Simulation Design and Parameter Optimization of Microwave Cavities for Lighter-Mass Dark Matter Axion Detection Applications (Postprint)

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Abstract

Dark matter detection has long constituted a major scientific objective in modern astronomy and physics. Among the various candidates, the axion arising from Quantum Chromodynamics (QCD) is regarded as a natural dark matter candidate. Presently, the most extensively studied approach concerns the detection of electromagnetic responses from axions with masses at the micro-electron-volt scale; however, multiple operational experimental apparatuses have reported null results. Consequently, the detection of lower-mass axions has become imperative. Addressing the demand for detecting electromagnetic responses from lighter axions with sub-electron-volt masses, this work investigates the design of tunable microwave cavities operating in the hundreds-of-MHz frequency band, and optimizes parameters including the optimal resonant mode, form factor, and frequency scanning rate. Numerical simulation results indicate that, compared with conventional cavities in the same frequency band, the proposed eight-rod cavity structure achieves a nearly hundredfold improvement in scanning rate, while the axion detection sensitivity degrades by only approximately a factor of three. While these results derive from numerical simulations and await experimental validation, they nonetheless offer prospective reference value for the future construction of experimental facilities aimed at detecting electromagnetic responses from QCD axions with even lighter masses at the sub-micro-electron-volt scale.

Full Text

Preamble

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Abstract

Dark matter detection has long been a paramount scientific objective in modern astronomy and physics. Among various candidates, the axion arising from Quantum Chromodynamics (QCD) is considered a natural dark matter candidate. Current efforts primarily focus on detecting axions with micro-electronvolt masses through their electromagnetic responses, yet multiple operating experiments have yielded null results. Consequently, probing lower-mass axions has become imperative. Addressing the need for detecting lighter axions with sub-electronvolt masses, this paper explores the design of tunable microwave cavities operating in the hundreds of MHz band and optimizes key parameters including optimal resonant modes, shape factors, and frequency scanning rates. Numerical simulations demonstrate that compared to standard cavities in the same frequency band, the proposed eight-rod cavity structure increases the scanning rate by nearly two orders of magnitude while degrading axion detection sensitivity by only about threefold. Although these results are obtained from numerical simulations and await experimental verification, they provide forward-looking reference value for constructing future experimental apparatus for detecting electromagnetic responses of QCD axions with masses below the micro-electronvolt scale.

Key words instrumentation: detectors, methods: numerical, cosmology: dark matter

1 Introduction

Despite numerous theoretical models in physics and astronomy predicting the existence of dark matter, experimental detection of dark matter particles remains elusive. The axion, emerging naturally as a solution to the strong CP problem in Quantum Chromodynamics (QCD), represents a compelling dark matter candidate that would have been abundantly produced in the early universe. Consequently, axion detection carries profound significance for resolving the strong CP problem and understanding the fundamental structure and evolution of the universe. According to the two mainstream axion models—Kim-Shifman-Vainshtein-Zakharov (KSVZ), which posits axion coupling only to quarks, and Dine-Fischler-Srednicki-Zhitnitsky (DFSZ), which allows coupling to leptons—

axions can be probed through either high-energy physics experiments or interactions with Standard Model particles at lower energy scales, particularly photons.

The interaction between dark matter axions and ordinary matter is extremely weak, making experimental detection in low-energy physics experiments exceptionally challenging. Nevertheless, Haloscope technology based on the axion-photon conversion effect has garnered widespread international attention due to its exceptional detection sensitivity. Experimental implementations of this technology typically comprise three key components: a strong static magnetic field to enhance the probability of axion-to-photon conversion, a microwave resonant cavity to store the converted microwave photons (typically cooled to cryogenic temperatures to minimize thermal noise), and an ultra-low-noise microwave weak-signal detection system (necessitated by the inherently small conversion probability). Table 1 summarizes the primary parameters of current international implementations of such apparatus, demonstrating that different axion mass ranges require microwave cavities with different resonant frequencies.

