ACADÉMIE ROUMAINE

REVUE ROUMAINE DE PHYSIQUE

TIRAGE À PART

TOME 37
1992
N°5

EDITURA ACADEMIEI ROMÂNE

ON THE PARASITIC MODULATION OF THE H MASER FREQUENCY BY THE HEATING CURRENT INTENSITY *

L. C. GIURGIU **, B. M. MIHALCEA ***, M. P. DINCĂ **

** Faculty of Physics, University of Bucharest, P.O.B. MG – 11 Romania
*** Institute of Physics and Technology of Radiation Devices, Bucharest, Măgurele, POB MG–7, Romania

An altering effect of the H maser frequency stability due to the heating currents of the thermostating system was previously reported. The mechanism of this effect, involving the non-coaxiality of the heating cable produced by the thermal dilatation, is discussed here. The amount of the fractional frequency shift is computed for a practical design, showing a good accordance with the experimentally measured data. We also deal with the way to avoid this parasitic effect, by exciting the heating cable with alternating current having a null mean value and a sufficiently high frequency in order to assure a proper shielding of the magnetic field by the metallic thermostats bodies.

1. INTRODUCTION

The Hydrogen maser generates a microwave signal by stimulated emission between the hyperfine energy levels of the atomic Hydrogen ground state. The signal frequency, ν_M, is pulled if the resonant cavity is detuned. The maser frequency shift may be expressed as

$$\Delta\nu_M = \frac{Q_C}{Q_L}\Delta\nu_C \qquad (1)$$

where $\Delta\nu_M = \nu_M - \nu_0$, $\Delta\nu_C = \nu_C - \nu_0$; ν_C is the cavity frequency and ν_0 is the atomic line frequency, Q_C and Q_L being the cavity and the atomic line, respectively, quality factors [1].

The cavity frequency depends upon the cavity temperature. The maser frequency temperature coefficient, α_M, defined as [2]

$$\alpha_M = \frac{1}{\nu_M}\frac{\partial\nu_M}{\partial T} \qquad (2)$$

results from (1):

$$\alpha_M = \frac{Q_C}{Q_L}\alpha_C \qquad (3)$$

where α_C is the resonant cavity temperature coefficient.

* Received February 26, 1991

For a cavity made of alluminium $\alpha_C \simeq -2 \cdot 10^{-5}\,K^{-1}$. The typical values of the quality factors for the cavity and the atomic line are $Q_C = 3 \cdot 10^4$ and $Q_L = 10^9$, respectively. Taking these values into account from (3) we obtain that

$$\alpha_M = -6 \cdot 10^{-10} K^{-1}.$$

The long term stability of the maser frequency is altered by the temperature fluctuations of the resonant cavity :

$$\frac{\delta \nu_M}{\nu_M} = |\alpha_M| \cdot \delta T \simeq 6 \cdot 10^{-10} \cdot \delta T \qquad (4)$$

Thus, for obtaining a value of 10^{-14} for the long term stability, it is required to limit the cavity temperature fluctuations at the value $\delta T = 1.7 \cdot 10^{-5}$K, which implies a very good cavity thermostating.

Certainly, the short and medium term frequency stability is practically unaltered by these fluctuations due to the great thermal time-constant of the resonant cavity (over 10 hours).

