Low-noise Nonlinear Cavity for Cryogenic Interferometers

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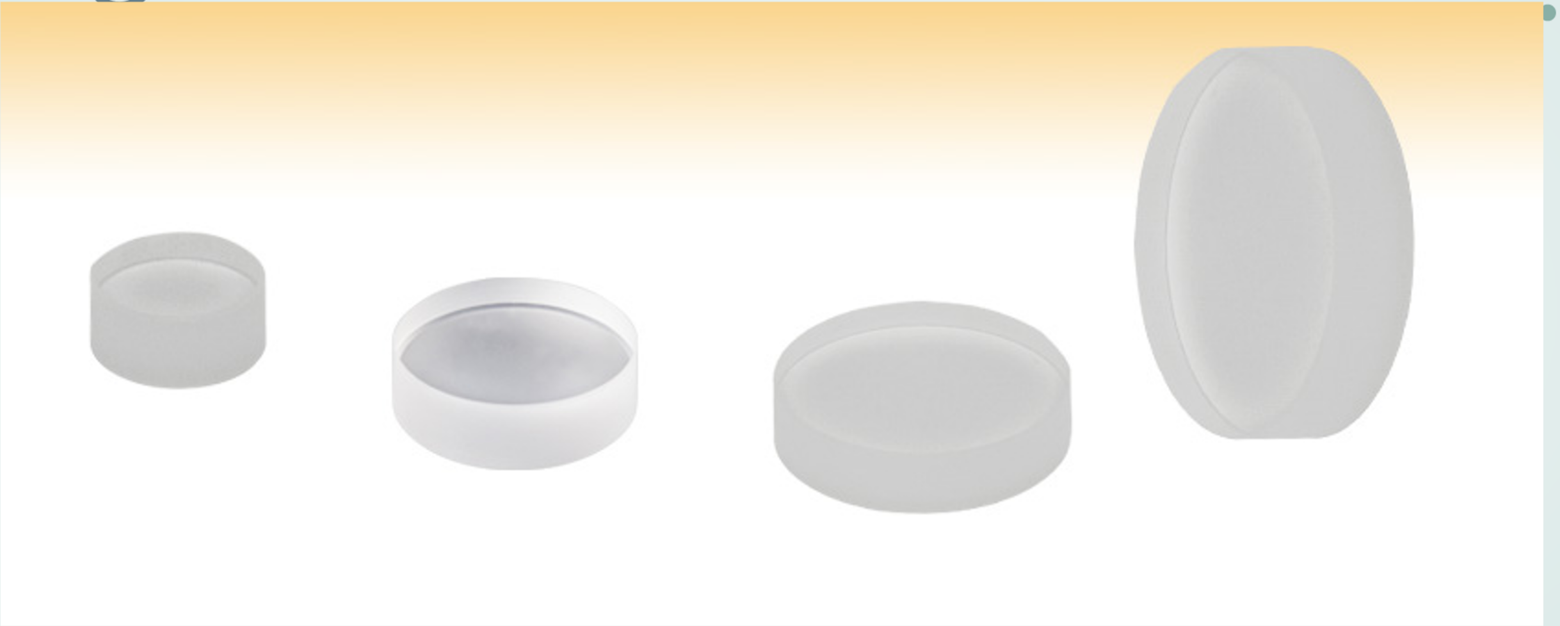
Motivation

Cryogenic GW Detection



Fused Silica Mirror
Image Credits:
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=141

What needs to change?

1) Crystalline silicon test masses held at 123 K.
2) Laser wavelength (> 1500 nm).

