DEVELOPMENT OF NEW RB CLOCKS IN OBSERVATOIRE DE NEUCHÂTEL

C. Affolderbach and G. Mileti
Observatoire Cantonal de Neuchâtel
Rue de l'Observatoire 58, 2000 Neuchâtel, Switzerland
Tel: ++41-32-8898822; Fax: +41-32-7220420
E-mail: *Gaetano.Mileti@ne.ch*

Abstract

We present our ongoing development of a compact (<1.5 liters) and high-performance (10^{-14} at 10^4 s) laser-pumped rubidium clock for space applications like, e.g., satellite navigation systems (GALILEO). A compact laser head was developed that includes frequency stabilization of the pump light to a reference cell. Recent clock stability results obtained with this laser head reach $2\cdot10^{-13}$ at 1000s, limited mainly by residual cell temperature coefficients and light shift effects. We discuss strategies to overcome these limitations and the relationship between the stabilities of the pump laser and the clock. Comparisons of the laser and clock frequency stabilities are presented for stabilization to both Doppler and sub-Doppler spectroscopy.

INTRODUCTION

Optically pumped vapor-cell atomic frequency standards, often referred to as rubidium clocks, combine the competitive frequency stabilities of a secondary frequency standard with the advantages of a compact size, low mass, low power consumption, and relatively low unit prices, making them interesting for a variety of scientific, commercial, and space-oriented applications. For example, lamp-pumped Rb clocks today also constitute one of the main foundations of the GPS satellite navigation system.

It has been demonstrated, that the short-term and – to some extent – long-term stability of Rb clocks can be significantly improved when the discharge lamp implemented for optical pumping is replaced by a narrow-band laser source **[1-3]**. In order to exploit this advantage, our ongoing activity aims to develop a compact and high-performace laser-pumped Rb clock for space applications, e.g., as a possible upgrade candidate for future generations of the GALILEO satellite navigation system. Our design goal is to demonstrate a compact clock unit (< 1.5 liters, < 1.5 kg) with an improved stability of 10^{-14} at 10^4 seconds.

LASER-PUMPED SPACE RB STANDARD

The implementation of laser pumping instead of the discharge lamps widely used in Rb clocks offers the possibility of improved control of the pump light spectrum, as well as reduced intrinsic linewidths (down to 500 Hz) and increased signal contrast (up to 25%) of the microwave resonance, leading to improved short-term stabilities of the clock **[1-3]**.

In the frame of an ARTES-5 project, supported by the European Space Agency and led by TEMEX Neuchâtel Time (TNT), we are evaluating this implementation of laser optical pumping to Rb atomic clocks. We are following a modular approach (cf. Figure 1): A lamp-removed, modified commercial rubidium clock **[4]** provides the physics package of the clock unit, and the pump light is provided by an independent laser-head module. This allows for easy modifications or even exchange of the pump light source, while maintaining full functionality of the clock unit. It is important to mention that before the lamp was removed, the TNT clock proved to have a frequency stability of $3\cdot10^{-12}$ at 1 second and below $5\cdot10^{-14}$ at 10,000 seconds. In this manner, we could directly benefit from all the already performed progress and focus directly on the laser-related issues. Even more important, we could be sure that any instability above these levels had to be connected with the laser and not from the rest of the frequency standard.

A COMPACT, FREQUENCY-STABILIZED LASER HEAD

We have developed a compact, frequency-stabilized laser head for optical pumping of the clock, that can also be utilized in stand-alone applications. The physics package of this laser head occupies a volume of only 200 cm^3 and is comprised of a Littrow-type external-cavity diode laser (ECDL) and a small Rb vapor cell used as atomic reference **[5]**. Frequency stabilization of the laser output is achieved by stabilization to sub-Doppler saturated absorption lines of the reference cell by using a FM modulation technique. The unit delivers an optical output power of more than 2 mW with a spectral linewidth below 1.5 MHz, quite sufficient for the operation of the Rb clock. To our knowledge, this constitutes the smallest frequency stabilized laser head of its type realized today. For further improvements and miniaturization, we envisage replacing the ECDL with more advanced diode lasers like, e.g., DBR or DFB lasers.

