Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

A COMPACT, FREQUENCY STABILIZED LASER HEAD FOR OPTICAL PUMPING IN SPACE RB CLOCKS

C. Affolderbach, G. Mileti

Observatoire Cantonal de Neuchâtel, Rue de l'Observatoire 58, 2000 Neuchâtel, Switzerland

Abstract – **We present the realization of a compact and frequency stabilized laser head operating on the D_2 line of Rubidium. This laser head will be used for optical pumping in rubidium atomic frequency standards and has potential for space applications. The design is based on an external cavity diode laser stabilized to a saturated absorption spectroscopy reference line. The volume of the complete laser head physics package including the reference Rb vapor cell totals 200cm^3 only. First performance measurements of a rubidium atomic clock using the laser head are presented.**

***Keywords* - rubidium frequency standard, laser optical pumping, space instrumentation.**

I. Introduction

Optically pumped vapor-cell atomic frequency standards [1] combine the competitive stability of a secondary frequency standard with the advantages of compact size, small mass, low power consumption, and comparably low unit prices. Many of such “Rubidium clocks” have a volume below 1500cm^3, masses of 1.5kg or less, and dissipate less than 15W. They have therefore proven to be a good system of choice for a variety of applications ranging from industrial timekeeping over scientific frequency references to space clocks for satellite navigation.

The large majority of such vapor-cell clocks in use today relies on the well-established technique to use a Rb discharge lamp for the production of the pumping light and a Rb vapor cell as the atomic reference. However, it has been shown that the clock performance can be significantly improved when the discharge lamp is replaced by a laser source [2,3]. In this paper we describe the realization of a compact and frequency stabilized laser head prototype which has been developed for use in space Rb clocks. Such space clocks with increased stability are of great interest in view of the second generation of the GALILEO satellite navigation system, as well as for other space applications such as telecommunications and science missions.

II. Performance Requirements

The improved performance of laser-pumped vapor-cell atomic clocks is mainly due to an increased contrast of the double-resonance signal caused by the higher pumping efficiency of the narrow-band laser light: The laser acts selectively on one of the two ground-state hyperfine transitions only, while the pump light spectrum from a lamp contains residual components at the second hyperfine transition and thus degrades the pumping process. This advantage of the laser pumping technique, however, comes along with an increased susceptibility of the clock to laser frequency fluctuations and drift, which is transferred into instabilities of the clock output frequency by the light shift [4,5]. With the narrow-band pump laser tuned to the center of the atomic transition - where optical pumping is most efficient - this source of instability is most severely pronounced due to the steep linear slope of the first-order light shift at the resonance center. Thus the frequency of the laser used for the optical pumping has to be precisely controlled and has to be ensured over the timescales of interest for the clock performance.

For the specifications of the frequency stability required for GALILEO clocks ($\sigma_y \leq 10^{-12}\ \tau^{-1/2}$ for τ up to 10^4s, $\sigma_y \approx 10^{-14}$ at one day) and with the given light shift measured for our clock module one can deduce the necessary frequency stability of the pump laser to be about $4{\cdot}10^{-11}\ \tau^{-1/2}$ for τ up to 10^3s and $\sigma_y \approx 10^{-12}$ for $\tau > 10^3$s. Our studies show that these levels of laser stability can be reached at least for τ up to 2000s, while at longer timescales good temperature stability becomes crucial.

III. Device Realization

For the realization of the laser head a stand-alone approach was chosen rather than a direct integration of the laser source into the clock module. In this way, the design of the clock part stays independent of the pumping light source used, and the laser head constitutes an universal tool that can be easily adapted to serve other similar needs for stabilized laser sources.

The laser head design scheme is sketched in Fig. 1. The

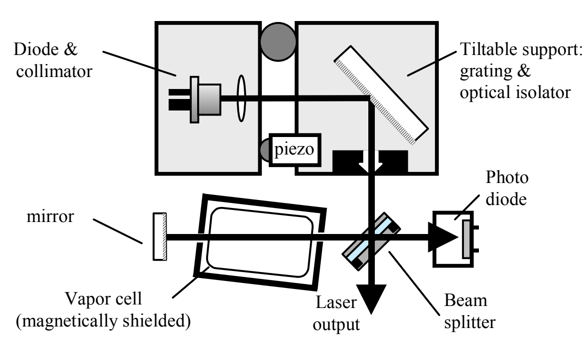

Fig. 1. Design sketch of the laser head

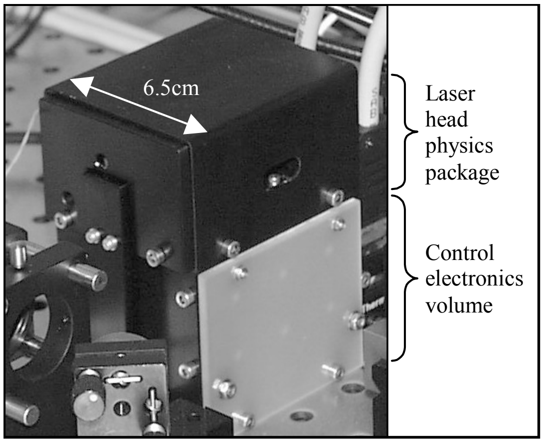

Fig. 2. Fully assembled stand-alone laser head in the test setup. The upper part (black cover) contains the physics package, the lower part (bright cover) accepts control electronics.