Designing microwave cavities for Haloscope-type axion detection requires careful optimization of two critical technical metrics. First, a high form factor necessitates selecting electromagnetic modes with high quality factors whose frequencies closely match the axion conversion frequency, thereby enabling efficient extraction and storage of axion electromagnetic signals for detection. Second, fast frequency scanning capability allows rapid tuning of the cavity resonant frequency to target axions of different masses, typically achieved through tuning rods. In the HAYSTAC experiment, for instance, the axion search scanning rate is merely 40 MHz/yr, requiring several years to complete scanning across the designed frequency band. Consequently, optimizing these two cavity parameters has become a priority in upgrade proposals for existing Haloscope-type detectors. For example, Simanovskaia et al. (2021) designed a seven-rod cavity to enhance the form factor; Golm et al. (2022) proposed superconducting coating technology that increased the quality factor by 50% compared to conventional copper cavities; Di Vora et al. (2022) suggested using annular tuning rods to optimize cavity tuning; and Bae et al. (2023) designed a novel cavity employing high-quality dielectric lattice structures to substantially improve quality factors and frequency scanning rates.

Our research group aims to construct a Haloscope-type detection apparatus targeting lighter-mass axions. Beyond developing the strong static magnet and ultra-high-sensitivity electromagnetic signal reception system, this paper presents our proposed microwave cavity design. The primary objectives are: enabling tunable resonant frequencies in the hundreds of MHz band for the TM mode; optimizing the ratio between central and tuning rod radii by introducing a fixed central conductor that does not participate in tuning; achieving higher form factors and faster frequency scanning rates compared to standard cavities in the same band; and establishing the foundation for constructing MHz-band Haloscope-type detectors for lighter axions.

2 Microwave Cavity Design Requirements for Axion Dark Matter Detection

The axion is a pseudoscalar particle denoted by a that can spontaneously decay into two photons. Its lifetime can be estimated as

$$\tau_a \approx \frac{10^{47}\ \text{yr}}{(1\ \text{g}^{-1})m_a^5} \sim 10^{10}\left(\frac{10^{-5}\ \text{eV}}{m_a}\right)\ \text{yr}$$

where $g_{a\gamma\gamma}$ is a model-dependent constant and m_a is the axion mass in micro-electronvolts (μeV). This decay time far exceeds the age of the universe (~10¹ yr), making direct detection through axion decay impractical. To enhance conversion efficiency, one can exploit the inverse Primakoff effect. Figure 1 [Figure 1: see original paper] illustrates the principle: (a) an axion spontaneously decaying into a pair of photons, and (b) an axion converting into a photon via the inverse Primakoff effect in an external static magnetic field $\mathbf{B}_0$. In 1983, Sikivie proposed the Haloscope detection scheme based on this effect. The axion-photon coupling can be described by the Lagrangian term $\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a\mathbf{E}\cdot\mathbf{B}$, where $g_{a\gamma\gamma}$ is the axion-photon coupling coefficient proportional to axion mass, $a(\mathbf{r},t) = \text{Re}[A(\mathbf{r})e^{-i\omega_a t}]$ is the axion field amplitude (spatially independent for isotropic axion dark matter), $\mathbf{r}$ is the position vector, ω_a is the axion field angular frequency, and $\mathbf{E}$ and $\mathbf{B}$ represent electric and magnetic field intensities. The external magnetic field provides an additional interaction medium that amplifies the axion-to-photon conversion probability, with the converted photon energy equaling the total axion energy.

When axion dark matter enters a microwave cavity in a strong static magnetic field, the axion converts to a photon with frequency $\nu = m_a c^2/h$ via the inverse Primakoff effect, equivalent to generating an effective current density in the cavity:

$$\mathbf{j}_a = -g_{a\gamma\gamma}\mathbf{B}_0 \times \nabla a$$

The resulting photons excite the cavity' s eigen electric field mode $\mathbf{E}_{mnp}(\mathbf{r})$, where m,n,p are the transverse (radial and azimuthal) and longitudinal mode numbers. This coupling is governed by the forced oscillation equation:

$$\left(\frac{d^2}{dt^2} + \frac{\omega_{mnp}}{Q_{mnp}}\frac{d}{dt} + \omega_{mnp}^2\right)\beta_{mnp}(t) = -g_{a\gamma\gamma}\int_V \mathbf{B}_0(\mathbf{r})\cdot\mathbf{E}_{mnp}(\mathbf{r})\text{Re}(Ae^{-i\omega_a t})d^3r$$

