A Laser Heterodyne Polarimeter to Search for VMB
with ALPS IIc Hardware

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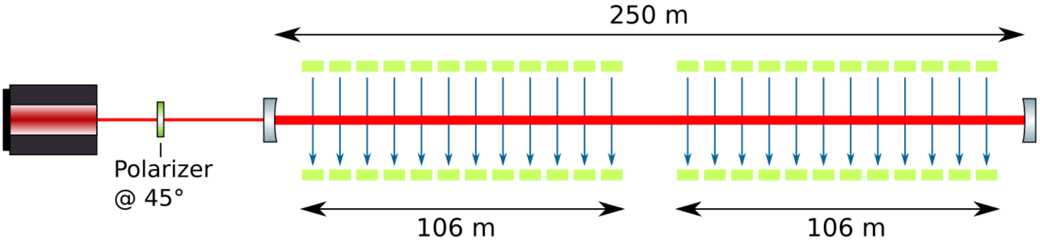
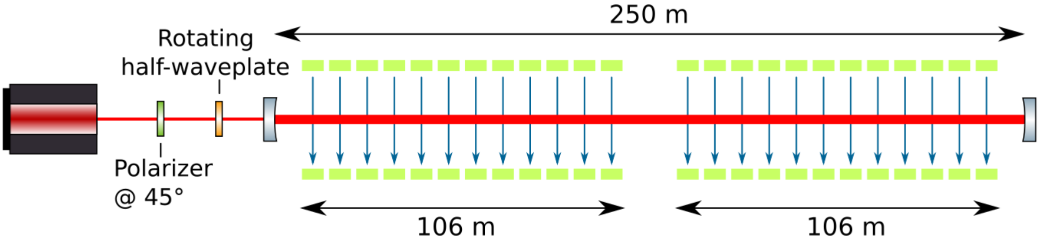
ALPS IIc hardware for VMB experiment



For incident light polarized linearly at 45° to $\vec{B}$:

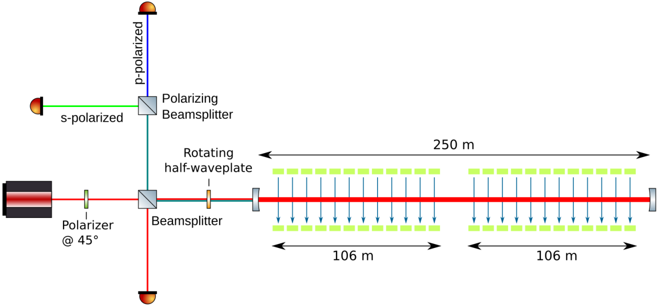
- $212\,\mathrm{m}$ HERA dipole string: $\psi_1 \approx 6.9 \times 10^{-14}\,\mathrm{rad}$
- Cavity multiplier: $G_{\mathrm{cav}} \approx 8 \times 10^4$
- $\psi_N = G_{\mathrm{cav}} \cdot \psi_1 \approx 8 \times 10^4 \cdot \psi_1 \approx 5.5\,\mathrm{nrad}$
- How to sense this?

Make ψ Time Dependent



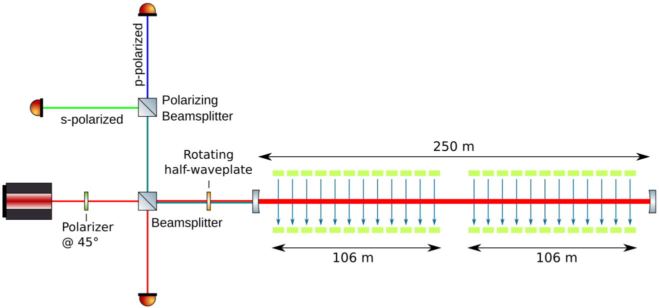
- Insert rotating half waveplate to rotate incident polarization through angle $\theta(t)$
- Now $\psi_N(\theta) = \psi_N \sin(2\theta)$ where $\theta(t) = 2\omega_\pi \cdot t$

