Advanced Resonators for High Frequency Axion Searches

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Abstract: Dark matter axions coupled to photons are detectable by method of positioning closed resonant microwave frequency cavities inside of magnetic fields. In collaboration with members of the University of Washington and the University of Western Australia, I present a number of resonant cavity prototypes for the closed cylindrical “Pizza Resonator”. These cavity prototypes have been constructed in order to search for high-frequency dark matter axion-like particles outside of the sensitivity range achieved by the Axion Dark Matter eXperiment with the use of alternating dielectric slices and vacuum.

Keywords: dark matter, axion, high-frequency, resonant cavity, dielectrics

1. INTRODUCTION

Independent astrophysical measurements confirm that dark matter makes up 27% of the energy density of the Universe. No experiment in existence has discovered the evasive dark matter particle. The simplest assumption concerning dark matter is that it has no significant interactions with other matter (it is non-relativistic and non-baryonic), and that its particles have a negligible velocity with regards to structure formation. Such dark matter is described as being “cold”, and candidates include WIMPs, MACHOs, and the axion. [1, 2] The axion emerges from the Peccei-Quinn solution to the strong CP problem. Axions are especially of interest because of their accessibility. With current technology, experiments can be carried out in the laboratory that will either detect or rule out axions within the expected axion mass range, and these axions may comprise some or all of dark matter. [3]

2. RESONATORS AS LOW MASS AXION HALOSCOPES

Most typical axion haloscopes consist of a closed microwave resonator immersed in a high static magnetic field in order to provide the cavity with source of virtual photons. In what is known as the inverse Primakoff effect, an axion will convert into a photon when another photon is present.

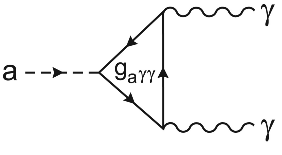

Fig. 1. The Feynman diagram corresponding to the natural dominant inelastic decay of the axion (a) into two photons (γ) [4]

The cavity is coupled to a low noise microwave receiver via the lowest frequency transverse magnetic (TM) mode of the resonator. As a result, the frequency of the generated real photon corresponds directly to the mass of the axion. Dark matter axions passing through the magnetic field can convert into photons inside the cavity with enhanced probability when an electromagnetic resonance in the cavity is tuned to correspond to the frequency of the photons produced. As dark matter candidates, the axion mass and photon coupling are highly constrained by cosmological observations. [3]

2.1 Cylindrical Resonators

Optimization An optimal resonant cavity for axion searches must have both a large volume and high quality factor. A large volume maximizes the area of potential interaction between the axions and magnetic field. However, the cavity volume must be optimized to detect the photon by matching the cavity’s dimensions to the photon wavelength. Larger axion mass and larger photon energy imply a shorter wavelength, higher photon frequency and a smaller cavity volume.

The quality factor of a resonator is related to the number of bounces a photon can experience before being absorbed by the resonator’s walls; it is a measure of strength of the damping of a cavity’s oscillations. With a high quality factor, there is a high probability for the excitation of photon oscillation due to an axion in the resonator. A larger photon lifetime implies a higher photon-detection efficiency.

When looking into smaller cavity geometries to reach higher axion masses, it can be shown that smaller resonator radii will lead to a higher resonant frequency. Lower and upper limits of a cavity’s resonant frequency for a given mode can be estimated using the following equation:

$$\omega_{mnp} = \frac{1}{\sqrt{\mu\epsilon}}\sqrt{\frac{x_{mn}^2}{R^2} + \frac{p^2\pi^2}{d^2}} \tag{1}$$

where μ is the permeability constant of a given dielectric, ϵ is the permittivity of the dielectric, x_{mn} is the n^{th} zero of the Bessel function J_m(x) [5]. It can be proven that a signal will be produced only when a predicted resonant mode's electric field integrates to a total nonzero z-component, meaning that the form factor of this mode is nonzero. A form factor of a given resonator provides a value between 0 and 1 describing how much of $\overrightarrow{E}$ and $\overrightarrow{B}$ overlap in the cavity, and is specifically defined as $\int \overrightarrow{E} \cdot \overrightarrow{B}$. A form factor closer to 1 will result in a higher power for the axion signal. All transverse electric modes (TE and TEM) will yield no detectable signal; only TM_{0n0} modes will couple well to axions. [6] Dark matter axions would be detected as excess power at this resonant frequency.