where $\beta_{mnp}(t)$ represents the time-dependent electric field amplitude for mode (m,n,p), ω_{mnp} is the eigenfrequency, V is the effective cavity volume, and d^3r is the volume element. The left side' s ω_{mnp} denotes the cavity mode angular frequency while the right side' s ω_a is the axion field frequency. Cavity response is maximized only when these frequencies match ($\omega_{mnp} \approx \omega_a$). In the long-time limit, the system reaches steady state where the cavity mode frequency aligns with the axion field frequency, yielding a steady-state electric field amplitude:

$$\beta_{mnp}(t) = \beta_{0mnp} e^{-i\omega_{mnp} t}$$

The signal power from axion-to-photon conversion can be calculated as:

$$P_{mnp} = \frac{\omega_{mnp}}{Q_{mnp}} \langle \dot{\beta}^2_{mnp}(t) \rangle = g^2_{a\gamma\gamma} \frac{\rho_a m_a B_0^2 V C_{mnp}}{2 \min(Q_c, Q_a)}$$

where $\langle\rangle$ denotes time averaging, ρ_a is the local dark matter axion density, C_{mnp} is the form factor quantifying coupling to cavity mode (m, n, p), Q_c is the cavity quality factor, and Q_a is the axion quality factor (dependent on axion velocity). The quality factor for a cavity mode is defined as $Q = \omega U / P_d$, where U is the stored energy and P_d is the power dissipation. The stored electromagnetic energy is determined by the electric field integral over the cavity volume:

$$U = \frac{\epsilon_r}{2} \int_V |\mathbf{E}|^2 dV$$

where ϵ_r is the permittivity. Power dissipation relates to the magnetic field integral over metallic surfaces:

$$P_d = \frac{\sigma_m}{2} \int_S |\mathbf{H}|^2 dS$$

where $\mathbf{H}$ is the magnetic field vector, S represents the metal surface, σ_m is metal conductivity, and δ is the skin depth. Consequently, each electromagnetic mode' s quality factor depends on both material properties and geometric structure, necessitating careful mode selection. Using high-conductivity materials reduces skin depth and enhances quality factor, which explains why oxygen-free copper (or even gold-plated) cavities and tuning rods are commonly employed.

Two additional parameters require optimization for Haloscope cavities: form factor and frequency scanning rate. The form factor for the electric field mode $\mathbf{E}_{mnp}(\mathbf{r})$ in a cylindrical cavity under a strong axial magnetic field is defined as:

$$C_{mnp} = \frac{\left| \int_V \mathbf{E}_{mnp}(\mathbf{r}) \cdot \hat{\mathbf{z}} d^3 r \right|^2}{V \int_V \epsilon_r |\mathbf{E}_{mnp}(\mathbf{r})|^2 d^3 r}$$

Only modes with non-zero z-components can store axion-generated photons. For the intended cylindrical cavity, only TM modes possess non-zero form factors; other modes either have canceling integrals due to field reversals or lack z-components entirely. Table 2 lists frequencies, quality factors, and form factors for various TM modes in a cylindrical cavity, showing that the TM mode has the largest form factor ($C_{010} = 0.692$), making it optimal for storing axion electromagnetic signals.

The frequency scanning rate represents another core metric for Haloscope cavity design, determining search time across a frequency range for given signal-to-noise ratio and sensitivity conditions. The scanning rate is given by:

$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2} \frac{g_{a\gamma\gamma}^4 \rho_a^2 B_0^4 C_{mnp}^2 V^2}{m_a^2 (k_B T_s)^2 \beta^2 (1+\beta)^2 Q_a \min(Q_L, Q_a)}$$

where SNR is the signal-to-noise ratio, $g_{a\gamma\gamma}$ is the axion-photon coupling strength, k_B is Boltzmann' s constant, T_s is the system noise temperature (combining cavity thermal noise and receiver chain noise, dominated by the first-stage amplifier noise temperature), β is the signal coupling strength to the receiver, $Q_L = Q_c/(1+\beta)$ is the loaded quality factor, and Q_a is the axion quality factor. According to equations (6) and (8), the scanning rate is proportional to the square of output power P_{mnp}, meaning a 16-fold scanning rate increase corresponds to a 4-fold power enhancement. The axion-photon coupling strength can be expressed as:

$$g_{a\gamma\gamma} \propto \left(\frac{df/dt}{f} \right)^{1/4}$$

Thus, increased scanning rate improves detectable axion-photon coupling strength but reduces detection sensitivity (minimum detectable coupling strength). For instance, a 16-fold scanning rate increase degrades sensitivity by a factor of two. Although sensitivity decreases with higher scanning rates, the benefits of increased output power and reduced search time make this trade-off worthwhile for practical experiments.

