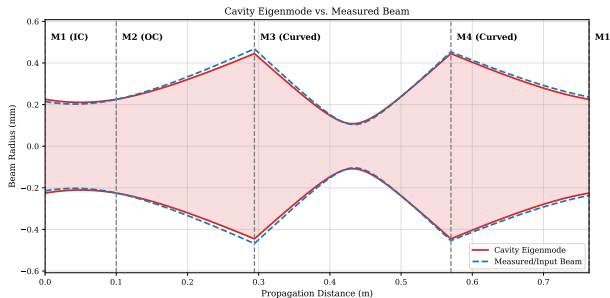
Evolution of Beam Profile



- Temperature setpoint sweep, operating current variation, lens alignment - Neither improved the spatial profile.

Investigation: Mode-Matching

However, profiling after the lens telescope showed excellent beam shape at cavity input.

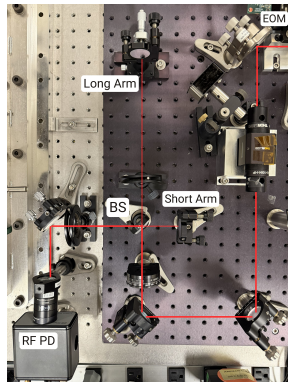


- ▶ Propagated: $q = -1.645 + i 4.769 \text{ in}$
- ▶ Eigenmode: $q_{\text{cav}} = -1.978 + i 5.117 \text{ in}$

Mode-Matching Efficiency

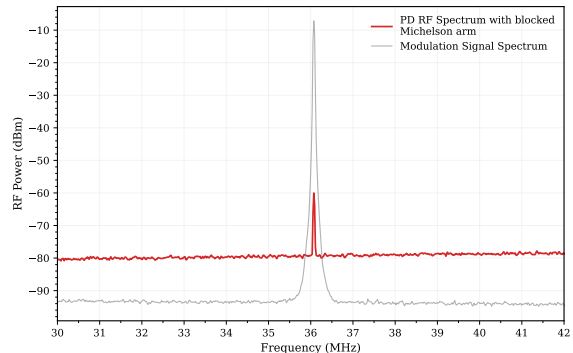
$$\eta = 99.7\%$$

Michelson Interferometer Setup



Michelson interferometer converts the EOM's phase modulation into detectable intensity modulation.

RF Spectrum (One Arm Blocked)



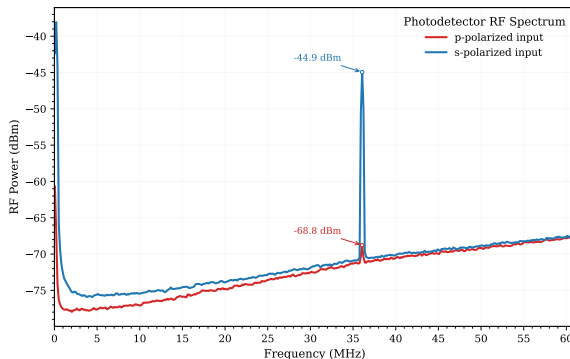
► Observation:

Sideband verified at modulation frequency, but persists even when one arm is blocked.

Investigation: Polarization

Residual Amplitude Modulation can arise if incident beam is not aligned within 1° to the EOM's crystal axis.

RF Spectrum with Polarization Filtering



Laser Polarization

Transmitted power measured while sweeping polarizer trans-axis through 360° :

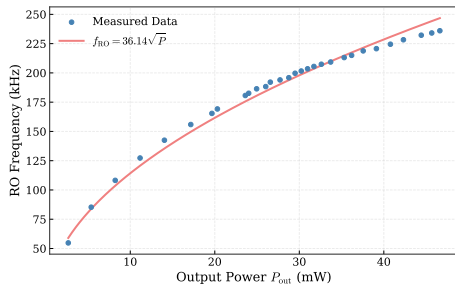
$$\frac{P_{\max}}{P_{\min}} \approx 4 : 1$$

- ▶ Corresponds to an ellipticity of 0.5 in the laser output.
- ▶ A HWP cannot correct this!
Fix: Polarizer retained despite loss in power.

