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PM/AM Conversion Measurement for Narrow-Linewidth Lasers with RIN and Shot-noise Reduction

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***Abstract*—Compact vapor-cell clocks are becoming a mature technology but there is still room for improvement to push their performance to their intrinsic limit. To this aim, we need to understand and characterize all the underlying noise processes. In this work, we present a setup to measure the PM-to-AM conversion in thick alkali vapors rejecting all other noise sources (AM, shot, electronics) by means of multichannel acquisition and cross-correlation.**

***Keywords*—laser; phase noise; alkali; atomic clocks.**

I. INTRODUCTION

The need for portable and high-performing atomic clocks is pushing the research towards innovative solutions and optimization of the existing technologies. The recent availability of compact frequency combs for frequency down-conversion is enabling the development of compact clocks based on optical transitions, delivering short-term stability in the 10^{-14} range and even below [1]–[3]. Microwave atomic clocks, on the other hand, still show room for improvement in the short-term stability, ensuring a higher degree of robustness and lower complexity [4]–[6]. In order to optimize these standards to their best performances, a complete understanding of all the noise sources is needed. Together with the laser AM noise (RIN) [7], the PM-to-AM conversion is recognized as the other main noise source currently limiting the short-term stability of compact vapor-cell clocks based on laser pumping and detection [8]. However, for narrow-linewidth lasers, it is often hard to isolate the latter contribution [9]. To this end, we developed a test setup to quantify the role of the laser phase noise, by rejecting the intensity noise and other noise sources. Specifically, the setup measures the intensity noise power spectral density at the output of a vapor cell containing Rb and buffer gas, subtracting the RIN and averaging down the contributions of electronic noise and laser shot noise thanks to the use of two identical channels and cross-correlation.

II. MEASUREMENT SETUP

The proposed setup, conceptually described in Fig. 1, treats the laser RIN as common mode noise. Differential photodiodes with high common mode rejection ratio performs laser AM-noise cancellation. The remaining noise contributions (electronics and laser shot noise) are instead averaged out by doubling the measurement system and performing cross-correlation [10], [11]. The spectra at the output of the two balanced detectors (S$_x$ and S$_y$) have the form:

$$S_x = S_{\text{PM/AM}} + S_{\text{shot1}} + S_{\text{shot2}} + S_{\text{ELNx}}$$
$$S_y = S_{\text{PM/AM}} + S_{\text{shot3}} + S_{\text{shot4}} + S_{\text{ELNy}}$$

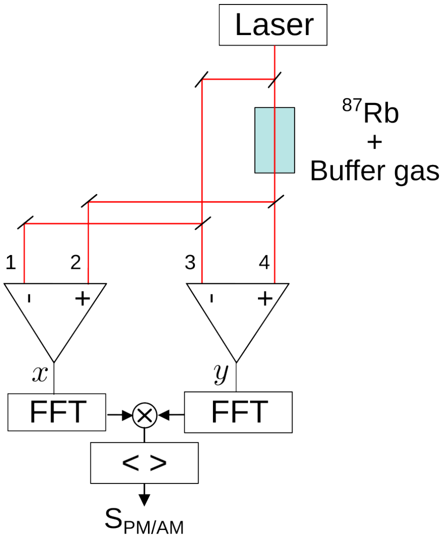

Fig. 1. Conceptual scheme of the setup. PD: photodiode, BS: Polarizing Beam Splitter

where the subscript ELN stands for electronic noise of the detectors and acquisition system and "shot" indicates the laser shot noise. The cross-spectral density S_{xy} of the two output channels enables to extract the PM-to-AM contribution alone, since other contributions are uncorrelated:

$$S_{xy} = S_{\text{PM/AM}} + \mathcal{O}\left(\sqrt{1/m}\right)$$

The letter m is the number of averages. Increasing m allows the convergence of the cross-spectrum to the power spectral

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density of the PM-to-AM noise and reduction of the the contribution of electronics and shot noises.

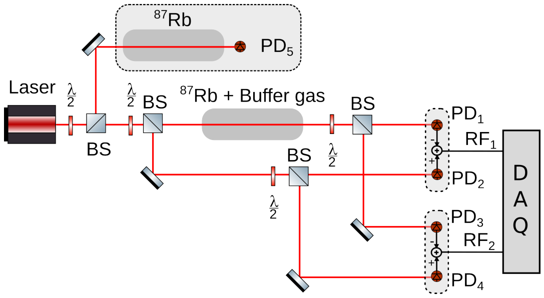

Fig. 2. Scheme of the optical setup. The optical power is distributed and balanced by means of half-wavelength plates and polarizing beam-splitters (BS). RF$_1$ and RF$_2$ are the output of the balanced photodetectors. The two signals are acquired on a fast digital acquisition system (DAQ) and processed to obtain the cross-correlation. PD: photodiode.

The complete optical setup, depicted in Fig. 2, presents an additional spectroscopy block on a cell without buffer gas which acts as a frequency reference. This allows proper tuning of the laser over the absorption profile of the cell under test.