Experimentally, scanning rates can be improved through stronger magnetic fields, reduced receiver chain noise, and optimized cavity performance. This study employs the dimensionless Figure of Merit (FOM):

$$F = \left[\frac{V^2 (C_{010})^2 Q}{V_0^2 C_0^2 Q_0} \right]^{1/4}$$

where C_{010} is the TM mode form factor, and V_0, C_0, Q_0 are the volume, form factor, and quality factor of a reference cavity (standard cavity in the same band). An FOM of 2 implies a 16-fold scanning rate increase relative to the reference cavity, equivalent to the search capability of four reference cavities or eight incoherent reference cavity power combinations. These analyses inform the cavity design for ultra-light axion detection presented in the following sections.

3 Microwave Cavity Design and Parameter Optimization for Ultra-Light Axion Detection

Given null results from all GHz-band Haloscope-type axion dark matter detection experiments, probing lighter-mass axions has become imperative. This section discusses the design and parameter optimization of microwave cavities for constructing a Haloscope-type detector operating in the hundreds of MHz band. For the required larger-radius cylindrical microwave cavity, we optimized the length of a 50 cm radius cylindrical cavity to achieve well-isolated TM modes. Using this mode for axion-to-photon conversion signal reception, we numerically optimized the form factor and scanning rate. Results demonstrate that multi-tuning-rod cavities with a central conductor represent a superior design, offering acceptable frequency search ranges. Compared to standard cavities in the same band, the optimized eight-rod cavity increases the frequency scanning rate by approximately 92-fold. Although sensitivity and scanning rate improvements are not simultaneous—higher scanning rates reduce sensitivity—the practical benefit of significantly shortened detection times justifies this trade-off.

Figure 2 [Figure 2: see original paper] illustrates how cavity height affects mode distribution. Panel (a) shows electromagnetic mode variations with different cylinder heights, revealing that height significantly influences mode frequencies and distributions. Panel (b) demonstrates that the TM mode remains stable near 229 MHz, with adjacent mode distributions strongly dependent on height. Mode overlap when frequencies approach reduces the TM form factor. For instance, at 100 cm height, TM and TE frequencies differ by only ~1 MHz. Further height increases introduce additional modes in the 200–400 MHz range, creating denser mode spacing near TM . Numerical results indicate that a 75 cm height optimally isolates the TM mode (229 MHz, corresponding to axion mass ~0.9 eV) from other modes. All subsequent analyses therefore use a 50 cm radius, 75 cm height cylindrical resonator as the basis for tuning rod design, enabling TM mode tuning across a broad frequency range to search for different ultra-light axion masses. The most feasible tuning method involves inserting metallic conductors—such as hollow spheres, rods, or other conductive shapes—to modify electromagnetic boundary conditions.

3.1 Single-Rod Tuning Cavity

The simplest traditional method for tuning cylindrical microwave cavities involves inserting a single asymmetric tuning rod. Figure 3 [Figure 3: see original paper] presents the single-rod cavity design and optimization results. Panel (a) shows cross-sectional and longitudinal schematics where a hollow metallic tuning rod of radius r_1 is positioned at distance S_1 from the cavity axis. Adjusting S_1 tunes the TM mode frequency, simultaneously altering quality factor, form factor, and figure of merit.

Panel (b) displays performance parameters for various rod radii r_1 and axial spacings S_1, with the horizontal axis representing rod-to-cavity-axis distance and the vertical axis showing rod radius. The TM resonant frequency increases with rod radius and decreases as the rod moves away from the center. The quality factor is lowest when the rod is centered, showing minimal variation with radius changes. The maximum figure of merit ($F_{\max} = 1.5$) occurs at $r_1 = 15$ cm with the rod centered ($S_1 = 0$). To achieve high FOM while maintaining form factor above 0.5, the optimal rod radius should be $r_1 = 15$ cm.

