Building a 3.5 m prototype interferometer for the Q & A vacuum birefringence experiment and high precision ellipsometry

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Abstract. We have built and tested a 3.5 m high-finesse Fabry-Perot prototype interferometer with a precision ellipsometer for the QED test and axion search (Q & A) experiment. We use X-pendulum-double-pendulum suspension designs and automatic control schemes developed by the gravitational-wave detection community. Verdet constant and Cotton-Mouton constant of the air are measured as a test. Double modulation with polarization modulation 100 Hz and magnetic-field modulation 0.05 Hz gives $10^{-7}$ rad phase noise for a 44-minute integration.

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1. Introduction

Quantum Electrodynamics (QED) predicts that in a background electromagnetic field, vacuum is refractive and birefringent. The refractive indices in a transverse external magnetic field $\vec{B}_{\text{ext}}$ are $n_{\parallel} = 1 + 3.5\alpha(B_{\text{ext}})^2/(45\pi B_c^2)$ and $n_{\perp} = 1 + 2\alpha(B_{\text{ext}})^2/(45\pi B_c^2)$ for linearly polarized lights whose polarizations are parallel and orthogonal to the magnetic field with $B_c = m^2 c^3/\epsilon \hbar = 4.4 \times 10^9$ T. For a transverse magnetic field (dipole field) of 2.5 T, $\Delta n = n_{\parallel} - n_{\perp} = 2.5 \times 10^{-23}$. This birefringence is measurable using double-modulation ultra-high sensitive interferometer techniques. In typical invisible axion models, axion-photon coupling induces both ellipticity and polarization-rotation for light propagation in a magnetic field; these effects are about 7 orders smaller in magnitude compared to the QED birefringence.

In 1994, we proposed the Q & A experiment to measure the vacuum birefringence and the axion-photon coupling [1], and began to construct and test a 3.5 m high-finesse Fabry-Perot prototype interferometer. In [1], we presented the motivation and background of this experiment in detail. In [2], we present methods of improvement and make a comparison of Q & A experiment, PVLAS experiment [3], and BMV experiment [4]. Here we present the experimental setup, and test-measurement results.

2. Experimental setup of the 3.5 m prototype interferometer

The 3.5 m prototype interferometer (figure 1) is formed using a high finesse Fabry-Perot interferometer together with a high precision ellipsometer. The two high-reflectivity mirrors of the 3.5 m prototype interferometer are suspended separately

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from two X-pendulum-double-pendulum suspensions (basically the design of ICRR, University of Tokyo [5]) mounted on two isolated tables fixed to ground using bellows inside two vacuum chambers. The characteristics of these vibration isolation sub-systems are to be discussed in [2]. Other sub-systems are described below.

![Figure 1. Schematic diagram of the 3.5 m prototype interferometer](image)

**Laser, cavity and finesse measurement** — We use a 1 W diode-pumped 1064 nm CW Nd:YAG laser made by Laser Zentrum Hannover as light source. The laser frequency can be tuned using thermal control and PZT control. We thermal-stabilize the laser at 25 °C and use Pound-Drever scheme to lock the laser frequency with the resonant frequency of the 3.5 m interferometer. The high-frequency (> 30 Hz) part of the phase error from the photodetector is fed to the PZT to frequency lock the laser to the cavity resonant frequency; this feedback circuit is a three stage amplification with lead-leg compensation. Lower frequency part (< 30 Hz) of the phase error goes to a DSP based digital control unit to control the cavity length of the interferometer. The laser goes through an isolator, a 882 MHz electro-optic modulator and a mode-matching lens to the 3.5 m cavity. The modulation frequency was chosen as the free spectral range of a 0.17 m mode cleaner which was built but not used. We measure the finesse of the 3.5 m cavity in 3 ways while the laser was locked to the resonant cavity. Two methods [6,7] are to analyze the transmission intensity profile, as shown in upper part of figure 2. The third approach is to measure the life time of intra-cavity photons. Lower part of figure 2 shows the decay of transmission intensity when the power of the input light was suddenly turned off. All three methods give finesse 17,000 to within 1 %. This finesse enhances the cavity birefringence measurement by \(10,800 \left(\frac{2F}{\pi}\right)\) times.

**Polarizing optics and ellipsometry** — A Glan-Thompson polarizer with measured extinction ratio \(2.60 \times 10^{-7}\) is placed before the 3.5 m cavity. A Glan-Laser polarizer
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with measured extinction ratio \(9.36 \times 10^{-7}\) is placed behind the cavity as analyzer. A Faraday glass made of terbium-boron-alumina-silicate oxide with terbium oxide greater than 50% by weight (Kigre model M-18) is placed before the analyzer for the purpose of signal modulation. This Faraday glass is housed in a Teflon mount wound around with 2500 turns of 0.2 mm enamel-insulated wire. Modulation response of the Faraday glass was measured to be \(\eta = 0.019\) rad \(\text{A}^{-1}\). The polarizer, the analyzer and the Faraday glass form a modulated Malus ellipsometer to measure the intra-cavity polarization change. Malus law \(P = P_0(e^2 + \psi^2)\) gives the polarization rotation angle \(\psi\) from the power received in the photodetector. \(e^2\) is the extinction ratio of the Malus ellipsometer.

