Multiple-Cavity Detectors for Axion Search

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Searching higher frequency regions for axion dark matter using microwave cavity detectors requires smaller size cavities as the resonant frequencies scale inversely with their radius. One of the intuitive ways to make an 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 phase-matching of the coherent axion signal. An extensive study for realistic design of the phase-matching mechanism is performed and an experimental demonstration is undertaken using a double-cavity system.

1 Introduction

Axion is an attractive dark matter candidate originally motivated by the Peccei-Quinn solution to the strong-CP problem [1]. The current technologies utilize the axion-to-photon conversion to detect the axion signal using microwave resonant cavities embedded in a strong magnetic field, suggested by P. Sikivie [2], and conventional experiments employ a single cavity fitting into the given magnet. Exploring higher frequency regions, on the other hand, requires smaller cavity sizes as the resonant frequency of our main interest, TM_{010}, is inversely proportional to their radius R ($f_{\mathrm{TM}_{010}} \sim R^{-1}$). As many experiments rely on a magnet with a fixed bore size, an intuitive way to increase the detection volume for the given magnet, and thereby to improve the experimental sensitivity, is to bundle multiple cavities together and combine their individual outputs in phase, which is referred to as "*phase-matching*".

The idea of multiple-cavity design was introduced in 1990 [3] and the first experimental trial was given in 2000 using a four-cavity detetor [4]. However, it failed to address the methodological advantage mainly because the phase-matching is very a challenging task. The Experiment of Axion Search aT CAPP (EAST-C) is a dedicated project at the Centre of Axion and Precision Physics Research (CAPP) of the Institute for Basic Science (IBS) in Korea to develop the phase-matching mechanism for multiple-cavity systems.

2 Configurations

There are three possible configurations for experimental design of a multiple(N)-cavity system, as summarized in Tab. 1. Configuration 1 is equivalent to N single-cavity experiments, which requires N independent complete readout chains. Configuration 2 represents a N-cavity experiment where the first stage amplification takes place before the signal combination, while configuration 3 represents a similar experiment where the signal combination precedes the first stage amplification. Assuming the axion signals are correlated while the system noises (from cavities and electronics) are uncorrelated, the former design, characterized by N amplifiers and a combiner, yields the highest sensitivity, while the latter, characterized by a single amplifier and a combiner, provides the simplest design. As a simpler design is significantly beneficial especially N goes large, configuration 3 is chosen as the final design.

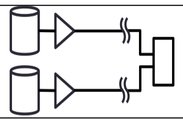
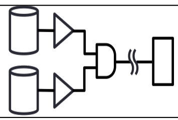
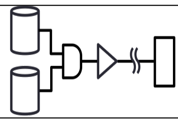
Configuration	1	2	3
Schematic			
Characteristics	N readout chains	N amplifiers 1 combiner	1 amplifier 1 combiner
Sensitivity (SNR)	$\sqrt{N} \cdot \mathrm{SNR}_{\mathrm{sngl}}$	$N \cdot \mathrm{SNR}_{\mathrm{sngl}}$	$N \cdot \mathrm{SNR}_{\mathrm{sngl}}$[1]
Pros	Individual accessibility	Highest sensitivity	Simplest design
Cons	Low sensitivity Complex design	N amplifiers	$\mathrm{SNR}_3 < \mathrm{SNR}_2$[2]

Table 1: Possible configurations for the multiple-cavity experiment design. $\mathrm{SNR}_{\mathrm{sngl}}$ refers to the signal-to-noise ratio (SNR) of a single-cavity experiment. [1]The combiner is assumed to be perfect, i.e., no power loss and no additional noise. [2]In reality, SNR degrades due to imperfection of the combiner, e.g. a system with a combiner with a noise figure of 0.5 and a amplifier with a gain of 12 and a noise figure of 6 yields a SNR reduction of $\sim$10%.

3 Phase matching

3.1 Phases

In multiple-cavity axion experiments, three uncorrelated phases are concerned. These are related to 1) coherence of the axion field; 2) resonant frequency matching among cavities; and 3) phase matching in signal combination.

First of all, according to cosmology, axions are entirely virialized in the early universe and thus the axion field is coherent in the present universe. In addition, the de Broglie wavelength of axion ($10^1 \sim 10^3$ m) is much longer than the typical size of axion detectors ($\sim 10^{-1}$ m). Therefore, if axions exist and are detectable, the signals from the cavities in an array are generated almost in phase in a static magnetic field. Secondly, in order to see the coherent axion signal, individual cavities must be tuned at the same resonant frequency. The phase-matching in the frequency domain is an essential and the most challenging part of the phase-matching mechanism. Lastly, the RF signals at the same frequency must interfere each other in a constructive manner at the power combiner to maximize the combined signal. The constructive interference, i.e., phase-matching in the time domain, requires identical cables with the same length.

