Summary

Compact Rubidium microwave clocks are a key component for precision-timing applications, both for industrial and for scientific applications. Modern global navigation satellite systems also demand always improving stability performances together with a small form factor. The Pulsed Optically Pumped (POP) clock developed at INRiM introduced the use of laser pumping together with a microwave Ramsey interrogation. The atomic sample constituting the frequency standard is a vapor-cell containing ^{87}Rb diluted in a buffer gas. The pulsed technique ensures a high atomic quality factor and lower sensitivity to fluctuations of the experimental parameters. Given these characteristics, a fractional frequency stability of $1.7 \times 10^{-13}\,\tau^{-1/2}$ was achieved, averaging down below 1×10^{-14} even after several days of measurement time in a laboratory environment. With an engineered model, comparable performances can be obtained with a total volume of less than 20 liters and 40 W of power consumption. This makes the technology appealing in particular for space application, where nowadays similar performances are only provided by hydrogen masers, at the expense of larger size, weight and power consumption (SWAP).

This thesis aims at improving the POP clock characterization and to provide different implementation and design options. We present a systematic analysis of the noise sources which currently describes the short-term behavior of the standard. Regarding the clock implementation, we present locking techniques which extend the basic frequency loop. Moreover, we present a compact design suitable for the POP scheme, which can be of interest where SWAP is a concern.

Concerning the short-term investigation, we notice that the noise budget is not limited by quantum noise sources, such as photon or atomic shot noise. The major limitations come from laser frequency and amplitude noises, which are converted into the amplitude of the detected atomic signal. In particular, we investigate in detail the AM-AM conversion with a signal theory formalism. Understanding such conversion mechanisms can point to the right strategy to mitigate them and improve the short-term stability.

On the clock implementation side, we introduce advanced locking algorithms to actively stabilize some physical parameters of interest for the clock operation. Given the low sensitivity of the POP architecture to laser frequency and microwave

amplitude, these parameters need to be stabilized with a low locking bandwidth. We introduce two methods that allow a stabilization of the laser frequency directly on the clock signal, without recurring to external references. This is possible with an extended interrogation sequence and digital processing of the signals. The stabilization of the microwave amplitude can be achieved in a similar manner, by exploiting the Rabi resonances. This last technique, already presented in a previous paper, is recalled and put in relation to the laser locking techniques.

In parallel, a re-design of the core of the physics package, with the purpose of significantly reducing the dimensions and weight of the whole assembly, is presented. In particular, a loaded microwave cavity is introduced, leading to a reduction of volume by a factor 8. A proof-of-principle prototype has been developed, exhibiting short-term stability below $5 \times 10^{-13}\,\tau^{-1/2}$ by using a $1\,\mathrm{cm}^3$ spectroscopic cell. The same mechanical design is used to investigate an alternative buffer-gas mixture (krypton-nitrogen) that provides a much smaller density-shift on the clock transition, compared to the traditional argon-nitrogen mixture. With this configuration, the clock sensitivity to ambient pressure and other barometric effects is reduced by at least one order of magnitude.

All these contributions facilitate the design process in different ways: first of all, by defining in more detail the laser noise specifications needed to reach a certain stability target. Secondly, by enlarging the design options, both from the operational point of view, with the introduction of alternative locking techniques, and from the constructive point of view, with the availability of a compact physics package architecture. Finally, the preliminary investigation of the krypton mixture poses the basis for either relaxed physical requirements or better performances, especially for a possible on-ground application, where the clock is operated at atmospheric pressure.

Finally, the thesis reports on the first experimental tests performed on an engineered physics package suitable for the POP technique. The prototype, produced by Leonardo S.p.A., was built in cooperation with INRiM under the supervision of the European Space Agency. The prototype is tested with INRiM electronics and optics and exhibits state-of-the-art short-term performances.