Split Reflected Light's Polarization Components



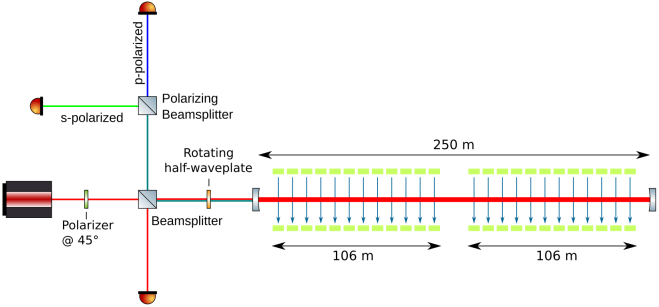
- Light reflects from the cavity back through the rotating half-waveplate.
- This 'de-rotates' the rotation given by the forward pass through.

Split Reflected Light's Polarization Components



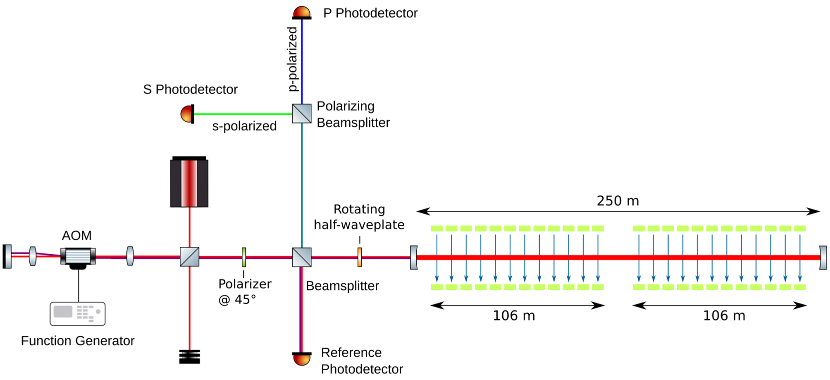
- Reflected light from the beamsplitter is split into the s-pol and p-pol components.
- Relative phase of these components varies with angular frequency $4 \cdot \omega_\pi$

Split Reflected Light's Polarization Components



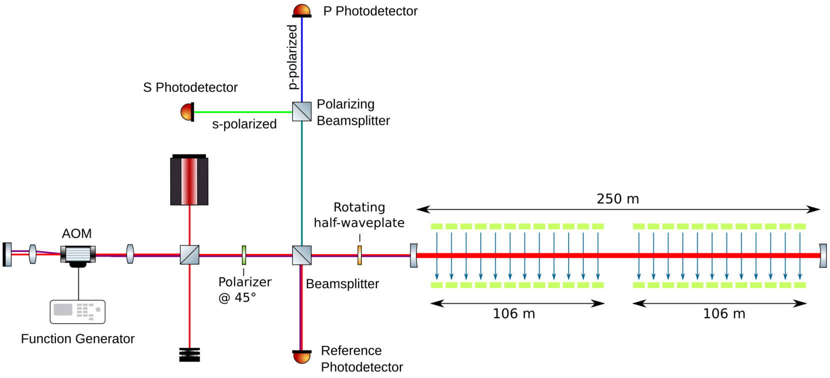
- Amplitude of relative phase variation is $4 \cdot \psi_N$.
- Use laser heterodyne method to read out this phase variation.

Laser Heterodyne Readout



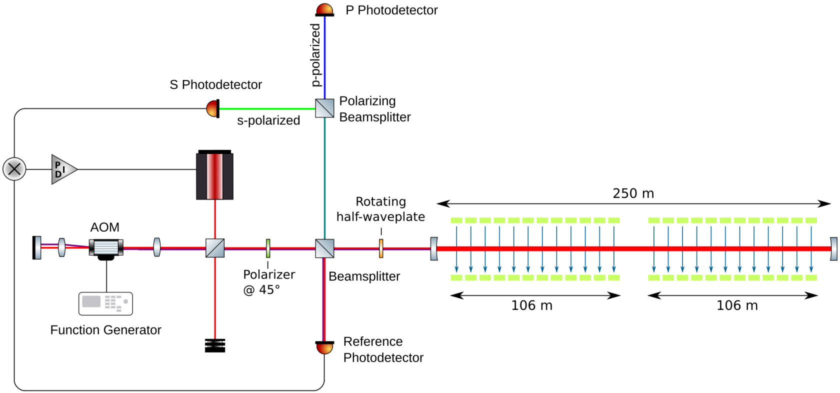
- Double-pass AOM produces two overlapped fields with fixed frequency offset Ω.
- Frequency offset field is non-resonant in cavity.