Since the first and last phase-matchings are theoretically resolved and experimentally archivable in ease, the phase matching in this regards is approximated to the frequency matching.

3.2 Phase (frequency) matching

One of the main sources of frequency mismatch between individual cavities in an array comes from the machining tolerance in cavity fabrication. A typical machining tolerance of ∼50 μm induces a frequency difference of ∼10 MHz for 5 GHz resonant cavities. However, an ideal frequency matching is not possible due to the non-zero position resolution of the turning system, e.g. a resolution of 0.1 m° of a rotator corresponds to a frequency resolution of ∼0.5 kHz for 5 GHz resonant cavities. Instead, a more realistic approach is to allow frequency mismatch up to a certain level where the combined power is not significantly degraded, i.e., the combined power is greater than 95% of that for the ideal case. We refer to the certain level as the frequency matching tolerance (FMT).

3.3 Frequency matching tolerance

In order to determine FMT for multiple-cavity systems, a pseudo-experiment study is performed using a quadruple-cavity detector with an unloaded cavity quality factor $Q_0 = 10^5$ searching for 6 GHz axion signal. Several values of frequency matching tolerance, tolerances under test (TUT), are considered - 0, 10, 20 ,30, 60, 100, 200 kHz, where 0 kHz represents the ideal combination. The cavities are randomly tuned to 6 GHz within the TUT to be concerned and a combined power spectrum is constructed by summing up the power spectra from the individual cavities. Each cavity is assumed to be critically coupled with a RF antenna. The procedure is repeated 1,000 times. The distributions of averaged combined power spectrum for each TUT, and its amplitude and full width at half maximum are shown in Fig. 1. It is drawn that the FMT for a quadruple detector with $Q_0 = 10^5$ for 6 GHz axion signal is 20 kHz. This is generalized for different Q_0 values as FMT = 2 GHz/Q_0.

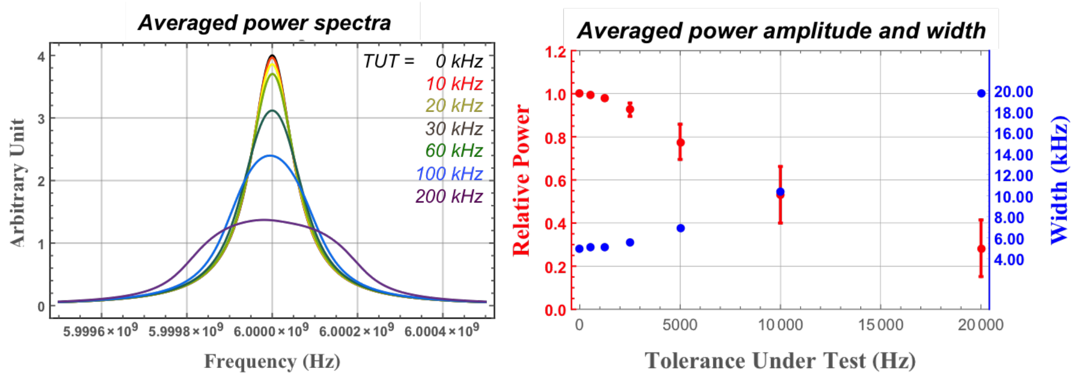


Figure 1: Combined power spectra averaged over 1,000 pseudo-experiments for several TUT values where the power amplitude from each cavity is normalized to the unity (left), and the power amplitude relative to the ideal case and full width at half maximum for the TUT values where the error bars represent the statistical uncertainties (right).

3.4 Tuning mechanism

The basic principle of the tuning mechanism for cavity-based experiments relies on critical coupling of the load with the cavity. The critical coupling is characterized in a network analyzer by a minimized reflection coefficient (Γ) and a circle passing through the center of the Smith Chart. For a single-cavity system, Γ is minimized when the system is critically coupled. For a multiple-cavity system, on the other hand, the combined Γ is minimized when frequency matching is successful as well as the entire system (each cavity) is critically coupled.

The tuning mechanism for a multiple-cavity system consists of three steps: 1) simultaneous operation of the frequency tuners to shift the target frequency; 2) finer operation of the individual tuners to achieve the frequency matching; 3) global adjustment of the load positions to achieve the critical coupling. The global adjustment is chosen at the sacrifice of a sensitivity loss of <0.5%, which is estimated from a machining tolerance of 50 μm and an uncertainty on surface conductivity of 2%.

