Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum

COMPARISON OF WGE AND WGH MODES FOR TEMPERATURE COMPENSATED SAPPHIRE - RUTILE RESONATOR

Y. Kersalé[1], N. Boubeker[1], P. Y Bourgeois[1], N. Bazin[1], S. Vives[2], C. Meunier[2] and V. Giordano[1]
[1]LPMO CNRS, UPR 3203, associé à l'université de Franche-Comté,32 avenue de l'observatoire 25044 Besançon, France
[2]CREST, UMR 6000, pôle universitaire, 4 place Tharradin, BP 71427, 25211 Montbéliard cedex, France

E-Mail : kersale@lpmo.edu

Abstract – **We present in this paper performances comparison of Whispering Gallery sapphire-rutile resonator excited on WGE or WGH modes. Q factor, turnover temperature, curvature and frequency stability of each mode family are presented. Frequency stability of 2.10^{-12} for $WGH_{7,0,0}$ and 8.10^{-13} for $WGE_{9,0,0}$ have been obtained for short integration times.**
Keywords - **Sapphire-resonator, temperature compensation, frequency stability**

I. INTRODUCTION

Whispering Gallery (WG) mode sapphire resonators are well known to exhibit exceptional high Q factor in the microwave frequency range [1]. Exceptional spectral purity has been obtained with such resonators introduced in an oscillator loop [2]. For integration times superior to 1 second and temperature higher than 6K the large temperature sensitivity presented by sapphire resonator limits drastically the achievable frequency stability. Near the liquid nitrogen temperature (77K) several thermal compensation techniques have been already proposed and tested [3, 4, 5, 6, 7]. Recently we have proposed a new thermal compensation technique associating sapphire and rutile which presents a temperature coefficient permittivity opposite to the sapphire one [8]. Our thermal compensation process consists in the deposit by a sol gel method of a thin film of rutile on the entire sapphire disk surface in order to obtain a monolithic resonator. Two whispering gallery mode families can be excited in the resonator the quasi TM (WGH) or the quasi TE (WGE) modes. WGE modes excited in sapphire crystal are less sensitive to temperature fluctuations than WGH modes [9] and then achievable frequency stability can be improved by the use of the WGE configuration.

In this paper we present the performances comparison of our resonator, excited on WGE or WGH modes, in term of Q factor, turnover temperature, curvature and frequency stability.

II. SAPPHIRE - RUTILE RESONATOR

The resonator consists of a low cost sapphire disk with 37 mm diameter and 9.2 mm high. A 2 µm thin film of rutile has been deposited using a sol gel method on the entire surface of the sapphire disk [10]. Sapphire presents a high temperature coefficient of permittivity (TCP) leading to a strong frequency-temperature sensitivity. Rutile is characterized by a negative TCP. Then the temperature sensitivity of the resonator will be affected by any amount of rutile added on the sapphire surface. The resonator is then centered in an OFHC copper cylindrical cavity. Two electrical probes (antenna) parallel to the symmetry axis are then used to excite WGH modes while two magnetic probes in the same plan enable to excite the H_φ component of WGE mode family.

For WGH modes the electrical field is essentially parallel to the cylindrical axis. Then the temperature sensitivity of WGH mode frequencies depends principally on the sapphire temperature coefficient of $\varepsilon_{//}$, i.e the relative permittivity in the axial direction. For WGE modes where the electrical field is essentially transverse, it is the temperature coefficient of $\varepsilon_{\perp}$ that determines the frequency sensitivity.

At 77K the TCP of sapphire leads to temperature sensitivity of frequency of the order of [9]:

$$\frac{1}{\Delta T}\frac{\Delta\nu}{\nu} \approx -11.3 \text{ ppm/K} \quad \text{for WGH modes}$$

$$\frac{1}{\Delta T}\frac{\Delta\nu}{\nu} \approx -6.5 \text{ ppm/K} \quad \text{for WGE modes}$$

The frequency temperature sensitivity of WGE modes is approximately half of the WGH modes one.

