A telecommunications system based on axion dark matter coherent transmission

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Abstract. In this manuscript we anticipate axion detection in order to theorize on a novel telecommunications system based on the coherent axion-two-photon vertex Primakoff effect conversion and reversion of microwave photons transmitting a modulated signal. We suggest a possible set-up for an experiment or industrial application using state-of-the-art technology and we estimate the output power and photon rate expected to be received as a function of the axion-photon coupling constant $g_{a\gamma\gamma}$. We find that, although challenging, this system has no physical restriction to render it unfeasible. Finally, we summarize the advantages and disadvantages of a hypothetical axion-based telecommunications system compared to traditional telecommunication systems. We then extend the discussion, noting the more important conclusions.

Keywords: Dark Matter detectors, Performance of High Energy Physics Detectors, Trigger concepts and systems, Data acquisition circuits, Axion.
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1. Introduction

The axion is a hypothetical pseudo-scalar Goldstone boson theorized by Weinberg and Wilczek ([1], [2]) as consequence of the dynamic solution to the strong CP-symmetry problem presented by Peccei and Quinn (PQ) [3] and is predicted in multiple extensions of the Standard Model (SM) of particle physics. Moreover, many extensions of the SM and string theory predict a set of particles similar to the axion, the so-called axion-like particles or ALPs. Axions and ALPs mix with ordinary photons within an external magnetic field. The axion–photon coupling constant is commonly expressed as $g_{a\gamma}$ in units of GeV$^{-1}$. The axion has a light mass, induced by interactions with SM particles, which scales inversely to a PQ-field scale ($f_a$) ([4], [5], [6]). For $f_a$ scales of the order of $10^{12}$ GeV, or equivalently masses of the order of the $\mu$eV, the axion is a well-grounded candidate for (cold) dark matter (DM) ([7], [8], [9]). Therefore, the axion could simultaneously explain two fundamental problems in modern physics: the strong CP problem and the mystery of DM. Furthermore, it could have an industrial application in telecommunications.

Given the expectations within the scientific community of a detection in the coming years, several countries have already established specific centers, departments, and institutions dedicated to axions. Anticipating a hypothetical detection, in this work we present the novel concept of a telecommunications system based on the coherent transmission of axions, looking at the first conceptual design from a purely theoretical point of view.

An axion is a hypothetical particle whose existence and characteristics are not confirmed. However, this work would be useful in the case of a detection in the coming years or in order to add an extra (and industrial) motivation for experimental axion search. The contribution to experimental axion search from this author and a comprehensive summary of the status for the research of the field are presented in [10].

The article is structured as follows. In section 2 the theoretical framework is briefly presented. In section 3 a conceptual design of a telecommunications system based on axion transmission is presented. Finally, conclusions and a discussion of future lines of work are presented in section 4.

2. Background

Within the classic limit, the axion field can be approximated by $a = \theta_0 \cos(m_a t) f_a$, where $m_a$ is the axion mass, $t$ is time, $\theta_0 \approx 4 \times 10^{-19}$, and $f_a$ is the above-mentioned PQ-scale. This means that axion field can be treated as a plane wave so that it can be modeled using Maxwell equations, similarly to electromagnetic (EM) waves [11].

In light shining through walls (LSW) experiments photons propagating within an external magnetic field ($B$) produce a coherent axion beam with a conversion probability given by

$$P \approx \frac{1}{4} (g_{a\gamma\gamma} BL)^2,$$  (1)
in the limit $m_a^2 L/2\Omega << 2\pi$, where $g_{a\gamma\gamma}$ is the axion-two-photon vertex rate in the Primakoff effect [12] and $L$ is the magnetized length-of-flight, $B$ being the external magnetic field inductance. Natural units are used.\[‡\]

![Figure 1. Light shining through walls axion-to-photon regeneration. All the photons received in '2' are induced by axions generated in '1'. Reprinted with permissions from [13].](image)

The classical set-up [14] shown in Fig. 1 consists of a laser pumping photons through a dipole magnet’s bore. If a second magnet is placed following the first one through the line-of-flight, and a wall acts as light shield between them, cancelling the incoming photon beam, all the photons within the second magnet bore are induced by axions or ALPs. Thus, LSW experiments require both axion-to-photon and photon-to-axion conversion, and thus the overall (re)conversion probability decreases to $P^2$. Novel LSW experiments propose the use of Fabry-Perot (FP) resonators, enhancing the conversion rate by a factor $\sim F_1 F_2 \beta_1 \beta_2$ compared to the classical layout, where $F$ is a number of the order of unity, the so-called finnese, while the resonant enhancement factor $\beta$ is $\mathcal{O}(10^4)$. Novel FP LSW experiments benefit from both interferometry and larger-bore magnets ([13], [15]).

