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ABSTRACT

Here, we present a frequency tuning mechanism for microwave cavities designed for axion dark matter searches and show that it provides a range of at least 200 MHz for the fundamental mode TM_{010} resonant at ~10 GHz. The apparatus is based on a clamshell cavity, with the two semi-cells held together at a fixed joint while the other side opens to tune the frequency of the resonant modes. Measurements of the cavity frequencies and quality factor were taken at liquid helium temperature as the aperture was increased incrementally to ~2°. We show that the frequency shift is approximately linear with respect to the angle of aperture with no mode crossings present for an aperture less than 2°. Furthermore, the form factor and quality factor of the TM_{010} mode remain relatively constant throughout the tuning as predicted by simulation.

I. INTRODUCTION

The rotation curves of galactic disks and other cosmological observations provide strong evidence for the existence of a currently undetectable form of matter known as dark matter.[1] Little is known about the nature of dark matter, and many theoretical candidate particles have been proposed.

One of the most promising dark matter candidates is the axion.[2] First introduced in 1977 as a solution to the strong CP problem,[3] it was later realized that the axion could also explain the existence of dark matter.[4] The two leading axion models, given by KSVZ[5,6] and DFSZ,[7,8] describe an extremely light boson that couples very weakly to standard model particles.

Due to the axion's extremely small mass and weak coupling, directly detecting such a particle is a very challenging problem. Nevertheless, in 1983, Pierre Sikivie proposed that axions could be detected via the inverse Primakoff effect in a device called a "haloscope," whereby photons are produced inside a microwave cavity as axions interact with a magnetic field.[9] If the cavity frequency ω_c and axion frequency $\omega_a \simeq m_a c^2/\hbar$ are tuned within the corresponding bandwidth, the signal will be amplified and potentially detectable. The axion mass (frequency) range that can be probed with haloscopes is $1(0.24) \lesssim m_a \lesssim 50\,\mu\text{eV}(12\text{ GHz})$. Note that the axion frequency is not a constant, but rather a quantity that can take a range of values specified by a probability density function, which is obtained from a model-dependent velocity distribution of axion particles.[10,11] From the standard halo model, which describes virialized axions as observed from the moving laboratory frame of our solar system, the fractional linewidth of the signal is $\Delta\nu_a/\nu_a \sim 10^{-6}$. Equivalently, the quality factor of the axion Q_a is of order a million. The signal power in a haloscope with cavity volume V and external magnetic field B_0 is given by

$$P_a = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \omega_c B_0^2 C_{mnl} V Q_0 \frac{\beta}{(1+\beta)^2}, \quad (1)$$

where $g_{a\gamma\gamma}$ is the axion–photon coupling constant, $\rho_a = 0.45$ GeV/cm^3 is the axion density,[12] and C_{mnl} is the form factor that depends on the cavity mode. Q_0 is the unloaded quality factor of the cavity mode, and β is the coupling coefficient of the antenna to the cavity mode. For a typical haloscope experiment, the signal power is several orders of magnitude lower than the receiver's noise, even when the cavity and low noise preamplifier are kept at liquid helium temperature or in dilution refrigerator systems for quantum-limited readout. Therefore, data must be acquired for a certain amount of time to exclude axions with a given frequency and photon coupling at a desired confidence level. As a result, the effectiveness of a microwave cavity for axion searches can be expressed as its scan rate or the rate at which the haloscope can search over a certain frequency range at a given sensitivity. It can be shown[13] that the scan rate is proportional to the figure of merit $F = B^4 C_{mnl}^2 V^2 Q_0$, and microwave cavities must then be designed to maximize the product $C_{mnl}^2 V^2 Q_0$.