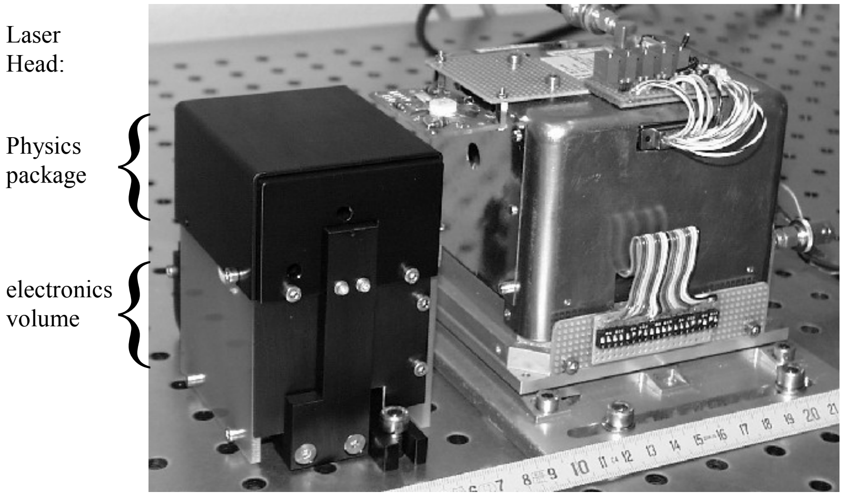

Figure 1. The modular laser-pumped Rb frequency standard. Left: Stabilized laser-head module, including the reference cell. Right: lamp-removed Rb clock unit.

CLOCK PERFORMANCE

Figure 2 shows the typical performance of our laser-pumped clock with the laser frequency stabilized to the cross-over CO 21-23 resonance in the laser reference cell (cf. Figure 5). The short-term performance up to about 1,000 seconds reproduces the stability of $3 \cdot 10^{-12}\ \tau^{-1/2}$ of the lamp-operated clock unit. We expect to improve this short-term stability by adapting the detection electronics to the strongly increased signal contrast of about 15% and by optimizing the quartz LO loop, which is currently degraded in order to allow a more flexible setup for experimental studies **[6]**. On the medium- and long-term timescales beyond 1,000 seconds, the frequency drifts are mainly caused by the temperature coefficient of the clock resonance cell and light shift effects due to laser intensity fluctuations (DC effect $\approx 10^{-9}$; see below for details). We are currently working on the reduction of these effects.

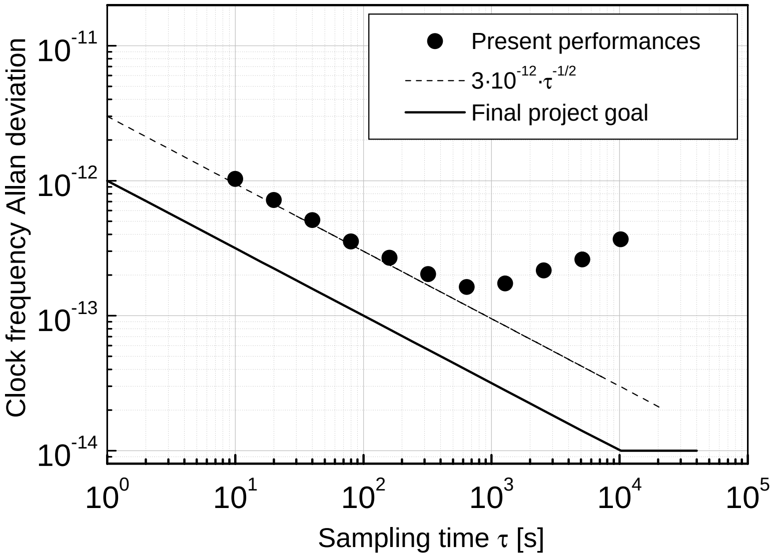

Figure 2. Typical stability performance of the modular Rb clock from Figure 1 in terms of the Allan standard deviation.

