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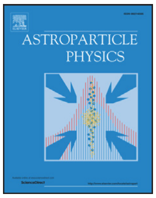

Phase-matching of multiple-cavity detectors for dark matter axion search

Junu Jeong[a], SungWoo Youn[b,*], Saebyeok Ahn[a], Chanshin Kang[a], Yannis K. Semertzidis[a,b]

[a] *Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, 34141, Republic of Korea*
[b] *Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34047, Republic of Korea*

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ABSTRACT

Conventional axion dark matter search experiments employ cylindrical microwave cavities immersed in a solenoidal magnetic field. Exploring higher frequency regions requires smaller size cavities as the TM_{010} resonant frequencies scale inversely with cavity radius. One intuitive way to make efficient use of a given magnet volume, and thereby to increase the experimental sensitivity, is to bundle multiple cavities together and combine their individual outputs, ensuring a phase-matching of the coherent axion signal. We perform an extensive study for realistic design of a phase-matching mechanism for multiple-cavity systems and demonstrate its experimental feasibility using a double-cavity system.

1. Introduction

The axion, motivated by R. Peccei and H. Quinn to solve the Strong-CP problem in quantum chromodynamics [1], is an attractive cold dark matter (CDM) candidate [2]. The most mature search method, suggested by P. Sikivie, utilizes microwave resonant cavities placed in a strong magnetic field, in which axions are converted to radio-frequency (RF) photons [3]. The axion-to-photon conversion power is expressed as

$$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C \min(Q_L, Q_a) \tag{1}$$

where $g_{a\gamma\gamma}$ is the axion-to-photon coupling, ρ_a is the local halo density, m_a is the axion mass, B_0 is the magnetic field, V is the cavity volume, C is the resonant mode form factor, and Q_L and Q_a are the loaded cavity and axion quality factors, respectively. It is noted that the detection volume determined by the cavity size is an important experimental parameter for improving the experimental sensitivity. An important quantity relevant to the experimental sensitivity is the signal-to-noise ratio (SNR), which is given by

$$\mathrm{SNR} \equiv \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{\mathrm{syst}}} \sqrt{\frac{t_{\mathrm{int}}}{\Delta f_a}}, \tag{2}$$

where k_B is the Boltzmann constant, T_{syst} is the total system temperature, t_{int} is the integration time, and Δf_a is the signal bandwidth.

Cavity-based axion search experiments typically employ a single resonant cavity, which fits within a given magnet bore. However, exploring higher frequency regions requires smaller cavity sizes as the frequency of the resonant mode of our main interest, TM_{010}, is inversely proportional to the cavity radius R, i.e., $f_{\mathrm{TM}_{010}} \sim R^{-1}$. As conventional experiments rely on a single magnet with a fixed bore, an intuitive way to increase the detection volume for higher frequencies is to bundle multiple cavities together and combine the individual outputs coherently; this is referred to as "phase-matching". The idea of multiple-cavity design was introduced in 1990 [4]; an experimental attempt to implement this design was attempted in 2000 using a quadruple-cavity detector [5], in which the methodological advantages of this design were not fully addressed because the reliability and increased complexity of operation were significant factors. Herein, we revisit this idea to convince readers that achieving phase-matching of an array of multiple cavities is realistically feasible and that the designed mechanism is certainly applicable to axion experiments in high frequency regions. In this paper, we present an extensive study of the conceptual design for a phase-matching mechanism and demonstrate its experimental feasibility using a double-cavity detector.

2. Receiver chain configuration

There are three possible configurations in the design of a receiver chain for a multiple(N)-cavity system. One configuration comprises N single-cavity experiments, consisting of N independent complete receiver chains, in which the signals are statistically

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* Corresponding author.
E-mail address: swyoun@ibs.re.kr (S. Youn).

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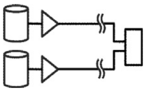
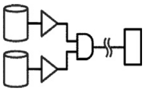
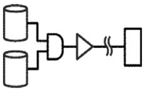
Table 1
Possible configurations of the receiver chain for a multiple(N)-cavity system. The cylinders, triangles, and D-shaped figures represent cavities, amplifiers, and combiners, respectively. $\mathrm{SNR}_{\mathrm{sgl}}$ refers to the signal-to-noise ratio (SNR) of a single-cavity experiment. The gain of the amplifiers is assumed to be sufficiently large.

Configuration	1	2	3
Schematic			
Components	N complete chains	N amplifiers 1 combiner	1 amplifier 1 combiner
Sensitivity	$\sqrt{N} \cdot \mathrm{SNR}_{\mathrm{sgl}}$	$N \cdot \mathrm{SNR}_{\mathrm{sgl}}$	$\lesssim N \cdot \mathrm{SNR}_{\mathrm{sgl}}$
Characteristic	Individual accessibility	Hightest sensitivity	Simplest design

combined at the end, eventually resulting in a $\sqrt{N}$ improvement in sensitivity. The other two configurations introduce a power combiner at an early stage of the receiver chain to build an N-cavity experiment; one with the first stage amplification taking place before the signal combination; and the other with the signal combination preceding the first stage amplification. Among these two configurations, the former is characterized by N amplifiers and a combiner, while the latter is characterized by a single amplifier and a combiner. Table 1 summarizes the schematics and characteristics of these three configurations. In any design, an independent frequency tuning system is required for each cavity. Assuming the axion signals from individual cavities are correlated, while the noises of the system components are uncorrelated, configuration 2 gains an additional $\sqrt{N}$ improvement, yielding the highest sensitivity (see Appendix A). On the other hand, configuration 3 provides the simplest design with a sensitivity compatible with that of configuration 2 [6]. As a simpler design is significantly beneficial especially for large cavity multiplicities, configuration 3 is chosen as the final design.