Several recent theoretical predictions motivate searches for heavier axions than those probed so far,[14–17] whose masses are greater than about 40 μeV. As the signal is suppressed due to poor scaling with frequency,[18] cavity haloscope searches addressing the high frequency range require broadly tunable cavities with quality factors comparable to or exceeding[13,19] that of the searched axion signal Q_a, as well as the use of broadband, quantum-limited receivers for their readout.[20] An open challenge in this field is the development of a frequency tuning mechanism that does not impact the quality factor and is free from intruder modes.[21] Conventional frequency tuning mechanisms for copper pill-box cavities involve revolving one or two metal cylindrical rods about the inside of the cavity to break the transverse symmetry.[22–24] Longitudinal insertion of rods is, however, inconvenient as it negatively affects the form factor. While rod tuning has proven successful at low frequencies, multiple rotating and translating post patterns must be considered to reach high frequencies, but these approaches are impractical for operation at cryogenic temperatures and are characterized by a reduced sensitivity.[18,25] Operation of these dark matter experiments in dilution refrigerators required for quantum-limited readout poses serious problems for tuning with rod systems, including the imperfect thermalization of the rods and frequently sticking rotational stages. In addition, while they are compatible with moderate quality factors, they are not expected to be effective for tuning in ultra-high Q microwave resonators like the Nb TESLA-shaped cavity recently employed for a dark photon search at a fixed frequency,[26] and those recently introduced in axion searches, such as the NbTi,[27] $NbSn_3$,[28] and ReBCO[29] superconducting cavities.

The frequency tuning method introduced in this work applies to clamshell cavity designs, in which the effective radius can be modified by separating the two halves until the RF leakage through the aperture becomes the dominant mechanism impacting F. To clarify, we refer to cuts along the direction where the microwave currents sustain the fundamental mode TM_{010} flow.[27] Here, we report about a clamshell cavity with a tuning range greater than 200 MHz at a frequency of ~10 GHz, corresponding to $m_a = 41.6\,\mu$eV. Tests are conducted at cryogenic temperature, and finite element method simulations are used to understand the cavity behavior at different apertures. The observed frequency shift is approximately linear with respect to the angle formed by the two copper clamshells, as predicted by the simulations. This method is not affected by mode crossing in the investigated range and is expected to allow for a relative frequency tuning range of as much as 5% with a better designed mechanism.

II. CAVITY AND TUNING MECHANISM

The microwave cavity chosen for this study was machined from oxygen-free high thermal conductivity copper and has an inner radius of 11.2 mm and a length of 400 mm for a total internal volume of 0.158 l. The frequency of the TM_{010} mode, as measured at room temperature, is 10.24 GHz. When cooled to 4.5 K, the TM_{010} frequency increases to 10.30 GHz due to the thermal contraction of the cavity.

The two copper clamshells have been machined from a bulk copper square stock to obtain a perfect cylinder when joined. They are fixed together with screws at a joint, where four centering pins ensure opening on the other hand without axial misalignment. To adjust the aperture of the open end of the cavity, two blocks of copper with conical indentations were fixed to the outside of the cavity. A conical wedge was then placed between the two pieces of copper such that pulling the wedge upward separates the open side of the cavity. A micrometric screw was used to adjust the vertical position of the cone. Two springs placed on the copper blocks provide tension against the force of the wedge. A picture of the cavity and tuning apparatus is shown in Fig. 1.

As the conical wedge is pulled upward, the two halves of the cavity are forced apart at the open edge, thereby increasing the effective volume of the cavity. As a result, the resonant modes can be tuned to lower frequencies. The setup allows for a maximum aperture of about 2°, equivalent to an increase in the effective volume of ~2%. It is expected that the frequency should scale approximately linearly with the tuning aperture for small angles. Simulations and experiments confirm this prediction.

