Phase-modulated cavity magnon polaritons as a precise magnetic field probe

Nicò Crescini,1,2,* Giovanni Carugno,1,3 and Giuseppe Ruoso2

1 Dipartimento di Fisica e Astronomia, Via Marzolo 8, 35131 Padova, Italy
2 INFN-Laboratori Nazionali di Legnaro, Viale dell’Università 2, 35020 Legnaro (PD), Italy
3 INFN - Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy

(Dated: March 7, 2022)

We describe and operate a spin-magnetometer based on the phase modulation of cavity magnon polaritons. In this scheme a rf magnetic field is detected through the sidebands it induces on a pump, and the experimental configuration allows for a negligible pump noise and a high frequency readout. The demonstrator setup, based on a copper cavity coupled to an yttrium iron garnet sphere hybrid system, reached a sensitivity of 2.0 pT/√Hz at 220 MHz, evading the pump noise and matching the theoretical previsions. An optimized setup can attain a rf magnetic field sensitivity of about 8 fT/√Hz at room temperature. An orders of magnitude improvement is expected at lower temperatures, making this instrument one of the few magnetometers accessing the sub-fT limit.

I. INTRODUCTION

The detection of ultra-low magnetic fields is a long standing technological challenge. The most sensitive types of magnetic field detectors are essentially two: superconducting quantum interference devices (SQUIDs) [1–5] and spin-exchange relaxation-free (SERFs) [6–8] magnetometers, which reach the fT/√Hz sensitivity. Medical applications, such as nuclear magnetic resonance (NMR) detection, is possibly the most studied utilization of such devices [9]. Remarkable results have been obtained with both SQUIDs [10–16] and SERFs [17–21]. In the last decades several magnetic field sensors were proposed or demonstrated [22–29, 29–33], making precision magnetometry an alive and dynamic field. SQUIDs are advantageous for cost and possible applications. SERF’s magnetometers do not need cryogenics, but require heavy shielding and their sensitivity is volume-dependent.

This letter presents a magnetometer which embodies room temperature operation, size-independent sensitivity, and rf working frequency. It is based on the phase modulation of a pump field exciting a cavity magnon polariton resonance. Measurements of extremely weak fields are possible by the detection of a sideband component induced on the input pump, allowing for the sensing of signals from a few MHz to some GHz. Its expected limit sensitivity is competitive with present state-of-the-art magnetometers and could find application, for example, in medical imaging, communication, and fundamental physics research [8, 34–36].

The working principle of this device is based on the excitation of the Larmor transition in a magnetic material. By taking a ferrite or a paramagnet and biasing it with a static field $B_0$ we obtain an electron spin resonance at the frequency $\omega_L = \gamma B_0$, where $\gamma = (2\pi)28$ GHz/T is the electron gyromagnetic ratio. The presence of a weak magnetic field $b_1$, with frequency $\omega_1$, has different effects. If $b_1$ is perpendicular to $B_0$ and on-resonance with $\omega_L$, it will accumulate power into the Larmor transition, whose amount is proportional to $b_1$ and can be used to measure it [37, 38]. In the complementary case where the direction of $b_1$ is parallel to the static field, the total field determining the Larmor transition is time modulated and will periodically change the frequency of the spin resonance. A microwave tone pumping the magnetic material at the frequency $\omega_L$ will thus be phase modulated due to $b_1$ with the result of producing sidebands at frequencies $\omega_1 \pm n\omega_b$, with $n$ an integer number. The detection of the sidebands will eventually give a measurement of the weak perturbing magnetic field [33]. The device we are presenting in this letter originate by embedding the second scheme in a photon magnon hybrid system (PMHS).

II. DETECTION SCHEME

A PMHS consists in two coupled harmonic oscillators, e.g. the normal mode of a microwave cavity and the electron spin resonance of a magnetic material [39–41]. A typical realization of such a system is obtained by properly inserting in a copper microwave cavity a sphere of yttrium iron garnet (YIG), a ferrimagnetic insulator with high spin density and low losses [42–44]. Antennas coupled to the cavity are used for inserting and extracting power from the system. An external static magnetic field $B_0$ is used to tune the Larmor frequency of electrons in YIG to the cavity mode frequency and couple the two systems. For $\omega_1$ close to the cavity frequency $\omega_0$, the cavity mode splits into two hybrid modes with frequencies $\omega_1$ and $\omega_2$, where $g_{21} = \min(\omega_2 - \omega_1)/2$ is the coupling strength. If $g_{21} > \gamma_1,\gamma_2$, the hybrid modes linewidth, the system is in the strong coupling regime. The resulting system can be described by quasiparticles called cavity magnon polaritons (CMPs), whose dispersion relation is an anticrossing curve [45–47].