III. COMPARISON OF WGE AND WGH PERFORMANCES

The resonator has been fixed on the cold finger of a cryo-cooler. Heaters and temperature sensor are anchored in the cold finger to enable temperature stabilization using a commercial PID regulator. The cavity was firstly cooled down to 10K and then the temperature was raised by step. At each temperature step, Q factor and the resonance frequency of each mode have been recorded using a vector network analyzer (VNA) with 1 Hz frequency resolution and referenced to a cesium clock to ensure long term frequency stability. This experiment has been conducted two times to characterize WGE and WGH modes.

A. Turnover temperature, T_0

Figure 1 shows the evolution of the turnover temperature of WGE and WGH modes for different azimuthal numbers.
As expected the turnover temperature decreases when the azimuthal number increases. Indeed the higher the azimuthal number is, the more confined in the sapphire disk the electrical field is. We observed lower turnover temperature for WGE modes. That can be explained by the fact that the electrical field confinement is more efficient for WGE modes. For the same rutile film thickness, the effect on resonance frequency is less.

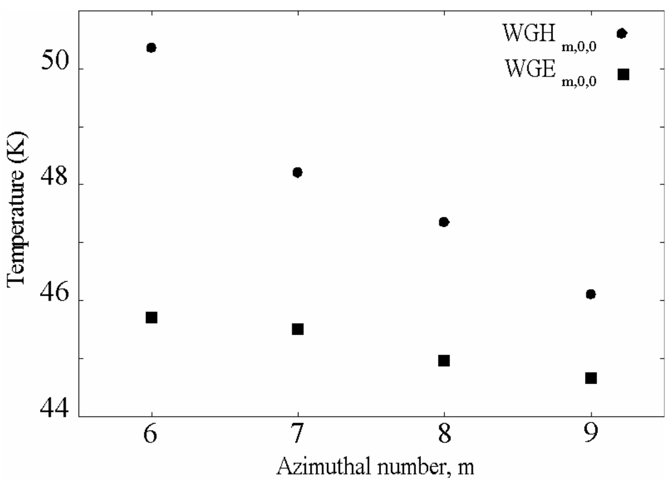

Fig. 1. Comparison of the temperature turning point of WGE and WGH modes versus the azimuthal number of the mode.

B. Curvature

The frequency – temperature characteristic of each mode has been fit by a second order polynomial near their temperature turning point T_0. Figure 2 shows the evolution of the $WGH_{7,0,0}$ frequency around its temperature turning point.
Around T_0 the residual frequency temperature sensibility can be expressed as:

$$\frac{1}{\Delta T}\frac{\Delta \nu}{\nu} = A\left(T - T_0\right) \quad (1)$$

where A is expressed in K^{-2}characterizes the curvature of the frequency temperature curve. We have obtained :

$A = 1.2.10^{-7}\ K^{-2}$ for WGH modes

$A = 7.10^{-8}\ K^{-2}$ for WGE modes

The curvature of the frequency temperature evolution depends only on the value of the sapphire TCP at the temperature turning point of the mode. Measured turnover temperatures of WGE and WGH modes don't differ drastically with the azimuthal number. Then for each mode family the curvature is approximately constant with the azimuthal number. For WGE modes the curvature is two times lower than the WGH one's which is in agreement with the TCP of sapphire [11].