III. ELECTROMAGNETIC SIMULATIONS

The clamshell cavity prototype was optimized through systematic 3D electromagnetic simulations. It is important to note that, as the cavity is opened, electromagnetic energy can radiate away, giving rise to standing waves when the resonator is enclosed in a metallic

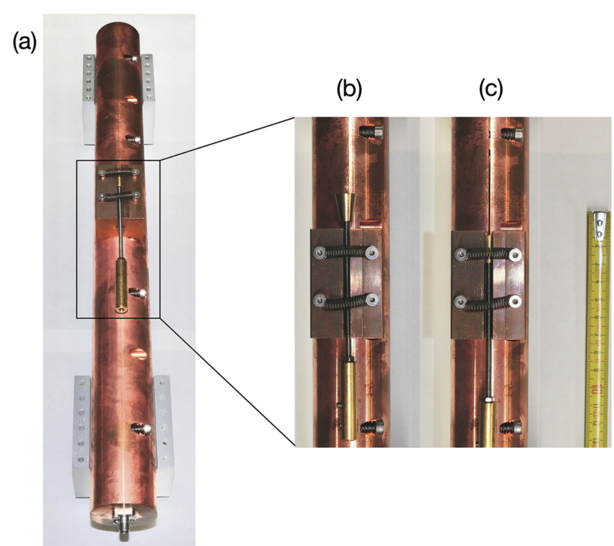

FIG. 1. The copper cavity and tuning apparatus used in this study (a). The brass conical wedge is shifted from an initial position (b) to (c) for cavity opening. It is connected to a micrometric positioning stage at room temperature through the small brass cylindrical body shown.

vessel for cooling to cryogenic temperatures. If the vessel diameter is large compared to that of the cavity, mode mixing of the axion-sensitive mode TM_{010} with high order modes supported by the vessel boundary is expected due to their high density. A cylindrical body has thus been designed and experimentally realized that encloses the main cavity, with a minimum diameter (63.5 mm) to ensure that the frequencies of the related electromagnetic modes exceed the main cavity TM_{010} mode frequency. The body is 432.1 mm long and its axis is offset by 0.95 mm with respect to the center of the main cavity toward the direction of the fixed joint, allowing the clamshell cavity to be opened up to 12°. The model used for the simulation with a cavity aperture of 12° is shown in Fig. 2 along with the obtained electric field mode profile. In the model, the same measurements of the real cavity have been used, except for the cylinder height that is halved to reduce computational time.

In Fig. 3, we report values of the TM_{010} mode frequency, quality factor, and effective volume $C_{010}V$ obtained from the simulations for several (71) aperture angles in the range 0° to 12°. To check for mode crossings, simulations were done at steps of 0.1° between 0° and 2°, with steps of 0.2° thereafter. In the range 0°–2°, the TM_{011} and TM_{012} modes were also monitored. Both the main cavity and external cylinder has been assigned a conductivity of 5.48 times the conductivity of copper at room temperature $\sigma = 5.8 \times 10^7$ S/m. Although not of interest for axion searches (their form factor is small), these two latter modes can help monitor the TM_{010} mode during experimental tests. In fact, the frequency difference between the three modes is independent of the radius, which provides a practical method to identify the studied modes as the cavity is opened.

The frequency shift of the TM_{011} that results from the simulations is linear up to 6° total aperture angle, with a slight deviation afterward. A similar behavior is reported for the effective volume, while the quality factor starts to decrease at the same aperture angle. Note that the effective volume is negatively impacted by mode mixing at 6° and 10°.

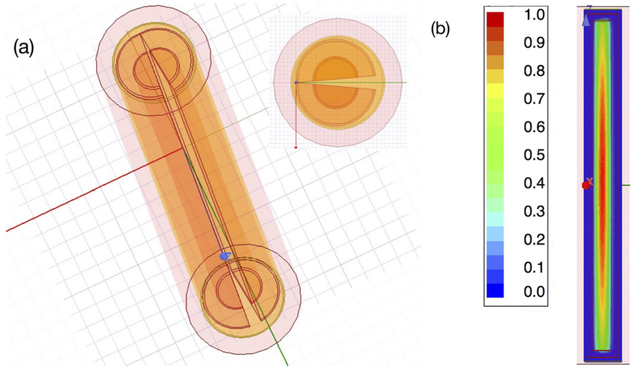

FIG. 2. (a) The model used in the 3D electromagnetic simulations consists of a right cylinder cavity enclosed by cylindrical body with diameters, respectively, 16.4 and 63.5 mm. The latter is offset by 0.95 mm with respect to the cavity axis to allow for opening the cavity up to 12° as in the figure. Simulations are run for a half (400 mm/2) the overall cavity length. (b) TM_{010} mode electric field profile, with normalized color scale.