2.2 Axion Dark Matter eXperiment

There are a number of axion haloscope searches currently underway, but most notably is the Axion Dark Matter eXperiment (ADMX). ADMX is the first axion search experiment to reach sensitivity for plausible axion coupling. (See Fig. 2.) [7] ADMX is a low mass axion haloscope that exercises the use of a cylindrical microwave-frequency resonant cavity in order to search for axion particles in the dark matter halo of our galaxy.

The Use of Dielectrics in Resonators One of the most obvious problems that arises in QCD axion detection is the unknown mass of the axion (other than some broad cosmological limits [3]). This in turn also means that the frequency of the photon yield is also not known. This, combined with the fact that the strength of axion coupling to photons is unknown, create a large parameter space for searching, which requires a number of experiments to probe different axion mass ranges.

In most cases as previously discussed, TM_{0n0} modes will couple well to axions. The TM_{010} mode has the largest form factor, with higher mode (TM_{020}, TM_{030}, TM_{040}, etc.) form factors decreasing as $\frac{1}{f^2}$ for simple right circular cylindrical resonators. [6] Because dielectrics will manipulate the waveforms inside of the cavity, we can use them to look at TM modes that stray from this convention, like the TM_{510} mode. By inserting dielectrics into a larger cavity, this actually splits the cavity up so that it functions like a number of smaller, higher-frequency cavities. (See Fig. 3.)

3. PROPOSED “PIZZA RESONATOR”

Simulations and Preliminary Calculations We arbitrarily chose to model a cavity with the teflon dielectric slices with a radius of the entire cavity. (See Fig. 3.) Although the simulated cavity is not tunable, it demonstrates field behavior inside of a cavity similar to what we expect to see in the final model of the Pizza Resonator. This simulation also acts as motivation to pursue the creation of similar cavities with a number of different tuning methods.

Analytically, this cavity geometry proved to be very difficult to solve, as we do not have azimuthal symmetry between dielectric and vacuum slices. Using Eqn. 1, the resonant frequency for the Pizza Resonator cavity both empty and filled with dielectric can be estimated. The true resonant frequency for a given mode of a cavity with some dielectric in it will lie between these two limits. For the first model of the Pizza Resonator, we expected to see a TM_{510} mode between approximately 9-12 GHz.

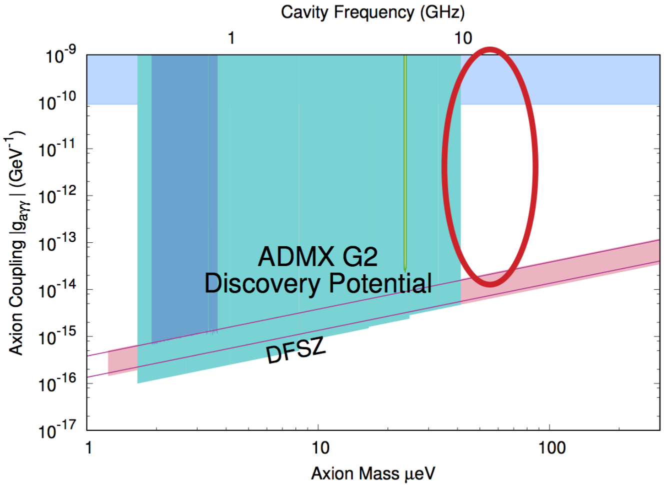

Fig. 2. ADMX Projected Sensitivity up to date Jan. 12 2017. Figure includes new resonant cavity frequency region of interest as highlighted by red ellipse [8]

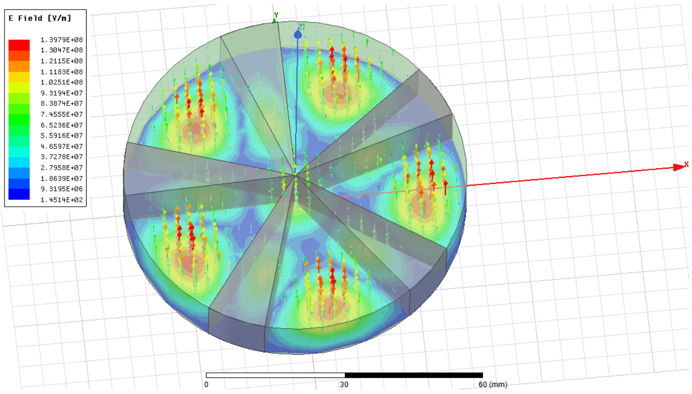

Fig. 3. A simulation demonstrating the strength of the electric field throughout the cavity at a quasi-TM_{510} mode with a frequency of 9.86 GHz. Dielectric slices in this simulation are exactly the radius of the entire inner cavity, making the cavity so that it cannot be tuned. The five teflon slices break up the cavity so that it functions as five small high-frequency cavities contained inside of one larger cavity. Teflon slices do not have the same inner angle as the slices of vacuum [9]

