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FERRIMAGNETIC RESONANCE, MAGNETOSTATIC WAVES AND OPEN RESONATORS FOR AXION DETECTION

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ABSTRACT

Assuming axion masses in the order of 10^{-5} to 10^{-6} eV, theory predicts coupling to microwave photons in the presence of a strong magnetic field. For the experimental detection of these photons, a cryogenic, tunable microwave cavity resonator followed by a very sensitive micro- wave narrowband receiver is in operation at BNL since several years. So far, no clearly axion related signals have been measured. In order to improve the sensivitiy of this type of detector, the open confocal resonator is proposed as a resonating cavity as it provides a considerable bigger volume and easier tuning than a pillbox like cavity. It is further suggested to take advantage of the ferrimagnetic resonance which shows up with a rather narrow line width in magnetically biased YIG (= Yttrium-Iron-Garnet) ferrite materials. Magnetostatic waves occur in YIG-films and find applications as variable delay lines and tunable filters in the 1-10 GHz range. Their phase velocity can be adjusted to match the velocity of cosmic axions (beta = 10^{-3}) thus permitting the construction of a directive detector.

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FERRI-MAGNETIC RESONANCE, MAGNETOSTATIC WAVES AND OPEN RESONATORS FOR AXION DETECTION

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The Peccei-Quinn symmetry [1] is the most plausible solution to the strong CP problem. Wilczek and Weinberg [2] predicted a pseudoscalar particle, the axion, which must be present as a result of this symmetry breaking. The mass range of this particle is a priori enormous, namely 10^{-12} eV < m_a < 10^{6} eV [3], but laboratory experiments put an upper limit of about 10^4 eV. If the axions are very light, they could also close the universe and a lower limit on the mass is set by the over- closure arguments ($m_a > 10^{-6}$ eV).

Therefore an open window of 10^{-6} < eV < 10^4 eV is left open to the experimenters to exercise their imagination in order to find an answer to the axion mystery. Several astrophysical obserations restrict the upper mass limit, with more stringent that of the SN1987a to 10^{-3} eV [3]. The limits depend on the particular model and axion coupling to matter.

Several models predict that axious couple to electrons with an interaction Lagrangian

$$L = i \left(\frac{a}{F}\right) m_e \bar{e} \gamma_5 e \qquad (1)$$

(the axion mass $m_a \sim 1/F$, where F is the energy scale of the symmetry breaking).

This Lagrangian can be reduced to [4] using the notation of reference (4).

$$L = \left(\frac{a}{F}\right) \left(\frac{e}{m_e}\right) \bar{S}.\bar{E} \qquad (2)$$

and can be compared to

$$L = \left(\frac{a}{F}\right) \left(\frac{e^2}{\pi^2}\right) \bar{B}.\bar{E} \qquad (3)$$

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used in the microwave cavity axion searches. From this, it is evident that a spin density of 5 x $10^{22}/cm^3$ corresponds to a 125 Tesla magnetic field for a Sikivie type experiment. In fact, this was about Krauss et al. argued by introducing the Ferrites in the axion research.

The 125 Tesla equivalent magnetic field would actually make the microwave cavity (Sikivie-type) searches able to find or exclude the DFSZ axion. The problems using ferrites are [5] :

1) for the insulators (ferrites) : because the axion mass is supposedly much lower ($\sim 10^{-5}$ eV) than the binding energy of the relevant electron(s) to the ($\omega_0 \sim 1$ eV), the interaction goes down by a factor of $(1-(\omega_0{}^2/m_a{}^2))^{-1}$. Essentially, the electrons are not free to follow the oscillations of the axion field and therefore the source of radiation is greatly reduced.

2) For the case of ferromagnetic metals: the electrons are free to move but the effective volume is confined within the microwave skin depth which is on the order of a few microns.

One way to bypass the avove problems is to use ferrimagnetic materials in resonance (FMR). A list of candidates could be YIG (Yttrium-Iron-Garnet), GaYIG, Lithium Ferrite, etc... The electrons in FMR are relatively free at resonance (28 GHz/Tesla) and the "skin depth" is on the order of 10 cm to a meter depending on the losses.

FERRIMAGNETIC RESONANCE

There are a number of single-crystal materials that have possible use as ferrimagnetic resonators in magnetically tunable microwave filters. Some materials of interest are:

(1) Yttrium-iron-garnet (YIG)
(2) Gallium-substituted yttrium-iron-garnet (GaYIG)
(3) Lithium ferrite
(4) Barium ferrite.