Let us consider an oscillating field $b_1$ parallel to the static one, and apply a monochromatic tone on one of

*Electronic address: nicolo.crescini@phd.unipd.it
the hybrid modes, like the one at the frequency $\omega_2$. As in the case of the simple system described before, the oscillating field will produce a frequency modulation of $\omega_2$, thus causing a phase modulation of the electromagnetic field stored in the PMHS, and sidebands are generated at the frequencies $\omega_2 \pm n\omega_b$. However, since the PMHS has only two resonant modes, for $\omega_b > \gamma_2$, only the sideband satisfying the relation $\omega_2 \pm n\omega_b = \omega_1$ will be present and all others will be suppressed. By detecting the power at $\omega_1$, it will be possible to obtain a measurement of the perturbing field. For small fields the only component with significant amplitude corresponds to $n = 1$ and this system is sensitive to fields whose frequency is $\omega_1 = 2\delta\nu_1$.

With a PMHS the transduction coefficient between $B_0$ and mode frequency is not given anymore by the gyromagnetic ratio but to a smaller coefficient $\alpha\gamma$. Such coefficient, extracted from $\partial\omega_{1,2}/\partial B_0$, is practically $\gamma$ for hybrid modes far away from the cavity resonance, while goes to zero for an hybrid mode close to it. In the case of full hybridization, namely $\omega_2 - \omega_0 = \omega_0 - \omega_1 = \delta\nu_1$, we have $\alpha = 1/2$.

A scheme of the spin-magnetometer principle is reported in Fig. 1a. The monochromatic tone can be written as $A_0 \cos(\omega_2 t + \phi_b(t))$, where $\phi_b(t)$ is an oscillating phase added by the field $|b_1| = b_1 \sin(\omega_b t)$. The resulting phase modulated signal is

$$\xi(t) = A_0 e^{-i\omega_2 t} e^{-ix \sin(\omega_b t)},$$

where $x$ is the modulation index given by the maximum deviation divided by the working frequency

$$x = \pi \alpha Q_2 b_1 / B_0.$$

Here, $Q_2 = \omega_2 / \gamma_2$ is the quality factor of the hybrid resonance. For small values of $x$, Eq. (1) can be recast in terms of the first kind Bessel functions $J_n(x)$ as

$$\xi(t) = \sum_{n=0}^{+\infty} \xi_n(t) = A_0 e^{-i\omega_2 t} \sum_{n=0}^{+\infty} J_n(x) e^{-i\omega_b t},$$

$$\approx A_0 e^{-i\omega_2 t} \sum_{n=0}^{+\infty} \frac{x^n}{2\pi n!} e^{-i\omega_b t},$$

where $n$ is a positive integer. The amplitudes of carrier and lower order sidebands are

$$|\xi_0| = A_0, \ |\xi_1| = \frac{\pi \alpha A_0 Q_2 b_1}{B_0}, \ |\xi_2| = \frac{1}{8} \left( \frac{\pi \alpha A_0 Q_2 b_1}{B_0} \right)^2.$$

The first order sideband $\xi_1$ has the higher amplitude, and by comparing it with the backgrounds it allows to calculate the magnetometer’s sensitivity to $b_1$.

The scheme for a possible experimental set-up is shown in Fig. 1b. A signal generator provides the tone at $\omega_2$, filtered by a waveguide with cut-off frequency between $\omega_1$ and $\omega_2$. The waveguide reduces the pump noise at the frequency $\omega_1$ by a factor $k_1$ that could be as large as 80 dB, depending on the separation between the cut-off and pump frequencies. The waveguide output is fed to the PMHS, namely a resonant cavity with YIG inside, in the total field $B_0 + b_1$. The antenna has couplings $\beta_{1,2}$ to the two resonant modes, respectively. The power reflected from the cavity is band-pass filtered and amplified before the readout. The filtering removes the residual pump tone avoiding saturation of the amplifier.