Laser Heterodyne Readout

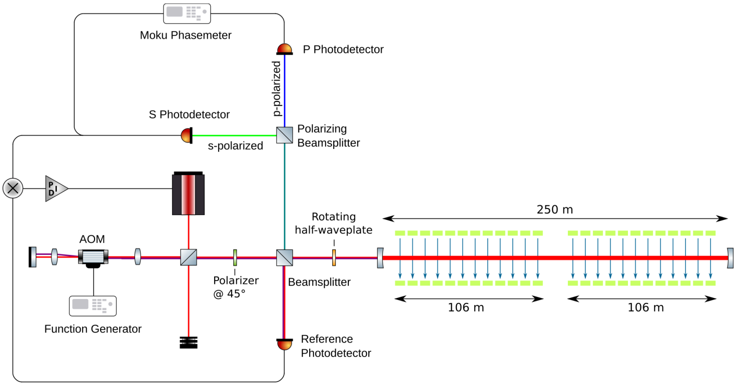


- The frequency offset fields produce a beatnote on the photodetectors.
- Beatnotes from Reference and S photodectors used to lock laser to cavity.

Laser Heterodyne Readout

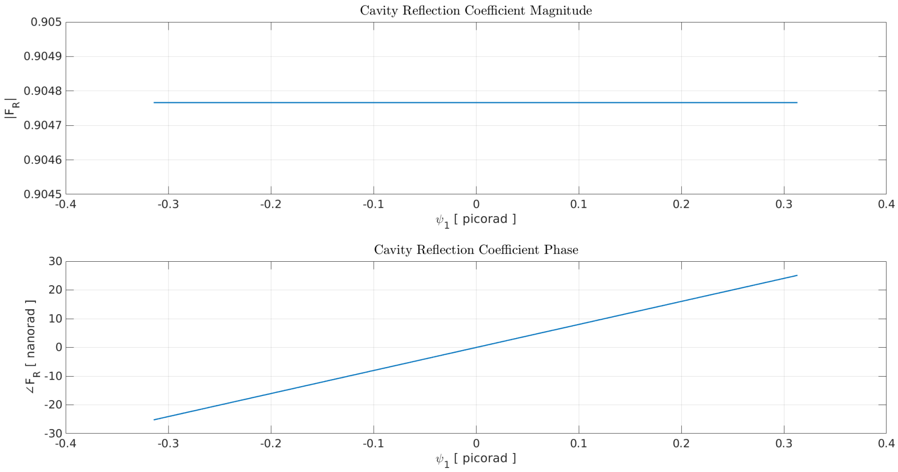


- The laser is locked to keep the s-polarized component (before rotation) resonant.
- The p-polarized component is alternately above and below resonance.



- Phase of p beat signal is compared to phase of s beat signal with a phasemeter.
- The amplitude of the time varying phase difference is proportional ψ_N.

Laser Heterodyne Readout



P Photodetector Signal

Output of P Photodetector is proportional to (ignoring noise)

$$
\begin{aligned}
|E_{LO}e^{i(\omega+\Omega)t} + F_r(\delta)E_M e^{i\omega t}|^2 = \\
E_{LO}^2 + |F_r(\delta)|^2 E_M^2 \\
+ 2E_{LO}|F_r(\delta)|E_M \cos(\Omega t + \angle F_r(\delta))
\end{aligned}
$$

where $\delta = 4\psi_1$ is the round-trip differential phase shift and

$$\angle F_r(\delta) = 4\psi_N \cdot \cos(4\omega_\pi \cdot t + \phi)$$

Intrinsic Cavity Bifringence

- Ideally, the cavity's resonance frequencies are independent of polarization.
- The resonance condition

$$\nu_m = \frac{c}{2L_C}\left(m + \frac{\phi_G - \phi_m}{\pi}\right) \tag{1}$$

includes the reflection phase of the cavity mirrors (assumed identical here).

