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Wire metamaterial use for dark matter detection

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Abstract – In this work we present our insights into the electromagnetic properties of a resonator recently suggested for the search of axions – a hypothetical candidate to particles of dark matter. A wire medium loaded resonator called a plasma haloscope when used to search for dark matter consists of a metal box filled with a dense array of parallel wires electrically connected to top and bottom walls. We show that the resonator quality $Q$ at the frequency of our interest drops versus the growth of the resonator volume $V$ until it is dominated by resistive losses in the wires. However, we find that in spite of these losses even at room temperature the metal like copper offer the quality factors in the thousands, an order of magnitude higher than the quality originally assumed by the authors of the concept. We have also found a way to tune the resonant frequency so that to better match the phases of the resonator eigenmode to that of the axion. It is achieved by mechanical movement of wires in relation to each other that allows up to 30% change in the resonance frequency. Finally, we discuss how to further improve the wire medium resonators for detection of axions.

I. INTRODUCTION

Wire media (WM), being one of the first known metamaterials [1], has been studied extensively [2] over the years. However, there are still new avenues being found in which WM prove to be useful. WM has seen applications in both in radio frequencies and optical from far-zone transport of near field images to drastic enhancement of thermophotovoltaic generators, with modern solar panels, microwave antennas with improved pattern and frequency selective thermal emitters for radiative cooling of microlasers and in near-field thermophotovoltaic systems being some of the latest use cases.

Nevertheless, the behavior of wire metamaterials in resonant systems has remained relatively unexplored, save for the applications in fluorescent emitters via the giant and broadband Purcell factor as it was shown in [3, 4]. On the first look this is understandable - introducing more losses into the system via the wires seems detrimental to most cases of the utilization of such resonators. Still, there exists an exotic application where the benefits have a potential to outweigh the downsides. This is the plasma haloscope, described in [5]. The resonator proposed in this paper is a metallic cavity filled with a uniaxial wire medium and resonating at a frequency close to the plasma frequency of the WM. This eigenmode may be in phase with the predicted phase of the axion de Broglie wave [5] and their overlapping integral turns ot to be nonzero that promises us the detection of axions via the excited resonator eigenmode.

II. WIRE MEDIA CAVITY

The plasma-like behavior of the wire medium allows for existence of an epsilon-near-zero regime, in which the real part of the dielectric permittivity becomes extremely small. Working in the vicinity of this regime allows for
an extensive control over the refractive index of the materials and the wavelength of photons within the resonator. This property is crucial for plasma haloscope’s operation, as it allows to match the resonant photon’s Compton wavelength to the De Broglie wavelength of the axion, strongly increasing the coupling. However, two important questions emerge at this point. Firstly, are we certain that introducing plasma into the microwave resonate will not undermine the quality factor to the point of it no longer being resonant. Secondly, since as of now the De Broglie wavelength of the axion is an unknown, how do we ensure sufficient tuning capability that would allow for a single haloscope to scan a wide range of frequencies? As it turns out, using wire media allows us to address both of these points.

Starting with the second point, the important property of wire media is the ease of engineering their plasma frequency. Tuning can be achieved by changing the two determining factors - the radius of the wires and the period of the lattice. For instance, we have shown that by splitting a square lattice into two sublattices and moving them relative to each other we may achieve up to 30% decrease in frequency relative to the one for the square lattice (Fig. 1a). While the operating frequency of the resonator does in fact depend on its dimensions as well, this contribution is relatively small and decreases quickly as the volume of the cavity is increased. This fact is, in fact, the point that has largely lead to the proposal of plasma haloscopes in the first place.

