Broadband EOM Characterization for use in ALPS IIc

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Axions and Axion-Like Particles are promising cold dark matter candidates. ALPS IIC hopes to detect them using resonant cavities in a light shining through walls experiment. In order for ALPS IIC to reach its desired sensitivity, it is important for both cavities to have the same resonance conditions, and for the light in the cavity before the 'wall' to be resonant with the axion field in the cavity after the 'wall'. Broadband electro-optic modulators can help maintain co-resonance by quickly modulating phase and frequency of light entering these cavities. This report shows one way to measure the effect of broadband electro-optic modulators via interferometric techniques and describes results obtained from such an experiment.

I. INTRODUCTION

The Standard Model of physics is useful for explaining much of our universe, but still falls short on numerous fronts such as its failure to incorporate gravity. Another question the Standard Model fails to answer is the strong CP (charge+parity) problem. Within the QCD Lagrangian, there are terms that can break CP symmetry for the strong force, yet all experiments to date show that the strong force obeys CP symmetry. [1]

In order to solve this problem, a new particle, the axion, was introduced by Peccei and Quinn.[2] The axion would have a non-zero mass, m_a, and be weakly interacting particles, most notably it would be coupled to two photons, with coupling strength, $g_{\alpha\gamma\gamma}$. Via the Primakoff effect, photons would convert into axions in the presence of a strong magnetic field (which supplies virtual photons), and axions would also convert into photons in the present of a strong magnetic field via the Sikivie effect. The QCD axion introduced by Peccei and Quinn may be just one of many similar particles, named axion like particles (ALPs). Axions and ALPs would provide an answer to other problems, such as TeV transparency and excessive stellar cooling and are cold dark matter candidates.

This has motivated several different axion searches. Helioscopes, such as CAST, search for axions originating in the sun. Haloscopes, such as ADMX, searches for axions within the Milky Way's cold dark matter halo. Another type of axion search is known as a "Light Shining through a Wall" (LSW) experiment, which attempts to generate and detect axions in the lab by taking advantage of the Primakoff and Sikivie effects.

II. ALPS

LSW experiments, such as Any Light Particle Search (ALPS), take advantage of axion-photon coupling in the presence of a magnetic field. In such experiments, photons are converted into axions by interacting with a virtual photon/magnetic field before a light tight barrier (such as a wall). These axions then pass through the wall, and some are converted back into photons in the presence of a second magnetic field.

The ALPS experiment is split into two generations, ALPS I and ALPS II. ALPS I, the first generation of the ALPS experiment, had a single cavity before a light tight barrier. ALPS II, which is being built in two stages (ALPS IIa and ALPS IIc) will increase sensitivity by including a second cavity after a light tight barrier and increasing cavity length. ALPS IIa has only 10m cavities without any magnets and will be used to test various optical systems for implementation in ALPS IIc.

Figure 1 shows the basic design of ALPS IIc. Current designs include two 120 meter cavity and 24 HERA dipole magnets. Laser light at 1064nm enters an optical cavity, known as the production cavity (PC), and is surrounded by a 5.3 T magnetic field. These newly converted axions then pass through a light tight barrier, where they enter another optical cavity, named the regeneration cavity (RC), immersed in a 5.3 T magnetic field. The axions in the RC then have the same likelihood of converting back into photons, with the same energy as the original photons they came from, and these photons can be detected.

Even with the inclusion of two optical cavities and increased cavity length, the probability of conversion (and reconversion) is very low, and ALPS IIc detection schemes have to be sensitive enough to detect a signal as weak as $2 * 10^{-5}$ photons per second. [3]

Currently there are two single photon detection schemes planned for ALPS IIc. Transition Edge Sensor (TES) involves a superconducting tungsten chip held near its critical temperature. If a single photon were to be absorbed by the chip, there would be a change in temperature and a sharp change in resistance, which can be measured. [4] The Heterodyne Detection Scheme (HET) relies on the interference of the local oscillator and a regenerated photon to create a beat note which can then be measured. [3]