Mirror Birefringence

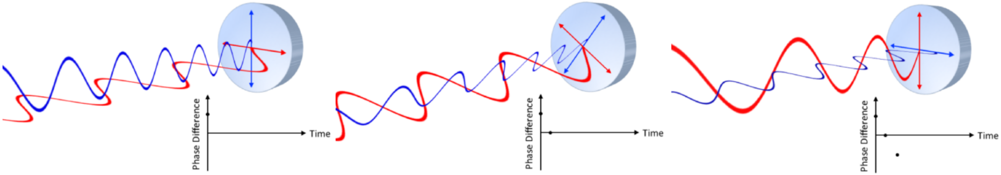


Image Credit: Baum, Clair (2016)

- But the cavity mirror's reflection phase ϕ_m does depend on polarization.
- This 'mirror birefringence' is roughly 6 orders of magnitude greater than VMB
- How to separate VMB from mirror birefringence?

Modulate Magnetic Field

- Modulate the magnet current such that the magnetic field strength is, e.g.,

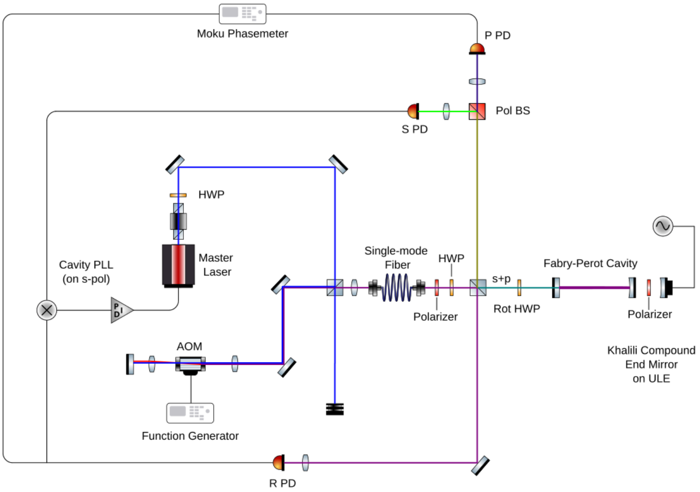
$$B = 5.3\,\mathrm{T} \cdot (1 + 0.01\cos(\omega_m \cdot t))$$

- then the maximum ellipticity is of the form

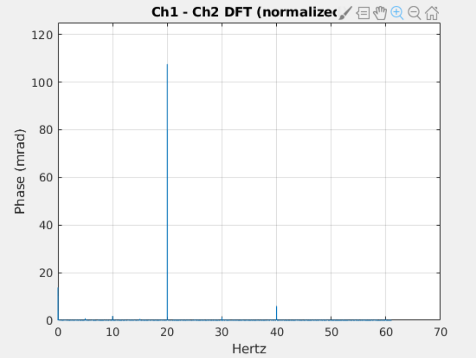
$$\psi_N \approx 5.5\,\mathrm{nrad} + 110\,\mathrm{prad} \cdot \cos(\omega_m \cdot t)$$

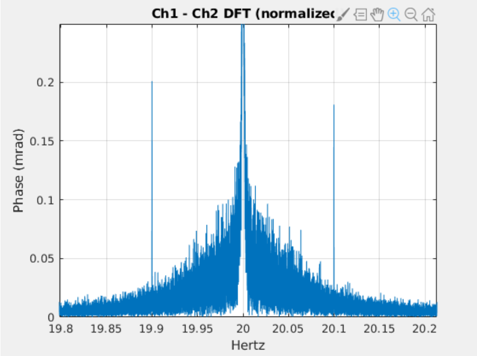
resulting in phase modulation sidebands at $4\omega_\pi \pm \omega_m$ with amplitude $220\,\mathrm{prad}$

UF Tabletop Cavity Birefringence Testbed



100 mHz Khalili modulation





Next Steps

- Continue Development of Tabletop Experiment
- Study Use of Light in Transmission
- Schedule