**Magnet** — We use a switching dipole magnet with a 25.4 mm borehole to induce the intra-cavity birefringence of the 3.5 m prototype interferometer. This magnet can generate up to 1.2 T transverse magnetic field with an effective magnetic length 0.2 m. A vacuum tube of ID/OD 21.4 mm/24.6 mm goes through the borehole of the magnet to connect the two mirror-hanging vacuum chambers.

### 3. Verdet constant of the air

Faraday effect is a property of transparent substance in a magnetic field which induces a rotation of the plane of polarization with distance for light propogated along the magnetic field. For dilute material like gas, the Faraday rotation is far smaller compared to substance like water or glass. We measure the Faraday rotation of air (polarization rotation angle \(\psi_v = C_v B_0 L_{eff}\)) and determine the Verdet constant \(C_v\) using the 3.5 m prototype interferometer. We use a 0.4 m long home-made solenoid to apply a 100 Hz axial magnetic field \(B = B_0 \cos(\omega t)\), to the 3.5 m cavity. From the response of the photodetector, we obtain the polarization signal \(\rho \equiv \frac{P}{P_0} = e^2 + \frac{4F^2}{\pi^2}[(\Delta \psi_v^2)/2 + (\Delta \psi_v^2)/2(cos(2\omega t))]\). When the amplitude of applied magnetic field is varied from \(4.4 \times 10^{-4}\) T to \(8.8 \times 10^{-4}\) T, the 200 Hz demodulated signals gives \(\Delta \psi_v^2\) shown as ordinates in Fig. 3. A quadratic fit to the magnetic field determines the Verdet constant to be \(C_v = (3.91 \pm 0.02) \times 10^{-4}\) rad T\(^{-1}\)m\(^{-1}\) at 25.5°C and 1 atm for \(\lambda = 1064\) nm.

### 4. Cotton-Mouton effect

Cotton-Mouton effect is quadratic to transverse magnetic field: \(\psi_{CM} = \pi C_{CM} B^2 L_{eff}\). For measuring the Cotton-Mouton effect, we replace the axial field by the transverse field \(B = B_0 + B_m \cos(\omega_m t)\) of the switching magnet and follow a similar procedure as described above. Since the alignment of the magnet axis and optical axis is not perfect, there is a small axial magnetic field \(B_{ax} = kB\) to induce a Faraday rotation. The detected polarization signal \(\rho(t) = e^2 + \frac{4F^2}{\pi^2}(\pi C_{CM}(B_0 + B_m \cos(\omega_m t))^2 L_{eff} + \Delta \psi_v^2)\).
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Table 1. Data of $B_0$, $B_m$, and $\rho_{\omega m}$ for 7 experimental runs of measuring Cotton-Mouton effect.

| $B_0$ (10^{-3} T) | 64.56 | 87.60 | 111.84 | 134.64 | 156.48 | 180.24 | 204.72 |
|------------------|-------|-------|-------|-------|-------|-------|-------|
| $B_m$ (10^{-3} T) | 46.56 | 58.56 | 70.32 | 82.08 | 94.08 | 105.84 | 117.60 |
| $\rho_{\omega m}$ ($10^{-7}$) | 1.22 | 1.94 | 2.29 | 3.31 | 3.90 | 5.18 | 6.26 |

$kC_v(B_0 + B_m \cos(\omega_m t))L_{eff} + \psi_c)^2$. Where $\psi_c$ is the birefringence of mirror coating.

Demodulating $\rho(t)$ at $\omega_m$ we obtain

$$
\rho_{\omega m} = \epsilon^2 + \frac{2F^2}{\pi^2}B_mL_{eff}(kC_v + 2B_0C_{CM}\pi)
$$

$$
+ (B_0C_vkL_{eff} + 4B_0^2C_{CM}L_{eff}\pi + 3B_m^2C_{CM}L_{eff}\pi + 4\psi_c).
$$

We modulate the magnetic field, and demodulate the detected signal at $\omega_m = 0.05$ Hz to give $\rho_{\omega m}$. By varying $B_0$ and $B_m$, we obtain 7 sets of data (Table I). Fitting the 7 data points of $\rho_{\omega m}$ using simplex methods, build-in Matlab function of nonlinear fitting, we obtain $C_{CM} = (5.50 \pm 0.48) \times 10^{-7}$ rad T^{-2} m^{-1} and $k = (9.58 \pm 1.29) \times 10^{-4}$.

5. Sensitivity curve of prototype interferometer

The sensitivity for detecting polarization rotation of prototype interferometer can be estimated by Fourier analyzing the double modulated signal (polarization modulation at 100 Hz using Faraday cell and magnetic field modulation at 0.05 Hz using switching dipole magnet) to obtain power spectrum using Welch’s average and Hanning window. The two side peaks are due to the coupling between the static birefringence of the Faraday cell and Cotton-Mouton effect of the air. The noise floor near modulated frequency 100 Hz $\pm 0.05$ Hz is around $10^{-7}$ rad ($5 \times 10^{-6}$ rad Hz^{-1/2}) as shown in figure 4 for a 44-minute integration. For measuring vacuum birefringence, a quarter-wave plate needs to be introduced between the output cavity mirror and Faraday cell. In [2], we present the schemes and current status of the 2nd and 3rd phases of the Q & A experiment.

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