R. X. Adhikari et al. “A Cryogenic Silicon Interferometer for Gravitational-wave Detection”. July

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Degenerate Optical Parametric Oscillator (DOPO)

Degenerate Optical Parametric Oscillator

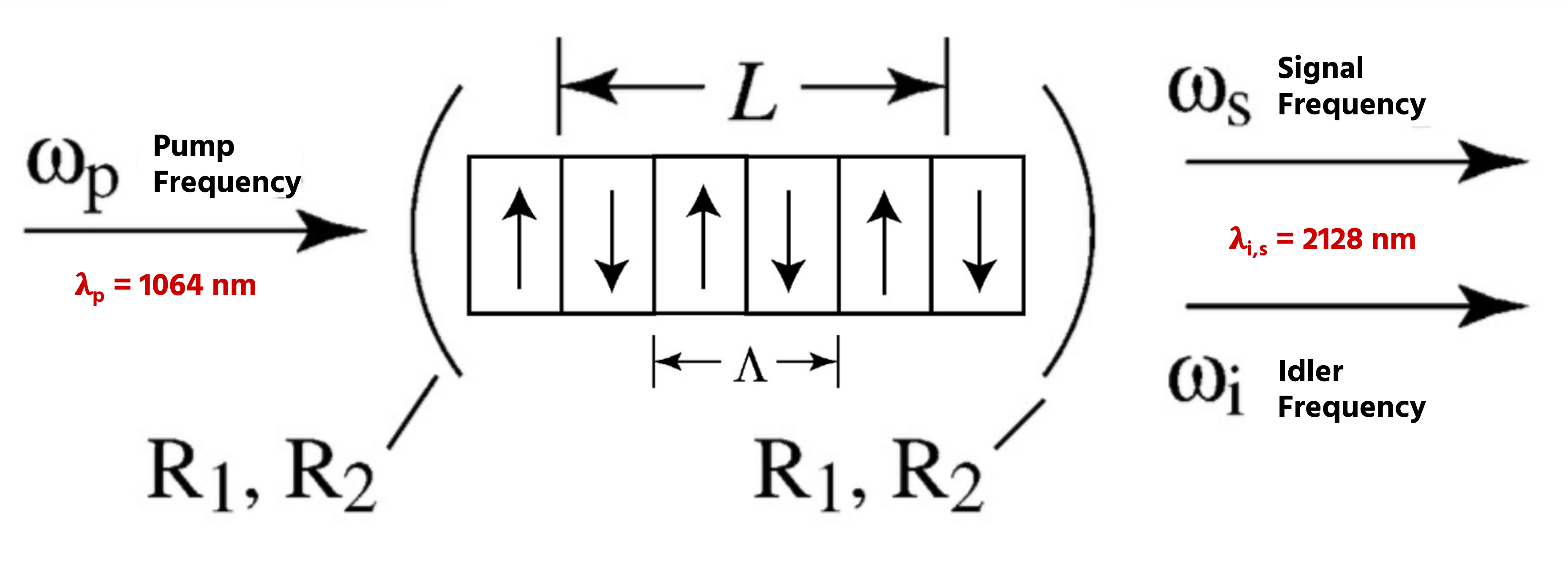

Figure 1. *Boyd, Robert (2008).* P 109

Goals

1) Design an experiment to measure DOPO's frequency noise.
2) Understand noise injections in the frequency conversion process.
3) Developing noise mitigation techniques.

