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Influence of Laser Sources with Different Spectral Properties on the Performance of Vapor Cell Atomic Clocks Based on lin||lin CPT

Evelina Breschi, George Kazakov, Roland Lammegger, Boris Matisov, Laurentius Windholz,
and Gaetano Mileti

***Abstract*—We evaluate the influence of 2 types of laser sources with different spectral profiles on the performance of vapor cell atomic clocks based on lin||lin coherent population trapping (CPT) resonances. We show that a short-term stability of 1 – 2 · $10^{-11}\tau^{-1/2}$ may be reached in a compact system using a modulated vertical cavity surface-emitting laser. Here the stability is limited by the detection noise level and can be improved up to a factor of 4 by increasing the lock-in detection frequency to several tens of kilohertz, which is not possible in standard double resonance atomic clocks. We compare these results with CPT prepared under the same experimental conditions, using 2 phase-locked extended cavity diode lasers, with which we predict a challenging short-term stability of 1 – 3 · $10^{-13}\tau^{-1/2}$, comparable to the state-of-the-art laser-pumped Rb-clocks.**

COHERENT POPULATION TRAPPING, VAPOR CELL FREQUENCY STANDARD

CONTRARY to the microwave-optical double resonance scheme, coherent population trapping (CPT) does not require a microwave cavity, which may be an advantage in compact or miniature atomic clocks [1], [2]. CPT usually suffers from smaller signal contrast, because of the losses induced by the presence of trapping states not contributing to the clock signal.

The short-term stability of an atomic clock can be evaluated by the Allan deviation [3]:

$$\sigma_y = \frac{k}{Q \cdot S/N} \cdot \tau^{-1/2}, \tag{1}$$

where S is the signal (here the CPT resonance) amplitude measured in microamperes; N is the detection noise expressed in terms of noise density (μA $\text{Hz}^{-1/2}$); k is a constant that depends on the type of modulation used and is of the order of 0.2; and Q is the resonance quality factor, i.e., the ratio between the resonance frequency (v) and the signal (here CPT resonance) line width (Γ).

We have investigated the case of ^{87}Rb D_1 when a longitudinal magnetic field is applied and CPT resonances are excited by a linearly polarized, unidirectional, and multifrequency light field (the so-called lin||lin CPT) [4]–[6], [8]. The main advantage of this interaction scheme with respect to the CPT state prepared with circularly polarized light field is that there is no trapped state in which the atomic population can be accumulated through the optical pumping. The CPT resonances were prepared by using either a modulated vertical cavity surface-emitting laser (VCSEL) or 2 phase-locked (PL) extended cavity diode lasers (ECDL). We predict the achievable clock frequency stability, basing our considerations on measurements of the signal-to-noise ratio in our setup. The current-modulated VCSEL has a multifrequency spectrum with broad line width (in our case, 100 MHz, measured by a heterodyne beat-note), but it is very compact, robust, and has low power consumption. Therefore, VCSELs are suitable for applications in commercial devices. The VCSEL was modulated with the frequency $v \approx 3.4$ GHz (i.e., half of ground state hyperfine separation in ^{87}Rb). The phase-modulation index was estimated to be about 1.8, corresponding to the maximum power in the 1st-order side-bands[1] which are used for CPT preparation. On the other hand, the PL ECDL have, in good approximation, a pure bichromatic light field. The frequency difference between the 2 spectral components (containing 99.5% of the laser power) is $\Delta v \approx 6.8$ GHz. The laser line width of each spectral component is about 40 kHz reached by a fast stabilization servo loop. The root mean square phase noise level of the PL ECDL system is $\phi_{\text{rms}} \leq 50$ mrad (measured in the band of 1 Hz to 1 MHz) [9]. However, the PL ECDL system is bulkier than a modulated VCSEL and has been used only in the laboratory so far. During the experiments, we ensured that we had almost the same resonant power of 50 μW in those frequency components used for CPT resonance excitation. As in the best case, a fraction of 68% of the spectral VCSEL power is contained in both 1st-order sidebands used for CPT resonance exci-

E. Breschi and G. Mileti are with the Laboratoire Temps-Fréquence, University of Neuchâtel, Neuchâtel, Switzerland.

G. Kazakov and B. Matisov are with the St. Petersburg State Polytechnic University, St. Petersburg, Russia.

R. Lammegger and L. Windholz are with the Institute of Experimental Physics, Graz, Austria.

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[1] The maximum power that can be stored up in the 1st-order sidebands is the 68% of the total laser power.

