Cryogenic Sapphire Microwave Oscillators for Space, Metrology and Scientific Applications

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Abstract

We recently demonstrated a Cryogenic Sapphire Oscillator (CSO) presenting a short term frequency stability better than 3×10^{-15} for 1 s $\le \tau \le$ 1000 s and achieving 4.5×10^{-15} for one day integration. This CSO incorporates a pulse-tube cooler instead of a bath cryostat –thus eliminating the need for regular supplies and manual transferring of liquid helium. The advent of reliable and cryocooled CSO open the possibility to implement such an ultra-stable reference not only in metrological laboratories with liquid helium facilities but also in remote sites like base stations for space navigation, VBLI antenna sites, ...

1 Introduction

A growing number of scientific or technical applications requires ultra-high frequency stability signal sources. Thus a relative frequency stability better than 1×10^{-14} for integration time between 1 and 10^4 s is now required for metrology, future space programs and some tests of fundamental physics [1, 2, 3]. These new requirements impose to surpass the performances of the state-of-the-art quartz crystal oscillators whose short term frequency stability is limited to around 1×10^{-13}.

Microwave Cryogenic Sapphire Oscillators (CSO) exhibit the higest short-term stability, attaining parts in 10^{-16} near 10 s integration time [4, 5, 6]. A CSO incorporates a cryogenic whispering gallery mode resonator made in sapphire which provides a Q-factor as high as 1×10^9 at 4.2 K. In all functional realization up to now, the resonator is immersed in a liquid-helium bath and maintained at its optimum temperature (generally around 6 K), where its thermal sensitivity nulls to first order. CSOs have been used as local oscillators for atomic fountains clocks[7] and for fundamental physical experiments as Local Lorentz Invariance tests [2]. It is also planned to implement such oscillators in Deep Space Network ground stations to improve the tracking of space vehicules and in VLBI observatory for better data correlation. For these last applications, the use of liquid helium is inconvenient and a change of technology is needed. We recently validated in the frame of a European Space Agency research contract, an new instrument: ELISA based on a CSO operating in a specially designed cryocooler. The detailed design and preliminary characterisations can be found in [8, 9]. This CSO is associated with a frequency synthesis delivering round frequencies, i.e. 10 GHz, 100 MHz and 5 MHz. The ELISA's relative frequency stablity is better than 3×10^{-15} for $1\text{s} \le \tau \le 1{,}000\text{s}$ and can operate continuously for two years without maintenance. As an additional benefit, this new type of CSO presents an unprecedented frequency stability at long integration times: 4×10^{-15} over one day without any clearly observed drift. The aim of this paper is to summarize the design, the fonctionnalities and performances of this CSO as well as the new projects leaded in our laboratory and related to this technology.

2 Elisa's design

The scheme in figure 1-A describes the main sub-systems constituting the Elisa frequency reference. The heart of the system is a whispering gallery mode sapphire resonator made of a large and thick high purity sapphire cylinder

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placed in the center of a copper cavity. This assembly is thermally connected to the second stage of a pulse tube cryocooler. A special *soft* thermal link and a thermal ballast were designed in order to filter the vibrations and the temperature modulation at about 1 Hz induced by the gas flow in the cryocooler. Low thermal conductance coaxial cables are used to connect the Sapphire resonator to the sustaining loop placed at room temperature. The oscillating circuit is completed by two servos stabilizing the phase along the loop and the power injected into the resonator. These control loops use the same principle than those described in the reference [10]. Apart from the CSO signal at a frequency ν_0, three other frequencies required for ESA applications: 10 GHz, 100 MHz and 5 MHz. Moreover these useful signals should be phase locked at long term on a 100 MHz reference coming from a Hydrogen Maser (HM). A frequency synthesis was then designed to transfer the CSO's frequency stability to these useful signals with a slight degradation at 5 MHz as a result of the performance of typical RF components.