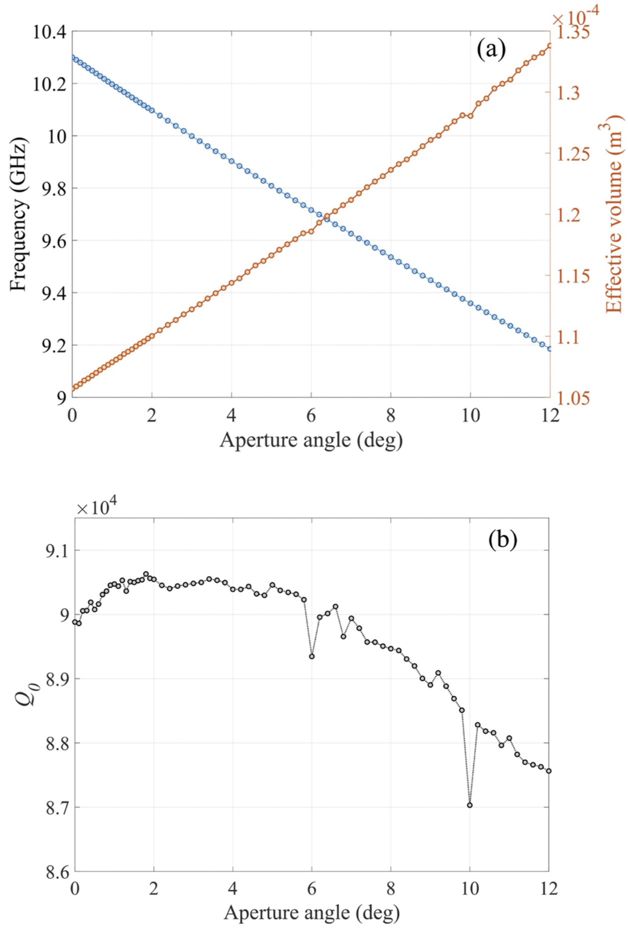

FIG. 3. 3D electromagnetic simulation results. (a) Cavity frequency, effective volume, and (b) quality factor vs aperture angle. The assumed copper resistivity is 5.48 times the conductivity of copper at room temperature $\sigma = 5.8 \times 10^7$ S/m.

IV. MEASUREMENTS

To assess the performance of the cavity and tuning apparatus, the frequency and Q factor of the TM_{010} mode were recorded as the aperture of the cavity was increased incrementally from 0° to about 2°.

The cavity was placed in a vacuum vessel, which itself was placed inside a cryogenic dewar filled with liquid helium, achieving 4.5 K as measured by a thermometer attached to the copper cavity.

Figure 4 shows the frequencies of the first three modes of the cavity as well as the simulated modes at cryogenic temperature. The observed frequency shift of 203.8 MHz for 2.0° opening is in good agreement with the value predicted by simulation. No mode crossings occur while tuning the cavity, and the frequency shift is approximately linear with respect to the aperture. Note that data at low aperture angles (second and third aperture angle values in Fig. 4) deviate from the data trend due to a limitation in the tuning mechanism. For small angles a systematic error in the aperture