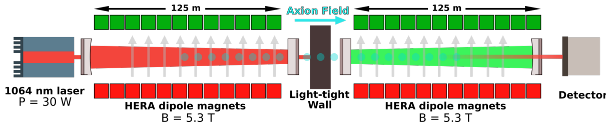

FIG. 1. Simplfied ALPS II Design

III. MOTIVATION

In order for ALPS IIc to reach its desired sensitivity, it is critical that the both the PC and RC have the same resonance conditions. This is because the axion field in the RC is directly related to the electric field circulating in the PC. The resonant axion field is generated from the circulating laser field in the PC, so the axion field and the laser field have the same resonant conditions. This means that the axion field will only be resonant in the RC if it has the same resonance conditions as the PC. Various noise sources can push either the RC or PC off of perfect resonance. One such source is high frequency noise which can come from random fluctuations in the frequency of the laser field. One way to account for this to modulate the incoming laser frequency using a broadband electro-optic modulator (BB EOM). A broadband EOM is ideal for this kind of application because it has a larger bandwidth with which it can modulate. A BB EOM can also be used for fast frequency modulation to maintain the RC's lock at the ALPS IIc end table. In order to use a BB EOM for these purposes, it would be necessary to be able to modulate up to frequencies up to a couple of megahertz.

IV. EXPERIMENTAL DESIGN

A. Mach Zehnder

Mach-Zehnder interferometers can be used to determine the relative phase shift between two collimated laser beams which originate from a single laser source. The optical set up for a Mach-Zehnder interferometer is shown in Figure 2. It begins with a single light source which then passes through a 50/50 power beam splitter (BS). This creates two separate optical paths, path 'A' and path 'B'.

First, we will consider light hitting photo detector one (PD1). Light from path 'A' is reflected off of BS 1, resulting in a π phase shift. It then reflects off of mirror 1 (M1), resulting in a second π phase shift. Light from path 'A' now transmits through a second 50/50 power beam splitter, BS 2, and hits PD1. During transmission, light in path 'A' will pick up a constant phase shift, k, which is based on the index of refraction of the material of the beam splitter.

Light from path 'B' transmits through the first BS, picking up a constant phase shift, k. It then reflects off of mirror 2 (M2), picking up a pi phase shift. Finally, it is reflected off of the final BS and into PD1, and picks up an additional π phase shift.

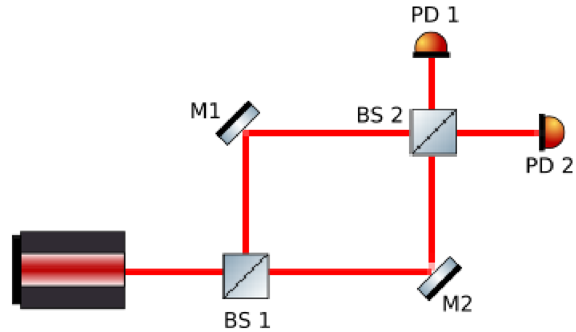

FIG. 2. Mach Zehnder Inteferometer

Both optical paths 'A' and 'B' are perfectly in phase as they reach PD1, since they both pick up two π phase shifts and one constant k phase shift. As such, they constructively interfere and there is a bright port at PD1.

Now we will consider light hitting photo detector 2 (PD2). Light in path 'A' reflects off of BS1, picking up a π phase shift, and then reflects off of M1, picking up a second π phase shift. Light in path A will then transmit through the power beam splitter, picking up a constant phase shift of k, and then reflect off of BS2. This time though, the material behind the reflecting surface of BS2 has a lower index of refraction than the material in front of the reflecting surface, and there is no phase change during reflection. Finally, light in path 'A' will then transmit through BS2, picking up another constant phase shift, k, and hit PD2.

Light in path 'B' transmits through BS2, picking up a constant phase shift, k, and then reflects off of M2, picking up a π phase shift. Finally it will transmit through BS2, picking up a k phase shift, and hit PD2.

Overall, light from path 'A' hitting PD2 picks up two π phase shifts and two 'k' phase shifts, while light from path 'B' picks up only one pi phase shift and two 'k' phase shifts. This means that the beams will be perfectly out of phase and destructively interfere. This will create a dark port at PD2 and thus no light should be detected at PD2.

Mach-Zehnder interferometers can be used to measure a relative phase shift between two beams by placing an object into one path of light. By measuring how the relative power difference at PD1 and PD2, one can calculate the relative phase shift between path 'A' and 'B'. I will construct a Mach-Zehnder interferometer with an electo-optic modulator (EOM).

B. EOM and Sideband Generation

Electro-Optic Modulators (EOMs) are optical devices which use the electro-optic effect to modulate a beam of light. EOMs consist of a crystal whose index of refraction can be changed via the application of an electric field in the form of a voltage and can modulate various parameters of a beam of light, such as phase, frequency, or amplitude.

