F-6

A FERRIMAGNETIC RESONANCE SENSOR FOR REMOTE WIRELESS TEMPERATURE MEASUREMENTS IN ORGANIC TISSUE

P. Röschmann, K.M. Lüdeke
P H I L I P S G M B H FORSCHUNGSLABORATORIUM HAMBURG
Vogt-Kölln-Str. 30, D 2000 Hamburg 54, FRG

ABSTRACT

FMR-sensors are used in a new system for remote medical thermometry. A new integrated torus shaped permanent-magnet-YIG-sphere sensor configuration led to considerable size reduction and generally improved thermometric properties as compared to earlier designs.

INTRODUCTION

The application of the temperature dependence of the ferrimagnetic resonance (FMR) frequency in small ferrimagnetic specimen for remote and wireless temperature measurements has been proposed recently [1,2]: The negative temperature coefficients of the magnetocrystalline anisotropy field Ha(T)/or of the saturation magnetization $4\pi M_S(T)$ of ferrimagnetic garnet spheres or rods in a fixed magnetic bias field can be utilized for remote ambient temperature measurements by interrogating the sensor's resonant frequency with low power microwave radiation. As no connecting wires or fibres are needed, this kind of sensor is attractive as a non-interfering and low-risk invasive thermometre for hyperthermia control. In order to avoid the complications from a body-size magnet for the bias field generation, it has been suggested to place small permanent magnets, made from microwave-'transparent', magnetically hard 'hexagonal' ferrite material, axially on both sides of an In-YIG rod resonator, thus forming an integrated FMR sensing element [1]. As an additional advantage the negative Tempco of - 0.2% of their remanent magnetization will enhance the total Tempco of the sensor. An experimental proof of the proposed integrated FMR-sensor was not given.

DISCUSSION

This paper presents experimental results of realized integrated FMR-temperature-sensors, consisting of single-crystalline YIG-spheres and Barium ferrite magnets (Ferroxdure^{TM}) of different size and shape. A complete temperature measurement system on the basis of these FMR-sensors has been developed for medical applications.

Key elements of the FMR-sensor determining the accuracy, resolution, response time and maximum distance in remote thermometry are the temperature coefficient (Tempco) of the resonance frequency f_0, the effective line width and the sensor size. The FMR frequency is given by:

$$f_0(T) = \gamma \cdot \left[H_0(T)+H_a(T)+(N_t-N_z)\cdot 4\pi M_S(T)\right] \qquad (1)$$

where γ = 2.8 MHz/Oe is the gyromagnetic ratio, N_t and N_z are the transverse and axial demagnetizing factors with respect to the direction of H_0 in the ferrimagnetic resonator with rotational symmetry. The permanent magnet bias field $H_0(T)$, the ferrimagnetic properties $H_a(T)$ and $4\pi M_S(T)$ for magnetization along the easy <111> direction decrease with rising temperature [3]. Although slender rods with N_t-N_z $\rightarrow$ 0.5 provide the largest Tempco of the FMR, spherical resonators having N_t-N_z=0 are to be preferred since they are smaller, require a smaller magnet, can be easier manufactured with the surface quality (polished) required for high Q, and most important, excel in lower linewidths Δf. A FMR-sensor configuration with axially arranged permanent magnets is shown in Fig. 1.

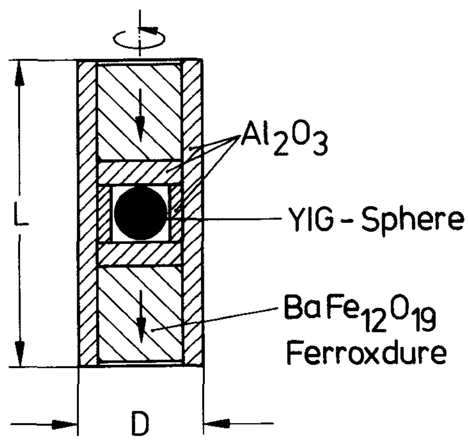

Fig. 1: Integrated axial permanent-magnet-YIG-sphere FMR-sensor for remote thermometry

The maximum distance for remote temperature measurements depends on the sensitivity of the rf-measurement technique which ultimately is related to the signal S scattered by the FMR-sensor:

$$S \propto V \cdot 4\pi M_S/\Delta f \qquad (2)$$

V: volume of the ferrimagnetic resonator.
The unloaded 3 dB linewidth Δf_0 of the YIG-spheres is less than 3 MHz and may be as low as 1 MHz. The effective linewidth Δf of the integrated FMR-sensor is broader due to inhomogeneities of the bias field and loss mechanisms in the ferrite magnets and the surrounding material (tissue). The operational linewidth effective in the realized system is even broader for reasons of a magnetic field modulation necessary for discrimination of the sphere's scattered signal against much stronger direct transmission between the transmitting and receiving antenna in a typical bistatic measurement set-up. Decreasing the magnet size for a given sphere resonator will increase the field inhomogeneity over the sphere's volume. The sphere's volume itself finds its upper limit by the onset of interfering higher modes of oscillation. To avoid excessive line broadening the space between the sphere and the magnets should at least equal a sphere radius. We have used spheres with diameters between 0.27 and 1.1 mm.