In practice, the RF field is applied via a loop (with a half winding). But YIG spheres may be also positionned in a cavity and coupled directly to the electro-magnetic fields inside that resonator.

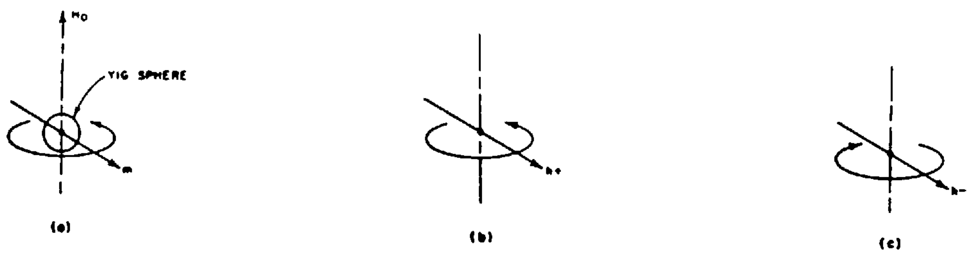

Fig. 1 (from reference 7)
A YIG sphere with a circularly polarized RF magnetic moment is shown at (a). Exterior circularly polarized RF magnetic fields are shown at (b) and (c)

Description of the resonance phenomenon

Let us suppose that a dc H-field of strength H_0 is applied to a YIG sphere in a horizontal direction, and then the direction of the H_0 field is rapidly switched to the vertical direction as shown in Fig. 1. When the dc H-field is rapidly switched to the vertical position, these spin magnetic moments (unpaired electrons) will precess about the vertical H-field H_0 at a rate of (if H_0 is in oersteds)

$$(f_0)_{MHz} = 2.8\ H_0\ \text{MHz}$$

Parameters of ferrimagnetic resonator material

Several parameters characterize the various types of materials that can be used to construct ferrimagnetic resonators:

(1) saturation magnetization, M_s
(2) line width ΔH, or unloaded Q, Q_u
(3) anisotropy field constant, K_1/M_s
(4) Curie temperature, T_c.

The saturation magnetization M_s is a function of the number of electron spins in the material per unit volume. The larger the M_s, the easier it is to couple from an exterior strip-line or waveguide circuit to a ferrimagnetic resonator.

Note that in Table 1, the ΔH = 0.22 oersted line width listed (which is for a very high-quality YIG resonator) corresponds to an unloaded Q of 6500 at 4 GHz. This line width was measured in a waveguide with the spherical resonator some distance from any metallic walls. In practical filters the YIG resonators must be closer to metal walls, and the disturbing effects of the currents in the walls may reduce the unloaded Q to 2000 or less.

PROPERTIES OF SINGLE-CRYSTAL FERRIMAGNETIC MATERIALS
FOR MAGNETICALLY TUNABLE FILTERS

MATERIAL	$4\pi M_s$ (AT ROOM TEMPERATURE) (gauss)	K_1/M_s (AT ROOM TEMPERATURE) (oersteds)	ΔH^* (AT ROOM TEMPERATURE) (oersteds)	T_c (°C)
Yttrium-Iron-Garnet (YIG)	1750	-43	0.22 (4 Gc),	292
Gallium-Substituted Yttrium-Iron-Garnet (GaYIG)	50 - 1750 600 950 ± 50	-- -55.8 -41.7	-- -- 0.7 - 2.0 (at 4.4 Gc)	-- 160 206
Lithium Ferrite	3550 ± 40	--	3§(5 Gc)	--
"Planar" Ferrite "Zn_2Y" ($Ba_{12}Zn_2Fe_{12}O_{22}$)	2850	4950	16 (X-band),	--

Table 1 (from [7]):
Properties of single-crystal ferrimagnetic materials
for magnetically tunable filters

A possible experimental apparatus would be that of reference [6] with the YIG spheres inside the microwave cavity at the end of the sapphire rod.

If the axion mass matches this frequency, then it is absorbed and the electrons radiate and excite e.g. the TM_{010} mode of the cavity. This excess of power can be detected by standard RF techniques. The relevant coupling is given by equations (2) and (3). Following the analysis of the Rochester, Brookhaven, Fermilab group [6] they conclude that they are at a factor of ~ 300 in power below the DFSZ model. Therefore, an improvement of a factor of 10 in the magnetic field (the power from axion → photon conversion is proportional to B^2, that is we gain a factor of 100) would make the experiment feasible.

