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ULISS-2G ultra stable cryocooled microwave sapphire oscillator: A mature and reproducible technology.

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Abstract

The Cryogenic Sapphire Oscillator (CSO) bridges the gap between high spectral purity oscillators and Hydrogen masers, providing a relative frequency stability better than 3×10^{-15} at short term and than 1×10^{-14} for one day of integration. These exceptional performances are no longer reserved only for well-equipped metrology laboratories with liquid helium facilities. In 2010, we demonstrated for the first time the possibility to use a cryocooler while maintaining a state-of-the-art frequency stability. Today, our upgraded technology, i.e. ULISS-2G, is able to meet the most demanding current needs in frequency stability while offering autonomy and reliability compatible with field applications. In this paper we present the frequency performances of the different CSOs (currently 10 units) we built and validated, demonstrating the reproducibility of our CSO technology.

1 Introduction

15 years ago, the most advanced CSO prototypes were still operating with liquid He bath and were reserved to well equipped metrological laboratories [1, 2, 3]. In 2010, we demonstrated the first generation of an autonomous CSO (ULISS-1G). The liquid He bath was replaced by a 6 kW Pulse-Tube cryocooler, without degrading the CSO short term frequency stability [4]. Four ULISS-1G units have been built and are still operating [5, 6]. Since, at the FEMTO-ST Institute, we undertaken large engineering efforts to rationalize the CSO design and its development, reduce its electrical consumption and improve its immunity to environmental perturbations [7, 8, 9, 10]. Our upgraded CSO technology (ULISS-2G), is today sufficiently mature to be offered as a commercial product consuming only 3 kW and able to run continuously during two years without maintenance. Today 6 ULISS-2G units have been built and validated, a last one is under construction.

2 ULISS-2G technology

The ULISS-2G technology exploits a high-Q cylindrical microwave dielectric resonator made in a high purity sapphire (Al_2O_3) monocrystal and cooled near the liquid helium temperature.

Figure 1. ULISS-2G CSO. The cryostat is integrated at the bottom of the 19" rack. On the left, the 3 kW water cooled He compressor. This unit is equipped with a 9,192 MHz synthesizer and can serve as a local oscillator for a cesium cold atoms fountain.

Designed to operate just bellow 10 GHz, i.e. 9.99 GHz ± 5 MHz, the resonator has a diameter of 54 mm and a height of 30 mm. This choice simplifies greatly the design of the frequency synthesizer that generates the useful output signals (10 MHz, 100 MHz and 10 GHz) with a fractional frequency resolution of 1×10^{-16}.

The confinement of the electromagnetic field inside the sapphire is ensured by the use of a high-order resonance mode called whispering gallery mode. Near 4 K, the Q-factor reaches 10^9. The sapphire resonator frequency shows just above 4 K a turnover temperature for which its sensitivity to temperature variations nulls at first order. The appearance of this turning point results from the presence in Al_2O_3 of paramagnetic impurities as Cr^{3+} or Mo^{3+}. The turnover temperature is thus specific to each resonator and is generaly found between 5 and 8 K depending on the provenience of the sapphire crystal .

To cool the resonator and stabilize its temperature while preserving it from the mechanical vibrations arising from the cryocooler we developed a specially designed cryostat equipped with a low consumption cryocooler. We opted for simple solutions, favoring passive thermal filtering and mechanical decoupling by flexible links, optimizing the trade offs using numerical simulations and experimental testings. The result of this engineering work is the development of a compact and cost effective cryostat that integrates into a 19" rack that also supports the control electronics and the frequency synthesis circuits generating various output signals: 10 MHz, 100 MHz, 10 GHz. Any other frequency between 5 MHz and 18 GHz can be synthesized if needed. The CSO can be also disciplined at long term by an external Hydrogen maser using a phase look loop with an adjustable time constant.

3 Frequency stability performances

Validating an ultra-stable oscillator presenting a flicker floor below 1×10^{-15} is metrological challenge. At Femto-ST, in the frame of the OSCILLATOR-IMP project, we developed a metrological platform facility dedicated to the measurement of noise and short-term stability of oscillators and devices in the whole radio spectrum (from MHz to THz), including microwave photonics, widely available to Agencies, to research institutions and to private companies [11]. The microwave reference section of the OSCILLATOR-IMP platform consists in three 6 kW CSOs of the first generation implemented in an dedicated room where the temperature is stabilized within ±0.5 °C. This set is completed with state-of-the-art digital instruments enabling the implementation of high resolution measurement methods. Thus, a new ultra-stable oscillator can be easily validated without ambiguity by applying the three-cornered-hat method [12, 13]. The figure 2 shows the relative frequency stability (Allan deviation, ADEV or $\sigma_y(\tau)$) of the nominal output signal at 9.99 GHz of the different CSOs we have built.

