Cross-Spectral Measurements for Cavity-based Axion and WISP Experiments

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We introduce the basic concepts of the cross-spectrum measurement technique whereby two spectrums are cross-correlated together, allowing for rejection of uncorrelated noise processes. We apply these ideas to microwave cavity-based searches for Weakly Interacting Slim Particles and provide a proof-of-concept measurement.

1 Introduction

Weakly Interacting Slim Particles (WISPs) are a broad class of hypothetical particles with sub-eV masses that provide elegant and compelling solutions to a host of outstanding issues in particle physics and cosmology [1]. Experimental searches for these particles typically involve exploiting WISP-to-photon couplings, which provide a sensitive portal for detection with minimal model dependency. Some of the most sensitive and mature techniques for WISP searches utilize microwave and RF cavity structures, such that the converted WISP signal is resonantly enhanced and then read out via an amplification chain coupled to the cavity [2, 3, 4]. The challenge is to resolve the very weak power associated with WISP-to-photon conversion, P_W, against the intrinsic system noise generated by the cavity, P_C, and the first-stage amplifier, P_A.

2 Cross-spectral WISP measurements

The cross-spectrum [5] of two spectrums rejects uncorrelated signals while retaining those that are correlated. In each individual measurement channel the measurement error associated with a noise process is reduced at a rate proportional to $\sqrt{m}$ (m = number of averages), while in the associated cross-spectrum the mean of uncorrelated processes is suppressed at the rate $\sqrt{2m}$ while the associated error remains proportionally constant.

Figure 1 outlines the cross-spectral measurement scheme for cavity-based WISP searches. Two separate nominally identical cavities each have a measurement channel coupled to them. When the cross-spectrum is computed on the FFT the first-stage amplifier noise and the thermal cavity noise is rejected, while a signal due to a flux of WISPs is correlated between the two cavities and thus remains in the cross-spectrum. As the noise being rejected is thermal (random), the performance of the system should be independent of the relative phase of the two measurement channels.

Assuming that both cavities are frequency-tuned such that their resonances overlap then the

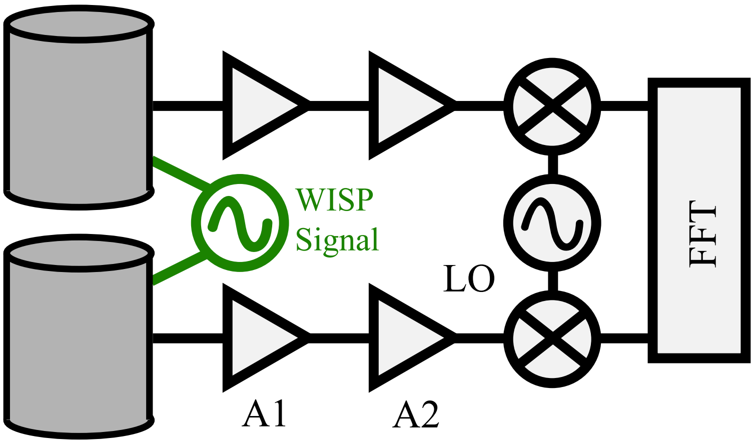

Figure 1: Schematic of the cross-spectral WISP measurement technique. The green signal source is used in the proof-of-concept measurements. A1 is the first-stage amplifier, LO is the local oscillator used to mix down the signal-of-interest to a lower frequency and FFT is the fast Fourier transform machine used to sample the spectrums.

expected Signal-to-Noise ratio for a correlated WISP signal is given by

$$\sqrt{2m}\frac{P_W}{P_C + P_A}. \tag{1}$$

This represents a $\sqrt{2}$ improvement compared to a single cavity measurement, owing to the addition of the second measurement system. It is important to note that the two cavities in Fig. 1 can be physically well-separated. This scheme therefore allows one to determine the coherence length of any candidate WISP signal.

Proof-of-concept measurements can be carried out using the system outlined in Fig. 1. A pair of nominally identical sapphire-loaded copper cavities with resonant frequencies of 9.3 GHz were housed in a vacuum chamber and connected to independent amplifier chains. The cavity resonance frequencies were tuned to overlap by adjusting the temperature control setpoint of the system. The spectrums from both channels were recorded as a function of averages taken with the cross-spectrum computed in-situ.

Figure 2 shows a single channel spectrum and the cross-spectrum of both measurement channels. The test WISP signal is resolvable in the single channel at the level 14σ, while in the cross-spectrum it is present at 20σ. This difference corresponds to a factor of $\sqrt{2}$ as outlined in Eq. (1). Fitting to the measured SNR as a function of averages indicates a starting SNR of $\sim$0.45, showing that the technique is valid for measurements with small initial SNRs, as is the typical situation in a WISP search.

Acknowledgments

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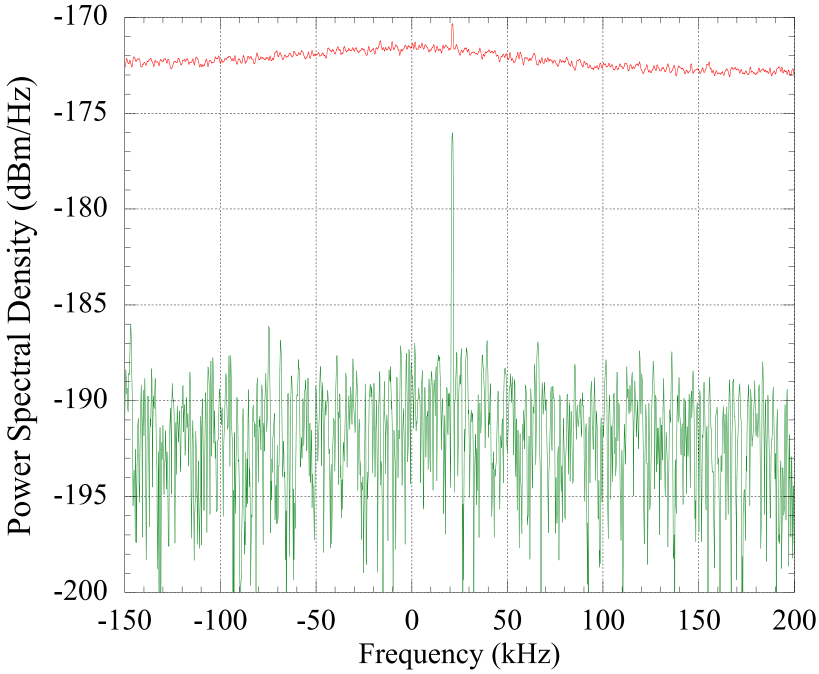

Figure 2: A 1600 point power spectrum after 1000 averages for the measurement scheme illustrated in Fig. 1. Single channel trace is shown in red and the cross-spectrum is shown in green.

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