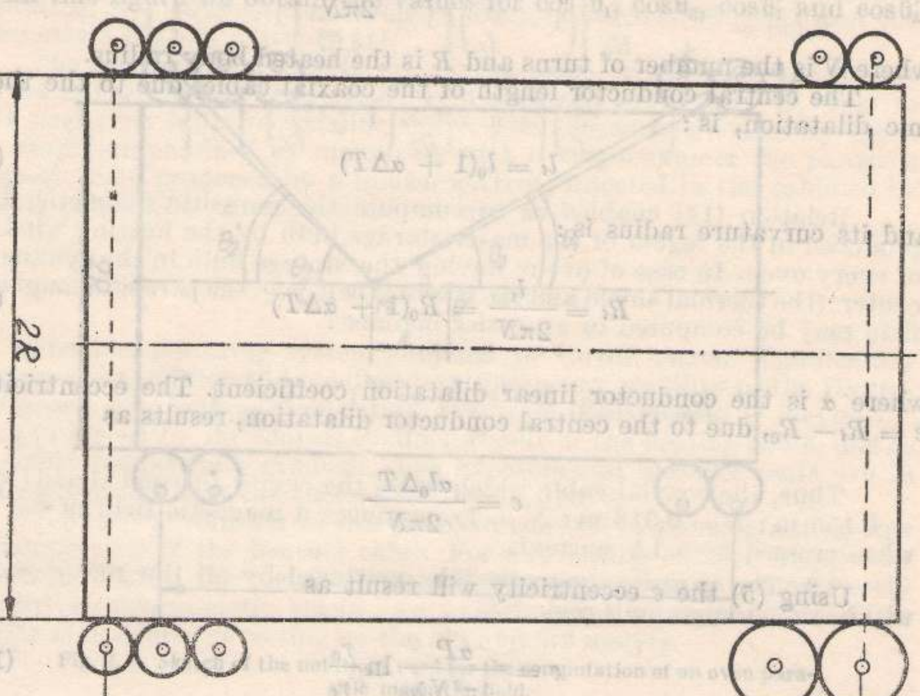
The maser cavity temperature variations are limited at $10^{-3} - 10^{-5}$ K by its ultrathermostating. For the 3rd generation Romanian masers the thermostating system consists of 5(five) cascade connected thermostats. Every heating element of the thermostats is a coaxial cable shortcircuited at one end and supplied by a direct current. This cable is in good thermal contact with the body that has to be heated. As temperature sensors, specially selected low drift, N.T.C. thermistors are used. These thermistors are in good thermal contact with both the heater and the body to be heated (resonant cavity, thermal shield, the vacuum bell, etc.) [2], [3].

Unfortunately, due to the heating current of the ovens a disturbing process was reported [4]. This effect consists in the maser frequency modulation produced by the variation of the heating current intensity. The cause, as shown below, is the residual magnetic field appearing in the storage bulb region due to the imperfections of the shielded heating cable.

2. THE PARASITIC MAGNETIC FIELD OF THE OVENS AND THE MASER FREQUENCY STABILITY

2.1. The coaxial heating cable is helically wound on every thermostat body. The heating current is injected through one end of the coaxial cable, the other end being shortcircuited.

The magnetic fields produced by the two equal currents, which pass through the outer and inner conductors of the heating cable, mutually cancel out, if the cable is perfectly coaxial. Even in this situation, during operation an e displacement of the axial conductor appears, due to the temperature gradient between the axial conductor and the shielding one (Fig. 1).



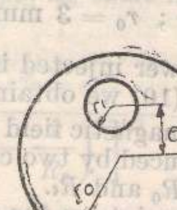


Fig. 1. — The typical arrangement of the heating coaxial cable for the maser ovens.

Denoting by T_i and T_0 the axial, respectively the shielding conductor temperature and by P the electrical power injected into the cable, with l_0 the cable's length, r_i and r_0 the axial, respectively, the shielding conductors' radius, λ the dielectric's thermal conductivity, after resolving the Fourier equation we obtain

$$T = T_i - T_0 = \frac{P}{2\pi\lambda l_0} \ln \frac{r_0}{r_i} \tag{5}$$

Since the cable is helically wound on the cylindrical body, the curvature radius of the cable symmetry axis may be expressed as

$$R_0 = R + r_0 = \frac{l_0}{2\pi N} \quad (6)$$

where N is the number of turns and R is the heated body radius.

The central conductor length of the coaxial cable, due to the thermic dilatation, is :

$$l_t = l_0(1 + \alpha\Delta T) \quad (7)$$

and its curvature radius is :

$$R_t = \frac{l_t}{2\pi N} = R_0(1 + \alpha\Delta T) \quad (8)$$

where α is the conductor linear dilatation coefficient. The eccentricity, $e = R_t - R_0$, due to the central conductor dilatation, results as

$$e = \frac{\alpha l_0 \Delta T}{2\pi N} \quad (9)$$

Using (5) the e eccentricity will result as

$$e = \frac{\alpha P}{4\pi^2 N \lambda} \ln \frac{r_0}{r_i} \quad (10)$$

The typical values for the constants implied in this relation are : $\lambda = 0{,}25 \dfrac{W}{K\,\mathrm{m}}$; $r_0 = 3$ mm, $r_i = 1$ mm, $\alpha = 16.5 \cdot 10^{-6}\,\mathrm{K}^{-1}$; $N = 7$. Because the power injected in the heating cable reaches a value of $P = 10$ W, from (10) we obtain an eccentricity $e = 2.6$ μm.

