# Low Phase Noise Photonic-Based Rb Atomic Frequency Standard

Ersoy Şahin, Çağrı Şenel, Adem Gedik, Yücel Deniz, Demet Çakrak and Ramiz Hamid National Metrology Institute of Turkey (TUBITAK UME),
P.K.54, 41470 Gebze, KOCAELİ, Turkey
e-mail:ersoy.sahin@tubitak.gov.tr

*Abstract*— **The photonics-based Rb standard was being realized using the low phase noise Er-doped mode-locked femtosecond fiber laser, extended cavity diode laser, dielectric resonator and Sagnac interferometer. The locked voltage controlled oscillator (VCO) was connected to the reference input of the phase-locked dielectric oscillator and consequently, ultra-low phase noise 6.834 GHz MW signal, which was locked to the fiber laser, was obtained. The measured phase noise reaches -200 dBc/Hz for an offset frequency of 10 MHz. The achievd frequency stability of the photonic-based Rb atomic clock is $3x10^{-12}$@1 s and decreased to $2.5x10^{-13}$@400 s and $7.1x10^{-13}$@$10^4$ s.**

***Keywords—atomic frequency standard; Er-doped mode-locked femtosecond fiber laser; extended cavity diode laser; sagnac interferometer***

## I. Introduction

The development of low-phase-noise sources are important for a wide-ranging set of applications, including development of atomic frequency standards with better short-time stability, phase noise calibration of signal generators, precise time synchronization and distribution in particle accelerator and free electron laser facilities, calibration of astrocombs and advanced radar technologies. Femtosecond laser oscillators are currently the best candidates for generation of low-phase-noise microwave signals. The development of the microwave atomic frequency standard based on a low phase noise photonic oscillator is very important. Because the most important advantage of these standards is that the produced microwave signal has better short-term (phase noise) and long-term stability.

In the development of the Rb atomic frequency standard a microwave frequency, corresponds to ground-state hyperfine energy levels, is required. This frequency is obtained using the low phase noise crystal oscillators as the reference sources (Oven- Controlled Crystal Oscillator-OCXO, VCO, etc.). The desired RF frequency is realized with frequency synthesizers by using the frequency multiplication method. The phase noise of the RF frequency worsens rather after the use of the phase-locked frequency synthesizer circuits. Ultra-low phase noise microwave frequency generation can be produced optically by utilizing femtosecond fiber lasers, with lower phase noise than frequency synthesizer [1-5].

In this study, the preliminary experimental results of low phase noise photonics-based Rb Atomic Frequency standard was being realized at the National Metrology Institute of Turkey (TÜBİTAK UME), will be presented. The photonics-based Rb standard installed by using the low phase noise Er-doped mode-locked femtosecond fiber laser, extended cavity diode laser (ECDL), dielectric resonator (DRO), and Sagnac interferometer. The 6.8 GHz RF signal corresponding to the ground state hyperfine energy transitions of the Rb atomic gas is being created using the mode-locked femtosecond fiber laser, Sagnac interferometer, and the DRO. The ECDL laser electromagnetic radiation and the low phase noise phase-locked 6.8 GHz RF signal simultaneously activated to interact with the Rb atomic gas situated in the temperature-controlled microwave cavity. As a result of the interaction, the double radio optic resonance (DROR) was detected and the derivative of resonance was being used to stabilize the repetition frequency of the mode-locked fiber laser. With this method implemented, both the short and long-term frequency stability of the output frequency of the VCO was maintained and photonics-based Rb atomic frequency standard was realized.

.

## II. Low phase noise photonic-based Rb Atomic Frequency Standard

The schematic of the photonic-based Rb atomic clock is shown in Figure 1. The system consists of five main parts, which are a mode-locked femtosecond fiber laser, an Erbium-doped fiber amplifier (EDFA), fiber-loop optical-microwave phase detector (FLOM-PD), frequency stabilized extended cavity diode laser (ECDL), and magnetically-shielded temperature-stabilized microwave cavity (μW cavity).

The internal dynamics of the fiber laser determine the phase noise of the pulse train besides many other parameters such as pulse duration, repetition rate, pulse energy, and optical spectrum. Soliton-similariton fiber lasers have been shown to have high pulse energies, low phase and intensity noise, and be stable in the long term [6]. For this reason, the homemade mode-locked femtosecond fiber laser, operating at a wavelength of 1550 nm, was built in the soliton-similariton architecture. The mode-locked femtosecond fiber laser was built in a temperature-controlled box. One of the collimators was placed on a translation stage, which can be moved from

