A FERRIMAGNETIC RESONANCE THERMOMETER FOR MICROWAVE POWER ENVIRONMENT*

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ABSTRACT

A thermometric technique employing microwave observation of temperature-dependent magnetic resonance of a small ferrimagnetic sensing element is described. This device is suitable for use in enclosures in which microwave power is used for research or in industrial processing.

Introduction

Measurement of temperature is often a major requirement and a major vexation in research and in industrial processing. Familiar devices are gas and fluid-expansion thermometers, thermocouples, bimetallic expansion devices, and semiconductor thermal sensors. For determination of temperature within a microwave oven or other enclosure involving the use of microwave power for medical treatment or for scientific or industrial purposes, such devices suffer from several disadvantages. Their metallic parts tend to disrupt the microwave field and thereby to interfere with the phenomena they are intended to monitor. They are themselves susceptible to microwave power absorption, leading to spuriously high temperature readings. They require leads or other connecting members which must pass through the path of microwave power flow, where they constitute a mechanical obstacle and a microwave scatterer. The leads must somehow pass out of the chamber in order to reach the observer or recording device located outside; provision for suitable feed-through fittings involves a troublesome design and construction problem in order to avoid impairing the function of the enclosure, whether it be to confine microwave energy or to maintain a pressure state.

Magnetic Resonance Thermometry

A technique of temperature measurement which is free of the foregoing disadvantages will be described. It involves the use of a sensing element in the form of a small ferrimagnetic specimen which is interrogated by means of a magnetic resonance observation. By appropriate design of the composition and shape of the specimen, the temperature-dependence of the resonance may be made suitable for this purpose. The ferrimagnetic resonance may be observed by use of a low-power signal at a microwave frequency which is different from that of the microwave power, if present in the same enclosure; generation and detection of that signal takes place completely independently of such power. Under all but extraordinary conditions the sensing element is transparent to any microwave fields other than its own interrogating signal.

The Temperature-Sensing Specimen

An example of a suitable sensing specimen for this magnetic-resonance thermometer is a small rod of indium-substituted yttrium-iron garnet (In-YIG; for example, $Y_3In_{0.5}Fe_{4.5}O_{12}$). The temperature-dependence of the saturation magnetization of such a material[1], illustrated in Fig. 1, declines approximately linearly with slope of about 7 gauss per kelvin in the range 100-400 K. To exploit this property, we note that the Kittel relation[2]

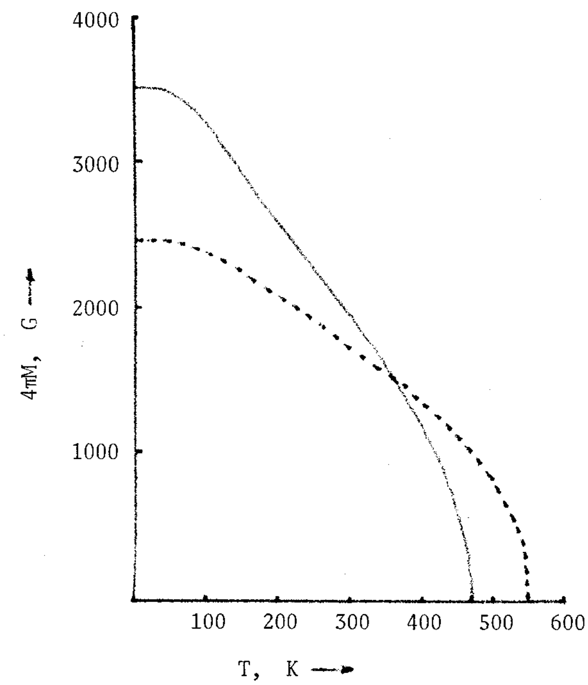

Fig. 1. Saturation magnetization vs. temperature; theoretical curves computed with use of molecular-field coefficients of Dionne, Ref. 1.

Solid curve: In-YIG, $Y_3In_{0.5}Fe_{4.5}O_{12}$

Dashed curve: YIG, $Y_3Fe_5O_{12}$

for ferrimagnetic resonance,

$$\nu = \frac{\gamma}{2\pi}\sqrt{[H_o+(N_x-N_z)4\pi M]\,[H_o+(N_y-N_z)4\pi M]}$$

(where ν is the resonant frequency, γ is the gyromagnetic ratio, H_o is the applied static magnetic field, $4\pi M$ is the magnetization, and N_x, N_y, N_z are the demagnetization factors, with the direction of the z-axis parallel to the direction of H_o) incorporates a dependence on $4\pi M$ through the influence of static and oscillating demagnetization fields on the resonance. One appropriate method of temperature interrogation is to observe the resonance frequency as a function of the temperature-related variation of $4\pi M$ while holding fixed the applied field H_o.

For an illustrative specimen in the form of a rod of the In-YIG material cited above having a ten-to-one

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ratio of axial length to diameter, magnetized parallel to its axis, we have $N_z = 0.0172$ and the transverse demagnetization factor N_t $(= N_x = N_y) = 0.491$; thus, the resonance condition for this case is

$$\nu = \frac{\gamma}{2\pi}[H_o + 0.474(4\pi M)]$$

which leads to a predicted temperature-coefficient of resonance frequency equal to 9.29 MHz K^{-1}. Considering that frequency measurement is routinely performed with very high precision, it is evident that this technique has the potential to provide very precise temperature determinations. The accuracy achievable depends on certain design details and on adequate calibration, as indicated below.