Degenerate Optical Parametric Oscillator

- Momentum

1 Conservation: $\frac{2\pi}{\Lambda}$

$$\Delta k = K_p - (k_i + k_s) - $$

2 Energy Conservation:

$$\omega_p = (\omega_i + \omega_s)$$

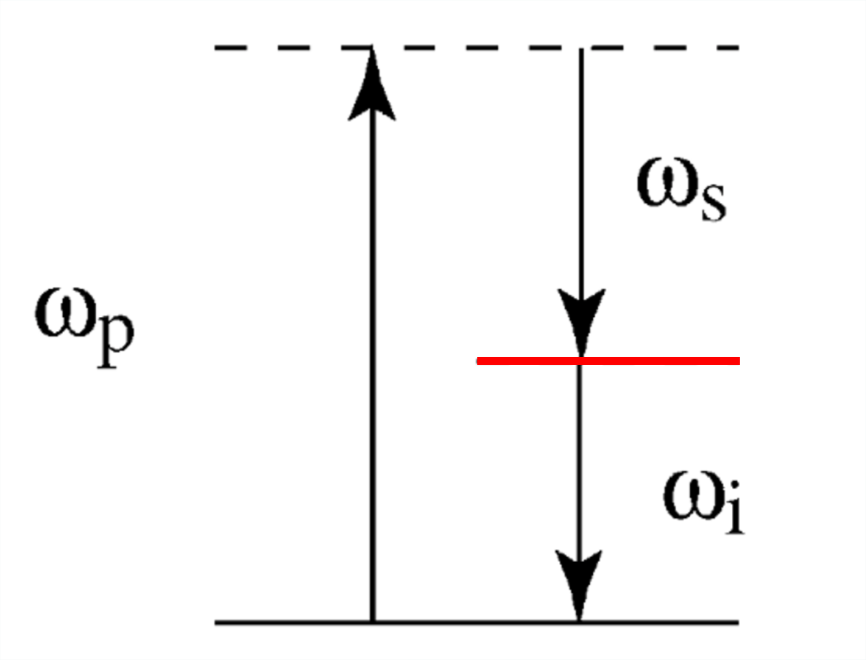

Figure 2. *Boyd, Robert (2008).* P 109

Dispersion Near Degeneracy

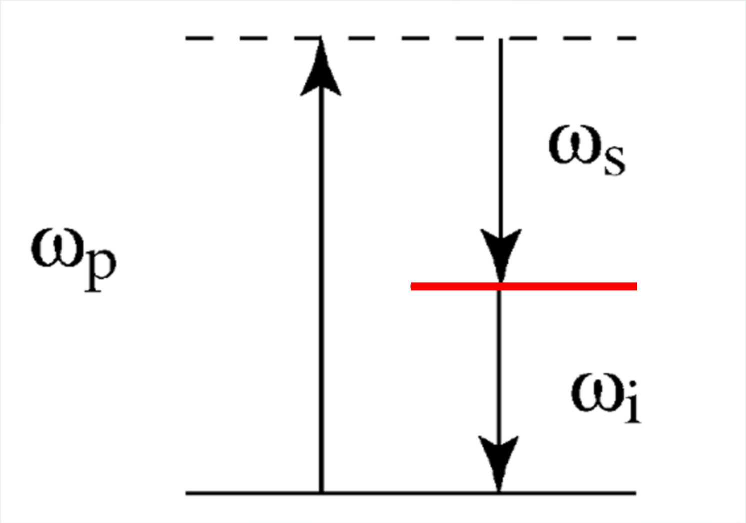

Figure 2. *Boyd, Robert (2008).* P 109

- Phase-matching condition:
  - Δk = 0
- Near degeneracy:

1. Assume $\omega_i = \frac{\omega_p}{2} - \Delta\omega$ and $\omega_s = \frac{\omega_p}{2} + \Delta\omega$.
2. Taylor expand around $\frac{\omega_p}{2}$ to get $k(\omega_1) - 2k(\frac{\omega_1}{2}) + \beta\Delta\omega^2 - \frac{2\pi}{\Lambda(T)} = 0$

Dispersion Near Degeneracy

3. Finally, we find that $\omega_{i,s} = \frac{\omega_p}{2} \pm \sqrt{\frac{2\pi}{\beta \Lambda(T)} - \frac{\omega_p(n_p - n_s)}{\beta c}}$

BUT…

$$\Lambda(T) = \Lambda_0(1 + \alpha \Delta T) \qquad n_{p,s} = n_z + x_1(T - 298) + x_2(T - 298)^2$$

- **n_z using Sellmeier equations.**
- **$X_{1,2}$: parabolic coefficients.**

Aerie. Ady et al. "Temperature-dependant Dispersion Equations for $KTiOPO_4$ and $KTiOASO_4$". December 2003.
Kato, Kiyoshi et al. "Sellmeier and thermo-optic dispersion formulas for KTP". 2002.