Investigation: Relaxation Oscillations

Stray Noise Peak

- ▶ Observation: Sharp 200 kHz peak present throughout experiment, even without modulation.
- ▶ Hypothesis: Relaxation Oscillations (RO)
- ▶ Changes in pump power $\Rightarrow$ Damped oscillations in output power



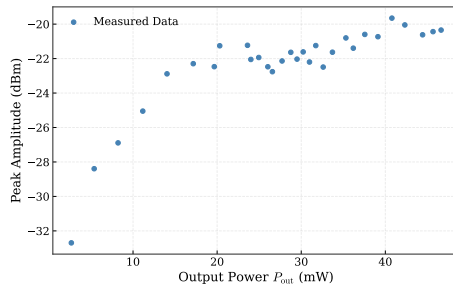
(a) f_{RO} vs $\sqrt{P_{out}}$

Testing the Hypothesis

$$f_{RO} = \frac{1}{2\pi} \sqrt{\frac{\gamma-1}{T_c T_g}}$$

γ : Pump Parameter
 T_c : Cavity Damping Time
 T_g : Upper State Lifetime

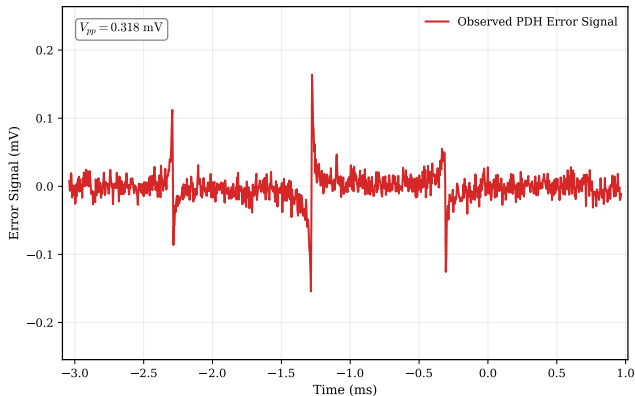
$$\gamma-1 \propto \sqrt{P_{out}} \Rightarrow f_{RO} \propto \sqrt{P_{out}}$$



(b) RO peak amplitude

Returning to PDH Locking

After all these checks & improvements, finally, we looked for the error signal again -

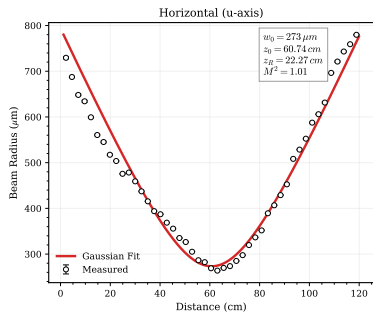
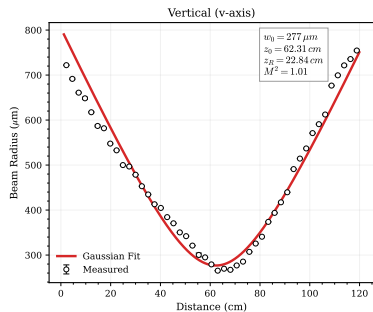
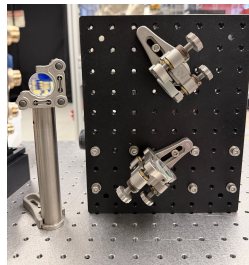
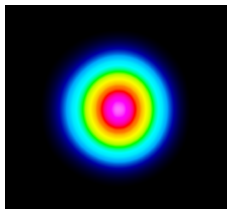
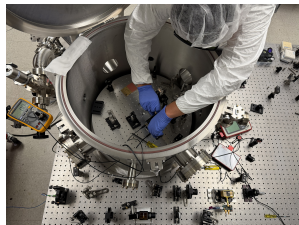


Three orders of magnitude weaker than expected

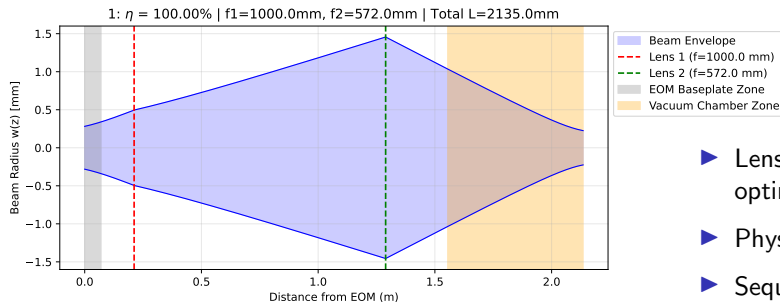
Decision to replace the NPRO laser and start anew.