In order to gain the most with the use of the YIG spheres inside the cavity, we should tune the precession frequency of the electrons to the exact frequency of the microwave cavity. The magnetic field has to be rather homogeneous (and known) and a Q-value of the ferrite in the same order of magnitude as the cavity Q (~ 10^5), divided by the fractional volume occupied by the ferrite material.

If the ferrite is not on its FMR, the coupling to the cavity is strongly reduced. This is comparable to the case of two coupled resonators where significant energy exchange occurs only if both resonators are roughly at the same frequency. However, for a fractional cavity volume of, say, more than 10% filled with ferrite, coupling is assured and the ferrite does not need to be on FMR. This mode of operation has been applied at LANL for orthogonally biased (to the RF B-field) magnetically tuned accelerator cavities around 60 MHz.

2. MAGNETOSTATIC WAVES

As magnetostatic waves are not known very well in general, a short introduction is given now. In particular, they open the possibility to match the low β of cosmic axions and also take advantage of the strong fields in a crystal; this might provide a directional detector.

MSW propagation occurs for three principal orientations of the bias field, H, with respect to the wave vector, k, in the plane of the slab. In terms of the unit normal to the plane of the slab, n, the orientations are:

(1) $H_0 \times n = 0$, which gives rise to the quasi-isotropic magnetostatic forward volume wave (MSFVW)

(2) $H_0 \times n$ parallel to k, which gives rise to the magnetostatic surface wave (MSSW)

(3) H_0 parallel to k, which gives rise to the magnetostatic backward volume wave (MSBVW).

The MSFVW is characterized by multimode propagation that is quasi-isotropic in the slab plane (although in actual application, propagation is dominated by the lowest order mode), and energy that is distributed across the volume of the ferrite slab. The MSSW is characterized by magnetic energy confined primarily to one surface of the ferrite slab. The MSBVW is characterized by multi-mode propagation with energy distributed across the ferrite slab and a negative group-phase velocity product. The wavelength and delay per centimeter as a function of frequency for representative MSFVW and MSSW configurations (the modes of particular interest for device applications) at S-band are presented in Fig. 3.

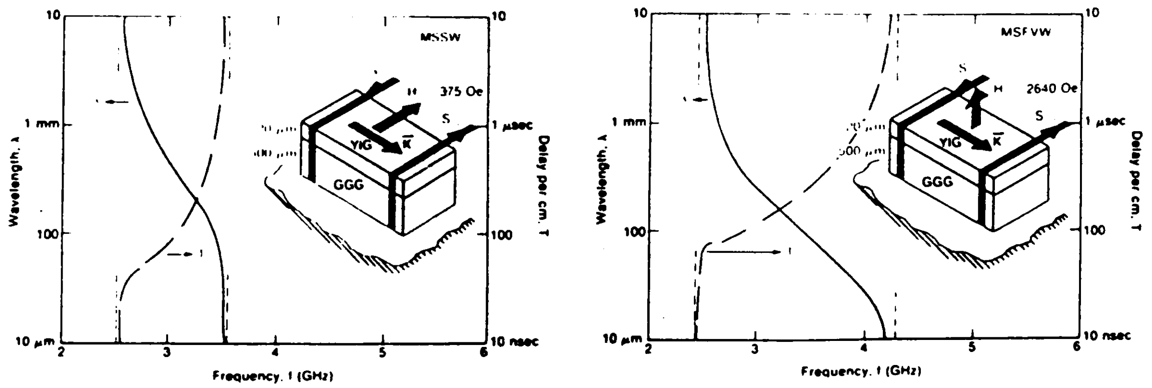

Fig. 3 : orientation of the bias field H, determines the mode of propagation when H x n is parallel to k, the magnetostatic surface wave occurs; if the cross product is zero, the quasi-isotropic magnetostatic forward wave propagatges in the YIG medium. Wavelength is plotted against frequency (from [8]).

Note that MSW have velocities of 3-300 km/s and wavelength from 1 μm to 1 mm for 10 μs thick epitaxial films.