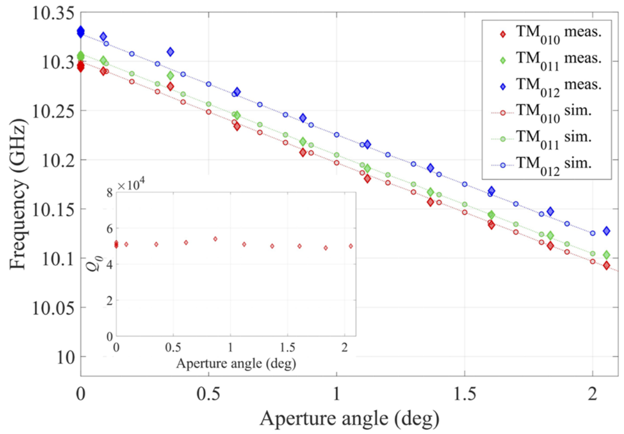

FIG. 4. Aperture dependence of the frequency of the first three modes of the microwave cavity at 4.5 K. Results from 3D electromagnetic simulations of the TM_{010} mode are also shown. To the calculated frequency values, a negative offset of 90 MHz has been added. Inset: quality factor Q_0 vs cavity aperture. Within ~3% measurement error, the quality factor is shown to be constant for cavity apertures up to 2°.

angle, readout should, thus, be taken into account. The measured quality factor of the TM_{010} mode is independent of the aperture with values around ≈50 000 at 4.5 K. This quality factor is obtained if we assume a conductivity value smaller than the one used in the simulations [see Fig. 3(b)], which can be determined by the poor surface quality in the real cavity that had not been subjected to any chemical treatment.

V. CONCLUSIONS

A microwave cavity designed to search for axion dark matter candidates must be tunable over a large range of frequencies and exhibit easily identifiable resonant modes. Here, we have demonstrated a novel tuning mechanism for microwave cavities with a TM_{010} frequency that can be tuned by at least 2% with no mode crossings while the quality factor remains constant within few percent. According to the simulations, the frequency range could be increased to as much as 10%, or even more with a more carefully designed tuning apparatus. For instance, the two cavity halves could be moved apart by increasing the gap symmetrically on both sides. However, in this case, the moving mechanism should be carefully devised as to prevent breaking of the longitudinal symmetry that negatively impacts on the form factor. This simple tuning mechanism is applicable to high quality factor, type II superconducting resonators whose quality factor would be otherwise severely impacted using the conventional method of cavity tuning. Moreover, the simulations and the experimental results reported in this work lay the ground for tuning the resonant frequency of higher order modes in dielectric-boosted resonators.[19,30] This latter type of cavity has been introduced in the field of axion detection with haloscopes to address challenges at high frequency, where a simple pill-box cavity can provide only small volumes. By exploiting higher order modes properly shaped via the insertion of dielectric shells, a significant gain in effective volume is obtained with these resonators compared to conventional cylindrical cavities. For instance, a single sapphire shell can be used to reshape the TM_{030}-like mode field profile, and the frequency tuning is accomplished by opening the external copper cylinder as described in this work.

In addition to the lack of mode crossings, the frequency tuning is also approximately linear with respect to the aperture of the cavity. This allows for easy identification and tracking of the resonant modes as the cavity is tuned. Moreover, such a device does not need to rely on intensive simulations to calculate the quality factor and resonant frequencies. As mentioned previously, one of the greatest challenges in probing heavier axions, with cavities resonating around 10 GHz frequency, is the reduced cavity volume. Due to the mechanical simplicity of this tuning apparatus and the absence of mode crossings, a feasible mechanical system for tuning multiple cavities simultaneously to increase the scan rate can now be considered.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

C. Braggio: Data curation (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Supervision (equal); Visualization (equal); Writing – original draft (supporting); Writing – review & editing (lead). **G. Carugno**: Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (lead); Resources (equal); Supervision (equal); Writing – review & editing (supporting). **R. Di Vora**: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Validation (equal); Writing – review & editing (supporting). **A. Ortolan**: Data curation (equal); Writing – review & editing (supporting). **G. Ruoso**: Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Resources (equal); Supervision (equal); Writing – review & editing (equal). **D. Seyler**: Data curation (equal); Investigation (equal); Methodology (equal); Validation (equal); Writing – original draft (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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