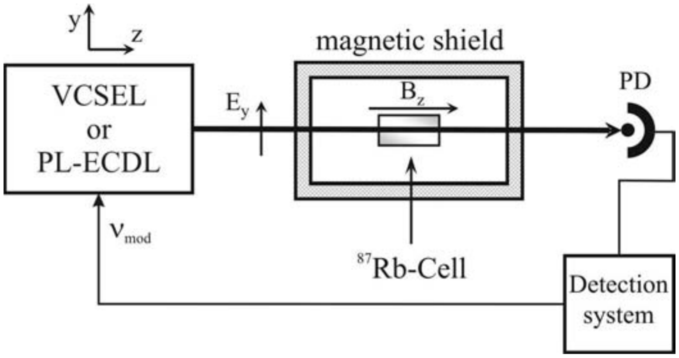

Fig. 1. Block diagram of the experimental setup. In case of short-term stability measurements, a lock-in amplifier can be used as a detection system. In case of CPT-resonance contrast determination, only a current amplifier (no modulation of the laser source) directly connected with the photodiode PD was used.

tation, and the total VCSEL power is chosen to be about 80 µW in comparison to 50 µW total power of the bichromatic light field in case of the PL ECDL setup. In addition, we verified that, for typical values of modulation frequencies used in the experiments, the contribution of amplitude modulation to the current-modulated VCSEL spectrum can be ignored, and the ratio between the two 1st-order sidebands is in good approximation equal to 1. The beam diameter in both cases was 0.8 cm, to obtain the maximum amplitude and the minimum line-width of the signal.

Fig. 1 shows the simplified block diagram of our setup. The Rb atoms are confined in a cylindrical glass cell (diameter and length of 1 cm) placed in a cylindrical magnetic shield (volume 40 cm^3). The cell temperature is stabilized at the optimal temperature of 50°C; the absorbance of the cell at this temperature is about 0.6. A longitudinal magnetic field ($B \approx 3$ µT) is provided by a solenoid placed inside the magnetic shield, and B_z is parallel to the laser beam propagation vector. The experiments were performed by using a cell containing 1.5 kPa of N_2 as buffer gas. The choice of the buffer gas pressure can be favorably understood in terms of a stimulated 2-photon excitation process coupling an initial and a final state (via an intermediate), forming a so called Λ system. For buffer gas pressures bigger than approximately 2 kPa, the homogenous line-width[2] exceeds the Doppler width of the optical transitions (approximately 470 MHz for ^{87}Rb at room temperature) both upper states start to be mixed coherently. As a result, a gradual cancellation of both CPT dark states—originating from Λ systems with intermediate states $|F_e = 1\rangle$ and $|F_e = 2\rangle$—takes place with increasing buffer gas pressure [10]. According to (1), the Allan deviation σ_y is being increased for such high buffer pressures as a consequence of a reduced signal to noise (S/N) ratio. Note that this intrinsic characteristic prohibits the application of the lin||lin CPT in miniature clocks unless wall coating is used, because in the mini-cells (volume < 1 mm^3), a buffer gas pressure of several tens of kilopascals is necessary to reduce the influence of collisions of Rb atoms and cell walls. These collisions destroy the atomic coherence, causing the broadening of the CPT resonance.