Tuning Mechanisms Two different tuning mechanisms for the proposed Pizza Resonator were discussed. The first of these two tuning methods involved machining teflon slices smaller than the resonant cavity, allowing for the slices to be pulled apart from one another allowing for a range of tunability within the cavity. (Fig. 4.) The second of the two methods involved cutting the slices of teflon in half horizontally, resulting in two five-slice systems that could be pulled apart vertically from one another, also changing the frequency of the cavity. (Fig. 5.) Research conducted this summer focused solely on resonators that use the first of the two tuning methods; the latter may be explored further in the future.

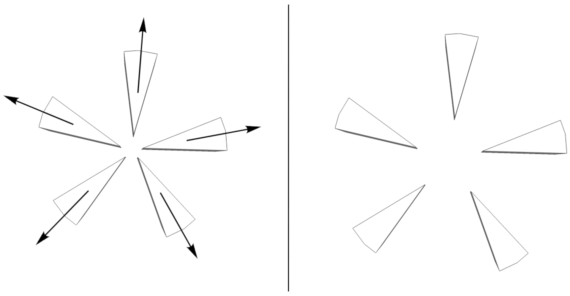

Fig. 4. First of two proposed tuning methods in which dielectric slices are pulled apart from one another radially outwards (top view)

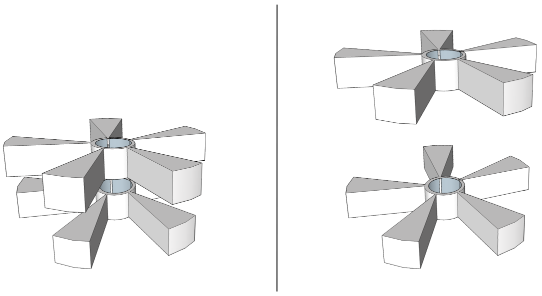

Fig. 5. Second of two proposed tuning methods in which two dielectric slice set-ups are distanced vertically (side view)

3.1 Model 1

Hardware A resonant cavity was constructed with the same parameters as the one modeled, with the exception of the size of the teflon slices. The device was constructed with an aluminum pipe, and this pipe was sandwiched between two aluminum end-caps. The most obvious difference between the simulation and the constructed resonator is that the dielectric slices of teflon do not have a radius that is the same as the inner part of the cavity, leaving a large amount of space between the dielectrics and the walls of the cavity. (See Fig. 6.) This distance allows for tuning by movement of the dielectrics radially outwards from the center of the cavity, but the distance also introduces losses of modes as they slowly bleed out of the dielectric. Modes stop being confined within the teflon dielectric slices and become empty cavity whispering gallery modes, which are modes not sensitive to the axion.

Preliminary Results from Model 1 Using a network analyzer, a signal was sent into an antenna inserted into Model 1 of the Pizza Resonator. A few reflection measurements were then taken from this cavity prior to inserting the dielectrics into the cavity. A reflection measurement is the ratio of the reflected signal to the incident signal.

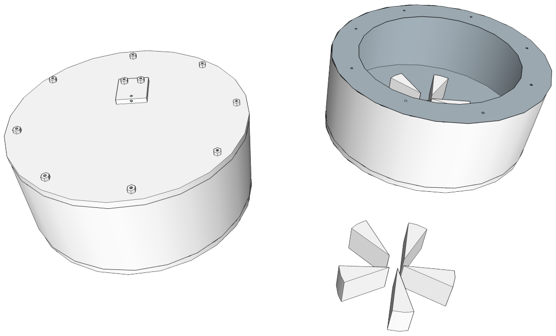

Fig. 6. A 3D rendering of the original aluminum cavity. Dimensions: 8” OD, 6” ID, 3” tall. 1/4” thick aluminum caps. Teflon slices are 1” tall, 1.5” in length

Upon finding a resonant mode of interest, a dip in the data is expected to demonstrate that the signal is not being perfectly reflected and is instead lost to the mode of interest. (See Fig. 7.)