LASER FREQUENCY-STABILIZATION SCHEMES

While the sub-Doppler stabilization scheme implemented in the laser head gives satisfactory results, in a commercial product, a simpler and more robust scheme like, e.g., based on simple Doppler-broadened absorption spectroscopy, is desirable. This approach would result in only one (broader) reference line and, thus, avoid the need to distinguish between several closely spaced references lines to which the laser can be locked (cf. the three narrow lines in the bottom trace of Figure 5). We have therefore studied whether the laser frequency stability of the simpler Doppler scheme would still be sufficient for a successful operation of the envisaged high-performance Rb clock. The experimental results for the comparison of the laser frequency stability reached with the "Doppler" and "sub-Doppler" stabilization are shown in Figure 3 **[7]**. As can be seen, the "sub-Doppler" stabilization fulfills the laser frequency requirements imposed by the clock stability specifications on all timescales shown. In contrast, the

"Doppler" scheme shows drifts that are too large on timescales larger than 100 seconds, mainly due to temperature variations of the reference cell. However, this frequency stability might still be useful for a Rb clock with lower performance goals or other instruments involving a compact, stabilized laser source.

Figure 4 shows the results of clock stability measurements, where for comparison both the "Doppler" and "sub-Doppler" schemes were used. Obviously, the clock performance is degraded with the "Doppler" laser stabilization already at very short integration times, and remains essentially constant at a level around $3\cdot10^{-12}$, although the laser *frequency* stability from Figure 4 should be sufficient to meet the same clock performance as with the "sub-Doppler" stabilization for up to 100 seconds. We attribute the difference in clock stability mainly to the fact that with the "Doppler" scheme the laser is stabilized at a frequency detuning of about 250 MHz from the point of zero light shift, where light-shift effects due to laser *intensity* fluctuations are strongly increased compared to the much smaller detuning around 40 MHz for sub-Doppler stabilization to the cross-over CO 21-23 line. Furthermore, the "Doppler" stabilization scheme requires a much larger FM modulation amplitude on the laser, which can contribute to additional detection noise via conversion in the clock resonance cell.

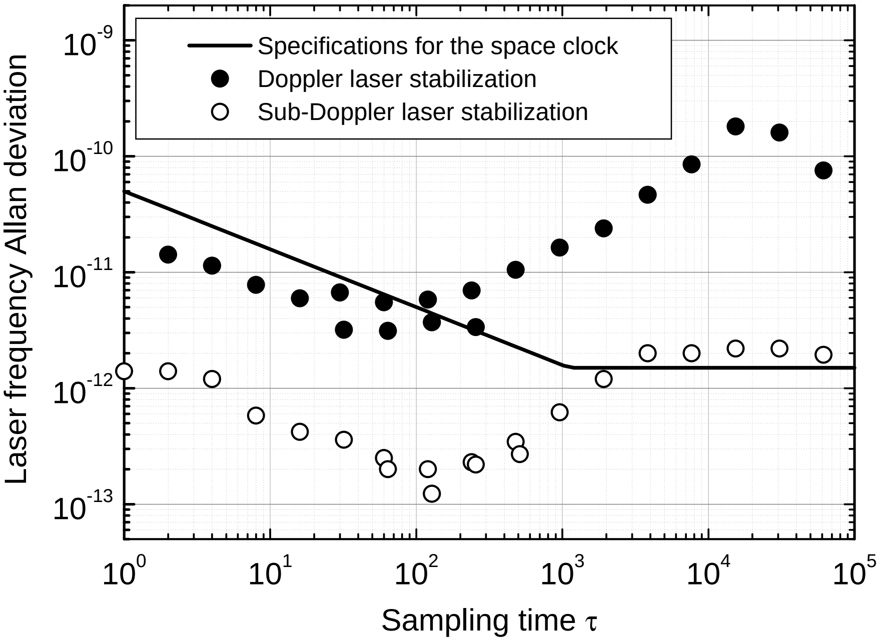

Figure 3. Laser frequency stability performance for stabilization to sub-Doppler saturated absorption or simple Doppler-broadened Rb vapor absorption lines. The stability specification is derived from the slope of the light-shift curves in Figure 5 for typical clock operation conditions.

LIGHT-SHIFT EFFECTS

One major limitation in laser-pumped Rb clocks arises from the light-shift effect, i.e. from the change of atomic level energies induced by the interacting pump light field. Figure 5 shows the resulting light shift of the clock frequency measured for our laser-pumped clock as a function of both the laser frequency and intensity, where the bottom trace also shows the absorption signal of the laser-head reference cell. As can be seen, the depicted situation does not allow one to stabilize the laser frequency exactly to the zero light-shift point, but even for stabilization to the closest reference line (CO 21-23), a detuning of about 40 MHz persists. Accordingly, in addition to the light shift related to frequency instabilities of the laser, light shifts mediated by pump light intensity fluctuations will also degrade the clock stability. In order to reduce these limitations, the laser detuning from the zero light-shift point and laser fluctuations have to be reduced, or the susceptibility of the clock to the light shift, i.e., the slopes and offsets of the curves in Figure 5, needs to be diminished, as described in the next paragraph.