2.2. The magnetic field produced by this "altered" cable is the same as the one produced by two coaxial solenoids of the same length, but with different radii R_0 and R_t.

In the M point, on the system axis, at a x distance from the center, the magnetic induction is (Fig. 2) :

$$B_p(x) = B_0(x) - B_t(x) \quad (11)$$

with $B_0(x) = \dfrac{\mu_0}{2} NI(\cos\theta_1 + \cos\theta_2)$

$$(12)$$

and $B_t(x) = \dfrac{\mu_0}{2} NI(\cos\theta_1' + \cos\theta_2')$

where I is the current intensity, $\mu_0 = 4\pi \cdot 10^{-7} \frac{\mathrm{H}}{\mathrm{m}}$ the vacuum magnetic permeability while the θ_1, θ_2, θ_1' and θ_2' angles are shown in Fig. 2. From this figure we obtain the values for $\cos\theta_1$, $\cos\theta_2$, $\cos\theta_1'$ and $\cos\theta_2'$.

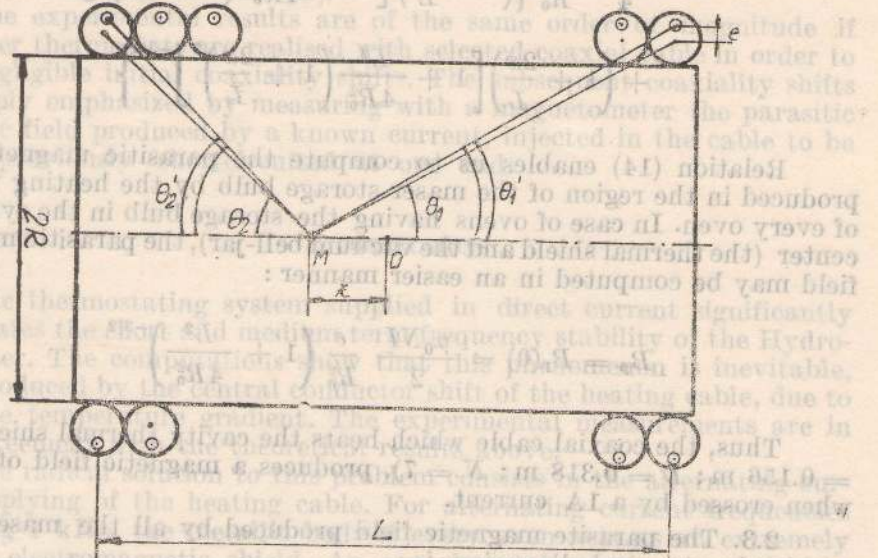


Fig. 2. — Sketch of the notations used for the computation of an oven parasitic magnetic field.

The magnetic field on the symmetry axis of the two coaxial solenoids, equivalent to the eccentrical coaxial heating cable is:

$$B_p(x) = \frac{\mu_0 NI}{2LR_0}\left\{\frac{\frac{L}{2}-x}{\left[1+\left(\frac{L}{2R_0}-\frac{x}{R_0}\right)^2\right]^{1/2}} + \frac{\frac{L}{2}+x}{\left[1+\left(\frac{L}{2R_0}+\frac{x}{R_0}\right)^2\right]^{1/2}} - \frac{\frac{L}{2}-x}{\left[\left(1+\frac{e}{R_0}\right)^2+\left(\frac{L}{2R_0}-\frac{x}{R_0}\right)^2\right]^{1/2}} - \frac{\frac{L}{2}+x}{\left[\left(1+\frac{e}{R_0}\right)+\left(\frac{L}{2R_0}+\frac{x}{R_0}\right)^2\right]^{1/2}}\right\} \quad (13)$$