In an experimental setup we consider $Q_2 = Q_2^{(0)}/(1 + \beta_2) = Q_2^{(0)}$, the loaded quality factor of the CMP resonance. The output power at the frequency $\omega_1 = \omega_2 - \omega_0$, normalized with the amplifier gain $G_1$ and filter transmittance $c_1$, results

$$\frac{P_0(\omega_1)}{G_1 c_1} = \frac{\beta_1}{1 + \beta_1} |\xi_1|^2 + k_1 \left( \frac{1 - \beta_1}{1 + \beta_1} \right)^2 A_p^2 |\text{RAM}(\omega_b)|^2 \delta\nu + k_B \left[ \frac{4\beta_1}{(1 + \beta_1)^2 T + T_n} \right] \delta\nu$$

$$= A_p^2 \left[ \frac{\beta_1}{1 + \beta_1} \frac{4\beta_2}{(1 + \beta_2)^2} \pi \alpha Q_2^{(0)} b_1 \right]^2 + k_1 \left( \frac{1 - \beta_1}{1 + \beta_1} \right)^2 |\text{RAM}(\omega_b)|^2 \delta\nu + k_B \left[ \frac{4\beta_1 T}{(1 + \beta_1)^2 T + T_n} \right] \delta\nu.$$
Here \( \text{RAM}(\omega_b) \) is the relative residual amplitude modulation of the pump at \( \omega_b \). The absorbed pump power at \( \omega_2 \) is \( A_p^2 = 4\beta_2 A_p^2/(1 + \beta_2)^2 \), \( k_1 \) is the waveguide transmittance at \( \omega_1 \), \( k_B \) is the Boltzmann constant, \( T \) the cavity temperature, \( T_n \) the detection chain noise temperature and \( \delta \nu \) the resolution bandwidth. Cables and circulators have been considered lossless. The first term present in Eq. (5) is the searched-for signal, and consists essentially in the sideband power \( |\xi_1|^2 \). The following terms are the sources of noise, which are related to the pump and to the system noise temperature. The typical behavior of \( \text{RAM}(\omega) \) shows large values at low frequencies with \( 1/f \)-like trend up to a few MHz. All the terms are weighted with the appropriate combination of the antenna coupling constant to the first hybrid mode \( \beta_1 \). At more than 10 MHz the noise of a commercial pump is flat with values \( \text{[RAM(\omega)]}^2 \simeq -160 \text{ dBC/Hz}; \) the best oscillators reduce this limit down to \(-180\text{dBC/Hz} \) [48]. This noise can then further reduced to a negligible level by using the waveguide filtering accounted by the term \( k_1 \), obtaining a thermal-noise limited device. In this limit we calculate the sensitivity \( \sigma_b_1 \) of the apparatus, defined as the value of \( b_1 \) giving a SNR = 1 in the unit time,

\[
\sigma_b_1 = \frac{2\eta B_0}{\pi \alpha Q_2} \sqrt{\frac{k_B T_s}{A_p^2}},
\]  

where the antennas coupling correction \( \eta \) and system noise temperature \( T_s \) are

\[
\eta = \frac{(1 + \beta_2)}{2} \sqrt{\frac{1 + \beta_1}{\beta_2 \beta_1}} , \quad T_s = \frac{4\beta_1 T}{(1 + \beta_1)^2} + T_n.
\]  

With typical values \( \beta_{1,2} \simeq 1, Q_2^2 = 10^4, B_0 = 0.4 \text{ T}, A_p^2 = 100 \text{ mW}, T_s = 350 \text{ K}, \) and by working in the dispersive regime (i.e. with \( \alpha \sim 1 \)) a sensitivity \( \sigma_b_1 \simeq 8 \text{ fT}/\sqrt{\text{Hz}} \) is expected already at room temperature.

Notably, the sensitivity reported in Eq. (6) is unrelated to any extensive property of the setup. This is expected in a scheme based on phase-modulation rather than absorption [33, 37], and paves the way to the miniaturization of the sensor without expecting a sensitivity loss. It needs to be considered that a strongly coupled PMHS often requires a large quantity of material, which might effectively limit the down-scaling of the setup. However, this can be compensated by a more concentrated cavity field, which increases the single spin coupling and allows for using less magnetic material.

