Generalized Electronics for Compact Atomic Clocks

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***Abstract*—We present the electronics we developed in the frame of IND55 EMRP project with the goal to support next generation sub-$10^{-13}/\sqrt{\tau}$ compact atomic clocks. In this regard, particular attention has been devoted to reduce the Dick/intermodulation effect in the low 10^{-14}, very close to the shot-noise limit. The scheme can adapt to Cs and Rb clocks with minimal modifications. The digital implementation guarantees a high degree of flexibility that allows to run very different clock typologies and to implement innovative schemes such as the frequency lock of the laser to the internal cell.**

***Keywords*—Dick effect, digital electronics, compact atomic clocks;**

Recently, the European Metrology Research Programme (EMRP) has funded the IND55 Mclocks joint research project [1] to develop compact and high-performing microwave clocks for industrial applications such as navigation, telecommunication, defence and precision instruments. This project aims at taking full advantage of better performing laser and microwave sources and innovative techniques to prepare and detect the atoms. In this regard, several European national metrological institutes (NMIs) or research institutes, devised new cell-based prototypes that exhibit unprecedented frequency stability performances, of the order of 10^{-13} at 1 s with a medium long-term in the range of 10^{-14} or better. Three typologies have been selected: vapour-cell clock based on pulsed optical pumping (POP) [2], on cold atoms [3] and coherent population trapping (CPT) [4, 5, 6]. They are very different and allow matching many industrial applications having different levels of accuracy, stability, compactness, power consumption.

Despite their diversity, we decided to develop a generalized electronics able to run all of them with minimal modifications. This demanding task has been achieved by sharing the competences of the main NMIs involved in the project with the goal of obtaining a high-performing, flexible and simple platform. Particular attention has been devoted to generate a low phase noise and agile microwave [7], in order to interrogate the atoms with minimal Dick and intermodulation effect. The core is a module [8] that integrates an ultra-low

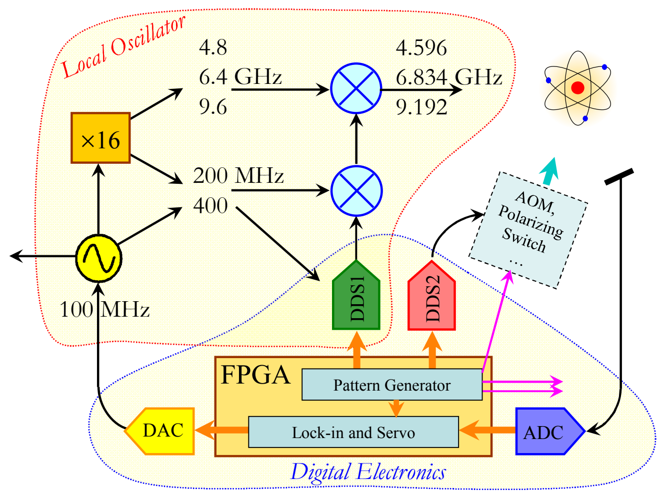

Fig. 1. Block diagram of the generalized electronics. It can subdivided into local oscillator and digital electronics. The dashed box contains the parts that are peculiar of each clock: acousto-optic modulator for POP, polarization switch for DMCPT…

noise 100 MHz oven controlled crystal oscillator (OCXO) and the first ×16 direct frequency multiplier stage. From its output at 1.6 GHz, three frequencies are generated by direct multiplication (1), programmable division (2) and direct digital synthesis (DDS) (3) and then mixed together. By changing the multiplier device (×3, ×4, ×6), the division factor and the numerical frequency of the DDS, we can obtain 4.596, 6.834 and 9.192 GHz as required by rubidium and caesium atoms. The DDS also provides simultaneous and fast phase, amplitude and frequency modulations and allows implementing the patterns required by these clocks typologies. During the development of this scheme, we faced with new criticalities: AM to PM cross-correlation collapse in the measurement of ultra-low noise sources; DDS spurs and residual phase noise; very-low noise voltage required by the

OCXO tuning. In order to provide compactness and flexibility, we integrated into a single board the low-frequency part of the scheme (two of the three arms) together with the electronics in charge of atomic signal detection and of frequency stabilization of the OCXO. This board is composed of DDSs, analog to digital converters (ADC) and digital to analog converters (DAC) driven by a field programmable gate array (FPGA) that provides synchronous operation at the level of 100 ns. The operational parameters are stored into the local memory and are used by a pattern generator to drive the DDSs (microwave and laser modulations) as well as several generalized loop controllers that process the atomic signals to extract the required information.

This platform has been tested with the POP clock at INRIM (Torino, Italy) and with the double modulation coherent population trapping (DM-CPT) clock at SYRTE (Paris, France). For these clocks, the noise contribution to the short-term stability of each part has been evaluated. The total contribution is in the low 10^{-14} at 1 s, very close to the expected shot-noise limit. In this regard, it was important to reduce the Dick effect down to 2×10^{-14}.

Besides clocks' characterization, the electronics, thanks to its flexibility, allowed the implementation of new schemes, like the laser frequency lock to the internal cell. In this regard, it's interesting to note the case of the POP clock, where, by simply processing the atomic signal from the internal cell, and without any additional hardware, we demonstrated the possibility to retrieve the frequency error and power level both of the microwave and of the laser. This information can be used to stabilize all these quantities at the same time. The result is a significant reduction of the clock setup, very important, for example, in the frame of compact atomic clocks.

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