Constants

Quantity	Symbol	Value	Units
Pump frequency	ω_p	980×10^{14}	Hz
Signal and idler frequency	$\omega_{i,s}$	490×10^{14}	Hz
Nominal periodic poling value	Λ_0	38.85	μ m
Pump refractive index	n_p	1.82	–
Signal refractive index	n_s	1.80	–
Thermal expansion coefficient	α	6.7×10^{-6}	$\frac{m}{k}$
Anomalous dispersion	β	-108×10^{-30}	$\frac{s^2}{m}$
Speed of light	c	3×10^8	$\frac{m}{s}$

Table 1. Temperature tuning constants

Aerie. Ady et al. "Temperature-dependant Dispersion Equations for $KTiOPO_4$ and $KTiOASO_4$". December 2003.
Kato, Kiyoshi et al. "Sellmeier and thermo-optic dispersion formulas for KTP". 2002.
Refractiveindex.info

Temperature Tuning Curve

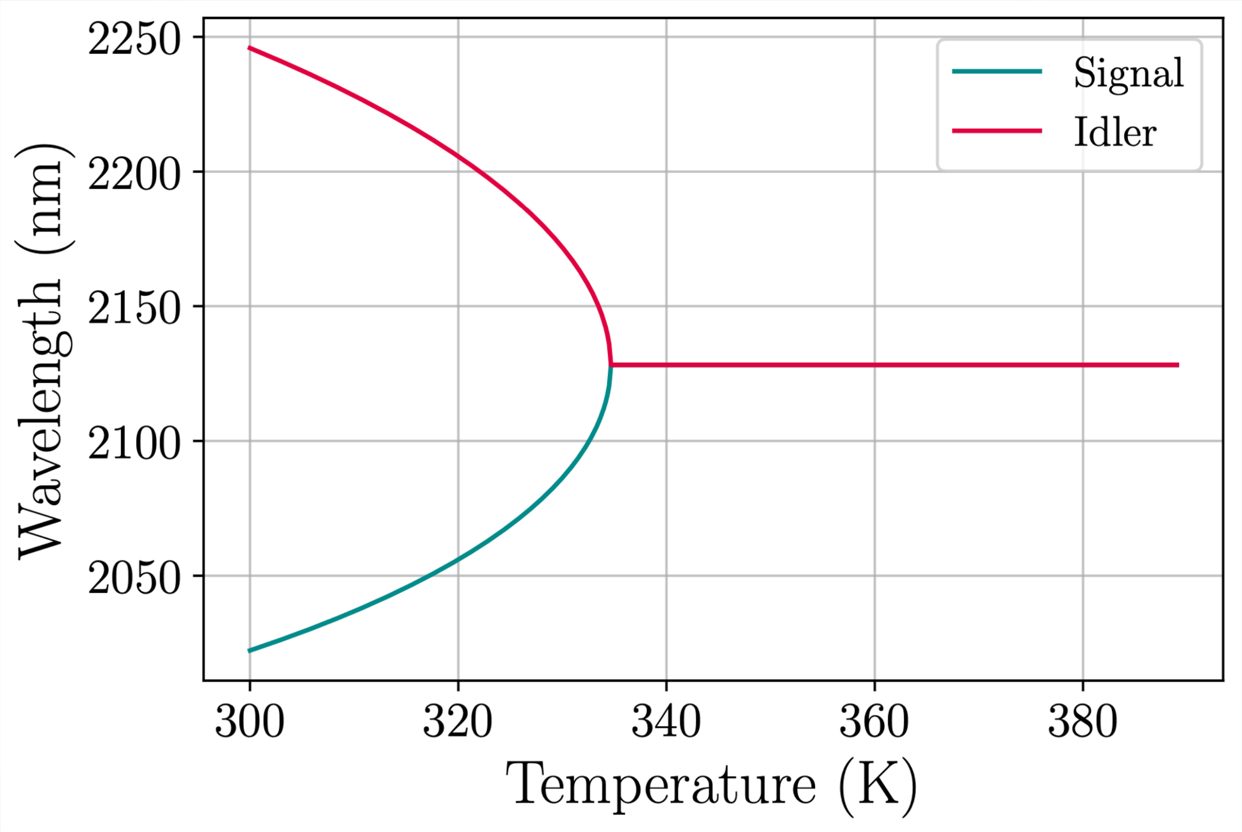

Figure 4. Temperature Tuning Curve

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Experimental Setup

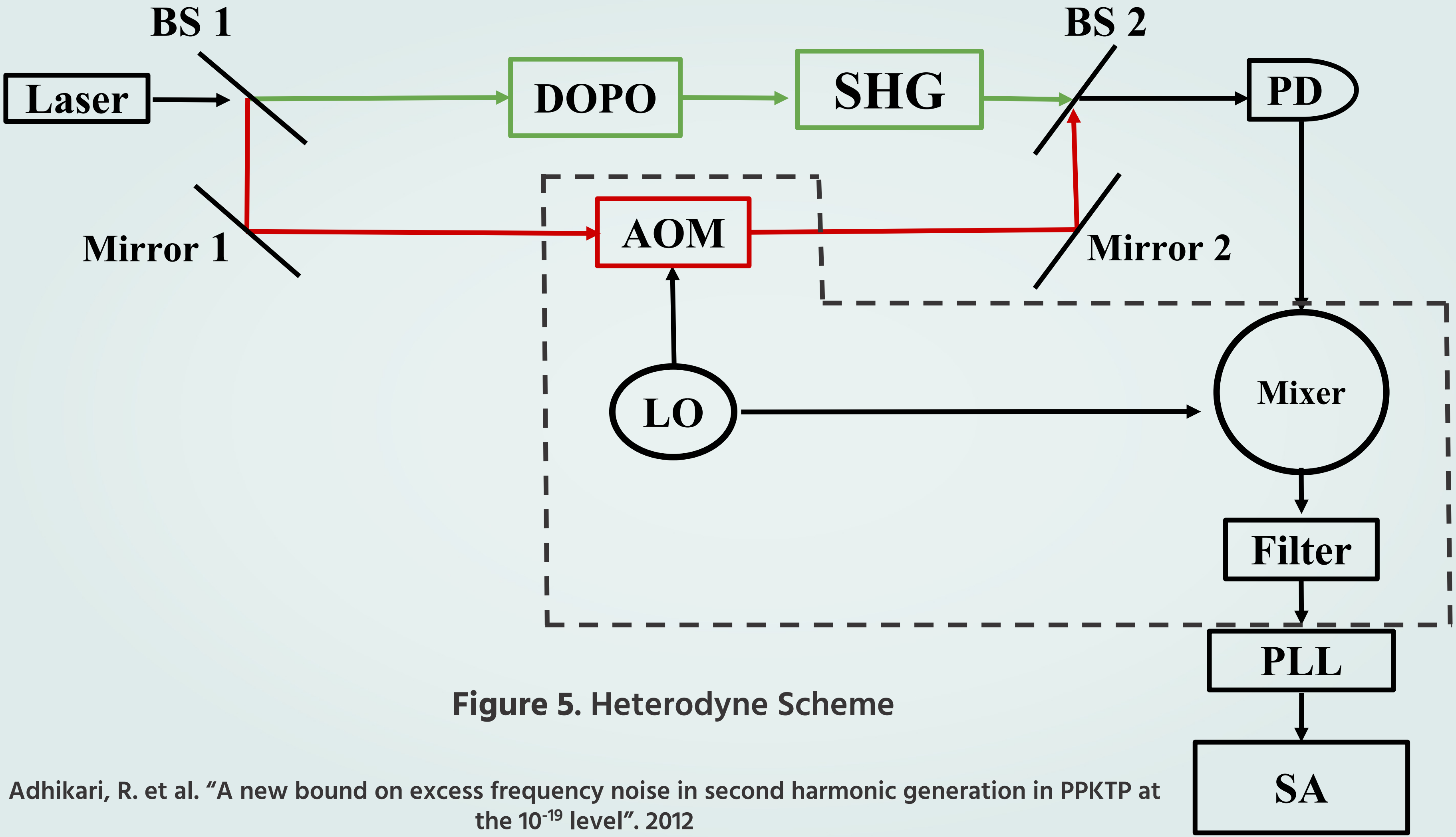


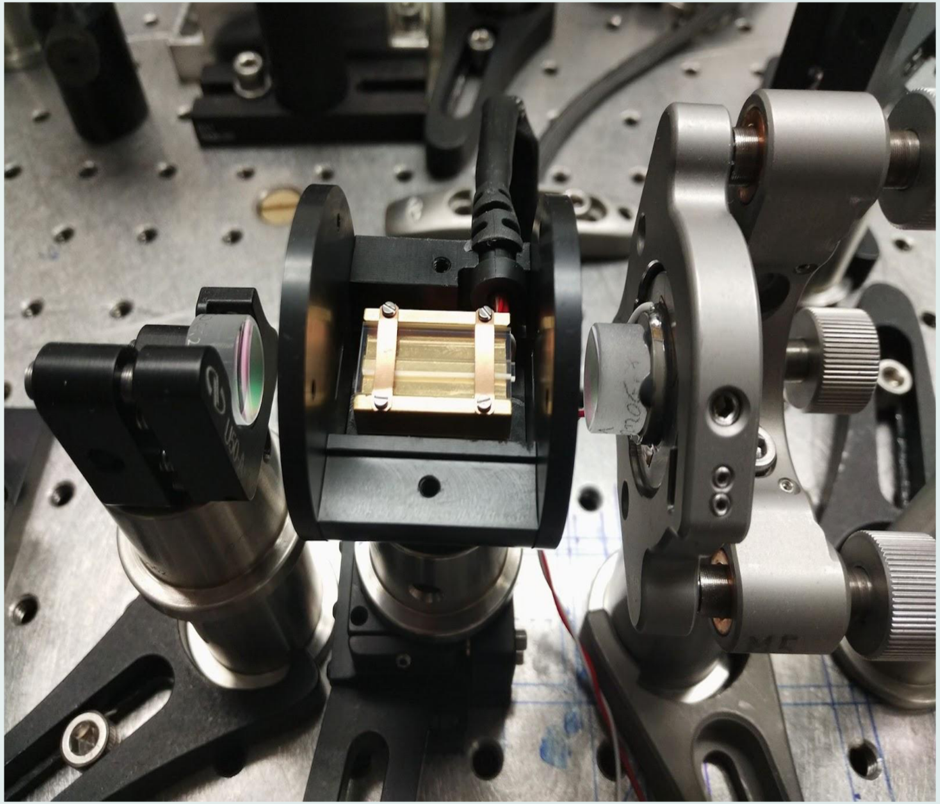
Figure 5. Heterodyne Scheme

Adhikari, R. et al. “A new bound on excess frequency noise in second harmonic generation in PPKTP at the 10^{-19} level”. 2012

4 Future Work

Future Work

- Measure DOPO's frequency noise.
- Develop noise mitigation systems.



DOPO Setup

Acknowledgements

- Francisco Salces Carcoba, Anchal Gupta, and Rana Adhikari.
- National Science Foundation.
- LIGO Lab.
- LIGO SURF mentors and interns.