This magnetometer only works in a narrow frequency band corresponding to the linewidth \( \gamma_1 \) of the detection mode \( \omega_1 \). For a strongly coupled PMHS this means detection of ac magnetic fields with frequency of order \( 2\gamma_1 \), which in the present case is about 200 MHz. Since \( \omega_1 \) can be tuned via \( B_0 \), the working frequency of the device can be changed, with the downside of reducing the sensitivity. Although a dedicated model has not yet been written, the reduction is expected to be \( O(1) \) for a tuning of about 100 MHz [49], where the dispersive coupling might even increase the sensitivity as \( \alpha \to 1 \). We refer to this frequency range as the dynamical bandwidth of the magnetometer [49]. More in general, the operational frequency of this class of magnetometers is limited from above by the larger strong coupling which can be reached, and from below by a combination of pump noise and filtering. While the former only depends on the hybrid system under consideration and can be of several GHz, the latter is mostly instrumental. To preserve the validity of Eq. (6), the \( \text{RAM}(\omega_b) \) must be reduced of \( k_1 \) to have \( k_1 \text{RAM}(\omega_b) \lesssim k_B T_s \), which is increasingly difficult at lower \( \omega_b \) due to the filter slope and to the higher pump noise. With present means, a lower limit for this frequency can be set around 10 MHz. Arbitrarily low frequencies can be reached at the price of a much lower sensitivity.

\section*{III. EXPERIMENTAL DEMONSTRATION}

To demonstrate the operation of the magnetometer we built the apparatus of Fig. 2. It features a microwave copper cavity 32.1 mm long, with a quasi-rectangular section of \( 14.8 \times 24.8 \text{ mm}^2 \), and the shorter sides were rounded. A 2 mm-diameter YIG sphere is placed at the center of the cavity, where the rf magnetic field of the chosen TM_{102} mode is maximum. The mode frequency is \( \omega_1/2\pi \simeq 11.43 \text{ GHz}, \) and the static field necessary to create the PMHS is \( B_0 = \omega_1/\gamma \simeq 0.4 \text{ T}, \) provided by an electromagnet with a bore of 10 cm diameter. The resulting hybrid modes resonate at \( \omega_2 \simeq (2\pi) 11.33 \text{ GHz} \) and \( \omega_2 \simeq (2\pi) 11.55 \text{ GHz}, \) obtaining \( 2g_{21} = \omega_2 - \omega_1 \simeq (2\pi) 220 \text{ MHz} \) close to the full hybridization, and thus with \( \alpha \simeq 0.5 \).

The cavity is equipped with a hole on one side, hosting a \( \sim 1 \text{ cm}-\text{diameter} \) loop to generate a known test

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{Scheme of the magnetometer demonstrator. The calibration signal \( b_1 \) (dark red) is provided by a generator connected to a loop on the holed side of the cavity, and is monitored with an oscilloscope. The cavity (orange) houses a YIG sphere (black), which is biased with the static field \( B_0 \) supplied by an electromagnet represented with its north (N, blue) and south (S, red) poles. The rf cavity field is extracted by an antenna with variable coupling (grey), and passes through a circulator before being amplified by Amp.1 and Amp.2, while the filter cavity avoids the saturation of the second amplifier. The microwave pumping line delivers to the cavity a monochromatic tone filtered with a waveguide.
\end{figure}
field \( b_1 \) parallel to the static field \( B_0 \). A scope measures the current provided to the loop to infer the generated field. The current-to-field conversion constant was measured by analysing the effect of the loop dc-field on the Larmor frequency of the YIG sample, accessible by working in the dispersive regime. The conversion constant results \( 4.8 \mu \text{T/A} \), and is compatible with the calculated loop field. Two more measurement followed, which were performed using a sensing coil with a diameter of about 1 mm, much smaller than the loop. In the first one, a \( \sim 100 \text{Hz} \)-frequency field amplitude is compared with one at high frequency. We found a 10% decrease of the field amplitude due to the operation at 220 MHz, which is probably related to the loop impedance. The second one is performed to take into account the screening effect of the cavity walls. We used the sensing coil to measure the loop field at the position of the YIG sphere with and without the cavity. The ratio of the two gives a reduction factor of \( k_0 = 0.09 \pm 0.03 \). The overall current-to-field conversion results \( 4.8 \mu \text{T/A} \times 0.9 \times k_0 = (0.39 \pm 0.11) \mu \text{T/A} \). The generator for the pump \( A_p \) could deliver a power up to 26 dBm, injected to a in-house fabricated waveguide with a cut off frequency at about \( \omega_0 \). The waveguide has a cross section of 12.8 \times 6.3 \text{mm}^2. The antenna is movable in order to choose appropriate coupling. The two amplifiers are low noise high-electron-mobility transistor (HEMT), with nominal gains \( G_1 = 34 \text{ dB} \), \( G_2 = 35 \text{ dB} \), and the band-pass filter is done with a resonant cavity tuned to \( \omega_2 \). The readout is done with a spectrum analyzer.

