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# Magnetic detection of millimeter waves

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**Abstract.** – In this paper we show experimental results for the detection of millimeter waves based upon the response of the magnetisation of a material inside a resonator. The experimental evidence is that the magnetisation of the materials shows dramatic changes for the frequencies that match the modes of the resonator-magnetic-material system. The results shown here refer to the use of gadolinium at room temperature and hexa-hydrated iron chloride at low temperature inside a copper loop having resonant frequencies below 20 GHz.

Microwave energies in solids correspond mostly to lower vibrational and rotational energy levels whose intensities depend on temperature. There are also magnetic solids, like paramagnets, ferromagnets and the so-called high spin molecular clusters, which have magnetisation and spin electronic levels separated by microwave energies. Using magnetic measurements for the detection of microwaves may be only possible when the magnetisation values are highly influenced by the microwave absorption. Because of the large variety of energy levels capable of absorbing microwaves, the aforementioned magnetic materials could also be used in a broad frequency spectrum [1, 2].

The detection of microwave energy using resonators is based upon the fact that the energy density and, consequently, the attenuation caused by the absorption lines are large at the resonant frequencies. When the input frequency is changed slightly, the section becomes antiresonant and the energy density and the attenuation produced by the line become smaller. Resonators are usually characterized measuring the absorbed or reflected energy as a function of the frequency, and the amplitude and phase of the reflection coefficient [3–7]. This implies the use of sophisticated equipment, like network and swept amplitude analyzers, which do only work for limited ranges of frequencies. The main idea of the microwave detection method described in this paper is to use the energy density associated to the resonant modes to change the magnetisation of a strong temperature-sensitive material placed inside the resonator. To this end, it is necessary to use a sensitive detector of the magnetisation and to have a precise control of the temperature of the resonator. The main aim of all these methods is to offer high-resolution measurements of the quality factor $Q$ and resonant frequencies to make possible the study of the properties of the materials [8, 9] and the construction of microwave radiometers.

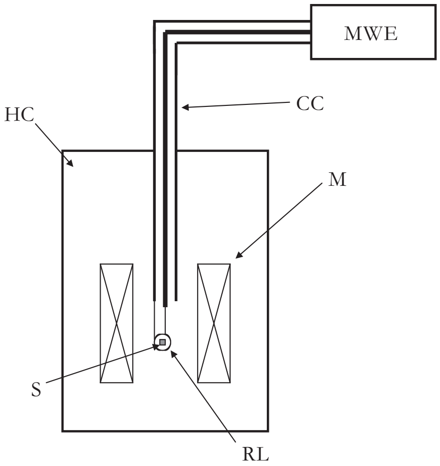

Fig. 1 – Experimental setup for the measurements described in the text. CC: coaxial cable, HC: helium cryostat, M: magnet, MWE: microwave equipment, RL: resonant loop, S: sample.

In our experiments we used gadolinium as the magnetic sensor close to room temperature and hexa-hydrated iron chloride salts near the liquid-helium temperature. The magnetic samples were fixed in the center of two very similar resonant loops with a 5.42 mm diameter, which were, respectively, made up of five and six coils of 0.1 mm thick 99.9% pure copper (Cu) wire. The power was coupled to the resonator-magnetic-material system (RMMS) through a coaxial cable that took the microwaves from the generator to the sample. The microwave radiation was generated using HP83621B synthesized sweepers and the analysis of the reflected and transmitted power was performed with a HP8510C network analyzer system. In the experiments shown here, we swept the radiation from 0.1 to 25 GHz in steps of 0.02 GHz. A nominal power of 30 mW was sent and a 0.1 mW power was checked to reach the RMMS. We placed both the coaxial cable and the resonator inside a commercial MPMS sample magnetometer that allows to change the temperature between 1.8 and 300 K and apply magnetic fields up to 50 kOe. A low-pressure helium gas bath surrounded the magnetic sample and the resonator and its temperature was monitored to be constant during the experiment, the accuracy being better than 0.1 K at 300 K and better than 0.002 K at 2 K. Figure 1 shows the experimental setup.

Data sets corresponding to the magnetic characterization of the samples outside and inside the resonator were identical after subtracting to the latter the signal due to the resonator. Figure 2 shows the magnetic moment of gadolinium as a function of temperature when a magnetic field of 3 kOe was applied. We used a 0.25 mm thick 99.9% pure foil of gadolinium with a mass of 32 mg. Gadolinium is a metallic element that behaves as a paramagnet at room temperature and rapidly becomes ferromagnetic with a huge magnetic moment at lower temperatures. This transition occurs in a narrow interval around the so-called Curie temperature, $T_\mathrm{c}$, and involves a very large variation of the magnetic moment. According to the inset of fig. 2, which presents the temperature dependence of the thermal derivative of the magnetic moment, $\mathrm{d}M/\mathrm{d}T$, the maximum negative variation for our sample occurs at $T_\mathrm{c} \simeq 294\,\mathrm{K}$.