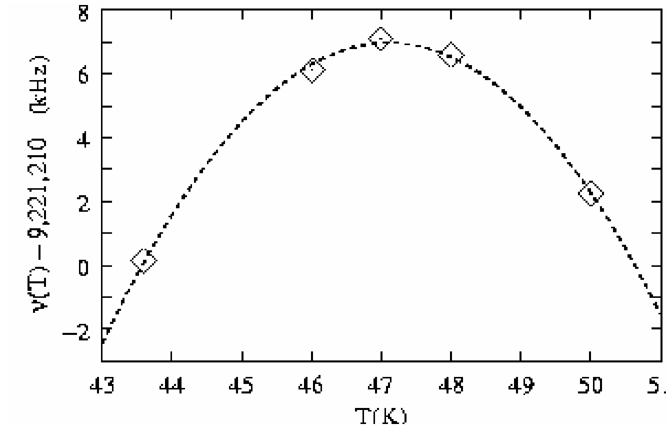

Fig. 2. Evolution of the $WGH_{7,0,0}$ frequency as a function of temperature just near its turning point. The dashed line represents the second order polynomial fit

C. Q Factor

In figure 3 the unloaded Q factor has been plotted versus the azimuthal number at the turnover temperature of the considered mode.

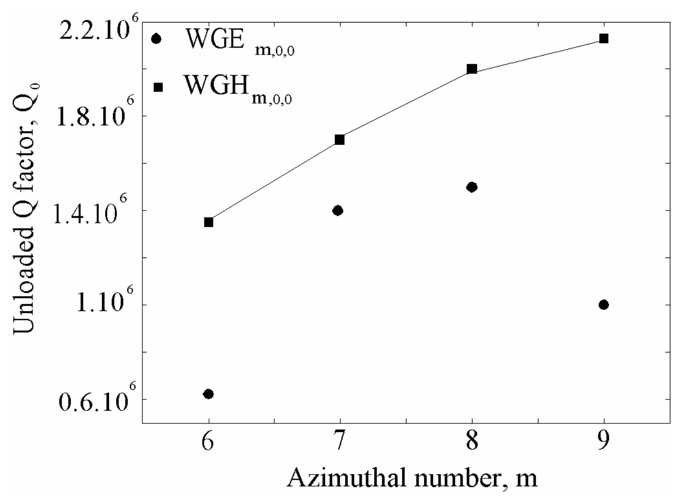

Fig. 3. Evolution of the unloaded Q factor of WGE and WGH mode versus the azimuthal number m.

Unloaded Q factor of WGH and WGE modes increases with the azimuthal number except for the $WGE_{9,0,0}$. For this mode the Q factor is limited by a low Q spurious mode which is at 30 MHz from the principal resonance.
WGH modes Q factor are higher than WGE ones. We ascribe this discrepancy by the large number of spurious modes observed near each WGE resonance. For WGH and for some unexplained reasons, observed spectra are less perturbed by

low Q spurious resonance.

D. Loss tangent of the rutile film

Q factor of the temperature compensated resonator can be expressed as [11]:

$$\frac{1}{Q_0} = p_s \,.\, \tan\delta_s + p_r \,.\, \tan\delta_r \qquad (2)$$

Where p_s and p_r are the electric energy filling factors in sapphire and rutile respectively and $\tan\delta_i$ the dielectric loss tangent of the considered material. For WG modes we can assume that $p_s + p_r \approx 1$ and for a small dielectric perturbation that the ratio p_r / p_s represents the ratio of the effective volume of the two dielectric materials.
The above equation becomes :

$$\frac{1}{Q_0} \approx \tan\delta_s + \frac{p_r}{P_s} \,.\, \tan\delta_r \qquad (3)$$

This formula leads to a $\tan\delta_r \approx 1.10^{-4}$ at 50 K which is 10 times higher than the one for a single crystal of rutile [12].
It should be noted that this loss tangent can be improved by doping the TiO_2 film with Al_2O_3. In that case $\tan\delta_r \approx 1.10^{-5}$ at 50 K has been measured [12]. With such a loss tangent unloaded Q factor of the order 13.10^6 can be obtained using a high quality sapphire crystal with 20.10^6 of unloaded Q factor.