Panel (c) shows optimized single-rod cavity performance metrics and electric field distributions at maximum and minimum FOM. Red indicates high field intensity, blue low intensity. When the rod contacts the cavity wall ($S_1 =$ 35 cm), FOM is minimized and the field concentrates in the largest interior region. Conversely, a centered rod ($S_1 = 0$) yields maximum FOM and optimal form factor, with uniform, symmetric field distribution. Under these conditions, the optimized single-rod cavity achieves FOM 1.5, corresponding to a ~5-fold scanning rate increase. However, the FOM remains relatively low in the low-frequency region, resulting in non-uniform search times across frequencies and suboptimal search efficiency.

3.2 Dual-Rod Tuning Cavity

Single-rod optimization revealed that symmetric electric field distributions enhance form factor and FOM. We therefore increased the number of tuning rods while maintaining symmetry to produce more uniform field distributions. Figure 4 [Figure 4: see original paper] presents the dual-rod cavity design and optimization results. Panel (a) shows the two-rod configuration with symmetric placement maintained during tuning. This design' s key feature is preserving cavity symmetry to maintain high FOM across the tuning range. Both rods have radius r_2 and are positioned at distance S_2 from the cavity axis. Using the same optimization method, the optimal dual-rod cavity parameters were determined.

Panel (b) displays optimized dual-rod cavity performance and electric field distributions at extreme FOM values. Since TM mode frequency is independent of azimuthal angle, we selected the linear frequency-tuning region where S_2 varies between 15-35 cm. Minimum FOM occurs at $S_2 = 35$ cm with fields concentrated at the cavity center. As S_2 decreases, metallic rods expel fields from the central region, increasing FOM while decreasing quality factor. Over a ~100 MHz frequency search range ($S_2 = 15$–35 cm), the dual-rod cavity exhibits higher FOM than the single-rod cavity, though its maximum FOM is lower. The single-rod cavity' s peak FOM occurs with a centered rod, which the dual-rod configuration cannot achieve. Additionally, dual-rod cavities show similarly low FOM in low-frequency regions, resulting in slower scanning rates.

3.3 Three-Rod Tuning Cavity

Dual-rod optimization showed that field concentration toward the cavity center reduces FOM. To enhance FOM, we introduced a non-tuning central conductor rod to disperse fields and prevent central concentration. We first examine a three-rod design without a central conductor for comparison.

Figure 5 [Figure 5: see original paper] presents the three-rod cavity design and optimization results. Panel (a) shows the configuration without a central conductor, where three rods of radius r_3 are placed at distance S_3 from the cavity axis with 120° angular separation. Numerical optimization identified $r_3 = 10$ cm as optimal.

Panel (b) shows optimized performance for the $r_3 = 10$ cm design. The TM frequency is 517 MHz at $S_3 = 15$ cm, decreasing to 291 MHz at $S_3 = 35$ cm. In the low-frequency region, fields tend to concentrate at the cavity center, reducing FOM. The right panel shows field distribution at maximum FOM, where central field intensity is nearly zero. Increased rod count introduces more field perturbations, expanding the frequency search range by ~100 MHz compared to the dual-rod cavity. However, FOM improvement remains modest, with low-frequency scanning rates still limited.

To enhance FOM, we introduced a non-tuning central conductor rod. Figure 6 [Figure 6: see original paper] shows this design, where panel (a) illustrates the structure with central rod radius r_0 and tuning rod radius r_3'. Panel (b) demonstrates how central conductor radius affects FOM for optimal dual-rod tuning rod radius $r_3' = 10$ cm. For fixed spacing S_3', FOM increases with central rod radius. For fixed r_0, FOM remains nearly constant with varying S_3'. Therefore, fixing r_0 and studying various r_3' and S_3' combinations identifies the optimal three-rod cavity with central conductor.