Performance of Magnetostatic Wave Devices

Parameter	Transducer Array		Reflective Array		Resonator	
	Current	Future	Current	Future	Current	Future
Center frequency (GHz) (tunable)	1–20	1–30	1–20	1–30	1–20	1–30
Bandwidth (MHz)	30-800	10-1200	30-5000	10–1800	3 (Q_L = 1000)	1.2 (Q_L = 2500)
Time dispersion (μs)	0 5	2	0 5	5	–	-
Time bandwidth product	N A	200	50	>1000	–	-
AM ripple [dB (P-P)]	2	>1	4	>1	–	-
Phase error deg (RMS)	N A	N A	20	5	–	-
Sidelobes (dB)	30	<40	25	<40	15	<30
Temperature stability	1 10^5/°C	1 10^6/°C	1 10^5/°C	1 10^6/°C	1:10^5/°C	1 10^6/°C

Table 2 : Performance of magnetostatic wave devices (from [8])

3. OPEN RESONATOR

As for axion detection experiments with microwave resonators, a big resonator volume, high Q and easy tunability are required, the open confocal resonator may be an interesting device to consider. Such a resonator could be placed in the core of a dipole (= bending) magnet in order to have the RF E-field parallel with the bias B-field. From the huge body of literature, which exists on this subject, a few references are given [10-13], which permit easy scaling for axion detection cavities.

Higher order modes (compared to TEM_{00n}) are attenuated by diffraction losses (Fig. 4)

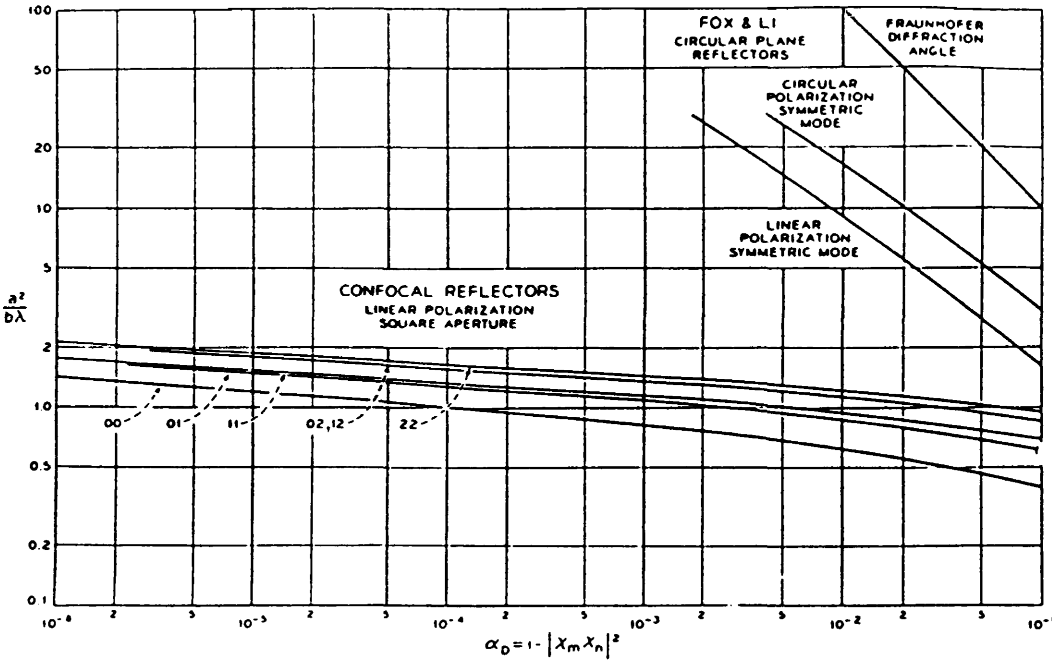

Fig. 4: Diffraction losses for confocal and plane parallel resonators (from [13])

The frequency of higher order modes is always higher than that of the corresponding fundamental mode (Fig. 5).

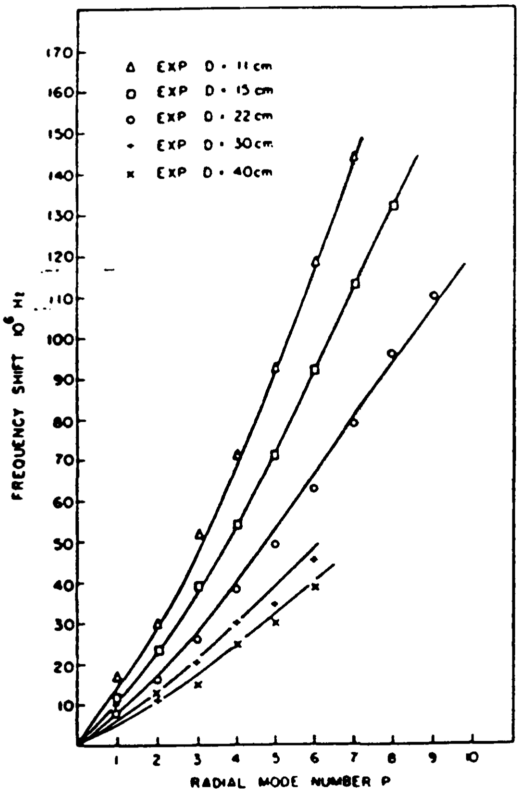

Fig. 5 : Theoretical and experimental frequency shifts as a function of radial mode number for various mirror spacings. The shifts are given relative to that of the fundamental mode which was less than 3 MHz for all spacings (from [10]).