Fig. 3 shows a spectroscopic measurement of the PMHS, from which we measure \( \gamma_1 \approx (2\pi) 2.2 \text{MHz} \), \( \gamma_2 \approx (2\pi) 4.2 \text{MHz} \). Magnonic dissipation is limiting the coherence of this PMHS, as the magnon linewidth is estimated to be of about 3.6 MHz. The asymmetry of the modes was adjusted to match the waveguide transmission, and is not expected to have an important impact on the sensor. The antenna couplings to the hybrid modes are \( \beta_1 \simeq 0.3 \) at \( \omega_1 \), and \( \beta_2 \simeq 1 \) at \( \omega_2 \). Even with the band-pass filter, these couplings are necessary to avoid the saturation of the amplifier due to the pump, and still extract some power from \( \omega_1 \). The reflected tone power at \( \omega_2 \) is reduced of more than 30 dB. By injecting calibrated rf signals in the antenna input of the circulator (see Fig. 2), we measured \( T_s \simeq 337 \text{K} \), compatible with the amplifiers specifications. We fed the system with a pump of power \( A_p^2 = 0.2 \text{ mW} \) at the antenna input. Following Eq. (7), the expected sensitivity results

\[
\sigma_{b_1} = 1.9 \text{ pT/} \sqrt{\text{Hz}}.
\]  

We remind that this spin-magnetometer is sensitive to a field at the frequency \( 2g_21 \simeq (2\pi) 220 \text{MHz} \) on a bandwidth as large as the linewidth \( \gamma_1 \).

The system was tested using the small loop placed on the cavity side hole (see Fig. 2). Fig. 4a shows the spectra of the output signal for different input test fields. The experimental points reported in Fig. 4b shaw the voltage \( A_s \), measured on a \( R = 50 \Omega \) load at the signal frequency \( \omega_1 \approx (2\pi) 11.33 \text{GHz} \) vs the field generated with the loop. The errors on the values \( A_s \) are estimated from repeated measurements with the same input field, they account for an \( \sim 18 \% \) of the average value and are essentially due to instabilities in the experimental set-up. The uncertainty on the input field, 28%, is almost totally due to the determination of the loop current-to-field coefficient. Data have been fitted with a linear function, giving the slope \( m_{hit} = (1.1 \pm 0.3) \times 10^5 \text{ V/T} \). The expected value, derived from Eq. (5), is

\[
\frac{\sqrt{RP_s(\omega_1)}}{b_1} = \sqrt{RG_1G_2c_1} \pi \alpha L_2 A_p \frac{2}{2 \eta B_0} = (1.6 \pm 0.3) \times 10^5 \text{ V/T},
\]

where the total gain \( G_1G_2c_1 = 56 \pm 1 \text{ dB} \) has been measured independently. The discrepancy can be due to unaccounted losses in the cables, but essentially the measured value agrees with the expected one, confirming the validity of the proposed device.

From this data we obtained the noise \( P_n = -99.8 \text{ dBm} \) with a resolution bandwidth of \( \text{RBW} = 100 \text{ Hz} \), resulting in a voltage sensitivity of \( 2.2 \times 10^{-7} \text{ V/} \sqrt{\text{Hz}} \). By using the measured transduction coefficient \( m_{hit} \), the field sensitivity results

\[
\sigma_{b_1} = (2.0 \pm 0.7) \text{ pT/} \sqrt{\text{Hz}},
\]

which agrees with the calculated one given by Eq. (8).