IV. OSCILLATOR LOOP

The compensated resonator stabilized around its turnover temperature has been implemented in an oscillator loop schematized on figure 4. Oscillation on $WGH_{7,0,0}$ and $WGE_{9,0,0}$ is ensured by a commercial GaAs amplifier and a dielectric filter. Voltage controlled phase shifter (VCPS) and attenuator (VCA) have been inserted in the loop to control signal phase and amplitude. Resonator reference plans are fixed by a set of three ferrite isolators. Resonator couplings have been set near unity for β_1 (input) and near zero for β_2 (output). A circulator placed at the input resonator access enables to extract the reflected signal which is directed to a high efficient backward diode (D1) placed outside the cryo-cooler for $WGH_{7,0,0}$ configuration and inside the cryo-cooler for the WGE ones.

The resonator is regulated around its temperature turning point with a commercial PID using a 1 mK temperature resolution cernox sensor [13]. Assuming that both the ultimate temperature stability and the departure from the turning point are of the order of magnitude of the temperature sensor resolution, we get from equation (1) the frequency stability limitation due to temperature control :

$\Delta\nu/\nu = 1.2\times10^{-13}$ for the $WGH_{7,0,0}$

$\Delta\nu/\nu = 7.10^{-14}$ for the $WGE_{9,0,0}$.

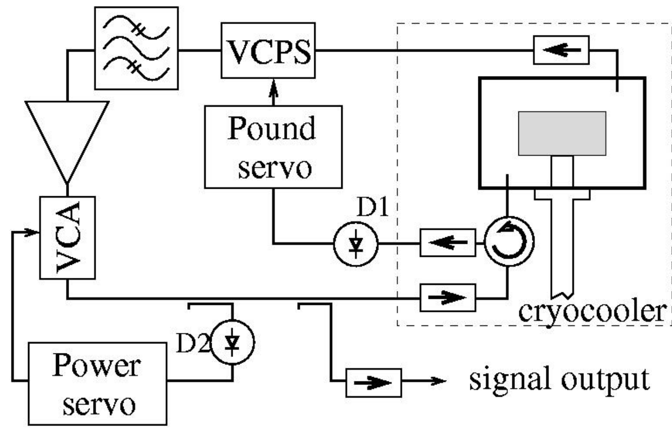

Fig. 4. Oscillator circuit

The loop electrical length is controlled by a Pound frequency stabilization servo by locking the oscillation frequency to the center of resonance [14]. The carrier is phase modulated by the VCPS at a frequency of 1.2 MHz for WGH configuration and 680 kHz for the WGE configuration. The backward diode signal is then demodulated by synchronous detection. The resulting error signal is filtered and sent back to the VCPS bias stage. The noise floor of the frequency stabilization servo has been evaluated considering the experimental slope of the error signal (1.7×10^{-5} V/Hz for the $WGH_{7,0,0}$ mode and 4.7×10^{-6} for the $WGE_{9,0,0}$ mode) and the noise at the input of the lock-in amplifier (11.2 nV/$\sqrt{Hz}$ white noise). The Pound servo limitations are :

$\Delta\nu/\nu = 5.10^{-14}\,\tau^{-1/2}$ for the $WGH_{7,0,0}$

$\Delta\nu/\nu = 2.10^{-13}\,\tau^{-1/2}$ for the $WGE_{9,0,0}$

We have also implemented a DC power stabilization servo to prevent frequency instability due to power fluctuations [15]. The resonator frequency sensitivity to power fluctuations has been measured and is of the order of 1500 Hz/W. In the operating oscillator conditions, the output voltage noise of the schottky diode detector (D2) presents a flicker component of –127dBV/$\sqrt{Hz}$ at 1 Hz. This voltage noise induces flicker frequency noise and then leads to a frequency stability flicker floor of $\Delta\nu/\nu = 2.10^{-15}$.