4 Experimental demonstration

The feasibility of the tuning mechanism for multiple-cavity systems is experimentally demonstrated using a double-cavity detector. It is comprised of two copper cavities with an inner diameter of 3.88 cm whose corresponding resonant frequency is 5.92 GHz and a loaded quality factor of 9,000 at room temperature. A dielectric rod made of 95% of alumina with a diameter of 0.4 mm is introduced to each cavity for frequency tuning and operated by a piezoelectric rotator. With the tuning rod positioned at the center of the cavity, the resonant frequency decreased to 4.54 GHz and Q_L degrades to 2,500. A pair of antennas, each of which is coupled to each cavity, sustained by a holder attached to a linear piezoelectric positioner so that their positions are adjusted in a global manner.

The sequence of the demonstration is shown in Fig. 2. Assembly of a double-cavity system begins with connection of a wilkinson type power combiner to a network analyzer. A calibration is made up to the two couplers using two sets of calibration kits. The critical coupling of a cavity is made while the port of the combiner which is connected to the other cavity is terminated with a 50 Ω impedance, and vice versa. Two cavities are critically coupled at slightly different resonant frequencies. The initial values of Q_L and scattering parameter S_{11} are measured. The system is fully assembled with the two cavities connected to the combiner. Two reflection peaks with S_{11}=6 dB at the above frequencies and two small circles with half radius are observed. At this stage we assume that the slightly different frequencies are the consequence of a global operation of the frequency tuners to shift the target frequency. Now one of the piezoelectric rotators is operated to finely tune its frequency until the combined reflection coefficient becomes minimized, which corresponds to frequency matching. It is also observed that the two small circles become one larger circle. However, it fails to pass the center of the Smith Chart, indicating the critical coupling is not made. The linear positioner is operated to adjust the antenna positions in a global manner to achieve the critical coupling. It is noted that the reflection peak becomes deeper and the circle passes through the center of the Smith Chart. The final Q_L and S_{11} values are measured, and it is seen that they are consistent with the initial values. This confirms that the turning mechanism with phase (frequency) matching for multiple-cavity systems is feasible in real experiments.

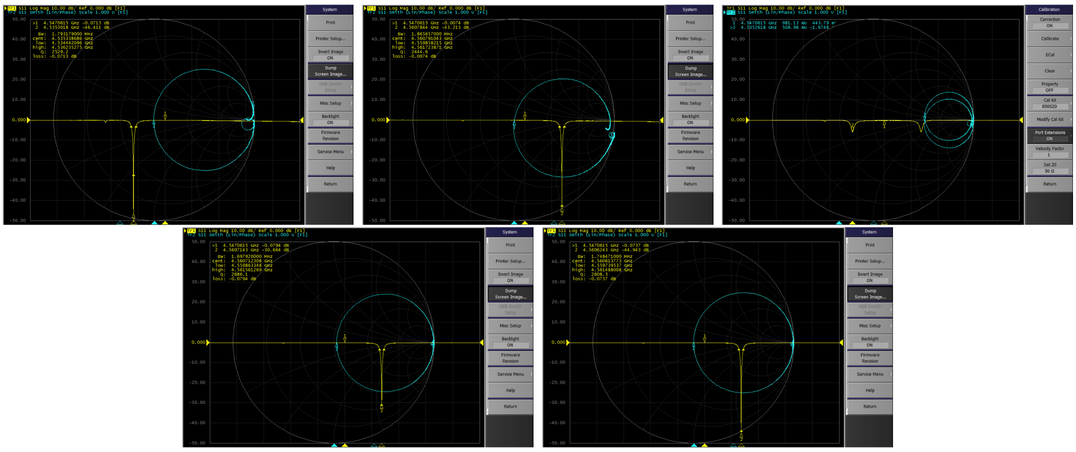


Figure 2: Sequence of the demonstration of the tuning mechanism described in the text using a double-cavity system. Yellow lines are the scattering parameters, S_{11}, in a logarithmic scale and circles in cyan are the representations in the Smith Chart. The first (second) cavity is critically coupled individually, and the initial S_{11} and Q_L read -46.4 (-43.2) dB and 2530 (2440) respectively (Top left and top middle). Two -6 dB peaks and two small circles are observed after the system is fully assembled (Top right). When the frequency matching is achieved, a single deep peak and a single large circle are formed (Bottom left). Once the critical coupling is made in a global manner, the peak becomes deeper and the circle passes through the center of the Smith Chart (Bottom right). The final S_{11} and Q_L read -44.4 dB and 2610.

5 Summary

Multiple-cavity design is an effective way to increase the sensitivity of axion search experiments in higher frequency regions. The frequency matching between individual cavities is a key component of the phase-matching mechanism. A readout chain where signal combination precedes the first stage amplification is beneficial with the simpest setup and minimal signal power degradation. For a realistic approach for phase (frequency) matching, the frequency matching tolerance is introduced and numerically determined for a quadruple-cavity detector for 6 GHz axion signal. An experimental demonstration of the tuning mechanism (phase-matching and critical coupling), successfully made using a double-cavity detector, verifies its feasibility in real experiments.

6 Acknowledgments

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