Questions

Dispersion Near Degeneracy

3. Since $k = \frac{n\omega}{c}$ we get $\frac{n_p\omega_p}{c} - \frac{n_s\omega_p}{c} + \beta\Delta\omega^2 - \frac{2\pi}{\Lambda(T)} = 0$.

4. Finally, we find that $\omega_{1,s} = \frac{\omega_p}{2} \pm \sqrt{\frac{2\pi}{\beta\Lambda(T)} - \frac{\omega_p(n_p - n_s)}{\beta c}}$

BUT...

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- n_z using Sellmeier equations.
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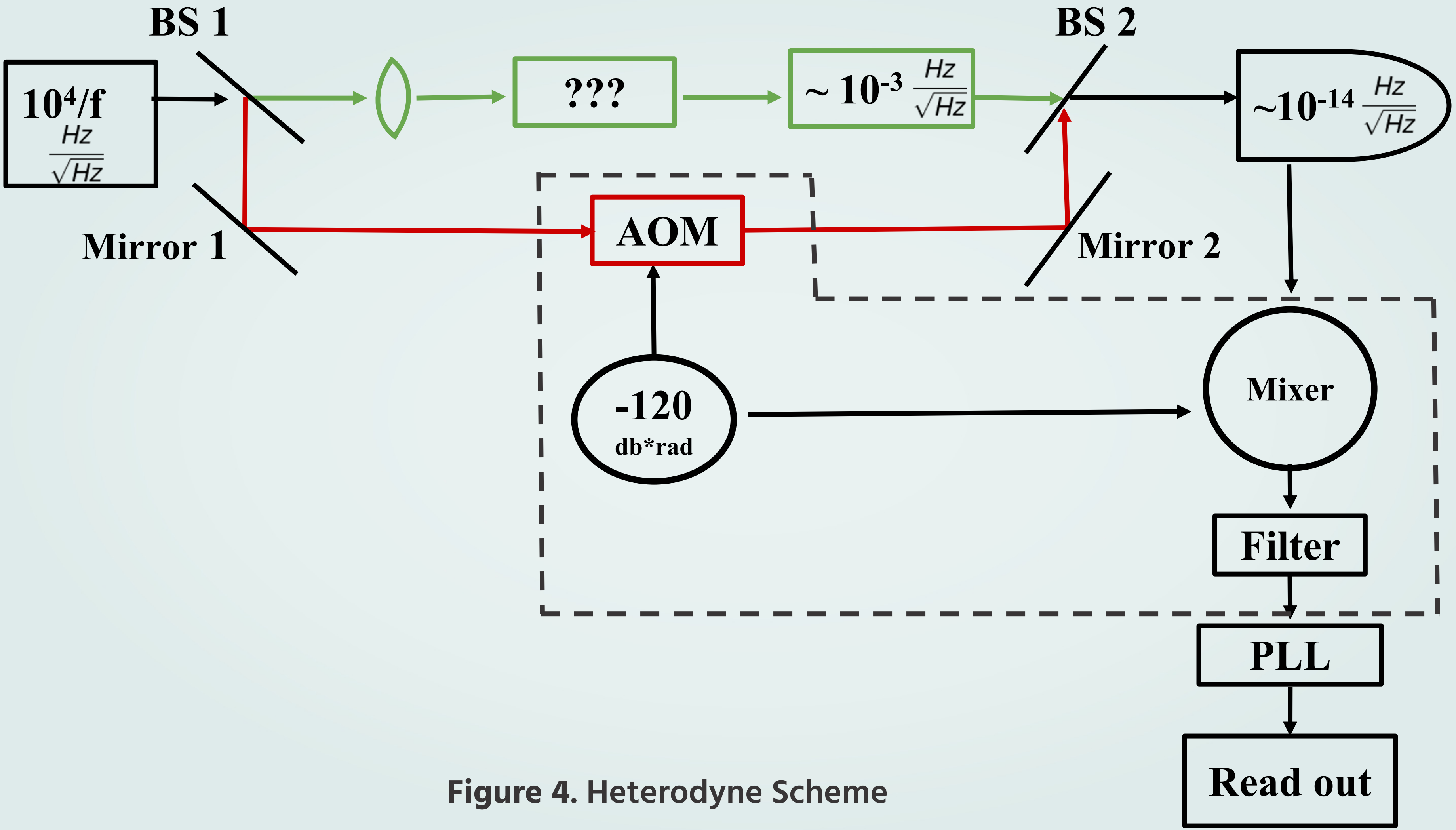