Fig. 2 shows the relevant atomic levels and possible transitions for the ^{87}Rb D_1 line induced by the σ^+ and σ^- components of the linearly polarized light fields. We focus our attention on the group of transitions from the ground state $F_g = 1,2$ toward the excited state $F_e = 1$ because the maximum contrast is expected in this configuration [5]. For the application in frequency standards, we consider the resonance with lowest sensitivity to the magnetic field. With a lin||lin interaction scheme, it is the CPT signal occurring between ground state Zeeman sublevels with $m_e = 0$ and $m_g = \pm 1$. Note that, in the case of linear polarization, the $\sigma^+ - \sigma^+$ and $\sigma^- - \sigma^-$ groups of transitions starting from the ground state Zeeman sublevels with $m_g = 0$, give rise to 2 orthogonal CPT states that interfere destructively and do not contribute to the CPT signal [6]. As a consequence, we have to consider only the 2 CPT states created by the coherent superposition of $|F_g = 1, m_F = \pm 1\rangle$, and $|F_g = 2, m_F = \pm 1\rangle$, represented by the dashed and solid line in Fig. 2(b), respectively. These 2 CPT resonances are symmetrically split by the magnetic field, each with a factor of ±14 Hz µT^{-1} determined by the nuclear g-factor, and they are both additionally shifted with a rate of +0.0575 Hz µT^{-2} [7]. In principle, the sensitivity to the magnetic field makes these CPT states unsuitable for atomic clocks. However, their supposed high contrast induced several studies of their metrological properties [5], [6], [8]. In particular in [6], a theoretical analysis of the lin||lin CPT line shape is presented, and it was proposed that the maximum of absorption between the 2 CPT peaks when degeneracy is removed (so-called pseudo-resonance) be used as frequency discriminator; in fact, the pseudo-resonance does not experience a first-order magnetic shift. Zibrov *et al.* [8] accounted for measuring the main metrological characteristic of the lin||lin CPT and pseudo-resonance, concluding that the CPT is the best solution for application in atomic clocks. However, their experimental setups were not optimized for reaching the challenging short-term stability theoretically expected with this interaction scheme; the pseudo-resonance-based prediction in [6] showed a σ_y below $1 \cdot 10^{-13} \cdot \tau^{-1/2}$. Taking into account the results obtained in [8], we based our study on the degenerate lin||lin CPT signal, and we optimize the experimental parameters with the support of the model developed in [6].

Figs. 3(a) and (b) show the CPT signal obtained by using the modulated VCSEL and the PL ECDL, respectively. The asymmetry of the signal is still under study. By comparing the 2 CPT signals in (a) and (b), it can be seen that the amplitude and the line width of both signals are equal in good approximation. However, the main differences in both plots are the photo-detector background levels mainly caused by different spectral properties of the modulated VCSEL and the PL ECDL. In contrast to the

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[2] We assume a collision-broadening factor of about 260 MHz/kPa [11].

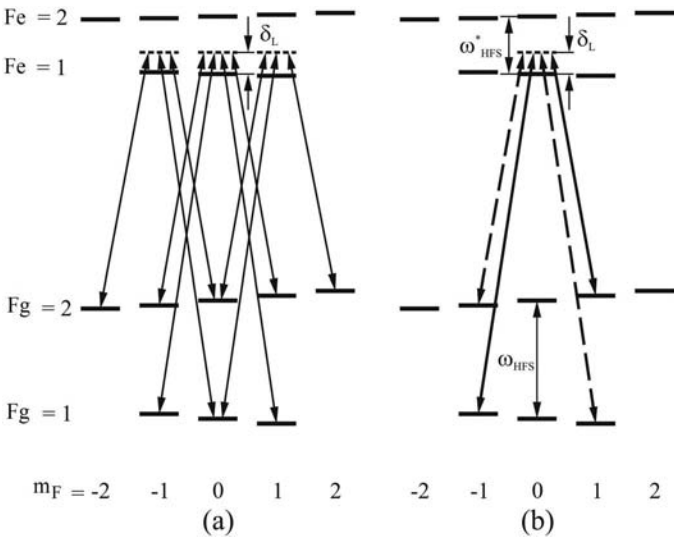

Fig. 2. Interaction scheme for lin||lin hyperfine CPT; (a) represents all $\sigma^{+}(\Delta m_F = +1)$ and $\sigma^{-}(\Delta m_F = -1)$ allowed transitions; while (b) represents the transitions contributing to the resonance approaching the unperturbed resonance frequency.