Figure 3 presents the temperature variation of the magnetic moment of a commercial $\mathrm{FeCl_3 \cdot 6H_2O}$ salt, measured when a magnetic field of 3 kOe was applied. We used a 98% pure sample with a mass of 10 mg. The inset of the figure shows a perfect linear temperature

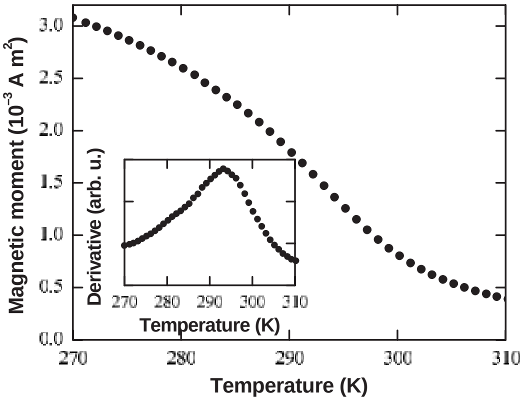

Fig. 2 – Thermal variation of the magnetic moment of the gadolinium sample when we applied a magnetic field of 3 kOe to reach saturation. The inset shows the thermal dependence of the derivative $dM/dT$ to demonstrate the rapid variation of the magnetic moment around the Curie temperature (294 K).

dependence of the inverse of the magnetic moment (IMM), which indicates that the sample behaves as a paramagnet in the whole temperature range investigated, with a Curie-Weiss temperature $\theta \simeq 1.4$ K.

Figure 4 presents the magnetic moment of gadolinium inside the Cu resonant loop at 294 K when the applied magnetic field was 3 kOe. The measurement of each point took $10 \pm 0.2$ seconds. For certain frequency values, sharp peaks are clearly outlined against a background level with a less than 0.01% experimental error. The intensity of these peaks is dramatically reduced when the temperature deviates from 294 K. We found a similar behaviour for the magnetisation of $FeCl_3 \cdot 6H_2O$ at low temperatures ($T = 2$ K) in the same experimental conditions, see fig. 5. Large deviations in the magnetic moment were obtained when the temperature of the sample was much larger than 2 K, and the intensity of the

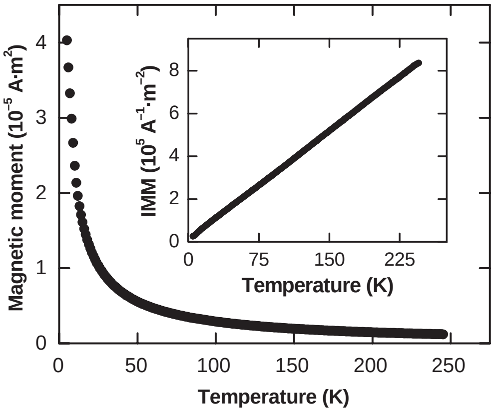

Fig. 3 – Temperature dependence of the magnetic moment of the $FeCl_3 \cdot 6H_2O$ sample when a magnetic field of 3 kOe was applied to reach saturation. The inset shows the thermal dependence of the inverse of the magnetic moment (IMM).

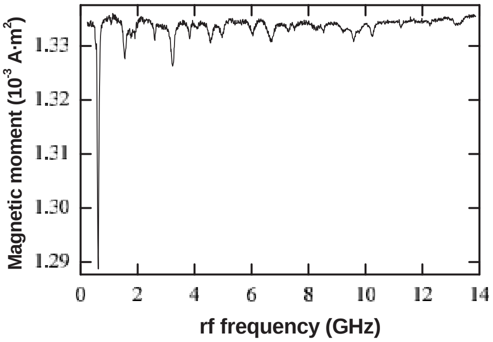

Fig. 4 – Magnetic moment of the gadolinium sample inside the Cu resonant loop at $T = 294\,\mathrm{K}$ and $H = 3\,\mathrm{kOe}$ as a function of the frequency of a 300 mW microwave radiation.

peaks was observed to reduce when increasing the temperature. In all cases, we also verified that when we changed the power of the radiation, the intensity of the peaks varied but their positions remained unaltered. We also verified that the magnetisation peaks observed for the gadolinium sample coincide with those recorded for the reflection coefficient measured at room temperature with the HP8510C network analyzer. The reproducibility of all these data was checked by performing the same measurements several times.

To interpret these data, the primary fact to consider is that the magnetisation peaks occur at the resonant frequencies of the RMMS, so that if the frequency of the microwave radiation that enters the device does not match any resonant mode, it gets reflected and does not produce any variation in the magnetisation of the magnetic material. At the resonant modes, however, standing waves form and live a certain time that depends on the quality factor, $Q$, which can be estimated at each magnetisation peak by dividing the frequency of the maximum by the full width at half-maximum (FWHM) of the same peak. The values of $Q$ obtained for the different resonances range from 100 to 300 and so the value estimated for the lifetime of the standing waves formed at the resonance frequencies is of about $10^{-8}$ s. Consequently, these standing waves deposit energy into the RMMS during the ten seconds that the measurement of each magnetisation point takes. This energy is therefore partially dissipated at the surface