3. Phase-matching

3.1. Frequency-matching

Under the cosmological assumption that dark matter axions are virialized in our galaxy, a condensate of CDM is represented by coherent oscillations of the axion field. The corresponding de Broglie wavelength of $10^1 \sim 10^3$ m is much larger than the typical size of axion detectors ($< 10^{\circ}$ m). Individual detectors in a cavity array see approximately the same oscillation phase of the axion field and thus the electromagnetic (EM) fields of the cavity resonant modes coherently oscillate in a common external magnetic field. This theoretical assumption enables a multiple-cavity approach to be experimentally plausible.

Since the axion mass (equivalently the frequency of the converted photons) is unknown, a cavity must be tunable to scan the frequency range allowed by the cavity. In addition, to enhance signal power, which is added linearly with the cavity multiplicity, the cavities in an array must be independently tuned to the same frequency. Failure in phase-matching broadens the width of the combined power spectrum, causing degradation of the effective quality factor, and eventually reduces the experimental sensitivity. This phase-matching in the frequency domain turns out to be the critical and challenging part of designing multiple-cavity systems.

The coherent axion signals extracted from individual cavities must interfere in a constructive manner at the combination level. Phase-matching in the time domain, i.e., constructive interference, requires RF cables of the same length between the cavities and the power combiner. Based on a simulation study, it is found that in order to see more than 95% of the ideally interfered signal, the cable length difference must be less than 18 mm $/f$[GHz] for a quadruple cavity system.

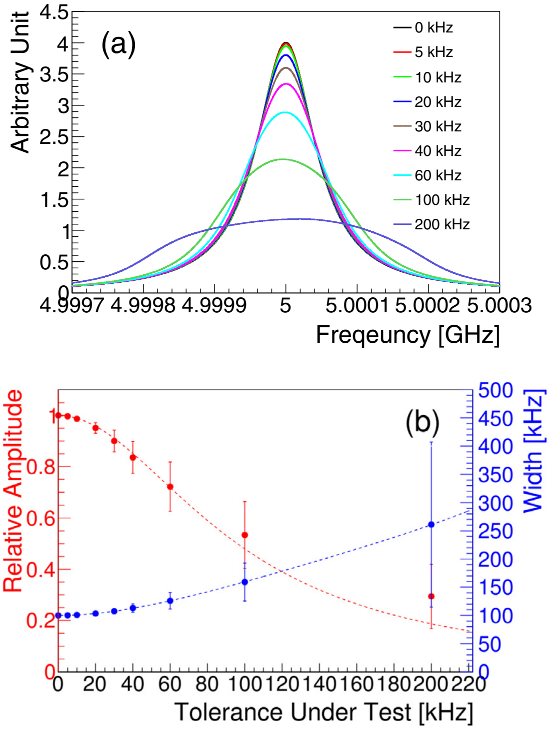


Fig. 1. (a) Combined power spectra averaged over 1000 Monte Carlo experiments for several TUT values. The power amplitude of each cavity is normalized to unity. (b) Relative power amplitude in red and full width at half maximum in blue as a function of TUT. The error bars represent the statistical uncertainties. These distributions are fitted with the Lorentzian and forth order polynomial functions, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Due to the large wavelength of the coherent axion field and the relatively facile achievement of constructive interference in signal combination, the phase-matching of a multiple-cavity system is in practice equivalent to frequency tuning of the individual cavities to the same resonant frequency, which is referred to as frequency-matching. The cavity frequency varies with disturbances of the EM field of the resonant mode, typically by means of a (pair of) dielectric or metal rod(s) inserted inside the cavity. Unfortunately, ideal frequency-matching of multiple cavities is not possible mainly because of the machining tolerance for cavity fabrication and the non-zero step size of the tuning system. Typical values of machining tolerance and step size of piezoelectric rotators are 50 µm and 0.1 m°, respectively. These values correspond to a frequency difference of ~ 10 MHz and a frequency step of ~ 0.5 kHz for the TM_{010} mode of a 5 GHz resonant cavity. Instead, a more realistic approach is to permit frequency mismatch up to a certain level at which the combined power is still sufficiently high that the resulting sensitivity is not significantly degraded. We refer to this certain level as the frequency matching tolerance (FMT).

3.2. Frequency matching tolerance

To determine FMT for multiple-cavity systems, a Monte Carlo simuation study is performed using a quadruple-cavity detector to search for a 5 GHz axion signal. The unloaded quality factors of the cavities are assumed to be the same at $Q_0 = 10^5$. Supposing $Q_a \gg Q_0$, the signal power spectrum is expected to follow the Lorentzian distribution with a mean of 5 GHz and half width of 50 kHz. Several values of frequency matching tolerance, also