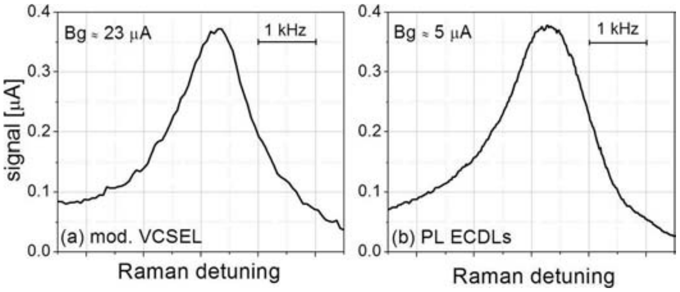

Fig. 3. The degenerate lin||lin CPT signal prepared with (a) VCSEL and (b) PL ECDL in the same experimental condition optimized for clock application. The Raman detuning is the difference between the frequency distance of the 2 resonant frequencies in the light beam and the microwave hyperfine transition. The CPT line-width and amplitude are approximately the same in both cases, $\Gamma \approx 900$ Hz and $S \approx 0.3$ μA, respectively. The main difference in the 2 cases relies to the background signal (Bg) in the photo-detector that determines the signal contrast. The contrast reaches 7% in experiments performed with PL ECDL while is only 1.4% in the experiments performed with modulated VCSEL because of the off-resonance frequency components.

PL ECDL setup where 99.5% of the laser power is contained within the frequency components responsible for the CPT resonance excitation, a fraction of about 68% of the VCSEL power is covered in both 1st-order sidebands used for CPT resonance preparation. The residual 32% of the spectral power is distributed among the carrier and higher order sidebands being off resonant with respect to any atomic transition. As a result, these off-resonant spectral components are not absorbed by the ^{87}Rb vapor, and they increase the background light (and an additional shot noise level) on the photo-detector. The difference in the contrast—C ≈ 1.4% in (a) and 7% in (b)—is thus directly caused by the off-resonant background of the VCSEL source. These off-resonance frequency components of the modulated VCSEL contribute also to the AC stark shift of the CPT signal, which is not studied here.

In Fig. 4, the detection noise measured with either modulated VCSEL or PL ECDL is compared with the shot-noise limit. The solid line represents the shot-noise, depending on the laser power measured after the cell in front of the photo-detector; while the points are the results of a noise measurement at a Fourier frequency of 1.5 kHz. Note that the detection noise of PL ECDL is only 30% worse than the shot-noise limit, while it is noticeably worse for modulated VCSEL. We verified that the pure AM noise of the current-modulated VCSEL is about 4 times the shot-noise limit; the detection noise increases when the modulated laser pass through the absorption cell. We measure the detection noise by varying the laser detuning such as the first order side-bands are spanned through the transitions $F_g = 1 -> F_e =$ 1,2, , respectively. In Fig. 4, points (1), (2), and (3) refer to the sidebands tuned out, to the maximum, and at the edge of the Rb absorption, respectively. These results show that the FM-to-AM conversion [12] due to VCSEL line-width and to the multifrequency spectrum, gives the largest contribution to the detection noise. Further analysis is necessary, however, to quantify each noise source precisely.

By using phase-sensitive detection techniques with modulation frequencies (v_{mod}) up to several tens of kilohertz, the $1/f$ noise contributions of the photo-detector and amplifier as well as power line interferences can be suppressed to a large extent. Thus, for CPT-based atomic clocks, the detection noise can be noticeably reduced. In such a case, v_{mod} is larger than the line width Γ of the monitored signal[3] [13], [14], which cannot be implemented in the microwave optical double resonance (DR) clock scheme as presently used. On the contrary, in reference [13], the authors showed that it is possible to realize a CPT clock using $v_{\mathrm{mod}} \approx 10 \cdot \Gamma$. In our experiments with modulated VCSEL, we verified that a modulation frequency v_{mod} up to 40 kHz (mostly limited by the speed of the photo-detector) could be used for phase-sensitive detection. As in our experiments, the CPT signal's linewidth of about 1 kHz $v_{\mathrm{mod}} = 40 \cdot \Gamma$ can be reached. Under such conditions, a reduction of the discriminator signal amplitude by a factor 5 and of the detection noise density by a factor 20 was observed, when v_{mod} was changed from 0.4 to 40 kHz, resulting in an improvement by a factor 4 in the signal-to-noise ratio. The possibility of using the v_{mod} $> \Gamma$ is connected to the optical detection in CPT experiments (because the microwave field is applied to the laser and not directly to the atoms); thus, it is independent of the light polarization.