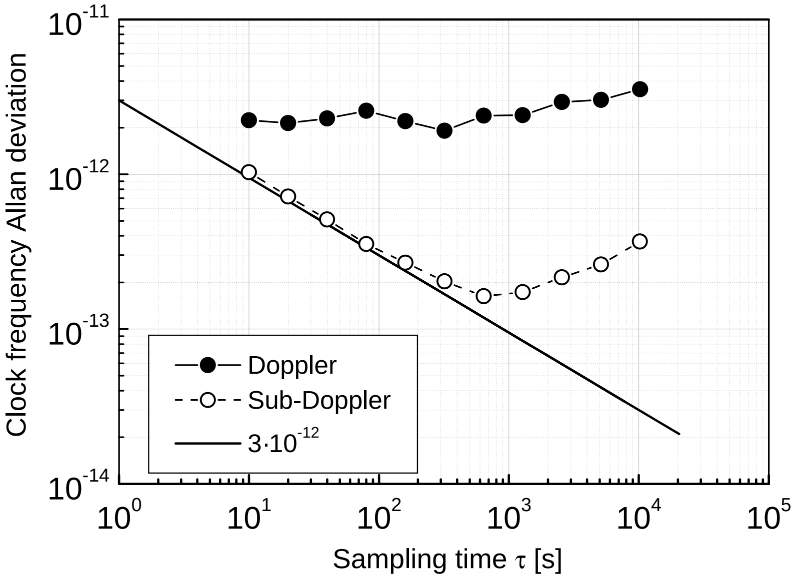

Figure 4. Laser frequency stability performance for stabilization to sub-Doppler saturated absorption or simple Doppler-broadened Rb vapor absorption lines.

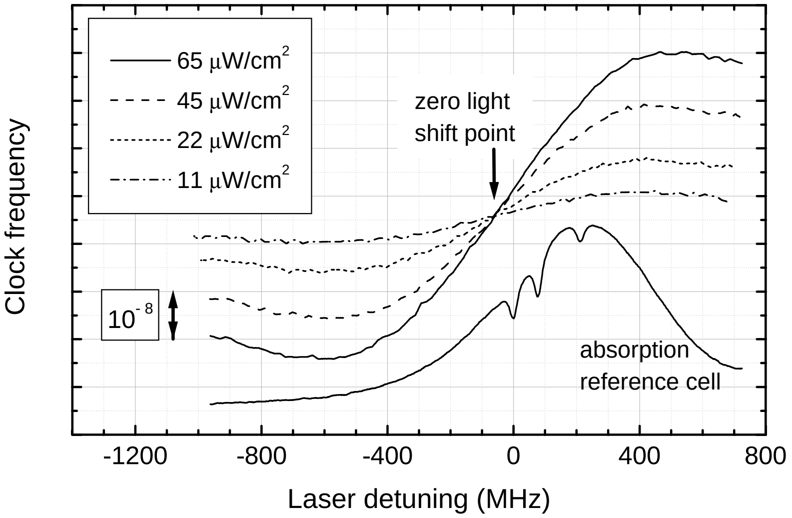

Figure 5. Light shift of the clock frequency as a function of pump light frequency and intensity. Frequency detuning is given relative to the cross-over resonance arising from the ^{87}Rb F=2→1 and F=2→3 transitions in the (laser) reference cell (denoted CO 21-23 in the

text).

NEW STRATEGIES FOR LIGHT-SHIFT REDUCTION

The reduction of light shift effects has been an active field of research in the past, and several approaches have been developed for atomic clocks based on optical pumping **[8]** and coherent population trapping **[9,10]**, which however often complicate the physical clock realization. We have recently developed a new and simple method to suppress the influence of the light shift on the clock transition, with respect to both frequency and intensity fluctuations **[11]**. This method relies on frequency modulation of the laser pump light at a frequency around 500-600 MHz, corresponding to the width of the light-shift curve of the clock transition. At suitably chosen modulation parameters, one can balance the light-shift contributions from the resulting sidebands in the laser spectrum in such a way that their respective positive and negative light- shift contributions cancel out. This results in a "self-correction plateau" of several hundreds of MHz width (region of the dashed ellipse in Figure 6), where the slope of the light shift curves and, thus, the susceptibility to laser frequency fluctuations are strongly suppressed. Furthermore, as shown in Figure 6, the offset of the self-correction plateau can be made to coincide with the level of zero light shift, thus resulting in a simultaneous suppression of the light shift due to intensity variations as well **[12]**. This technique provides an excellent possibility to relax the requirements on the frequency and intensity stability of the pump light source.