Instrument Considerations

Transformation of this thermometric principle into a functioning instrument requires the solution of some design problems. For the interrogation circuit, a low-power microwave source and detection capability are required with bandwidth of the order of one gigahertz, and with at least moderate qualities of sensitivity and noise rejection. A solid-state device such as a Gunn diode would be suitable as a source, when furnished with simple tuning capability to track the resonant frequency, and possibly also with amplitude modulation for synchronous detection.

In our experimental investigations, we have used a low-power klystron tuned to 9.0 GHz and a conventional microwave diode rectifier followed by a lock-in amplifier. To shelter these components from damage and interference by the high-power microwave fields (about 200 watts c-w at the ISM frequency of 2.45 GHz), we connected them to the system by means of X-band waveguide which served as a high-pass filter.

In our laboratory studies, the static magnetic field H_o was furnished by a laboratory electromagnet having pole faces four inches in diameter. This would, of course, not be appropriate for most of the temperature-measurement applications contemplated for this technique. We have proposed to construct a small unit composed of the In-YIG sensing rod surrounded by permanent-magnet members, encapsulated and capable of being placed within the enclosure at the point of interest. Magnetically "hard" materials of the class of hexagonal ferrimagnetic oxides[3] would be suitable for the purpose. Fig. 2 illustrates the idea. With this arrangement, the temperature-dependence of the applied field H_o itself would be a complication. Commercially available materials of this class are capable of being stabilized against irreversible changes in magnetization; this is accomplished by thermal cycling over the range of temperature envisioned for the application. In this stabilized state, the magnetization still exhibits a reversible temperature dependence, with temperature coefficient of remanent magnetization approximately equal to 0.2 % per K for typical materials under operating conditions. In the present application, this variation of the applied field H_o would actually enhance the temperature coefficient of the resonance frequency by an amount comparable to that of the change in sensor magnetization itself.

Such permanent-magnet materials are quite transparent to microwave power: a typical loss-tangent value is in the range from 0.001 to 0.005, and the dielectric constant, which may lie in the range from 12 to 23 (depending on composition) would result in only a small localized modification of the microwave power field. These properties would also have the undesirable effect of shielding the In-YIG specimen to some degree from its own interrogation signal, but this is estimated to be a minor problem. Spurious dielectric resonances of the encapsulated sensing unit would have to be avoided, but this would be accomplished if its dimensions are small -- of the order of 0.5 cm or less. The effects of magnetic permeability, including that of spurious magnetic resonances in the permanent-magnet material, are estimated to be slight. A consideration which relates to the maximum tolerable ambient microwave power level is the onset of nonlinear spin-wave instability[4] in the sensing specimen, leading to the appearance of a subsidiary resonance and to broadening of the principal resonance under high power. Choosing the interrogating frequency higher than that of the ambient microwave power field results in the specimen operating on the "high-field" side which is favorable for resistance to such nonlinear breakdown effects. This phenomenon would interfere with the accuracy of the temperature measurement only at extraordinarily high power levels or under conditions of unusual concentration of the power within a small volume.

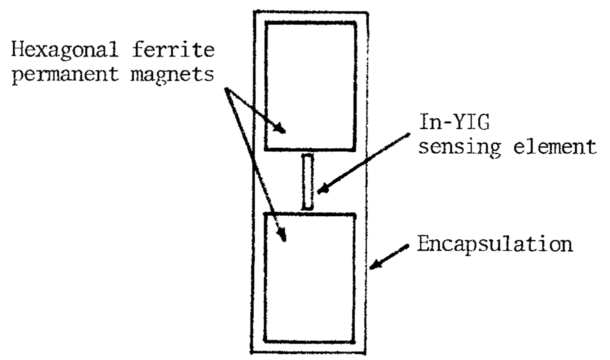

Fig. 2. Illustrating a thermal sensing unit which incorporates an In-YIG ferrimagnetic-resonance element and permanent magnets furnishing the applied field. Dimensions: about 0.5 cm long.

The ferrimagnetic resonance linewidth of the garnets is about 40 G (corresponding to 112 MHz) at room temperature for polycrystalline materials, due mostly to randomly oriented magnetocrystalline anisotropy. With the simplest methods of detection, the resonance can be measured to within about one-tenth of this, yielding a temperature uncertainty of about one K. With synchronous detection, determination of the resonance can be made at least an order of magnitude more precise. Making the sensing specimen out of a single crystal of In-YIG would provide reduction of the resonance linewidth by about a factor of forty, which would yield additional improvement of about that order in both precision and sensitivity. There would be a corresponding reduction in the maximum tolerable microwave power.

Our experience up to the present has included experimental determination of the temperature-dependence of the resonance, when viewed by variation of frequency at fixed applied magnetic field and vice versa[5]. The specimen is a polycrystalline In-YIG rod[6] of dimensions 0.1 cm diameter by 1.0 cm long placed in X-band waveguide. The results are consistent with the known magnetization function[1] for this type of material and confirmed the expected shape effect cited in the above discussion. We have also performed a simple observation of the temperature rise of a microwave-absorbing object immersed in the flow field of 2.45 GHz microwave power in S-band waveguide, at 200 watts c-w, and have obtained approximate agreement with the expected heating, considering the heat capacity of the object and the estimated net power absorption.

The magnetic-resonance thermometry technique proposed here appears to be worthy of development as a potentially simple, convenient, and accurate method of temperature measurement under difficult conditions, on the basis of the estimates and measurements summarized above. This is an important application for which few comparable techniques[7] have been proposed.

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