laser source is an external-cavity diode laser (ECDL) with mode selection by optical feedback from a diffraction grating in a standard Littrow configuration. The medium- and long-term stability of the laser frequency is ensured by locking to the saturated absorption signal from a Rb reference cell included in the laser head. Back-reflections of laser light from the locking cell or the clock itself to the laser chip are suppressed by a miniature optical isolator. The reference cell is protected against stray magnetic fields originating from the isolator by a 2-layer magnetic shield.

Figure 2 shows a photograph of the fully assembled laser head, where the upper part (black cover) contains the physics package and the lower, slightly larger part (bright cover) is designated to contain the miniaturized control electronics. In the ongoing development phase, however, laser head control is achieved by our standard laboratory laser electronics. Slow coarse tuning of the laser frequency is achieved by tilting the grating mount using a piezo-electric actuator and locking to the atomic reference lines is achieved by frequency modulation of the laser output via the injection current and subsequent lock-in detection. The entire laser head module including both the external cavity and the reference cell is temperature stabilized and an independent peltier element is used to control the temperature of the laser diode only.

The operating laser head delivers an optical output power of more than 3mW with a laser linewidth of less than 1.5MHz (measured with a Fabry-Perot cavity). At the required atomic resonance frequency the mode-hop free tuning range via the piezo voltage is more than 3GHz, and several adjacent modes offer laser operation at the pump frequency. Figure 3 shows an example of the saturated absorption signals from the laser head, as well as the error signal derived from the same signal via frequency modulation of the laser output. The width of the lines is around 10MHz (full width at half-maximum) and allows

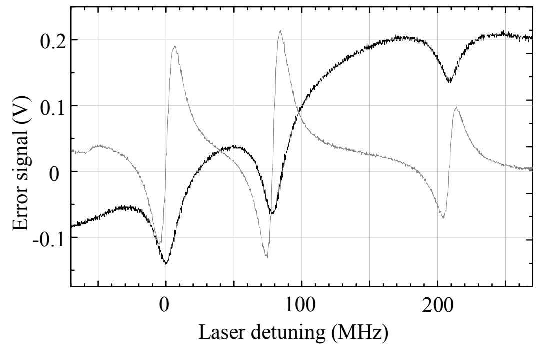

Fig. 3. Saturation spectrum obtained with the laser head on the ^{87}Rb, F=2 resonance (black curve) and corresponding error signal (gray curve) for laser stabilization.

precise stabilization of the laser frequency to the reference transitions.

Figure 4 gives typical noise levels measured on the photo diode in the modulation frequency ranges used for the microwave stabilization and the laser locking, respectively. From the noise level around 55kHz and the error signals of Fig. 3 the short-term frequency stability of the laser can be estimated to be $\sigma_y^{laser} \approx 2 \cdot 10^{-12}\ \tau^{-1/2}$, which is consistent with our previous laboratory measurements (see Fig. 5). Following the method described in [2] we can estimate from this a limit on the short-term stability of the clock to be $\sigma_y^{clock} \approx 8 \cdot 10^{-13}\ \tau^{-1/2}$ (here we assume an increase of the noise level due to FM to AM conversion by a factor of 5, in agreement with previous experiments [2]).

As a first evaluation we have used the laser head for optical pumping of a modified Rb clock module from which the discharge lamp has been removed (RAFS series, Temex Neuchâtel Time). The beam from the laser head was expanded with a telescope but otherwise directed directly to the clock module. The measured clock stability is shown in Fig. 6 in terms of the Allan deviation. While for short integration times the performance of the lamp-pumped clock unit is reproduced, the laser pumped stability at longer timescales still needs to be improved considerably. In these first results the comparably worse performance of the laser-pumped clock can be attributed to, e.g., air draught between

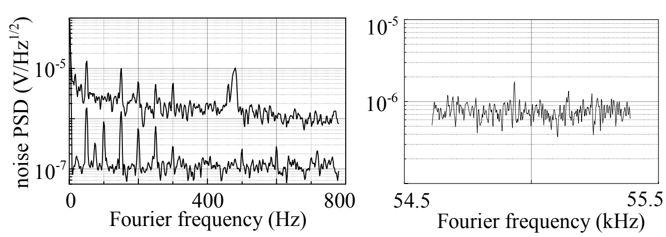

Fig. 4. Measured noise (power spectral density) on the photo detector in the two frequency ranges of interest for locking of the quartz local oscillator (a, upper curve: locked laser, lower curve: no laser) and the pump laser (b).