To ensure adequate tuning rod movement, we constrained $S_3' \leq 35$ cm. Figure 7 [Figure 7: see original paper] presents optimization results for this configuration. Panel (a) shows performance variations with central conductor and tuning rod dimensions. TM frequency increases with added metal volume, while increasing r_0 pushes fields toward cavity walls, reducing quality factor. High form factor occurs at $r_0 = 5$ cm, $r_3' = 9$ cm. Maximum FOM occurs at $r_0 = 5$ cm, $r_3' = 10$ cm, so we fixed both radii at 5 cm.

Panel (b) shows optimized performance for the three-rod cavity with central conductor. At $S_3' = 20$ cm, TM frequency is 381 MHz with maximum FOM. As tuning rods move outward, the central conductor prevents field concentration, maintaining FOM 1.6 across the frequency range. In contrast, dual-rod and three-rod cavities without central conductors achieve only FOM 1.4 at equivalent frequencies, demonstrating the central conductor' s effectiveness in improving low-frequency scanning efficiency. However, even the optimal three-rod design provides insufficient frequency search range (~50 MHz), motivating multi-rod cavity designs.

3.4 Multi-Rod Tuning Cavity

We now discuss multi-tuning-rod cavities with central conductors. Let n be the number of tuning rods arranged symmetrically at angle $2\pi/n$ to maintain cavity symmetry during tuning. Central conductor radius is $r_0^{(n)}$ and individual tuning rod radius is r_n. Optimization follows the same methodology: exploring $r_0^{(n)}$ and r_n combinations to find optimal designs.

Figure 8 [Figure 8: see original paper] presents performance parameters for optimal multi-rod cavities. Numerical simulations reveal that for the optimal eight-rod design with $r_0^{(8)} = 10$ cm central conductor radius, $r_8 = 5$ cm tuning rod radius, and axis spacing $S_8 = 30$–34 cm, the frequency search range exceeds 200 MHz with form factor >0.5 and excellent FOM. Compared to standard cavities in the same band, this eight-rod cavity increases scanning rate by ~92-fold.

Table 3 compares our optimized designs with those from Ref. [23]. The "standard single cavity" refers to a reference cavity with the same frequency. The FOM ratio indicates scanning rate improvement relative to the reference cavity. According to equation (10), FOM compares designed cavities to reference cavities through volume, form factor, and quality factor ratios. Although Ref. [23] designs operate in the GHz band with smaller volumes, FOM provides a frequency- and volume-independent performance metric. Our central-conductor designs significantly outperform Ref. [23]' s rod-only approach. While Ref. [23] adjusted rod radii and spacing to reduce central field intensity, our central conductor method effectively prevents field concentration during tuning, maintaining high FOM. The eight-rod cavity achieves 1.6× higher FOM than Ref. [23], corresponding to ~6× scanning rate increase and ~2.4× power enhancement. Compared to standard cavities, our improved eight-rod design degrades sensitivity by ~3× but increases scanning rate ~92-fold and output power ~9.6×, representing a meaningful improvement.

4 Conclusions and Discussion

With null results from all GHz-band Haloscope-type axion dark matter detection experiments, probing lighter-mass axions has become imperative. To construct a Haloscope-type detector operating in the hundreds of MHz band for lighter axions, this paper discussed microwave cavity design and parameter optimization. For larger-radius cylindrical cavities required for MHz-band detection, we optimized a 50 cm radius, 75 cm height cylindrical cavity to achieve well-isolated TM modes. Using this mode for axion-to-photon conversion, we numerically optimized form factor and scanning rate. Results demonstrate that multi-tuning-rod cavities with central conductors represent a superior design, offering acceptable frequency search ranges. Compared to standard cavities, the optimized eight-rod cavity increases frequency scanning rate ~92-fold, though sensitivity and scanning rate improvements are not simultaneous—higher scanning rates reduce sensitivity.

This work is limited to numerical simulations; cavity electromagnetic boundary conditions and material parameters may not perfectly match real implementations, confirming only theoretical feasibility. More realistic parameter optimization will require experimental measurements. However, given maturing technologies for meter-scale high-field magnets and ultra-sensitive MHz-band electromagnetic signal reception, constructing a Haloscope-type detector for lighter-mass axion dark matter in the hundreds of MHz band appears at least fundamentally feasible. The microwave cavity designs presented here therefore provide valuable forward-looking reference for future experimental efforts.

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Note: Figure translations are in progress. See original paper for figures.