By applying (1) to the set of data previously discussed, the short-term stability of lin||lin CPT-based atomic clocks can be estimated. The results are summarized in Fig. 5 and compared with the relevant published results for commercial and high-performance vapor cell atomic clocks. We predict a short-term stability of $1 - 2{\cdot}10^{-11} \cdot \tau^{-1/2}$ for lin||lin CPT prepared by using a modulated VC-

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[3] For simplicity, we call the regime $v_{\mathrm{mod}} > \Gamma$ the *high-frequency FM.*

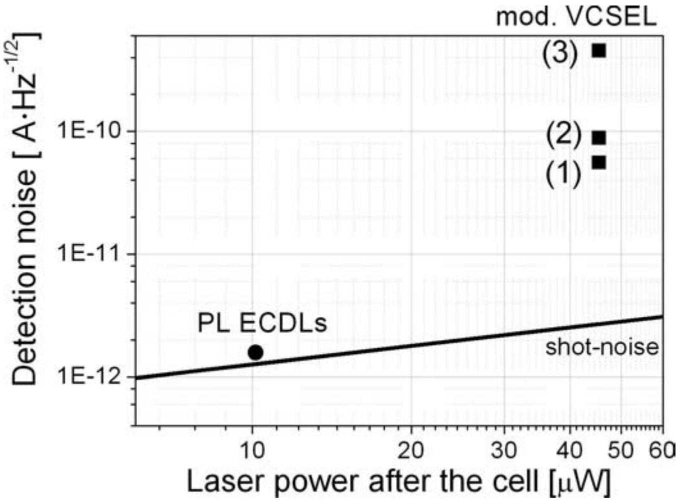

Fig. 4. Detection noise depending on the laser power measured after the cell in front of the photo-detector. The solid line represents the shot-noise limit while the points are the detection noise. The detection noise of PL ECDL is only about the 30% worse than the shot-noise limit. The detection noise is less favorable for the modulated VCSEL. We measure the detection noise by varying the laser detuning such that the first-order side-bands are spanned through the transitions $F_g = 1 \; -> \; F_e = 1,2$, respectively. In Fig. 4, points (1), (2), and (3) refer to the side-bands tuned out, to the maximum, and on the edge of the Rb absorption, respectively.

SEL, which is approaching the commercial clock based on σ-σ CPT resonance excited with modulated VCSEL [15], [16]. On the other hand, the performance of a CPT-based atomic clock can be improved by a factor of 4 (down to $5 - 6 \cdot 10^{-12} \cdot \tau^{-1/2}$ in our case) by using high-frequency FM-spectroscopy. This result is valid for each continuous CPT resonance preparation. Thus, using modulated VCSEL and implementing high-frequency FM, we can obtain a short-term stability comparable to either of the following:

- The value of state-of-the-art for continuous CPT resonance excitation, $\sigma_y = 1.3 \cdot 10^{-12} \cdot \tau^{-1/2}$ [17] observed with $\sigma - \sigma$ CPT resonance prepared with PL lasers.
- The short-term stability of commercial compact atomic clocks based on optical-microwave double resonance (DR), $\sigma_y \approx 1 - 5 \cdot 10^{-12} \cdot \tau^{-1/2}$ [18].

However, we conclude that the low spectral quality of the current-modulated VCSEL limits the attainable short-term stability, and one can attain the same performance using circular or linear laser polarization. On the contrary, we show that, by using a laser source with higher spectral quality, as the 2 PL-ECDL, with continuous lin$\|$lin CPT resonance excitation a short-term stability of $\sigma_y \approx 3 - 4 \cdot 10^{-13} \cdot \tau^{-1/2}$ can be reached, i.e., about 4 times better than the short-term stability expected with $\sigma - \sigma$ CPT. This final result is in very good agreement with the theoretical prediction for our experiment based on the model presented in [6], confirms our preliminary analysis [19], and introduces continuous lin$\|$lin CPT as a candidate for a high-performance vapor cell atomic clock. Comparable performances have been demonstrated in clocks based on continuous laser-pumped optical pumping [20]–[21], pulsed optical pumping [22], and pulsed CPT [23].