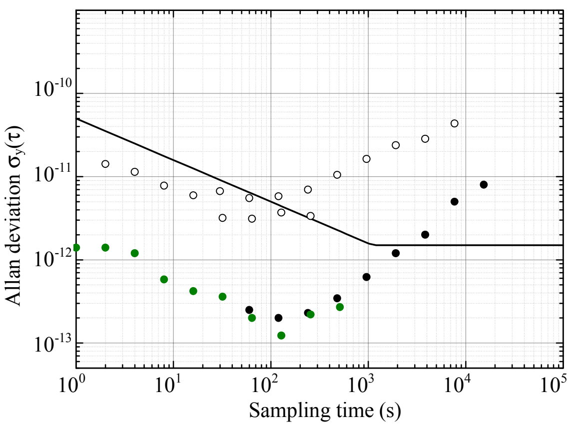

Fig. 5. Laboratory measurements on laser stability deduced from the beat-note signal of two independently stabilized lasers. Open circles: Doppler absorption, solid circles: sub-Doppler saturated absorption. The solid line gives the laser stability requirement for our clock module to meet the GALILEO specifications.

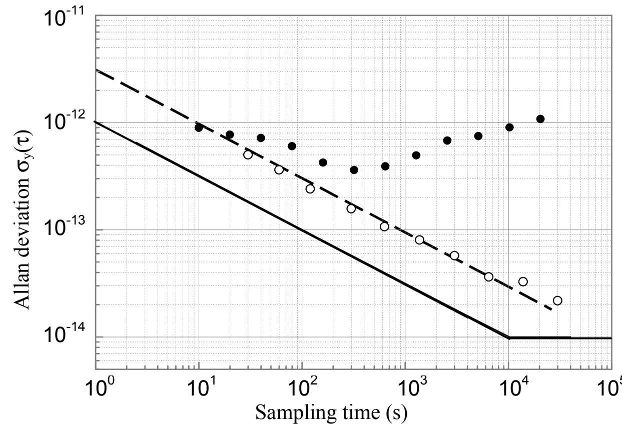

Fig. 6. First stability measurements of a Rb clock pumped with the realized laser head (dots). Open circles give the stability of the same clock with lamp pumping. The dashed line indicates $3 \cdot 10^{-12}\ \tau^{-1/2}$, the solid line gives the project goal.

the laser head and the clock module and residual temperature fluctuations of the laser head which are not yet perfectly controlled. As well, the operation parameters of the clock module were not yet optimized for laser pumping, thus giving rise to instabilities and drifts mediated by, for instance, the increased importance of the light shift. Now work is in progress for adjustment of all parameters to improve the clock stability towards and beyond the performance specifications of the envisioned laser-pumped Rb space clock.

IV. Conclusion

We have built and tested a compact, frequency stabilized laser head that will be used for optical pumping in vapor-cell rubidium clocks. The physics package occupies a volume of only 200 cm^3 and includes both the ECDL and the saturation spectroscopy cell for stabilization purposes. The laser head is self-contained in a modular design and can thus in principle be adapted easily for other space applications, as well.

Frequency stabilization was successfully achieved and first stability measurements of the laser-pumped clock could be performed. At short timescales the stability of the lamp-pumped clock is reproduced, while at longer integration times the clock performance is still degraded, because clock operation parameters are not yet fully adjusted to the new requirements with laser pumping.

Acknowledgment

This work was performed in collaboration with Temex Neuchâtel time, Switzerland, and financed by the European Space Agency (ESA), contract number 5280/01/NL/US. We thank E. Murphy (ESA /ESTEC) for his support.

References

[1] J. Vanier, C. Audoin, "The quantum physics of atomic frequency standards", Adam Hilger, Bristol and Philadelphia, 1988.

[2] G. Mileti, J. Deng, F. L. Walls, D. A. Jennings, R. E. Drullinger, "Laser-pumped rubidium frequency standards: New analysis and progress", *IEEE J. Quantum Electron.,* vol. 34, p. 233, 1998.

[3] Y. Ohuchi, H. Saga, M. Fujita, T. Suzuki, M. Uchino, K. Takahei, M. Tsuda, Y. Saburi, Y. Koga, K. Hagimoto, S. Ohshima, "A laser-pumped Cs gas-cell frequency standard with a high stability", Proc. ATF, 2000.

[4] J. P. Barrat, C. Cohen-Tannoudji, "Étude du pompage optique dans le formalisme de la matrice densité", *J. Phys. Radium*, vol. 22, pp. 329–336, 1961.

[5] J. Deng, "Light shift compensation in a Rb gas cell frequency standard with two-laser pumping", *IEEE Trans. UFFC*, vol. 48, pp. 1657–1661, 2001, and references therein.