### 3. Axion-based telecommunications systems

The CROWS ([16], [17]) experiment (see Fig. 2) has recently demonstrated that it is possible to transform the classical layout of the (optical) LSW experiment into a microwave system. In this novel experiment, the '1' (emitting) and '2' (receiving) resonant RF cavities are housed within a 3 T magnetic field, and a 50 W power signal of around 2 GHz of frequency is injected. Both cavities present a quality factor ($Q$) above $10^4$, and a geometrical factor $\Omega \sim 0.6$. Both cylindrical cavities are designed to be resonant in a narrow band centered at a frequency $\nu_a$ corresponding to an axion mass of approximately 7 $\mu$eV and so have dimensions of around 15 cm in diameter and height.\[‡\] Note that $1 \text{ eV}^{-1} \simeq 0.197 \times 10^{-7}$ m, $1 \text{ T} \simeq 195 \text{ eV}^2$ and $1 \text{ GHz} \simeq 4.136 \mu$eV.
The energy of the pump and inverse Primakoff effect reconverted photon is independent of axion mass. The overall conversion probability is given by

\[ P^2 \simeq \left( \frac{g_{a\gamma\gamma} B}{\nu_a} \right)^4 \Omega^2 Q_1 Q_2, \]

(2)

where \( \nu_a \) is the resonant frequency of the cavities, \( \Omega \lesssim 1 \) is the geometrical factor, and \( Q_{1,2} \) is the quality factor.

Since the energy of a photon is given by \( E = h\nu \), for a given input power more photons are generated in microwave-based experiments in comparison to (classical) optical LSW experiments, and this is the reason why axion-based telecommunications systems using an optical laser pump are not feasible, even with the benefit from larger magnet bores, high \( \mathcal{F}_1 \mathcal{F}_2 \beta_1 \beta_2 \), or implementing MW power optical pumps \[18\], presenting a flux rate \( \ll 1 \text{ photon}(\gamma)/\text{s} \), making information transmission extremely inefficient. The ALP spectral line width is narrow, quasi-monochromatic, although the spectral resolution of the system is not so high, of the order of kHz. A heterodyne receiver is used for the detection and low-conversion of the signal, and its output is digitized using an analog-to-digital converter (ADC), presenting high phase stability. The system presents sensitivity to \( g_{a\gamma\gamma} \sim 10^{-7} \text{ GeV}^{-1} \) after 1–2 days of stacking data. This corresponds to \( P^2 \sim 10^{-26} \) or \( 10^{-24} \text{ W} \) with a \( \sim 1 \gamma/\text{s} \) rate. Here, the margin for improvement may exist in order to make axion-based telecommunications feasible. In \[17\] the author points to a practical realization using superconducting cavities in order to enhance the quality factor. Furthermore, there is no reason why the geometrical factor (\( \Omega \)) cannot be enhanced with R&D. Although challenging, as far as this author is aware there is no fundamental or physical limitation on increasing the RF input power (source + amplifier) except the need for a low system temperature (\( T_{sys} \)) and high source stability. \( T_{sys} \) could be controlled by (higher-power) cryogenics, in principle. Another upgrade could be the replacement of the high electron mobility transistor (HEMT) heterodyne radiometers used in the original experiment by superconducting film detectors working at sub-K temperatures not far from the quantum limit.