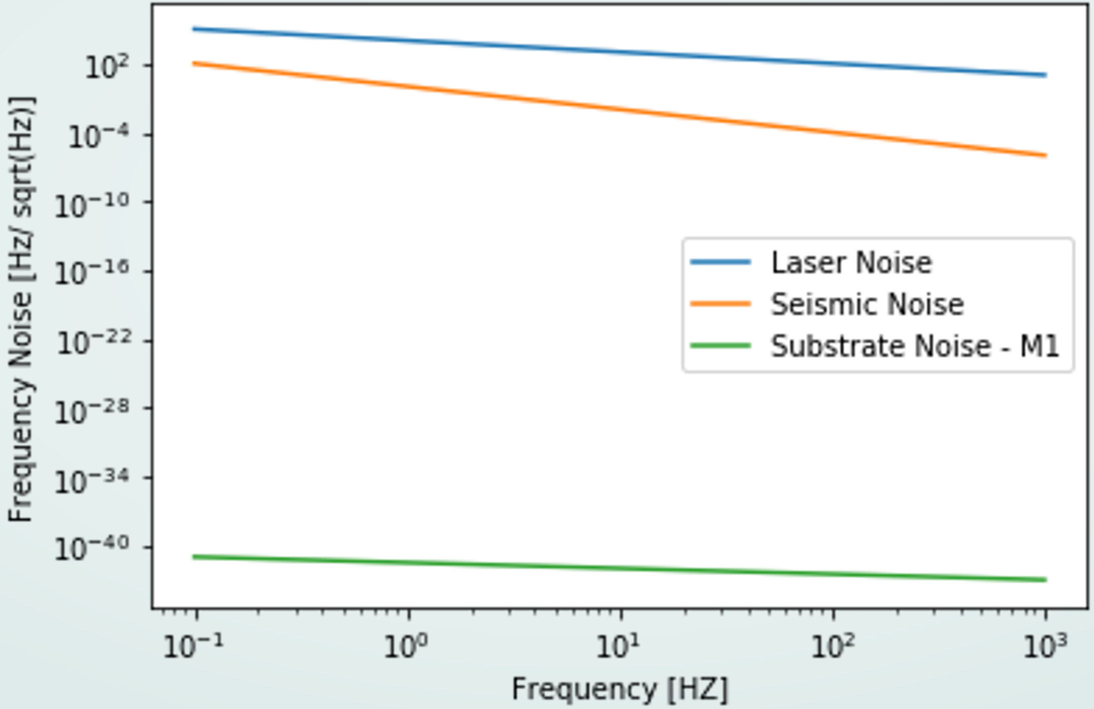


Figure 4. Heterodyne Scheme

Noise Estimates



Noise Estimates

- **Thermo-refractive:**

$$S(f) = \frac{4a\beta^2}{\pi^3 w^4 f^2}\frac{\kappa k_B T^2}{\rho^2 C^2}$$

- **Thermo-optic:**

$$S_{TO}^{\Delta z} \simeq S_{TO}^{\Delta T}\left(\bar{\alpha_c} d - \bar{\beta}\lambda - \bar{\alpha_s} d \frac{C_c}{C_s}\right)^2$$

where $S_{TO}^{\Delta T} = \frac{2\sqrt{2}}{\pi}\frac{k_B T^2}{r_G^2\sqrt{\kappa C \omega}}$