This value is an optimistic one. Indeed the schottky diode (D2) is placed outside the cryogenic can and it is sensible to ambient temperature fluctuations. This temperature sensitivity leads to injected power fluctuations of the order of 2 µW/K. The diode (D_2) has been then temperature controlled to null power fluctuations due to the ambient temperature fluctuations. The limitation of the power servo is : $\frac{\Delta\nu}{\nu} \approx 2.5\,10^{-13}$.

V. FREQUENCY STABILITY

The oscillator output signal (9.2 GHz for the $WGH_{7,0,0}$ and 11.8922 GHz for the $WGE_{9,0,0}$) has been mixed with the signal of a microwave synthesizer referenced to a cesium clock. The beat note has been analyzed by a frequency counter interfaced to a computer. In figure 5 we have represented the standard deviation (square root Allan variance $\sigma_y(\tau)$) of the relative frequency fluctuations of the two oscillators we built.

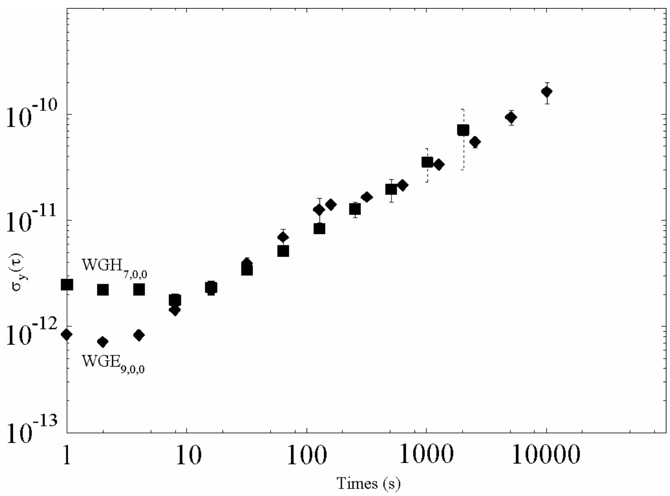

Fig. 5. Rutile-sapphire resonator oscillators frequency stability.

The use of the WGE configuration has considerably improved the short term frequency stability. Frequency instability better than 8.10^{-13} has been measured at short integration times for the $WGE_{9,0,0}$ which has to be compared to 2.10^{-12} obtained with the $WGH_{7,0,0}$. For longer integration times we have measured approximately the same frequency drift for the two modes. The frequency drift is of the order of 3.10^{-9} per day. Actually we don't have any convincing explanation for this frequency drift. We checked all the electronics servo (Pound and power) and measured their offset variations on large times scales. Any of these measurements can be correlated with the observed frequency drift. The best candidate to be responsible for the drift is the stress relaxation in the sapphire itself or in its mounting structure. Nevertheless WGE and WGH show the same drift which contradicts previous observation at lower temperature [16].

VI. CONCLUSION

We have demonstrated the potentiality of a new temperature compensated sapphire microwave resonator for which the thermal compensation has been obtained by the deposition of a rutile thin film on the sapphire disk by a sol gel method. This resonator has a number of advantages such as compactness, low cost, and intrinsic immunity to vibrations. This resonator excited both on the $WGH_{7,0,0}$ and the $WGE_{9,0,0}$ mode shows short term frequency stability of 2.10^{-12} and 8.10^{-13} respectively. For long integration times the frequency stability is limited by a resonator frequency drift of 3.10^{-9} per day. Careful checks of electronics servos have strengthened that this drift is due to internal resonator phenomenon. Thermal gradients, stress relaxation have to be considered and further experiments are then needed to understand the actual cause of this frequency drift.

REFERENCES

[1] A.N. Luiten, A.G. Mann and D.G. Blair, “Ultrahigh Q-factor cryogenic sapphire resonator,” *Electronics Letters*, 1993, 29, (10), pp. 879-881.

[2] R.A. Woode, M.E Tobar, E.N Ivanov and D.G. Blair, “An ultralow noise microwave oscillator based on a high-Q liquid nitrogen cooled sapphire resonator,” *IEEE Trans. UFFC,* 1996, **43**, (5), pp. 936-941.

