Recent Results on a Rb Pulsed Optically Pumped Clock for Space Applications

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***Abstract*—We report on the recent characterization of a Rb microwave clock based on the pulsed optical pumping (POP) principle. The clock is developed in the frame of a INRIM-Leonardo collaboration intended to implement a highly stable and compact device for space applications. The physics package developed by Leonardo S.p.A. includes space-graded components, weights less than 4 kg and occupies only a 4-liters volume. It has been characterized with custom optics and electronics developed at INRIM laboratories. By taking advantage of advanced stabilization techniques for the laser and microwave pulses, this arrangement exhibits state-of-the-art short- and mid-term stability, reaching $\sigma_y(40000\ \mathrm{s}) = 6 \times 10^{-16}$ (drift removed) for a 200 000 s run.**

***Index Terms*—rubidium; atomic clocks; telecom; GNSS.**

I. Introduction

Vapor-cell clocks based on a hot rubidium vapor are at the basis of many time-keeping applications, including modern global navigation satellite systems (GNSS) and telecommunications. These devices demonstrated to be reliable, robust and compact and are able to deliver a stable signal for one day of integration time or longer [1]. However, more recently, laser-pumped cell clocks have demonstrated improved stability performances compared to traditional lamp-pumped devices, maintaining at the same time the potential of reduced size weight and power consumption (SWaP) [2]–[6].

As a drawback, the simultaneous presence of laser and microwave signals during the clock interrogation introduces a rather high sensitivity of the clock frequency to the laser parameters (namely frequency and intensity). The pulsed approach allows to relax the specifications on the laser noise and stability, since the clock state spectroscopy is performed in the dark [7]. Nevertheless, due to experimental limitations (i.e. available pumping power, and not ideal extinction of the light during the Ramsey time), a residual sensitivity to the laser parameter remains. Moreover, coherent noise transfer from the laser remains mainly during the optical detection [8]. Thus, careful engineering of the laser pulses has proven to be crucial for obtaining the best clock performance [7].

Here, we present the most recent results obtained with advanced pulses-stabilization techniques. The results were obtained with an engineered physics package developed by Leonardo S.p.A. targeting the space market.

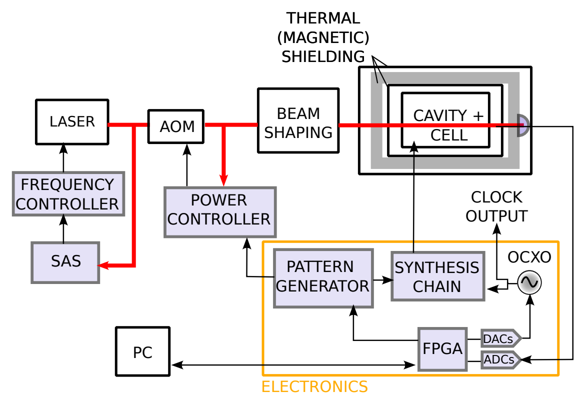

Fig. 1. Functional scheme of the laser-pumped Rb-POP clock. The laser diode used for optical pumping and atomic-state detection is frequency stabilized on an external spectroscopy setup. The main output is sent to a fiber coupled acousto-optic modulator (AOM). The diffracted beam mode is cleaned and expanded by means of an optical fiber patch and free-space optics. Finally, it is delivered to the clock physics package. The AOM acts as an optical switch for generating the pulses and also for reducing the intensity noise of the laser. The power controller is driven by the same custom digital-electronics package that is used for controlling the experiment. SAS: Saturation Absorption Setup. OCXO: Oven-controlled Crystal Oscillator. FPGA: Field-programmable Gate Array. DAC: Digital-to-Analog Converter. ADC: Analog-to-digital Converter.

II. Clock setup and results

The clock setup is composed of a laser source, a physics package, a low-noise synthesis chain to generate the coherent microwave pulses and a digital electronics to manage the clock operation (see Figure 1).

The laser source is a DFB laser diode emitting at $780.24\,\mathrm{nm}$. The laser pulses are generated by an active controller driving an acousto-optic modulator (AOM); in this way, it is possible to produce laser pulses of programmable length and amplitude. The controller has enough bandwidth to reduce the laser relative intensity noise (RIN) in a range of Fourier frequencies of interest for the clock signal processing (from $100\,\mathrm{Hz}$ to tens of kHz). On the other hand, for long averaging times, the controller stabilizes the pulses amplitude. The laser frequency is stabilized using a reference cell containing only a Rb vapor by means of saturated-absorption technique. The amplitude of the microwave pulses is also actively stabilized, using the technique depicted in [9]. Both laser and microwave amplitudes are stabilized with relative stability below 5×10^{-4}.

The physics package is an engineered model developed by Leonardo S.p.A. in the framework of an European Space Agency (ESA) General Support Technology Program (GSTP) [10]. The prototype has been already tested for vibrations, shock and has been also characterized in terms of thermal and magnetic sensitivity.

The electronics includes the microwave synthesis chain and the digital electronics needed for low-noise signal acquisition. It has been extensively described in [11].

The clock operates in a Ramsey mode. After optical pumping, the atoms interact with a couple of microwave pulses according to the Ramsey scheme. Finally, a second laser pulse probes the atoms that have made the clock transition.

When the local oscillator is frequency locked on the atomic reference signal, we obtained the frequency stability results showed in Figure 2. We measured a white-noise-limited frequency stability of $1.2 \times 10^{-13}\,\tau^{-1/2}$ up to 1000 s of averaging time. By selecting a 200 000 s long run under quite environmental conditions, it achieves the values of 6×10^{-16} for integration times of 40000 s (drift removed). These are, to our knowledge, record results for a vapor cell frequency standard.

The complete implementation of this new technology at the industrial level is expected to match GNSS requirements and to provide advantages reducing in orbit maintenance needs, increasing re-alignment intervals with a simultaneous reduction of size, mass and power consumption while providing frequency stability performances competitive with the passive hydrogen maser.

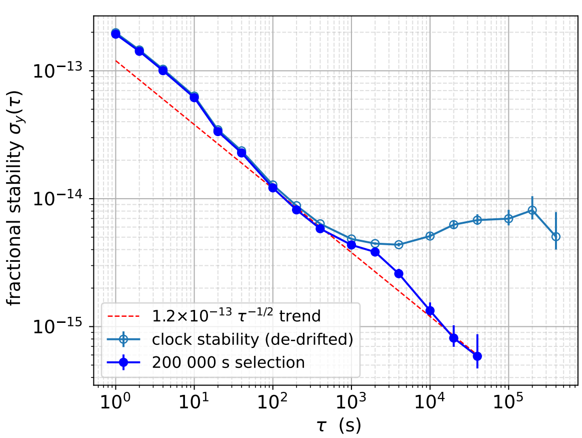

Fig. 2. Stability of the POP clock described in the text when measured with a stable hydrogen maser as a reference. Measurement bandwidth 5 Hz. A linear drift of 3.9×10^{-14}/d is removed from the whole measurement.

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