Among the factors that determine the power coupled from the haloscope are the cavity volume, quality factor and the geometric factor describing the overlap integral of the cavity mode and the DC magnetic field necessary for the axion-photon coupling. The latter is maximised when the cavity operates at its fundamental TM mode. As mentioned, the mode frequency is mostly determined by the lattice geometry, effectively removing the relation between cavity volume and the wavelength in the cavity inherent in conventional microwave resonators. This, in turn, seemingly allows to build cavities that are able to probe the range of tens of GHz without sacrificing the sensitivity due to small volume. However, we still have to consider the first question outlined above. This advantage, of course, would be meaningless if the quality factor of the resonator would suffer significantly due to introduction of the wires. We have shown, however, that this is not the case. As shown in Fig. 1b, as we increase the number of unit cells within the cavity (with its volume growing as \((N a)^3\)), the unloaded quality factor decreases to a plateauing value in a manner similar to how the resonance frequency approaches plasma frequency in the same scenario. Moreover, for copper cavity and wires, this value is shown to be over 3000 - an order of magnitude higher than previously assumed in [5].

![Graph](image)

(a) First resonance frequency of a 10 × 10 square resonator as a function of the relative shift between two sublattices. The initial configuration is a square lattice. We present it as two sublattices: with the wires in the odd rows (blue) and with the ones in the even rows (orange). When two sublattices are shrunk and the distance \(a − 2\Delta y\) between 2 closest minimized, the resonance frequency decreases down to 70%.

![Graph](image)

(b) Unloaded quality factor \(Q\) as a function of the number of wires \(N^2\) in a WM consisting of radius \(r = 1\) mm copper wires with a period \(a = 1\) cm placed inside a cubic cavity. Analytic results (red line) assuming a homogenisation model are compared with a numerical simulation (blue squares) in CST with square wires of thickness \(2r\), with a gap of \(a/2\) with the cavity walls.

**Fig. 1: Dependence of the WM resonator properties on its geometry.**

It is important to note, however, that the power coupled from resonator is in actuality determined by the loaded quality factor - given, in turn, by the unloaded quality factor and the coupling coefficient. As such, it becomes important to not only study the impact of the tuning process on the unloaded quality factor of the resonator,
but to also consider the impact the movement of wires has on their interaction with the coupling probe, inevitably changing the coupling coefficient. In order to look into it we have modeled a cubic $10 \times 10 \times 10 \text{cm}^3$ resonator made out of 65% brass approximating the planned realisation of an experimental prototype. Two SMA ports were present in the centers of the top and bottom walls with their 8 mm long cores acting as electrical monopole probes coupled to the TM modes of the structure. The results of the numerical modelling are presented in Fig. 2. As can be seen in Fig. 2a, the unloaded quality factor of the resonator rises by about 50% as the operating frequency is tuned down. However, the loaded quality factor (Fig. 2b) drops to less than a third of its original value. We hope that this can be counteracted by appropriately matching the probe in the process of tuning. The possibility of this will be the subject of future numerical simulations.

![Image](image-url)

(a) Loaded quality factor $Q_U$ as a function of tuning  
(b) Unloaded quality factor $Q_U$ as a function of tuning

Fig. 2: Quality factors of a $10 \times 10$ square resonator as a function of the relative shift between two sublattices. The initial configuration is a square lattice of radius $r = 1 \text{mm}$ brass wires with a period $a = 1 \text{cm}$. The lattice is split into two sublattices off odd and even rows of wires. The distance between the two closest rows changes as $a - 2\Delta y$. The ports are positioned in the centers of the top and bottom walls.

To conclude: we have shown that the microwave resonators filled with wire media do exhibit the properties allowing them to potentially be used for axion search in the range of tens of GHz. The quality factor of the resonator reaches a constant value as the volume is increased, which removes the constraint of operating frequency being inversely proportional to the cavity’s volume. The constant value amounts to several thousands at room temperature and can be expected to be boosted further in a cryogenic environment. Superconductive wires can potentially also contribute to further improving the Q-factor. This bodes very well for the sensitivity of the future experiment. Shifting the wire sublattices seems to be a promising way to achieve a good range of tuning in a given geometry. However, the exact mechanism by which the wires could be moved in such a way is yet to be designed and tested.

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