The above sensors were adjusted for resonance in the 2 - 2.7 GHz band. The Tempco measured was -6.5 MHz/K. The 0.1 K resolution required in the medical application corresponds to about 1/40 of the sensor's linewidth in tissue of high water content.

Table 1:

L/mm	D/mm	Ds/mm	Δ f/MHz in air	Δ f/MHz in water	operational Δ f/MHz in water	Rel.signal strength
6	3.2	1.02	13.6	26.7	30	0 dB
5.5	1.8	0.59	20	24	30	-10 dB

A significant improvement of the FMR-sensor has been achieved by replacing the two permanent magnet cylinders with a short torus-shape magnet as shown in Fig. 2.

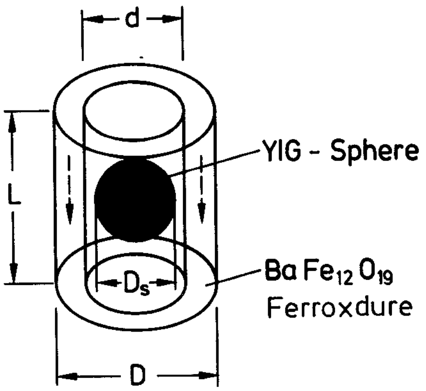

Fig. 2 Integrated torus permanent magnet YIG-sphere FMR-sensor for remote thermometry

The advantages are:

- length reduction to about twice the sphere diameter
- high mechanical stability
- self-alignment of the sphere
- smaller thermal time constant
- higher field homogeneity → narrower line width
- less resonance damping from the magnet and surrounding tissue
- higher Tempco/linewidth ratio.

Sensors have been assembled and tested using Ferroxdure FXD 330 for the magnet with dimensions varying from L = 2 mm, D = 2.5 mm down to L = 0.8 mm, D = 1 mm and D/d ≈ 2.

The FMR line broadening, $\Delta f_b = \Delta f - \Delta f_0$, increases rapidly for $D_s \to d$ and also for $D_s > 0{,}5 \cdot L$. For $D_s \approx 0.95 \cdot d$ typical values are $\Delta f_b = 8 \pm 2$ MHz. However, for $0.5 \cdot L > D_s \approx 0.5 \cdot d$ values of $\Delta f_b \approx 1$ MHz have been achieved. Recent investigations indicate that using Ferroxdure with higher BH-energy product, such as FXD 400 [4], results in $\Delta f_b < 1$ MHz even up to $D_s \approx 0.8$ d.

The resonance frequency is approximately a linear function of the ratio $R_m = (D-d)/L$ of the magnet, e.g. for $R_m = 1/3$ the resonance frequency at room temperature is 2.5 GHz including the effect from the anisotropy field for the YIG sphere of about 160 MHz.

Table 2 summarizes properties of some of the sensors. These devices have a Tempco of about -5.7 MHz/K. By inserting polycrystaline spheres (no effective Ha(T)) into a 2×2.5 Ø mm^2 magnet the Tempco of the magnet itself was found to be - 4.3 MHz/K.

A complete temperature measurement system on the basis of these sensors has been built for the 0 - 90 °C range, which achieves 0.1 K resolution. The system is sketched in Fig. 3. A homodyne quadrature receiver delivers the audio-frequency modulated complex phasor of the sphere's scattering response. After adaptive error-compensation and synchronous detection the response magnitude is derived and discriminated by a second modulation to drive a resonance tracking microwave VCO via an integrating controller. The VCO frequency is counted and converted to temperature by a microcomputer, allowing for programming of two-point calibration data of individual sensors, and optional linearization of the typical parabolic nonlinearity of these sensors (defined as $k = 4\,\Delta T_m/(T_2-T_1)$, ΔT_m: maximum deviation from straight line through T_2 and T_1.

Table 3: Nonlinearity between T_1 = 0 °C and T_2 = 80 °C

Sensor type	10^3 k
FMR sensor, Fig. 2	0.4 - 0.8
Thermoelement Type K	-0.34
Thermoelement Type T	-1
Platinum resistor PT100	0.16

Fig. 4 shows the resonance frequency versus temperature for a typical sensor.

Table 2: Properties of sensors constructed as shown in Fig. 2.