A hypothetical system with state-of-the-art inductance \( B = 45 \text{ T} \), feasible nowadays in small volumes \[19\], and a typical high-quality factor around \( Q \sim 10^5 \) is considered now. Moreover, the advances in research on GW RF power sources with carrier frequencies of around 1 GHz are remarkable, with relevant contributions being made as far back as from the 1990s until the present day \([20, 21, 22]\). The geometrical factor is set at \( \Omega \sim 0.75 \) as result of an effort in R&D. In the ALP energy sector \( g_{a\gamma\gamma} \sim 5 \times 10^{-12} \text{ GeV}^{-1} \) we obtain a conversion probability \( P^2 \sim 10^{-34} \), or equivalently \( \sim 10^{-22} \text{ W} \) produced by axion-induced photons to be detected and decoded if a 1 GW RF signal is pumped, for a number of \( \gamma/\text{s} \) \( \mathcal{O}(100) \). The well-known ideal radiometer

\[\text{§} \text{ Note that a sub-band within the energy sector } g_{a\gamma\gamma} \sim 10^{-11} \text{ GeV}^{-1} \text{ has already been excluded by haloscopes, helioscopes, and stellar clues from astronomical observations for below-eV axion mass (e.g., see [7, 8, 9])}\]
equation \[23\] in the form
\[
\Delta t = \left( \frac{\text{SNR} k_B T_{sys}}{P} \right)^2 \Delta \nu_a,
\]

where \(\text{SNR}\) is signal-to-noise ratio, \(k_B\) is the Boltzmann constant, \(T_{sys}\) is system temperature and \(P\) is power, establishes that the integration time (\(\Delta t\)) required to receive this power level at \(T_{sys} \sim 0.1\) K with 10\(\sigma\) significance (e.g.) is around \(10^{-2}\) s\(^2\)Hz, referred to the bandwidth in which the information is packed through the axion field \((\Delta \nu_a)\), which cannot be ideally monochromatic, as mentioned. This may establish a natural limit for the refresh time that this telecommunications system would present. A different state-of-the-art practical realization would use superconducting cavities to enhance the quality factor by up to \(Q \sim 10^{10}\) \[24\], maintaining similar values for the \(B\), \(\Omega\), and \(g_{a\gamma\gamma}\) parameters. However, owing to electric field breakdown and quenching issues, in this set-up the RF power supply should not exceed about 100 W in principle. Here, we obtain \(P^2 \sim 10^{-24}\) and a output of around \(10^{-22}\) W, for an identical axion-induced photon rate of around 100 \(\gamma/s\). Note that axion-based telecommunications sytems would be very sensitive to \(g_{a\gamma\gamma}\), so a small increase in the axion-to-photon coupling strength would result in a number of \(\gamma/s\ \mathcal{O}(1000)\) and hence a much higher transmission rate for telecommunications. The results are summarized in table \[1\].

Once axion or ALPs are detected, if this ever happens, and in the case that the particle exists in a favourable energy sector in terms of mass and coupling strength, the RF LSW experimental set-up may be reconverted into a telecommunications system.

\[\parallel\] In \[17\] the author suggest \(\Delta \nu_a \lesssim 10\ \mu\text{Hz}.\)

\[\parallel\] For example, a factor of 1.6.
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| $P_1 [W]$ | $v [\text{GHz}]$ | $g [\text{GeV}^{-1}]$ | $B [T]$ | $\Omega$ | $Q_{1,2}$ | $P_2 [W]$ | $\gamma / s$ |
|-----------|------------------|-----------------|--------|--------|---------|-----------|--------|
| 50        | 1.75             | $6 \times 10^{-8}$ | 3      | 0.6    | $10^4$  | $10^{-24}$ | 1      |
| $10^{12}$ | 1                | $5 \times 10^{-12}$ | 45     | 0.75   | $10^5$  | $7 \times 10^{-23}$ | $10^2$ |
| 100       | 1                | $5 \times 10^{-12}$ | 45     | 0.75   | $10^{10}$ | $7 \times 10^{-23}$ | $10^2$ |
| $10^{12}/100$ | 1            | $8 \times 10^{-12}$ | 45     | 0.75   | $10^5/10^{10}$ | $4 \times 10^{-22}$ | $10^3$ |

Table 1. Simulations for several systems. CROWS results (top-row) reported in [17] and three hypothetical systems are compared.