This allows to predict tuning ranges without mode-crossings (= blind spots for axions). As such a resonator is open, one may consider superconducting mirrors for further increasing the Q factor. With normal conducting mirrors in the microwave range Q-factors of 10^5 can easily be obtained. Superconducting mirrors permit Q_s of 10^9 (12) and have been investigated for applications as very sensitive gravity balances.

An other important aspect is the change of Q as a function of longitudinal mirror displacement. Here, the case of a "half" confocal resonator is shown (1 flat plate, one spherical mirror - Fig. 6).

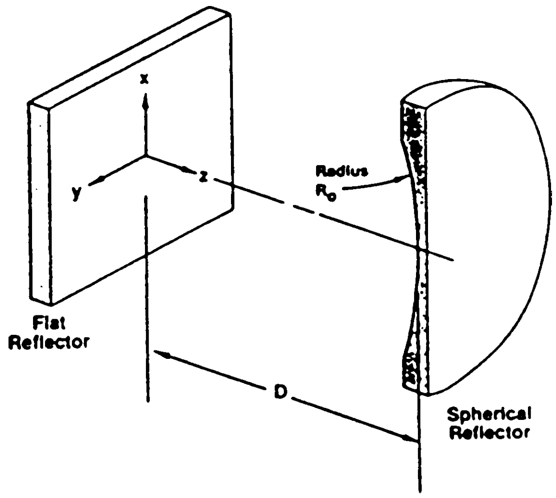

Fig. 6: Empty open-cavity microwave resonator (from 11)

The advantage of a structure as shown in Fig. 6 is that it permits easy realization of some microwave structure (e.g. stripline, ferrite substrate, YIG film etc.) on the surface of the flat reflector. Note that the Q measurements in Fig. 7 are taken at room temperature for a very short resonator (TEM_{003}).

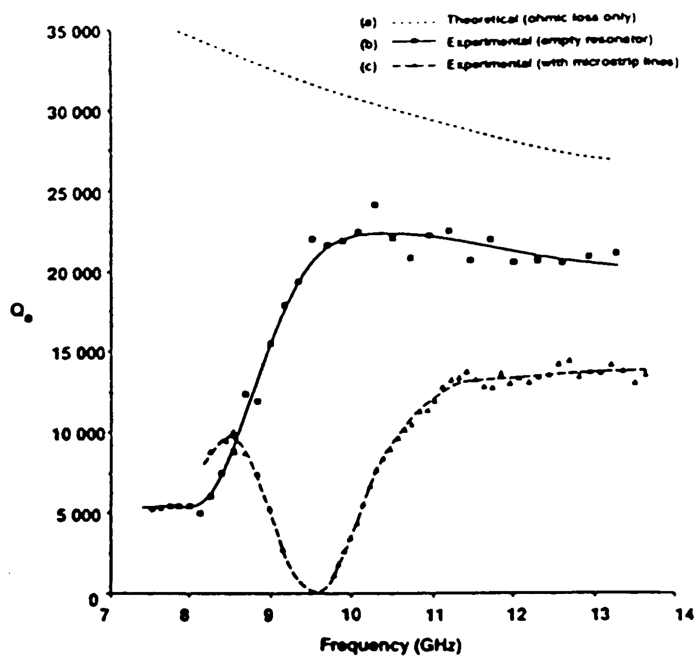

Fig. 7: Unloaded Q of TEM_{003} mode versus frequency as inter-reflector distance D is varied (a). Theoretical maximum Q_0 including ohmic loss only; (b) measured Q_0 of empty resonator; (c) measured Q_0 of resonator with substrate and microstrip lines (from 11).

Conclusion

Three ways to possibly increase the sensitivity of microwave based axion detectors have been discussed. The cases where ferrite materials are involved (ferrimagnetic resonance, magnetostatic waves) still need quantitative theoretical estimates about their efficiency. The confocal resonator seems to have several interesting features. But perhaps practical problems like its size for a few GHz make its use not too attractive now. A rather simple test on the YIG-FMR performance with the existing BNL-axion cavity would be to place such a YIG sphere at the end of the sapphire tuning rod inside the cavity and properly adjust the external H_0-field.

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