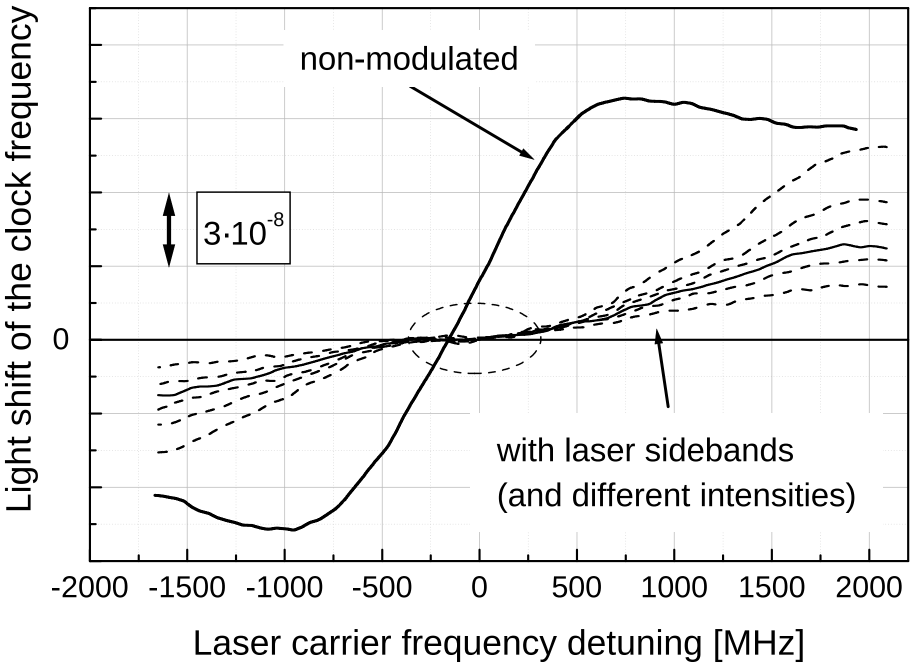

Figure 6. Light-shift reduction by multi-frequency optical pumping achieved by frequency modulation of the laser output. The dashed curves span incident pump light powers ranging from 36 to 105 µW. Both solid curves refer to the same incident power of 55 µW.

CONCLUSION

We have realized a compact, frequency-stabilized laser head and demonstrated its implementation in a laser-pumped Rb atomic clock. We have studied the influence of light-shift effects due to offsets and fluctuations of both frequency and intensity of the pump laser. These effects have different impact on the clock performance, depending which type of the laser-stabilization schemes studied (Doppler and sub-Doppler) was used in the clock. Limitations imposed by the reduced frequency stability of the Doppler scheme could be overcome by novel techniques for light-shift reduction based on multi-frequency optical pumping using FM modulation of the pump laser. The combination and optimization of these techniques should allow one to realize a compact high-performance Rb clock, reaching 10^{-14} at 10^{5} seconds, for space applications.

ACKNOWLEDGMENTS

This work was financially supported by the European Space Agency (ESA/ESTEC, contract 5280/01/NL/US), the Swiss National Science Foundation (contracts 2100-66821, R'Equip 2160-067498, SCOPES JRPBUPJ062412), Canton of Neuchâtel, and the Swiss Confederation (Art. 16). We thank Temex Neuchâtel Time – and in particular Fabien Droz and his team – for the fruitful collaboration and for providing the clock module and for its repeated modifications and improvements. We acknowledge collaborations with the Group of Prof. S. Cartaleva, Institute of Electronics, Bulgarian Academy of Sciences (Sofia, Bulgaria) and the Atomics Physics Group of Prof. Weis, University of Fribourg (Switzerland).