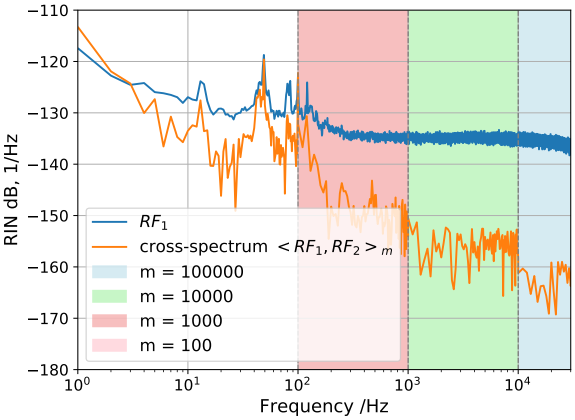

Fig. 3. Plot of acquired data with the laser out of resonance; One of the two differential outputs (blue) is compared with the cross-spectrum of the two balanced outputs (orange); For computing the cross-spectrum, we divided the analysis over the various decades, thus every spectral range (marked by a different background color) has a different averaging factor m.

We used a semiconductor distributed feedback (DFB) laser diode with a wavelength of 780 nm and a linewidth of about 2 MHz. Thanks to this optical setup it is possible to operate at low power beams (P < 100 µW), close to the operational conditions of compact Rb atomic clocks, despite the increment of the relative impact of the shot noise and electronic noise when the power is reduced.

Fig. 3 shows the noise floor of the laser and acquisition system without cross-correlation (blue trace) and after cross-correlation (orange trace) for an laser power on the photodetectors of $40\,\mu$W, demonstrating effective reduction of both shot and electronic noise.

III. CONCLUSIONS

In this work, we present a measurement setup that is able to subtract the intensity noise and achieve sub-shot noise detection in order to measure the PM-to-AM noise conversion even for narrow-linewidth lasers. We demonstrate effective AM and shot noise reduction for Fourier frequencies above 100 Hz, limited only by the averaging time. At the conference, we will present a results on the PM-to-AM noise profile measured in Rb vapors with Ar-N$_2$ buffer gas as a function of the laser detuning from the atomic resonance.

REFERENCES

[1] J. D. Roslund, A. Cingöz, W. D. Lunden, G. B. Partridge, A. S. Kowligy, F. Roller, D. B. Sheredy, G. E. Skulason, J. P. Song, J. R. Abo-Shaeer, and M. M. Boyd, “Optical clocks at sea,” 2023.

[2] E. J. Ahern, S. K. Scholten, C. Locke, N. Bourbeau-Hebert, B. White, A. N. Luiten, and C. Perrella, “Tailoring the stability of a two-color, two-photon rubidium frequency standard,” 2024.

[3] F. Kuschewski, J. Wüst, M. Oswald, T. Blomberg, M. Gohlke, J. Bischof, A. Boac, T. Alam, A. Bußmeier, K. Abich, N. Röder, K. Döringshoff, J. Hrabina, M. Holá, J. Oulehla, T. Schuldt, and C. Braxmaier, “Compasso mission and its iodine clock: outline of the clock design,” *GPS Solutions*, vol. 28, no. 1, Oct. 2023.

[4] J. Cui, G. Ming, F. Wang, J. Li, P. Wang, S. Kang, F. Zhao, D. Zhong, and G. Mei, “Realization of a rubidium atomic frequency standard with short-term stability in $10^{-14}\ \tau^{-1/2}$ level,” *IEEE Transactions on Instrumentation and Measurement*, vol. 73, pp. 1–7, 2024.

[5] M. Gozzelino, S. Micalizio, C. E. Calosso, J. Belfi, A. Sapia, M. Gioia, and F. Levi, “Realization of a pulsed optically pumped Rb clock with a frequency stability below 10^{-15},” *Scientific Reports*, vol. 13, no. 1, Aug. 2023.

[6] E. A. Burt, J. D. Prestage, R. L. Tjoelker, D. G. Enzer, D. Kuang, D. W. Murphy, D. E. Robison, J. M. Seubert, R. T. Wang, and T. A. Ely, “Demonstration of a trapped-ion atomic clock in space,” *Nature*, vol. 595, no. 7865, pp. 43–47, Jun. 2021.

[7] J. G. Coffer, M. Anderson, and J. C. Camparo, “Collisional dephasing and the reduction of laser phase-noise to amplitude-noise conversion in a resonant atomic vapor,” *Phys. Rev. A*, vol. 65, p. 033807, Feb 2002. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevA.65.033807

[8] C. E. Calosso, M. Gozzelino, A. Godone, H. Lin, F. Levi, and S. Micalizio, “Intensity detection noise in pulsed vapor-cell frequency standards,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 67, no. 5, pp. 1074–1079, May 2020.

[9] N. Almat, M. Pellaton, W. Moreno, F. Gruet, C. Affolderbach, and G. Mileti, “Rb vapor-cell clock demonstration with a frequency-doubled telecom laser,” *Applied Optics*, vol. 57, no. 16, p. 4707, Jun. 2018.

[10] E. Rubiola, “The magic of cross-correlation in measurement from dc to optics,” *EFTF 2008 - 22nd European Frequency and Time Forum*, 04 2008.

[11] T. Mitsui and K. Aoki, “Noise reduction and hyperfine level coherence in spontaneous noise spectroscopy of atomic vapor,” *Journal of the Optical Society of America B*, vol. 31, no. 2, p. 195, Jan. 2014.