Schedule

Development Schedule		
Task	Start	Finish
Tabletop Experiment v2.1	Feb 2021	Dec 2021
Paper v2.1	Jan 2022	May 2022
Tabletop Experiment v2.2	Aug 2021	Dec 2022
Paper v2.2	Jan 2023	May 2023
Final Design Doc	Jan 2023	July 2023
Procurement	July 2023	July 2024

Backup Slides

Reflection Phase Gain

For r_1, r_2 real, the cavity reflection coefficient is given by:

$$F_r(\phi) = \frac{r_1 - r_2 e^{i\phi}}{1 - r_1 r_2 e^{i\phi}} = \frac{(r_1 - r_2 \cos\phi - i r_2 \sin\phi)(1 - r_1 r_2 \cos\phi + i r_1 r_2 \sin\phi)}{|1 - r_1 r_2 e^{i\phi}|^2}$$

where ϕ is the round-trip accumulated propagation phase. For ϕ small enough, the numerator is approximately

$$(r_1 - r_2 - i r_2 \phi)(1 - r_1 r_2 + i r_1 r_2 \phi)$$

Grouping real and imaginary parts, the numerator becomes

$$(r_1 - r_2)(1 - r_1 r_2) + r_1 (r_2 \phi)^2 - i \left(1 - r_1^2\right) r_2 \phi$$

Reflection Phase Gain

For $r_2 = 1$, the numerator is

$$(r_1 - 1)(1 - r_1) + r_1 (\phi)^2 - i\left(1 - r_1^2\right)\phi = r_1\phi^2 - (1 - r_1)^2 - i\left(1 - r_1^2\right)\phi$$

and phase of the reflection coefficient is then approximately

$$\angle F_r \approx \tan^{-1}\left(\frac{1 - r_1^2}{(1 - r_1)^2}\phi\right) = \tan^{-1}\left(\frac{1 + r_1}{1 - r_1}\phi\right)$$

For $\frac{1+r_1}{1-r_1}\phi$ small enough, the phase of the reflection coefficient is approximately

$$\angle F_r \approx \frac{1 + r_1}{1 - r_1}\phi \approx \frac{2\sqrt{r_1}}{1 - r_1}\phi = \frac{2\mathcal{F}}{\pi}\phi$$

where we have used $2\sqrt{r_1} \approx 1 + r_1$ for $(1 - r_1)$ small

Double-pass AOM

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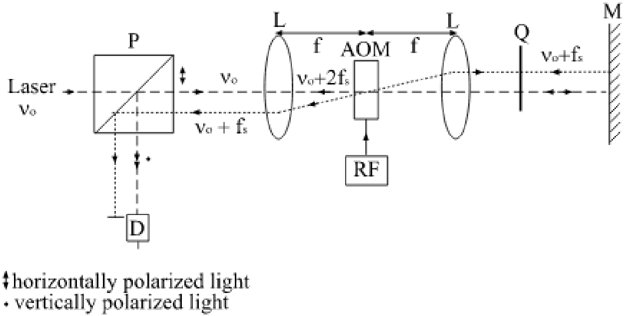
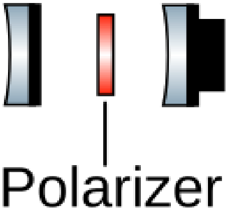
Fig. 2. Experimental setup: P, polarizing cube beam splitter; D, detector; L, lens; f, focal length; M, mirror; Q, 1/4 wave plate; and f_s, frequency of the acoustic wave. Laser beams with frequencies ν_0 and $\nu_0 + 2f_s$ are collinear and overlap on the detector.



Khalili Compound End Mirror

- Signal injection: How to introduce controlled, small cavity BF?



- A Khalili compound end mirror for variable reflection phase ϕ
- Originally proposed to reduce coating thermal noise in LIGO
- Displace final end mirror by (small) $\Delta l \to \Delta\phi \propto \Delta l$
- $\Delta\phi$ equivalent to changing cavity *optical* length
- Add polarizer between mirrors gives polarization dependent changes in optical length