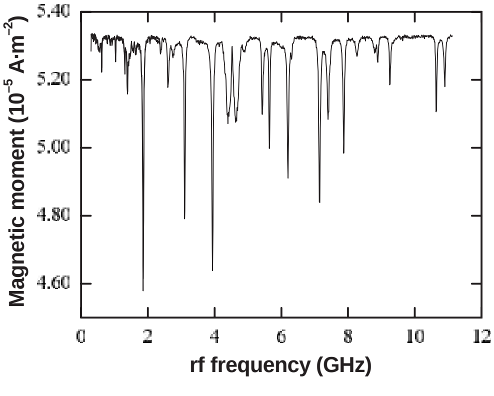

Fig. 5 – Magnetic moment at $T = 2\,\mathrm{K}$ and $H = 3\,\mathrm{kOe}$ of the $FeCl_3 \cdot 6H_2O$ sample inside the Cu resonant loop as a function of the frequency of a 300 mW microwave radiation.

of the copper wires and partially absorbed by the magnetic material. Both fractions should contribute to change the magnetisation, the first one heating the RMMS and the second one modifying the electronic, phonon and magnetic excitations of the sample.

The direct absorption of microwaves by the materials is due to magnetic- and electric-dipole transitions. In both cases, the amount of energy absorbed from the microwave power depends on the electric and magnetic ac fields associated to the standing waves formed in the RMMS at the resonant frequencies. For instance, in the case of the magnetic-dipole transitions, the ac magnetic field is easily derived from the Maxwell equations to be $H_{\text{ac}}^2 = 8\pi E/V$, where $V$ is the volume of the resonator, $E = QP/2\pi f$ is the energy stored within, $Q$ is the quality factor of the resonator, $P$ is the time-averaged power loss, and $f$ is the microwave frequency at a resonant mode [3]. Using typical values involved in our experiments, we obtained $H_{\text{ac}} \simeq 0.1$–$1\,\text{Oe}$, in good agreement with the usual ac fields in EPR experiments [10]. Similar results are obtained for the case of the ac electric field when electric-dipole transitions are considered. It seems therefore reasonable to expect to have quantum microwave absorptions by electronic and spin levels, in the case of the paramagnetic salt, or spin waves and other magnetisation excitation, in the case of gadolinium. We have experimentally observed that the intensity of the magnetisation peaks at the resonant frequencies depends on the power of the radiation as it is expected to occur when quantum microwave absorptions take place.

It could be argued that quantum microwave absorptions in both materials could be masked by pure phonon excitations. To clarify this point, we can compare the probabilities for both effects. The phonon absorption probability is given by [10]

$$\Gamma_{\text{phonon}} = \left(9\hbar\omega^5/12\pi\rho v^5\right)\left[\exp[\hbar\omega/k_{\text{B}}T] - 1\right]^{-1}, \tag{1}$$

where $\hbar\omega$ is the spacing between two consecutive energy levels, $\rho$ is the density of the material and $v$ is the speed of sound. Typical values for $\Gamma_{\text{phonon}}$ range from 10 to $10^5\,\text{s}^{-1}$. On the other hand, the spin transition probability due to photon absorption is given by [10]

$$\Gamma_{\text{photon}} = Sg^2\mu_{\text{B}}^2 H_{\text{ac}}^2/\pi\hbar^2\Delta\omega, \tag{2}$$

where $S$ is the spin, $g$ is the $g$-factor, $\mu_{\text{B}}$ is the Bohr magneton, and $\Delta\omega$ is the absorption width. $\Gamma_{\text{photon}}$ is of the order of $10^4\,\text{s}^{-1}$. We can thus conclude that the magnetisation changes of the samples inside the resonator may be well explained considering both effects, those due to phonon absorptions and those due to microwave excitations of the spin bath.

Apart from the experiments discussed in this paper, it is important to notice that we have extended our study to several different resonators, like cylindrical and coaxial cavities and superconductor coils, and have used different magnetic materials depending on the operational temperature. For example, using molecular magnets and both damped and superconductor coils we have seen [1,2,11] that molecular vibrations [12,13] and hyperfine levels [14] play a significant part in the tunneling mechanism detected in these materials. In the case of cylindrical cavities, we have also found strong variations in the resonant modes of the RMMS device that depend on the position and size of the sample, demonstrating that microwave absorption in such cavities is due to the different electrical and magnetic modes. Nevertheless, as long as our method is based upon the sensitive measurement of a magnetic signal, a compromise has to be achieved between the size of the sample and the magnitude of its magnetic moment. We can therefore not avoid the use of finite-size samples and, as a consequence, we cannot distinguish between the different electric and magnetic resonant modes of our resonators.

To summarize, we have shown and discussed the use of ferromagnets and paramagnets inside resonators to detect millimeter waves. The fact that the equilibrium magnetic moment of paramagnets is only sensitive to the ratio $H/T$ at which the experiment is performed allows having an absolute characterization of the RMMS. When the sample is magnetically ordered, it is also possible to study microwave phenomena if the magnetisation has a strong variation with temperature, as in the case of gadolinium near the Curie temperature.

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