L/mm	D/mm	Ds/mm	Δ f/MHz in air	Δ f/MHz in water	operational Δ f/MHz in water	Rel.signal strength
2	2.5	0.59	2.2	8	10	0 dB
1.65	2	0.57	4.6	9.7	12	-10 dB
1.2	1.5	0.64	5.8	18	23	
1	1.2	0.43	4.8	7.8	10.6	- 5 dB

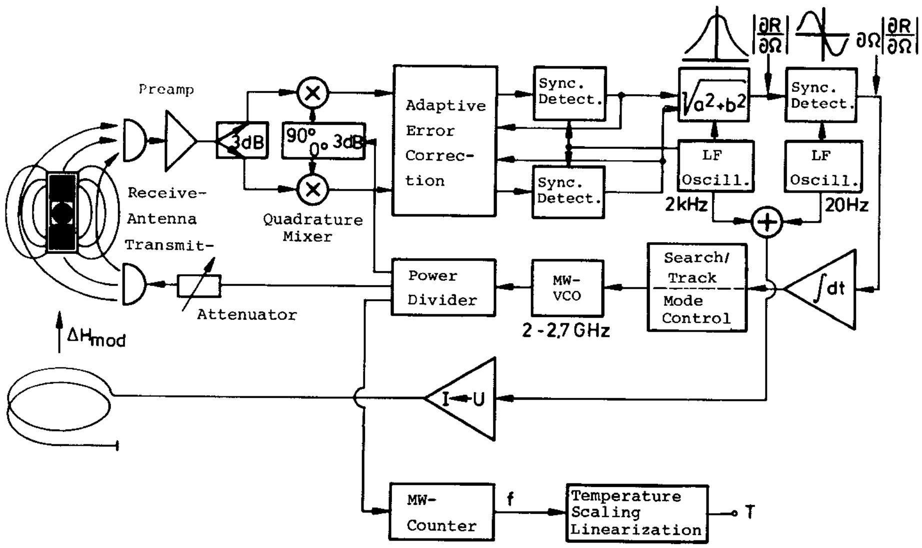

Fig. 3: FMR-thermometry system

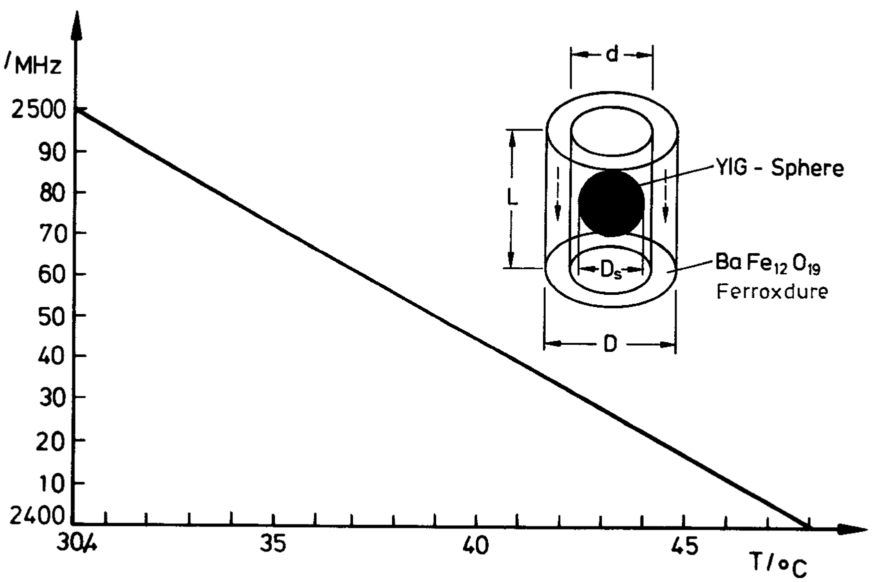

Fig. 4 Resonance frequency of an integrated permanent-magnet-YIG-sphere FMR-temperature-sensor as a function of temperature

CONCLUSION

The feasibility of remote wireless temperature measurements with integrated permanent-magnet-YIG-sphere FMR-sensors has been demonstrated by realizing a complete system suitable for the medical application. A new sensor configuration led to considerable size reduction and generally improved thermometric properties as compared to earlier designs.

The described work was sponsored by the German Federal Ministry for Research and Technology (BMFT) under grant no. 01 VF 019. Only the author(s) is (are) responsible for the contents of this publication(s).

REFERENCES

1 Weiss, J.A., Hawks, D.A., Dionne, G.F.: 'A ferrimagnetic resonance thermometer for microwave power environment'.IEEE MTT-S Int. Microwave Symp. Digest, 1981, pp. 290-292.

2 Beckmann, F.K., Doetsch, H., Roeschmann, P., Schilz, W.: 'Remote temperature sensing in organic tissue by ferrimagnetic resonance frequency measurements'. Proc.11th EuMC, Amsterdam, 1981, pp. 433-437.

3 Hansen, P.: 'Anisotropy and magnetostriction of gallium - substituted yttrium iron garnet', J. appl. Phys. 45, 1974, pp. 3638-3642.

4 Valvo Handbuch, Permanentmagnete 1981-82.