The noise level at the cavity output results \( P_{n} = P_n/(G_1G_2c_1) = (2.6 \pm 0.5) \times 10^{-21} \text{ W/Hz} \). In the absence of waveguide filtering, the pump noise at \( \omega_1 \) would be \( \sim 10^{-19} \text{ W/Hz} \), orders of magnitude higher than the measured thermal noise. By removing the waveguide we verified that the noise grows, and test signals has to be increased to obtain the same SNR. We conclude that the pump noise has been drastically reduced in this setup, and that the limiting background of the apparatus is
FIG. 4: (a) Signal spectra obtained with different test loop fields. The x-axis is the frequency offset from $\omega_1/2\pi$, while the y-axis is the voltage read at the spectrum analyser. The top-left spectrum corresponds to a SNR = 1 field with a resolution bandwidth of 100 Hz, i.e. an integration time of 10 ms. (b) Test measurement of the spin-magnetometer, showing the voltage at $\omega_1$ vs the calculated input field generated with the loop. The noise level was subtracted from the data points, which were then fitted to a linear function, giving a slope $m_{\text{fit}} = (1.1 \pm 0.3) \times 10^5$ V/T and an intercept $q_{\text{fit}} = (-1.9 \pm 0.7) \mu$V.

mostly due to room temperature thermodynamic fluctuations. The negative offset’s origin is unclear, but it might be attributed to systematic uncertainties in the measurement.

The time response of the system is limited by the relaxation time of the hybrid modes and is of order 100 ns. The maximum measurable field is given by the condition $Q_1b_1 \ll B_0$, which holds up to tens of $\mu$T amplitudes. The operational bandwidth is an interval of width $\gamma_1$ centered at $\omega_1$. The CMPs frequencies are tuned by varying the static field $B_0$, allowing us to obtain an effective bandwidth of hundreds of MHz [49]. The loop on the cavity side, which has been used for testing the setup, can be coupled to an external pick-up coil. With such a scheme it will be possible to measure magnetic fields not directly located on the YIG sample. By properly designing the loop impedance, optimum matching conditions can be achieved with the pick-up loop. We expect also the factor $k_b$ to be much closer to one in an optimized apparatus, allowing for a good transduction of an external signal to the PMHS.

IV. OUTLOOK AND CONCLUSIONS

The sensitivity can be further pushed by increasing the tone power, however, this value is limited due either to non-linearities of the YIG or thermal-induced instabilities that may arise. By using a cryogenically cooled device coupled with an ultra low noise first-stage amplifier, the limiting noise could be reduced to the standard quantum limit. By replacing the factor $k_B T_s$ with $\hbar \omega$ in Eq. (7), the quoted value $\sigma_b \approx 8 \text{fT}/\sqrt{\text{Hz}}$ can be further reduced to $\sigma_b \approx 0.3 \text{fT}/\sqrt{\text{Hz}}$.

As the device sensitivity is not dependent on its size, one can engineer a much smaller PMHS, consisting for example in printed circuits or dielectric cavities coupled to a suitable magnetic material. Miniaturization may allow for simpler construction and implementation of the device. Multiplexing is also a possibility, for example by means of superconducting circuits [50–52] resonating within the magnetometer bandwidth, which have demonstrated quality factors up to $10^8$ [53–55]. Thanks to the present demonstration of the measurement scheme, forthcoming works will study alternative implementations of the magnetometer, and the device itself on a more detailed level, including for example the experimental demonstration of its dynamical bandwidth, the long-term stability of the setup and an improved sensitivity.

In conclusion, we devised and tested a spin-magnetometer based on the phase modulation of cavity magnon polaritons. Our prototype demonstrated the working principle of the device by showing a $\text{pT}$ field sensitivity, and an optimized version of the same setup could measure magnetic fields with $\text{fT}/\sqrt{\text{Hz}}$ precision. The tested design is not the only realization of the experimental scheme, which can be implemented in a number of different configurations. The magnetometer has a variable input impedance, a large dynamic range, and a remarkable sensitivity, allowing for its application for example in the field on magnetic imaging. All these features are unprecedented, and make this instrument the first of a class of magnetometers based on photon-magnon hybrid system.

Acknowledgments

We acknowledge Enrico Berto, Mario Tessaro and Fulvio Calaon for their work on the building and operation of the prototype. We thank Federico Chiossi, Caterina Braggio, Antonello Ortolan and Pierre Sikivie for the stimulating discussion regarding the physics of the instrument. The support of INFN-Laboratori Nazionali di Legnaro and of INFN-CNTT is deeply acknowledged. The authors declare that there is a pending patent application related to this research.
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