Optical Reference Cavities for Frequency Stabilization of Lasers

E. Portuondo, G. Buchs, S. Kundermann, S. Lecomte

Optical Reference Cavities are highly stable optical resonators, which can be used as etalons to stabilize the frequency of a laser down to a 1-Hz precision. This approximately represents a fraction of 1/10^15 in terms of relative frequency stability. Such impressively stable optical sources find applications in domains where high-precision timing or distance measurements are required such as geo-positioning systems, RADARs, satellite formation flying, synchronization of large scientific facilities, as well as high-resolution optical spectroscopy. State of the art facilities for laser stabilization based on Optical Reference Cavities have been developed at CSEM in the last years and enable today further developments of high-precision instrumentation.

Optical Reference Cavities (ORC) constitute optical domain resonators of extreme frequency precision. As frequency references, ORCs outperform today all other types of resonators including mechanical, electro-mechanical (e.g. quartz), electronic and atomic in terms of relative frequency precision on a 1-second time scale.

An ORC is essentially constituted by a pair of highly-reflective mirrors fixed onto a spacer of high mechanical stability, facing each other in a Fabry-Perot interferometer configuration. Figure 1 presents a picture of such a cavity. The mirrors must be fabricated with the lowest possible losses (typically below 10 ppm), since this determines the width of the resonance line and hence the precision of the frequency reference. Also, the material (ultra-low expansion glass) and mechanical design of the spacer must be finely chosen to minimize the influence of external vibrations and temperature drifts of the cavity.

In order to obtain the ultimate laser stabilization performance, i.e., the highest frequency accuracy, it is necessary to operate the cavity in ultra-high vacuum (~10^{-8} mbar) and implement efficient sound, vibration and thermal insulation around it. In the end, it is the stability of the cavity length (distance between the mirrors) which determines the frequency stability of the resonator. When all the external perturbations are minimized, it is possible to reach a length stability level corresponding to the random thermal thickness fluctuations (thermal noise) of the mirror coatings. In this regime, the optical linewidth of a stabilized laser can reach the sub-Hz domain.

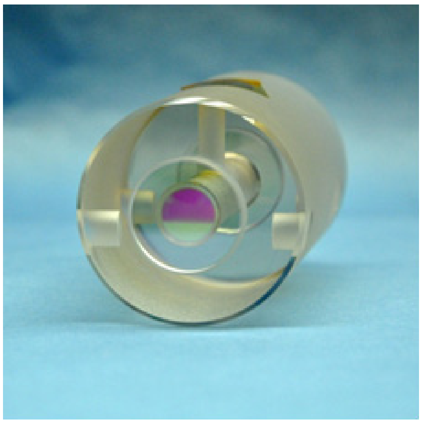

Figure 1: Optical reference cavity implemented at CSEM.

Two state of the art laser stabilization systems based on high-end Optical Reference Cavities were developed by CSEM during the last years in collaboration with several industrial partners. Today, these systems constitute an essential part of CSEM precision-laser laboratory infrastructure, providing two independent Hz-linewidth-level optical sources in the telecommunications wavelength range of 1.5 μm.

Highly precise optical frequency references can be directly applied to perform high resolution optical spectroscopy or as part of the local oscillator in optical atomic clocks. Also, the high precision of these optical oscillators can be transposed to the microwave domain thanks to the development of Optical Frequency Combs. By referencing a comb optical mode of a frequency comb to a cavity-stabilized reference laser, the pulse repetition rate of the frequency comb is stabilized with the same relative stability than the optical source. In this way, the optical frequency gets divided to the GHz-MHz range without loss of stability, enabling the generation of the purest microwave sources that can be obtained today [1]. This technology can serve numerous applications that depend on timing accuracy such as Geo-positioning systems, RADAR, satellite formation-flying, synchronization of large scientific facilities and research in fundamental physics (Figure 2).

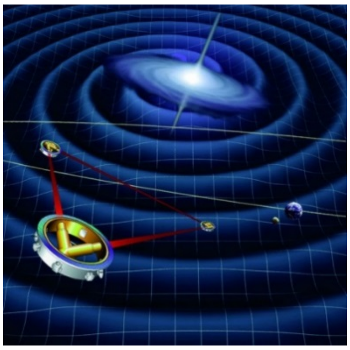

Figure 2: ESA mission candidate LISA will verify the existence of gravitational waves, relying on the accuracy of cavity stabilized laser sources. (Courtesy of ESA)

CSEM is today working in these fields as a research and development partner of several ESA and EU projects.

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[1] T. M. Fortier, M. S. Kirchner, F. Quinlan, J. Taylor, J. C. Bergquist, T. Rosenband, N. Lemke, A. Ludlow, Y. Jiang, C.W. Oates, S. A. Diddams, "Generation of ultrastable microwaves via optical frequency division", Nature Photonics Vol. 5, 425-429, (2011)