Using the Taylor — Mac Laurin series expansion in respect to $\frac{e}{R_0}$ and preserving only the first degree terms

$$B_p(x) = \frac{\mu_0 NI}{4}\,\frac{e}{R_0^2}\left\{\left(1-\frac{2x}{L}\right)\left[1+\frac{L^2}{4R_0^2}\left(1-\frac{2x}{L}\right)^2\right]^{-3/2} + \right.$$

$$\left. + \left(1+\frac{2x}{L}\right)\left[1+\frac{L^2}{4R_0^2}\left(1+\frac{2x}{L}\right)^2\right]^{-3/2}\right\} \tag{14}$$

Relation (14) enables us to compute the parasitic magnetic field produced in the region of the maser storage bulb by the heating winding of every oven. In case of ovens having the storage bulb in the symmetry center (the thermal shield and the vacuum bell-jar), the parasitic magnetic field may be computed in an easier manner :

$$B_p = B_p(0) = \frac{\mu_0 NI}{2}\,\frac{e}{R_0^2}\left(1+\frac{L^2}{4R_0^2}\right)^{-3/2} \tag{15}$$

Thus, the coaxial cable which heats the cavity thermal shield ($R_0 = 0.156$ m ; $L = 0.318$ m ; $N = 7$), produces a magnetic field of 0.5 nT when crossed by a 1A current.

2.3. The parasite magnetic field produced by all the maser ovens within the storage bulb region is :

$$B_p \simeq \sum_{i=1}^{n} B_{pi} \tag{16}$$

where B_{pi} is the field produced in the storage bulb center by the i oven. The computed value for normal working conditions of the four thermostats system is about 1.5 nT [3].

This parasitic magnetic field superimposes itself over the bias field B_b existing within the storage bulb. The total field is

$$B = B_b + B_p \tag{17}$$

with $B_p \ll B_b$.

In the presence of the B magnetic field the maser frequency is shifted from ν_0 to ν_B, according to the relation

$$\nu_B = \nu_0 + AB^2 \tag{18}$$

where $A \simeq 2.8 \cdot 10^{11}\,\frac{\text{Hz}}{\text{T}^2}$.

The fractional frequency shift, due to the parasitic field, is therefore :

$$\frac{\delta\nu_B}{\nu_0} \simeq \frac{2A}{\nu_0}\,B_b \cdot \delta B_p = 4 \cdot 10^2\,B_b \cdot \delta B_p \tag{19}$$

The δB_p fluctuations produced by the variation of heating currents through the thermostats may reach 1.5 nT. For a bias field $B_b = 1$ μT, the relation (19) shows a deterioration of the frequency stability by a value of $6 \cdot 10^{-13}$. The phenomenon can be easily identified experimentally recording in time both the beat frequency between two masers and the thermostats heating currents [4].

The experimental results are of the same order of magnitude if the maser thermostats are realised with selected coaxial cable in order to have negligible initial coaxiality shifts. The subsequent coaxiality shifts are simply emphasized by measuring with a magnetometer the parasitic magnetic field produced by a known current, injected in the cable to be tested, previously shortcircuited at one end.

3. CONCLUSIONS

The thermostating system supplied in direct current significantly deteriorates the short and medium term frequency stability of the Hydrogen maser. The computations show that this phenomenon is inevitable, being produced by the central conductor shift of the heating cable, due to the cable temperature gradient. The experimental measurements are in good agreement with the theoretical results above.

The radical solution to this problem consists in the alternating current supplying of the heating cable. For alternating current frequencies exceeding 1 kHz, the metallic body of every oven acts as an extremely efficient electromagnetic shield. An experimental solution operating at 20 kHz is in course of testing on the M8 and M9 masers.

REFERENCES

1. D. Kleppner, H. M. Goldenberg, N. F. Ramsey, Phys. Rev., **126**, 603 (1962).
2. L. C. Giurgiu, Proceedings of the Conference "Applied Electronics", Timişoara, Sept. 8–9, 1979, 240; Progress in Physics, Bucharest, Oct. 23–24, 1987, 247.
3. L. C. Giurgiu, Mihai P. Dincă, Bogdan M. Mihalcea, Progress in Physics, Oradea, 5–7, Oct., 1989, p. 472–473.
4. O. C. Gheorghiu, L. C. Giurgiu, D. Falie, C. Mandache, T. Bocaniciu, J. Phys, **42**, Supp. 12, C8, 519 (1981).