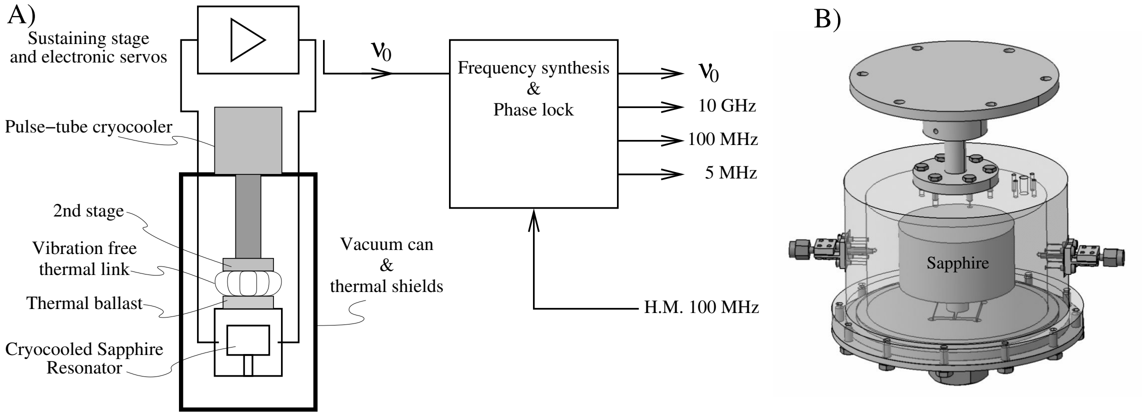

Figure 1: *A) Description of the Elisa's sub-systems.* *B) The Sapphire resonator in its cavity*

The resonator consists of a Crystal System HEMEX grade single-crystal sapphire, 54.2 mm diameter and 30 mm thickness with a 10 mm diameter spindle allowing a stable mechnical clamping in the center of a gold plated copper cavity. This assembly as schematised in figure 1-B is fixed on the experimental cold plate of a pulse-tube cryocooler. A special *soft* thermal link and a thermal ballast were designed in order to filter the vibrations and the temperature modulation at 1.4 Hz induced by the gas flow in the cryocooler. The use of particular resonance modes called Whispering Gallery (WG) modes allows to concentrate almost all the electromagnetic energy inside the sapphire cylinder. The mechanical tolerances in the resonator machining induce an uncertainty in the actual resonator frequency of ± 3.5 MHz. The resonator was designed to operate on the $WGH_{15,0,0}$ whispering gallery mode at 9.99 GHz. The intentional 10 MHz frequency offset from the 10 GHz round frequency was chosen to permit to compensate for the resonator frequency uncertainty by using a low noise Direct Digital Synthesizer (DDS) included in the frequency synthesis. By acting on th eDDS world command the synthetised ouputs can by phase locked on 100 MHz external signal. Thus the system can be disciplined at long integration times by an atomic frequency standard. The actual resonator frequency measured at 6.1 K is 9.989,121 GHz. The figure 2-A shows the transmission coefficient of the resonator, the Q-factor is 8×10^8. Figure 2-B shows the resonator frequency-temperature dependance around 6 K. The actual resonator frequency dependence on the temperature is quadratic due to the presence in the crystal of paramagnetic impurities as Cr3$^+$, Mo3$^+$ or Ti3$^+$[11]. This feature allows to greatly relax on resonator thermal regulation constraint. Indeed the resonator stabilized at T_0, its first order thermal sensitivity is nulled.

3 Elisa's performances

Elisa's relative frequency stability has been evaluated at short term by beating its output signal with those generated by an equivalent CSO but cooled into a liquid helium dewar. For integration time $\tau > 1,000$ s, Elisa was compared to an Hydrogen Maser. The figure 3 compares the Elisa relative frequency stability to the state-of-the-art performances of ultra-stable quartz oscillator and ULE cavity stabilized laser. The maximum frequency instability, i.e. 4.5×10^{-15}