[3] J.G. Hartnett, M.E. Tobar, A.G. Mann, J. Krupka and E.N. Ivanov, “Temperature dependence of Ti^{3+} doped sapphire whispering gallery mode resonator,” *Electronics Letters,* 1998, **34**, (2), pp. 195-196.

[4] G.J. Dick, D.G Santiago, R.T Wang, “Temperature - compensated sapphire resonator for ultra-stable oscillator capability at temperatures above 77K,” *IEEE Trans. UFFC,* 1995, **42**, (5), pp. 812-819.

[5] V. Giordano, Y. Kersalé, O. DiMonaco, M. Chaubet, “Progress report on the development of a microwave spectral references at the LPMO,” *European Physics Journal, Applied Physics*, 1999, **8**, pp. 269-274.

[6] M.E. Tobar, J.G Hartnett, E.N. Ivanov, D. Cros, P. Blondy and P. Guillon, “Cryogenically cooled sapphire-rutile dielectric resonators for ultrahigh frequency stable oscillators for terrestrial and space applications,” *IEEE Transactions on Microwave Theory and Techniques*, 2000, **48**, (7), pp. 1265-1269.

[7] M. Winter, N. Klein, L. Hao and J.C Gallop, “Cryogenic composite whispering gallery mode resonators for low phase noise frequency standards,” *Proc. of the IEEE/IEA IFCS*, Kansas city, Mi, USA, 2000, pp. 500-505.

[8] J. Krupka, K. Derzakowski, M.E. Tobar, J.G. Hartnett and R.G. Geyer, “Complex permittivity of some ultralow loss dielectric crystals at cryogenic temperatures,” *Meas. Sci. Technol.,* 1999, **10**, (4), pp. 387-392.

[9] M.E. Tobar, E.N. Ivanov, R.A. Woode, J.H. Searls, “Low noise microwave oscillators based on High-Q temperature stabilized sapphire resonators,” *Proc. of the IEEE-IFCS*, Boston, Ma, USA, 1994, pp. 433-440.

[10] Y.Kersalé, O.Vallet, S.Vives, C.Meunier and V.Giordano, “A New Temperature Compensated Sapphire-Rutile Microwave Whispering Gallery Mode Resonator,” *Electronics Letters*, 2001, **37**, (23), pp. 1392-1393.
[11] M.E. Tobar, J. Krupka, J.G Hartnett, E.N. Ivanov, R. Woode, “High-Q sapphire-rutile frequency temperature compensated microwave dielectric resonators,” *IEEE Trans. UFFC,* 1998, **45**, (3), pp. 830-835.
[12] A. Templeton, X. Wang, S.J. Penn, S.J. Webb, L.F. Cohen and N.McN. Alford, “Microwave dielectric loss of titanium oxide,” *J. Am. Ceram. Soc.,*2000, **83**, (1), pp. 95-100.
[13] Lake Shore Cryotronics Inc., 575 McCorkle Blvd, Westerville, OH (US), catalogue : Temperature measurement and control.
[14] A.N Luiten, A.G.Mann, N.J.McDonald and D.G Blair, “Latest results of the U.W.A cryogenic sapphire oscillator,” *Proc. of the IEEE IFCS,* San Francisco, Ca, USA, 1995 pp. 433-437.
[15] A.N. Luiten, A.G. Mann, M.E. Costa and D.G. Blair, “Power stabilized cryogenic sapphire oscillator,” *IEEE Transactions on Instrumentation and Measurement*, 1995, **44**, (2), pp. 132-135.
[16] S. Chang and A.G. Mann, “Mechanical stress caused frequency drift in cryogenic sapphire resonators,” *Proc. of the IEEE/IEA IFCS*, Seattle, Washington, USA, 2001, pp. 710-714.