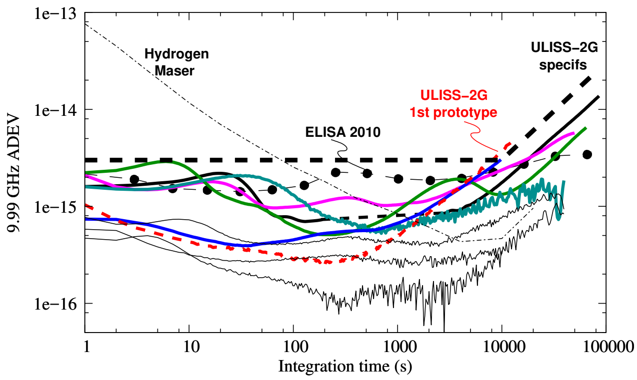

Figure 2. ADEV of the 9.99 GHz signal generated by the CSOs. (-•-) First cryocooled CSO: ELISA, developed for the European Space Agency. Thin lines: OSCILLATOR-IMP 6 kW 1st generation CSOs. Red dashed line: First ULISS-2G prototype, not optimized for long term behavior. Bold and colored lines: 5 ULISS-2G CSOs built between 2018 and 2021 and delivered to different national metrological institutes around the world. Black dashed line: ULISS-2G commercial specifications.

The bumps observed in several CSO ADEV plots for $\tau <$ 100 s have been attributed to a slow residual pumping of the resonator thermal control. The latter arises due to the limited resolution of the temperature sensor, the time lag between this sensor and the sapphire resonator and the slowness of the digital PID controller. The spread in the short term ADEV, results from i) the spread in turnover temperature, indeed the residual temperature sensitivity increases with T, ii) a better passive thermal filtering in high power CSO. At longer integration time, the CSO frequency fluctuations are governed by the environmental perturbations and especially by the temperature fluctuations. The CSOs under test were implemented in an electronic workshop equipped with a standard general purpose air conditioning system with limited performances. Depending on the time of the year, until 5 degrees amplitude temperature variations could be observed during the day.

The 3 CSOs of the OSCILLATOR-IMP platform have been implemented successively between 2012 and 2015. Since then, they have been running almost continuously. Several short stopping were carried out to enable i) their routine maintenance: one He filter should be changed every 2 years in the compressor circuit, ii) the maintenance of the building electric circuit. We also recorded two breakdowns: one CSO Rotary Valve and one cryogenic power detector. These defective elements were quickly replaced by new ones, and the faulty CSOs recovered rapidly their initial performances.

From these results, we can assert that for or 1 s $\leq \tau \leq$ 10,000 s. the typical CSO fractional frequency stability is better than 3×10^{-15}. For the best CSOs, we have $\sigma_y(1\text{s}) \sim 4 \times 10^{-16}$, the flicker floor in part of 10^{-16} and long term drift below 10^{-14} per day.

The choice of the resonator frequency, i.e 9.99 GHz $\pm$ 5 MHz, makes easy and cost effective the design of the frequency synthesizer. The CSO signal is mixed with 10 GHz signal coming from a low phase noise DRO. The 5-15 MHz obtained IF signal is compared to a high resolution DDS to phase lock the DRO on the CSO. VHF and RF output signals are generated by simple divider chains. The figure 3 shows the relative frequency stability (Allan deviation) of the 100 MHz synthesized output signals of the 5 ULISS-2G CSO built and delivered to several different national metrological institutes around the world. Compared to the 9.99 GHz ADEV, we observed a weak degradation at short term ($\sigma_y(\tau = 1\text{s}) \sim 4 \times 10^{-15}$), due to the intrinsic noise of the divider chain.

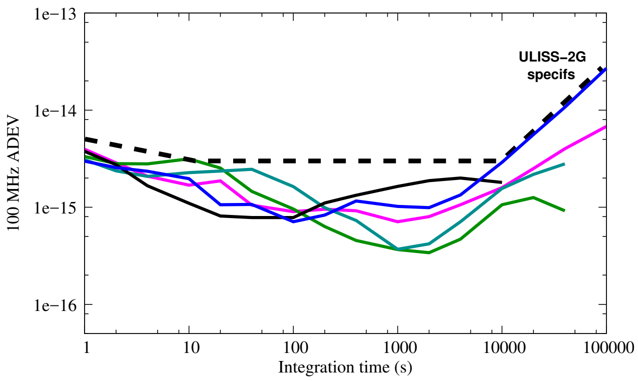

Figure 3. 100 MHz ADEV for the 5 ULISS-2G CSOs.

4 Acknowledgements

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