When an electric field/voltage is applied to a crystal, the phase of the light passing through is modulated as a result of the change of index of refraction of the crystal. The phase change of the laser beam is proportional to the strength of the applied voltage on the crystal.

As a result of phase modulation, EOMs create sidebands in a laser beam. Consider a laser beam with frequency ω whose electric field strength is given by the equation:

$$E = Ae^{i\omega t} \tag{1}$$

By applying a sinusoidally varying voltage to the EOM with a frequency Ω and small amplitude β, a time dependant phase is added such that:

$$E = Ae^{i\omega t + \beta sin(\Omega t)} \tag{2}$$

Because the value of β is small, this equation can be Taylor expanded to:

$$E = Ae^{i\omega t}(1 + \beta sin(\Omega t)) \tag{3}$$

Which is equivalent to:

$$E = Ae^{i\omega t}(1 + (\frac{\beta}{2}(e^{i\Omega t} - e^{i\Omega t})) \tag{4}$$

Which is then equivalent to:

$$E = A(e^{i\omega t} + \frac{\beta}{2}e^{i(\omega+\Omega)t} - \frac{\beta}{2}e^{i(\omega-\Omega)t}) \tag{5}$$

This equation represents a carrier frequency and two sideband frequencies. This equation can also be expanded to include an infinite number of terms, meaning there are an infinite number of sidebands. Beta represents the modulation depth of the EOM, which denotes how much power is present in the sidebands. If beta is small, almost all of the power is in the carrier and first sidebands.

C. Optical Bench Setup

The optical design shown in figure 3 was used. The faraday isolater prevents any back reflection into the laser. A CCD camera was used to check the alignment of both beams into the photodetectors. BS1 and BS2 are both 50/50 power beam splitters, while BS3 was 2 percent transmissive in power and 98 percent reflective.

A control loop was established using PD1, a digital PID controller (Moku), a high voltage amplifier and a piezo. The error signal at PD1 is sent to the digital PID controller which then sends out a control signal. This control signal is then amplified by the high voltage amplifier and sent to the piezo. Based on the signal received, the piezo will expand or contract to adjust M2. By adjusting M2, the control loop is able to phase lock both

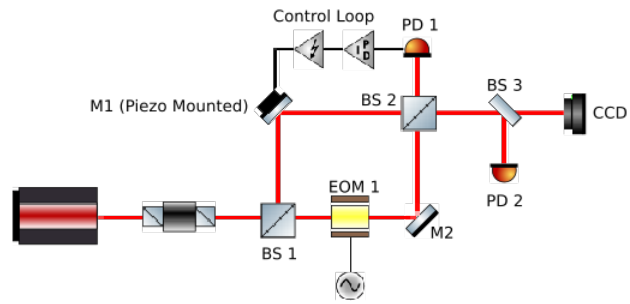

FIG. 3. Experimental Design

arms of the Mach Zehnder interferometer to each other and cancel out any laser frequency noise.

A signal from a function generator was then sent to a broadband EOM (EOM 1). This EOM phase modulates one arm of the interferometer and a transfer function can be obtained either from comparing the voltage sent to the EOM to the control signal sent to the piezo, or by comparing the voltage sent to the EOM to the voltage read on PD2.

V. DATA AND RESULTS

A. Transfer Functions

In order to characterize the EOM, it was necessary to measure its transfer function. The transfer function was measured by comparing the control signal sent to the piezo to the signal sent to EOM1 for frequencies up to 10KHz. Two different spectrum analyzers were used for measurements, the Agilent and SR785. This is because the SR785 was limited to measurements up to 100KHz and EOM 1 was characterized up to 100 MHz. Below are the transfer functions from both instruments at various ranges of frequencies.

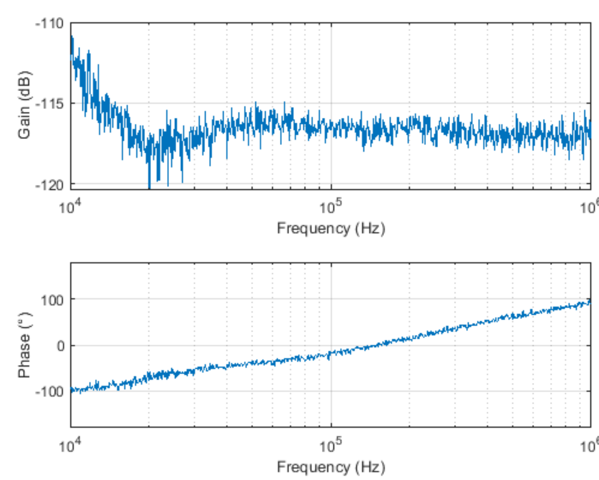

FIG. 4. Agilent Transfer function from 10KHz to 1MHz

The transfer function in figure 4 is very noisy from 10KHz to 1MHz. Because of this, we decided to look at measurements from a different instrument to compare.