This would be carried out simply by separating both cavities in different (and distant) regions in space. A modulator for the RF photon pump should be placed in the path of the transmitter unit. The schematic would be injection $\rightarrow$ encoding $\rightarrow$ photon-to-axion conversion $\rightarrow$ transmission $\rightarrow$ axion-to-photon reversion $\rightarrow$ reception $\rightarrow$ decoding. Since the axion-two-photon vertex Primakoff effect conversion and reversion are phase-coherent, the signal could be encoded (i.e., modulated) by the transmitter, and later decoded at the receiver point, thereby recovering the information. Since polarization in axion-to-photon mixing is degraded by the effects of the external magnetic field, a limitation exists and the encoding cannot involve polarization information. Discussion of the optimum technique for the signal modulation in axion-based telecommunications is not the aim of this article. Furthermore, discussion of the energetic efficiency and economic profitability of this novel telecommunications system is open, but that is not the focus of this study. On the other hand, axion-based telecommunications systems would have a number of advantages which would make the system of interest for specific uses. The different technological challenges and advantages or disadvantages of our idea are (preliminary) discussed in section 4.

4. Summary and discussion

In this letter we have briefly described a novel concept for an axion-based telecommunications system. The conceptual design relies on the theoretical prediction that axions and ALPs mix with ordinary photons within an external magnetic field. The axion-two-photon vertex Primakoff axion-to-photon conversion-reversion maintains phase information, resulting in a coherent transmission mechanism.

Is not the aim of this study to discuss the technical issues and systematics of this novelty in detail. We postpone this task for a hypothetical scenario in which an ALP is detected in a favourable energy sector (see section 3). However, several interesting points can be noted in advance in order to establish a number of fundamentals to provide a reference for researchers in telecommunications interested in investigating our concept in the coming years for both an axion detected scenario and in anticipation of such a scenario.

Since axions are weakly interactive with ordinary matter, telecommunications systems based on axion coherent transmission do not need to avoid topological
obstacles. An axion field would pass through the ordinary matter without suffering significant degradation of the signal, and two arbitrary points in the Earth or in the sky can be linked with axion-based telecommunications systems following the direct line of sight (l.o.s.). Furthermore, the signal is not attenuated by distance, so the transmitted and received powers are (ideally) matched. This is an advantage over classical telecommunications, which undergo distance-dependent attenuation of beam power. This would also eliminate the need for geostationary or low orbit satellites for telecommunications, resulting in a cleaner sky. Microwaves and radio transmission would not be necessary in the scenario of axion detection within a favourable energy sector. An axion-based system would be green.

Since axions are particles of light mass, their velocity is lower than the speed of light in vacuo. However, axions can be ultrarelativistic, so the delay in the transmission of the signal could in principle be controlled.

In this (conceptual) paper we avoid any discussion of standard encoding signal techniques and its feasibility in applications to axion-based telecommunications systems, something that should be carried out by specialists in case that this work is able to inspire these researchers move towards a new direction or approach.

The pointing model could be a practical limitation to axion-based telecommunications. Since the direction in which axions and photons are released depends on the accuracy which magnetic lines can be positioned, significant deviations in the transmission could exist. Techniques for controlling the transmission-reception of the beam should be studied in detail in future if a practical realization of this concept is required. Another future line of work could be the study of the spurious effects caused by external (strong) magnetic fields in the l.o.s. between the transmitter and receiver, resulting in a degradation of the quality of the signal.

On the other hand, the KVSZ axion sensitivity level is around $g_{a\gamma\gamma} \sim 10^{-14}$ GeV$^{-1}$ for axion masses of the order of 100 $\mu$eV ([25], [26]). This energy sector seems to be inaccessible for current technology or other set-ups in the mid-term (e.g., see [8] pp. 45–48 and references therein). Therefore, we may conclude that the feasibility of axion-based telecommunications systems would rely on the possibility that ALPs are discovered for $g_{a\gamma\gamma} \gtrsim 10^{-11} - 10^{-12}$ GeV$^{-1}$ for a given mass, or the availability of disruptive technologies in the future.

Finally, the dimensions of the resonant cavities used in the system proposed here depend on the Compton wavelength of the axion field, so higher masses (and therefore frequencies) are inaccessible for resonant cavity systems, as in the case of haloscopes used in axion search, where the limit is commonly established around an ALP mass of 40 $\mu$eV or around 10 GHz of frequency. However, it is in principle possible to include a PF resonator in a (non-resonant) cavity to obtain a power boost factor $(\beta) \mathcal{O}(10^5)$, of the same order as the $Q$ factor signal enhancement obtained in resonant cavities ([10], [27]).

As general conclusion, in this manuscript we have hypothesized how an axion DM-based telecommunications system could be, approaching the discussion from a
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Theoretical point of view. In case of axion detection, significant work should be carried out in order to convert this idea into a real and operative system.

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