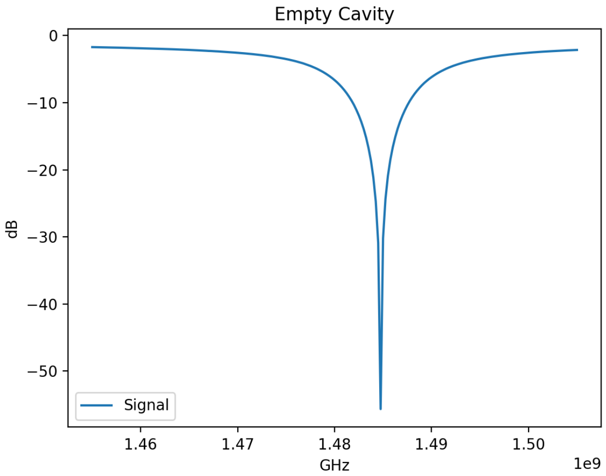

Fig. 7. An example reflection measurement of one very clean resonant mode taken from Model 1 of the cavity with no dielectrics. Sharp dip in the data demonstrates that the signal is not being perfectly reflected and is instead lost to the mode of interest

These initial measurements acted as an introduction to the process of reading and using network analyzers, and served as the validation that resonant modes can be both predicted and tracked inside of resonating cavities.

A measurement over a much larger frequency span of 0-12 GHz reveals that there is a resonant mode approximately every 10 MHz in Model 1 of the Pizza Resonator, making it extremely difficult to track and identify which mode is which. (See Fig. 8.) This makes predicting the frequency at which a given mode is located very difficult. This served as motivation for the construction of a second smaller cavity, in which we hoped that modes would be more prominent in the data.

3.2 Model 2

Hardware A second cylindrical resonant cavity was constructed with a shorter aluminum pipe, just taller than

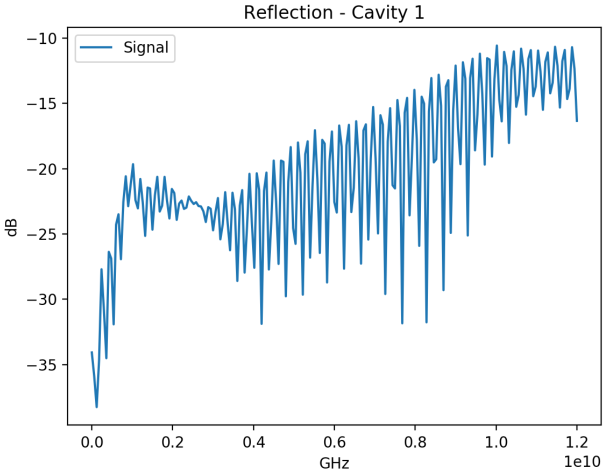

Fig. 8. A reflection measurement taken across all frequencies of interest in Model 1 of the cavity with no dielectrics. Mode occurring approximately every 10 MHz

the slices of aluminum that sit inside. This pipe was again sandwiched between two aluminum end-caps. This rendition of the cavity did not leave the same large amount of space between the dielectrics and the walls of the cavity, as it is approximately half the size of the first cavity. (See Fig. 9, 10.)

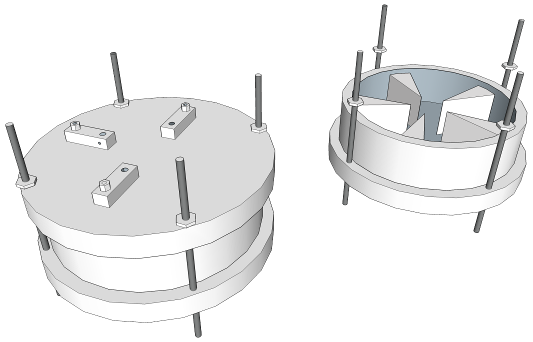

Fig. 9. A 3D rendering of the second aluminum cavity, almost half the size of the first design. Dimensions: 4 1/2" OD, 4" ID, 1.13" tall. Aluminum caps with 1/2" thickness, 5" in diameter

Preliminary Results from Model 2 Transmission measurements were taken with Model 2. This differs from the reflection measurement because it measures the passage of electromagnetic radiation through a medium. In our case, we would expect to see the signal input into the cavity through one antenna and absorbed into another. At a resonant frequency, we should expect to observe a spike in power, since the resonator acts as a band-pass filter for specific modes. A band-pass filter is a filter that passes frequencies within a certain range and attenuates frequencies outside of that range, resulting in data peaks.