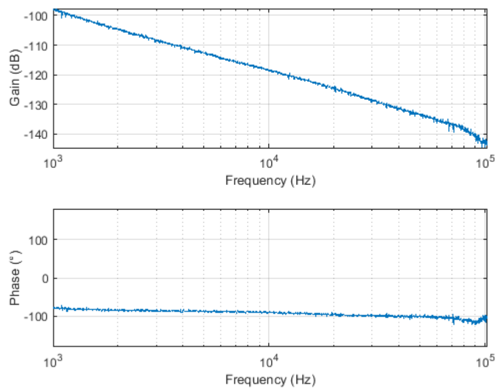

FIG. 5. SR785 Transfer function from 10KHz to 100KHz

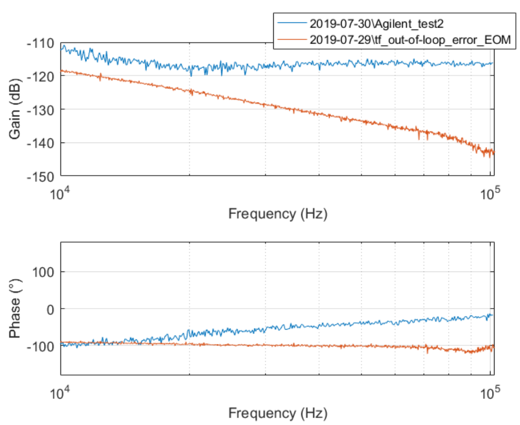

FIG. 6. Comparison Transfer function from 10KHz to 100KHz

The transfer function in figure 5 was measured using the SR785. The measurements are much less noisy, but also much lower, which can be seen in figure 6. This could be due to a possible noise floor on the Agilent Spectrum analyzer or due to impedance matching issues.

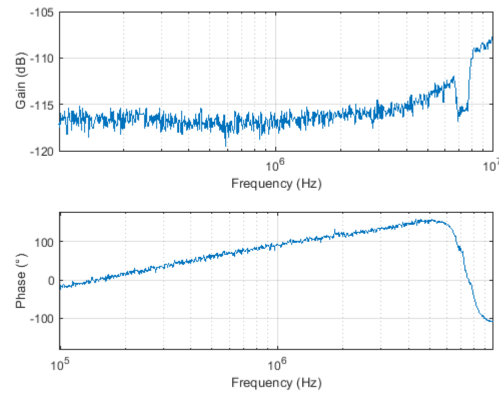

FIG. 7. Agilent Transfer function from 100KHz to 10MHz

Figure 7 shows the transfer function up to 10MHz. Here we can see a resonance around 7MHz.

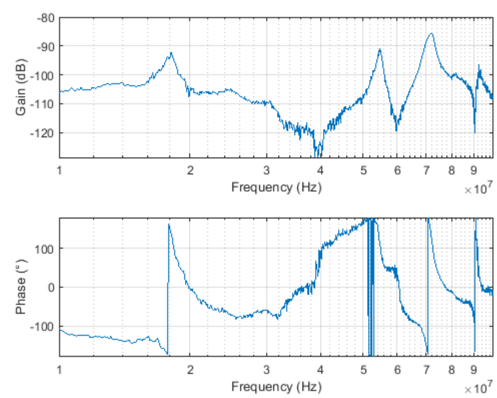

FIG. 8. Agilent Transfer function from 10MHz to 100MHz

Figure 8 shows higher order resonances up to 100MHz. This information is useful because it shows that a BB EOM can be useful for modulation up to a couple megahertz (before resonance effects take over).

B. Future Work

Because of the transfer function from 10KHz to 100Khz was so noisy, it is important to hunt down this noise source and eliminate it and then retake the measurements. Other future work includes testing how other parameters might affect the transfer function, such as beam position within the crystal in the EOM, voltage applied to the EOM and beam waist.

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