REFERENCES

[1] L. L. Lewis and M. Feldman, 1981, "*Optical pumping by lasers in atomic frequency standards*," in Proceedings of the 35th Annual Frequency Control Symposium, 27-29 May 1981, Philadelphia, Pennsylvania, USA (NTIS AD-A110870), pp. 612-624.

[2] G. Mileti, J. Deng, F. L. Walls, D. A. Jennings, and R. E. Drullinger, 1998, "*Laser-Pumped Rubidium Frequency Standards: New Analysis and Progress*," **IEEE Journal of Quantum Electronics, 34**, 233-237.

[3] Y. Ohuchi, H. Suga, M. Fujita, T. Suzuki, M. Uchino, K. Takahei, M. Tsuda, Y. Saburi, Y. Koga, K. Hagimoto, and S. Ohshima, 2000, *"A laser-pumped Cs gas-cell frequency standard with a high stability,"* in Proceedings of the Asia-Pacific Workshop on Time and Frequency (ATF2000), 31 October-2 November 2000, Tokyo, Japan, pp. 191-198.

[4] iSource+™ space qualified RAFS series, Temex Neuchâtel Time. See also: A. Jeanmaire, P. Rochat, and F. Emma, 2000, "*Rubidium Atomic Clock for Galileo*," in Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Dana Point, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 627-636.

[5] C. Affolderbach and G. Mileti, 2003, "*A compact, frequency stabilized laser head for optical pumping in space Rb clocks*," in Proceedings of the 2003 IEEE International Frequency Control Symposium & PDA Exhibition Jointly with the 17th European Frequency and Time Forum (EFTF), 5-8 May 2003, Tampa, Florida, USA (IEEE 03CH37409C), pp. 109-111.

[6] J. Q. Deng, G. Mileti, R. E. Drullinger, D. A. Jennings, and F. L. Walls, 1999, "*Noise considerations for locking to the center of a Lorentzian line*," **Physical Review A59**, 773-777.

[7] C. Affolderbach, G. Mileti, D. Slavov, C. Andreeva, and S. Cartaleva, "*Frequency stability comparison of diode lasers locked to Doppler and sub-Doppler resonances*," in Proceedings of the 35th Conference of the European Group for Atomic Spectroscopy (EGAS 2003), 15-18 July 2003, Brussels, Belgium, and Proceedings of the VIIIth International Conference on Laser and Laser Information Technologies (ILLA 2003) Jointly with the IIIth International Symposium on Laser Technologies and Lasers (LTL Plotdiv 2003), 27 September-1 October 2003, Plotdiv, Bulgaria; submitted for publication by SPIE.

[8] J. Deng, 2001, "*Light shift compensation in a Rb gas cell frequency standard with two-laser pumping*," **IEEE Transactions on Ultrasonics, Ferroelctrics, and Frequency Control, UFFC-48**, 1657-1661, and references therein.

[9] J. Vanier, A. Godone, and F. Levi, "*Coherent microwave emission in coherent population trapping: origin of the energy and of the quadratic light shift*," in Proceedings of the 1999 Joint Meeting of the European Frequency and Time Forum (EFTF) and the IEEE International Frequency Control Symposium, 13-16 April 1999, Besançon, France (IEEE 99CH36313), pp. 96-99. F. Levi, A. Godone, and J. Vanier, 2000, "*The Light Shift Effect in the Coherent Population Trapping Cesium Maser*," **IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, UFFC-47**, 466-470.

[10] M. Zhu and L. S. Cutler, 2001, "*Theoretical and experimental study of the light shift effect in CPT-based Rb vapor cell frequency standards*," in Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 28-30 November 2000, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 311-323.

[11] C. Affolderbach, G. Mileti, C. Andreeva, T. Karaulanov, and S. Cartaleva, 2003, "*Reducing light-shift effects in optically-pumped gas-cell atomic frequency standards*," in Proceedings of the 2003 IEEE International Frequency Control Symposium & PDA Exhibition Jointly with the 17th European Frequency and Time Forum (EFTF), 5-8 May 2003, Tampa, Florida, USA (IEEE 03CH37409C), pp. 27-30.

[12] C. Affolderbach, C. Andreeva, S. Cartaleva, T. Karaulanov, G. Mileti, and D. Slavov, "*Light-shift suppression in high-resolution optical pumping experiments*," submitted for publication.