Using Eqn. 1, upper and lower limits were calculated yielding an area of interest where one may find a quasi-TM_{510} mode. The TM_{510} mode was calculated to be located within the frequencies of approximately 5-8 GHz.

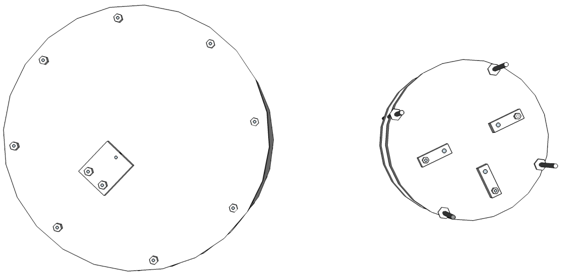

Fig. 10. A scaled size comparison between the first and second model of the cavity

When this region was explored with a network analyzer, it appeared that there were a number of unidentifiable modes along with TM_{510}. Through the use of tracking these modes, we will be able to tell in the future if these are in fact modes of interest to us with regards to this project.

While scanning frequencies between 5-8 GHz, the network analyzer displayed the most prominent modes between 5.5 and 6.25 GHz. We decided to focus on this region and tune the resonator to see if we could observe the displacement of these modes over different frequencies and potentially identify exactly which modes were observed. (See Fig. 11.) We had predicted that in pulling the teflon slices away from the center of the cavity, a mode's frequency would increase with distance. Instead we observed that after reaching a certain distance from the center of the resonator, the frequency of a mode would stop increasing and the frequency would begin to decrease.

4. FUTURE OF THE PIZZA RESONATOR

In our uncertainty regarding tuning mechanisms, it was difficult to determine whether it was more beneficial to position the dielectric flush with the walls of the cavity, or to change the cavity geometry to achieve a whispering gallery mode in order to produce a higher Q value. Teflon has such a low relative permittivity constant that it is difficult to sustain a whispering gallery-like scenario, but expensive dielectric materials like sapphire would be able to achieve this. It can be modeled to show that for other materials with higher dielectric constants that there is some benefit to having a smaller gap between the walls and the dielectric, which serves as the motivation in building additional models of the resonator. These whispering gallery modes would be much more pronounced and easy to track than any of the modes we saw in both Model 1 and Model 2 of this resonator.

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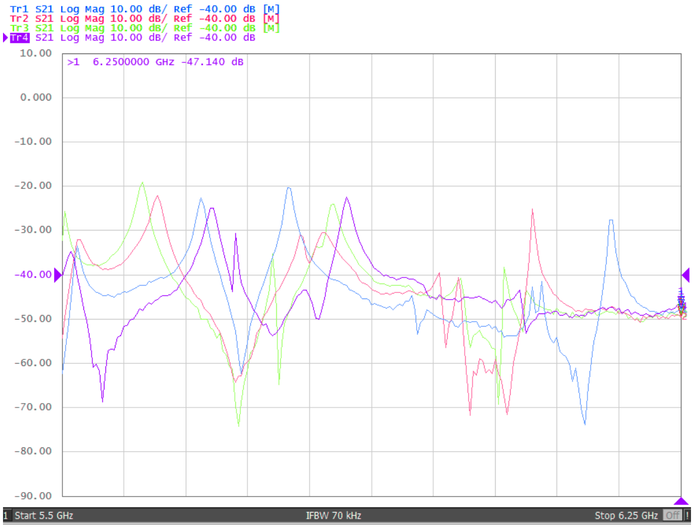

Fig. 11. Transmission measurement from Model 2 taken from 5.5-6.25 GHz range. Trace 1 (Tr1, blue) is an empty resonator. Trace 2 (pink) is a resonator with teflon slices placed in the center of the cavity. Trace 3 (green) has the teflon slices pulled a small distance away from the center. Trace 4 (purple) has the teflon slices almost against the walls of the cavity. Data shows that these unidentified modes have the ability to be tuned

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