RIO Laser Characterization & Setup

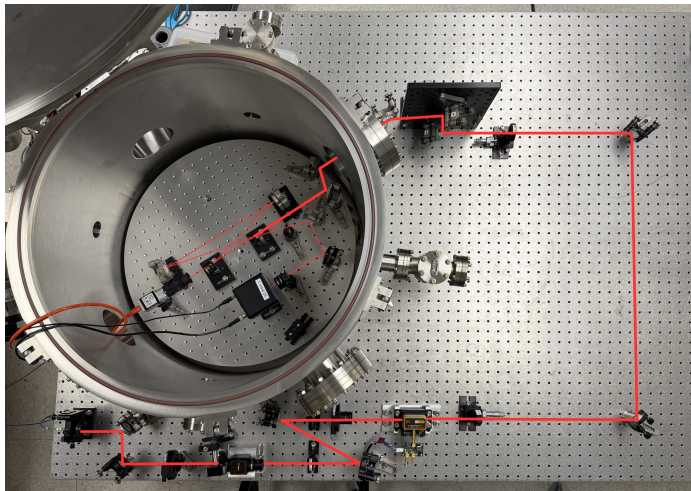


Mode-Matching Design



Peak Efficiency:	100.00 %
Robust Efficiency:	99.99 %
Lens 1:	$f = 1000.00\text{ mm}$
Lens 2:	$f = 572.00\text{ mm}$
Distance 1:	$d_1 = 162.1\text{ mm}$
Distance 2:	$d_2 = 1111.7\text{ mm}$
Distance 3:	$d_3 = 871.3\text{ mm}$
Total Dist:	$D = 2145.1\text{ mm}$

- ▶ Lens combination & distance optimization
- ▶ Physical spatial constraints
- ▶ Sequential Profiling:
 1. Place first computed lens
 2. Re-profile the beam
 3. Calculate a single-lens solution based on the new profile.
- ▶ Ranked for **robustness** against alignment errors



Some upgrades implemented from the lessons learnt:

- ▶ Robust mode-matching solution.
- ▶ Well-characterized laser
- ▶ Polarization control & checks
- ▶ Faraday isolator & mirror placement
- ▶ Steering control at each step
- ▶ Airflow and acoustic isolation with vacuum chamber (soon)

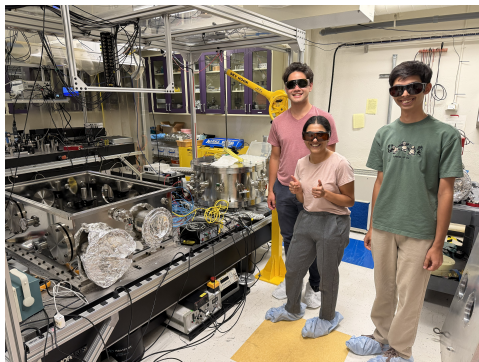
Cavity Aligned & Flashing Observed!



- ▶ Cavity Optics Aligned
- ▶ Stable TEM₀₀ flashing observed
- ▶ Ready to obtain strong PDH error signal and attain a stable lock

Acknowledgements

- ▶ I'm deeply grateful to Radhika Bhatt for her mentorship and for making the project so enjoyable.
- ▶ Thank you to Prof. Rana Adhikari for his guidance and insights.
- ▶ Special thanks to Kato for being an excellent project partner.
- ▶ Thank you to Georgia, Peter, Helen, Chris, Masaya, & everyone in the LIGO Lab for always being generous with their time and expertise.
- ▶ Finally, I thank the LIGO SURF Program and Caltech for making this unforgettable experience possible.



Thank You!