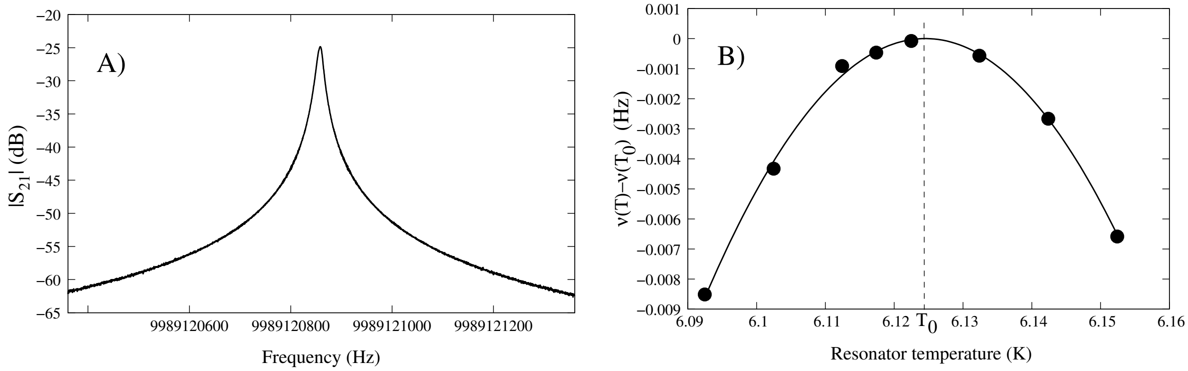

Figure 2: *Sapphire resonator main characteristics at low temperature*

arises near 1 day. It is likely that the hydrogen maser itself significantly contributes to this frequency instability. Indeed, its residual sensitivity has been measured to be $1.4 \times 10^{-14}/\mathrm{K}$ which is far from negligible given that the daily variation of the temperature in the laboratory was typically a few degrees Celsius.

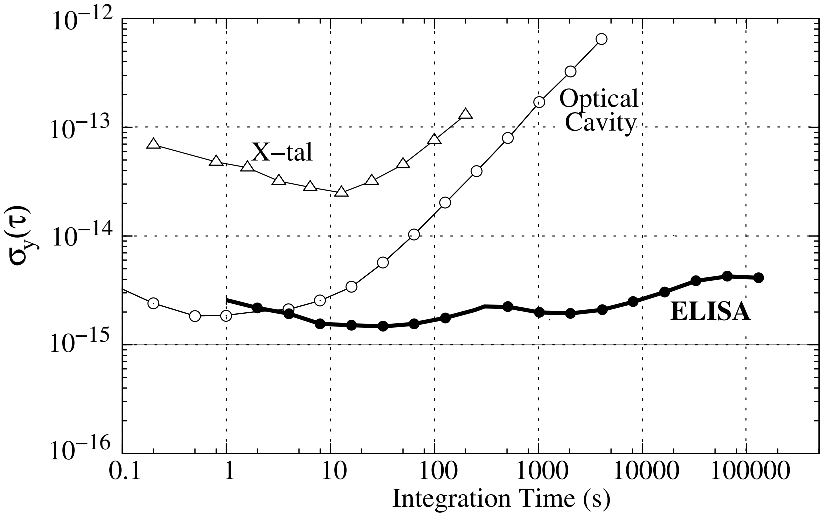

Figure 3: ● *: Estimated ELISA's relative frequency stability compared to some other frequency standards based on macroscopic resonator.* △*: 5 MHz quartz X-tal oscillator [12];* ○*: Laser stabilized on an ultra-stable optical cavity [13].*

4 Conclusion and future

We demonstrated an cryogenic oscillator presenting a relative frequency stablity is better than 3×10^{-15} for $1\mathrm{s} \leq \tau \leq 1{,}000\mathrm{s}$ and can operate continuously for two years without maintenance. As an additional benefit, this new type of CSO presents an unprecedented frequency stability at long integration times: 4×10^{-15} over one day without any clearly observed drift. These performance demonstrate that the technology of the CSO is now mature enough to envisage its implementation in applications requiring top-level performances and reliability.

Elisa owned by ESA will be implemented in the new Deep Space Station planned to be operational in March 2012. In Femto-St we are designing a new CSO nammed ULISS that is devoted to be transportable. The objective of this new

project is to test the new CSOduring 2012 in some potential user's site as primary metrolgical labs or radioastronomy stations around Europe. This project is founded by the Fonds Europen de DEveloppement Régional (FEDER), the Région de Franche-Comté and OSEO.

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