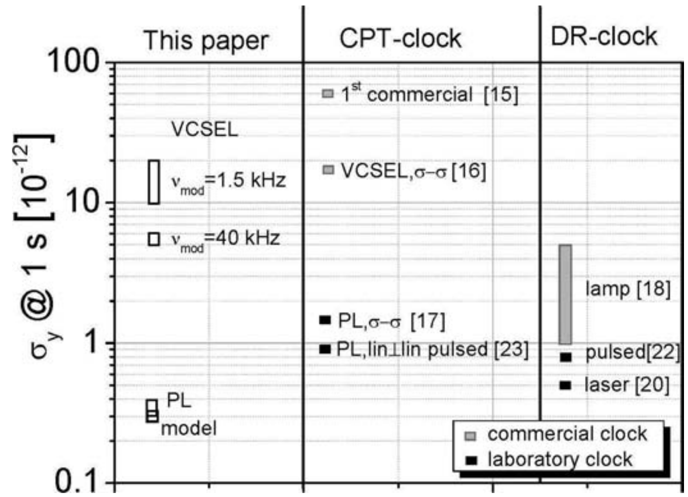

Fig. 5. Predicted short-term stability from our signal-to-noise measurements. The values discussed in this publication are compared with the published results for commercial and laboratory vapor-cell atomic clocks; v_{mod} is the lock-in modulation frequency.

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Evelina Breschi was born in Carrara, Italy, in 1977. She received the B.S. degree in physics from the University of Pisa, Italy, in 2002. In 2005, she received the Ph. D. degree in atomic physics from the University of Siena, Italy. The research activity was devoted to the development of a magnetometer based on the coherent population trapping (CPT) effect. She is now scientific collaborator with the Time and Frequency Laboratory at the University of Neuchâtel, Switzerland. Her research activity concerns the development of compact frequency standards based on CPT effect.

George A. Kazakov was born in Leningrad, USSR, in 1979. He received the M.S. degree in physics from the St. Petersburg State Polytechnic University, Russia, in 2002, and the Ph.D. degree in physics from the same university in 2007. He has collaborated with the Theoretical Physics Department since 1999, first conducting research on high-energy physics in the field of atomic physics. Since 2007, he has been engaged at the Theoretical Physics Department of St. Petersburg State Polytechnic University as docent. He investigates the coherent effects in quantum systems for atomic clock applications.

Roland Lammegger was born in Altenmarkt, Austria, in 1971. In 2001, he received the B.S. degree in physics and in 2006 the Ph.D. degree in experimental physics from the Graz University of Technology, Graz, Austria. His research activities are devoted to the development of compact CPT magnetometers and atomic clocks in earthbound and satellite applications. He is now with the Institute of Experimental Physics at Graz University of Technology.

Boris Matisov was born in Leningrad, USSR, in 1946. He received the B.S. degree in physics from the Leningrad Polytechnic Institute, USSR, in 1973. In 1979, he received the Ph.D. in quantum electronics from the Leningrad Polytechnic Institute. From 1979 to 1997, he was a lecturer (assistant, assistant professor, professor) in the Department of Theoretical Physics at St. Petersburg State Polytechnic University, Russia. Since 1998, he has been the head of the Theoretical Physics Department. His research activity is concerned with the theoretical studies of quantum frequency standards and related problems, such as coherent population trapping, electromagnetically induced transparency, laser cooling of atoms, and Bose-condensate.

Laurentius Windholz was born in 1949 and received the diploma and Ph.D. degrees from the Technical University of Graz in 1974 and 1979, respectively. In 1985, he became professor of experimental physics at Graz and is still working at the Institute of Experimental Physics, Technical University of Graz. His main research fields are laser spectroscopy of free atoms and quantum optics (coherent processes in multi-level systems).

Gaetano Mileti received an engineering degree in physics from the Ecole Polytechnique Fédérale de Lausanne, Switzerland, in 1990 and a Ph.D. degree in physics in 1995 from the University of Neuchâtel, Switzerland. From 1995 to 1997, he was guest scientist in the Time and Frequency Division at the National Institute of Standards and Technology, Boulder, CO. At the Observatory of Neuchâtel (ON) until 2007 (group leader since 2001), he has been involved in projects related to Rb clocks, laser spectroscopy, narrow-band transmitters and receivers for Lidar systems, laser cooling, and primary Cs frequency standards. Since 2007, he has been the deputy director of the Laboratoire Temps-Fréquence (LTF) at the University of Neuchâtel. His current research concerns the development of novel vapor-cell atomic clocks and the study of resonant laser-atom and microwave-atom interactions.