978-1-6654-3935-0/21/$31.00 ©2021 IEEE

outside the box through a small hole. The repetition rate of the laser can be tuned by approximately 500 kHz by moving the translation stage. By fine-tuning its position, the laser repetition rate was adjusted to be exactly 100 MHz. There is a piezo-based fiber phase shifter in the fiber laser cavity for fine-tuning and stabilization of the repetition rate. For amplifying and compressing the optical pulses, the EDFA was designed. The FLOM-PD is a system that allows the detection of the phase difference between an optical pulse train and an RF or MW signal [7]. The system can work with any RF-MW frequency that is an exact multiple of the pulse repetition rate. FLOM-PD comprises a circulator, a beam splitter (BS), an electro-optical modulator (EOM), a sub-setup to introduce 90° bias between opposing propagation directions in the Sagnac loop, and a balanced photodetector. The optical pulses from the EDFA pass through an optical circulator and reach the 50/50 BS. A Sagnac loop is formed on the other side of the BS. The Sagnac loop comprises an EOM, two 45° Faraday rotators (FR), and a quarter-wave plate (QWP). FRs and the QWP introduce 90° bias between the opposing propagation directions. If the bias is not introduced, then laser beams traveling in the opposite directions interfere constructively at the BS, and all the light back-propagates toward the circulator.

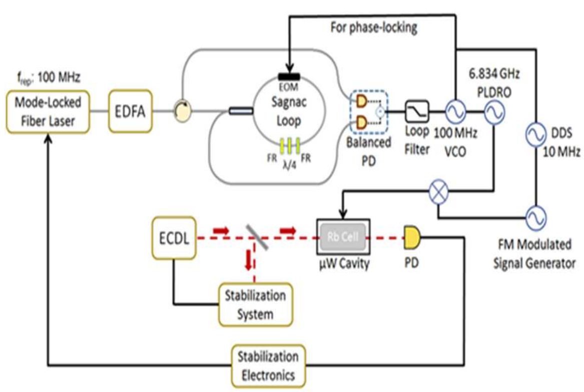


Fig 1. Schematics of the low phase noise photonic-based Rb Atomic Frequency Standard.

The 90° bias is introduced to ensure that the output power from the circulator and the BS are equal, when no signal is applied to the EOM or when the applied RF-MW signal is completely in-phase with the optical pulse train. The outputs from the circulator and BS are connected to the balanced photodetector to obtain an electrical signal proportional to the phase difference between the electrical and optical signals. The fiber lengths are adjusted such that the pulses reach both channels of the photodetector at the same time. The phase difference between the 100 MHz signal from a VCO and the optical pulses from the mode-locked fiber laser was detected by the FLOM-PD and the phase of the VCO (Morion Inc., MV317) was locked to the fiber laser. The locked VCO was connected to the reference input of the phase-locked dielectric oscillator (Meuro corp, PLDRO-6834-13-100E-C) and consequently, ultra-low phase noise 6.834 GHz MW signal, which was locked to the fiber laser, was obtained. The phase noise of PLDRO when MV317 was free-running or locked to the fiber laser is shown in Fig 2.

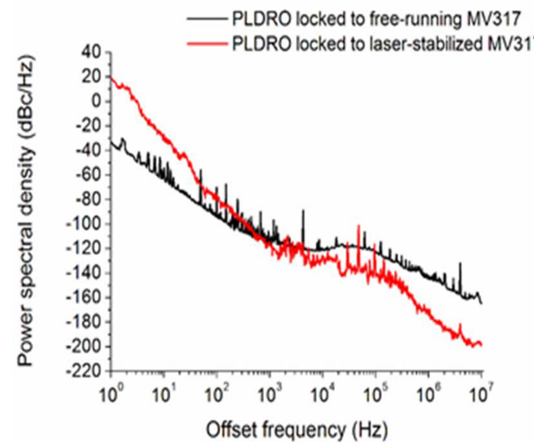


Fig 2. Phase noise of PLDRO when MV317 was free-running or locked to the fiber laser.

For offset frequencies below 500 Hz, the phase noise of the PLDRO output was lower while the VCO was free-running. However, for offset frequencies above 500 Hz, the phase noise was significantly lower when the VCO was locked to the fiber laser. The measured phase noise reaches -200 dBc/Hz for an offset frequency of 10 MHz, which is lower than the previous record-holders [8-9]. For obtaining the clock signal, the traditional optical scheme which consists of ECDL and magnetically shielded temperature stabilize μW cavity were used [10]. The linewidth ECDL is less than 150 kHz and was stabilized by the usage of the $3^{rd}$ derivatives of a crossover resonance of $F=1 \rightarrow F'=0,1$ signals obtained from hyperfine resonances of the $^{87}$Rb $D_2$ line [11]. The frequency stabilized laser beam sent to the magnetically shielded temperature stabilized the microwave cavity. The microwave cavity has a cylindrical geometry and resonates on the $TE_{011}$ mode at the $^{87}$Rb ground-state hyperfine frequency (6.834 GHz). The cell is filled with enriched $^{87}$Rb and a total pressure of 25 Torr $Ar\text{-}N_2$ buffer gases. To scan the microwave frequency at the transition frequency of the Rb atoms, the output of the PLDRO is mixed with the output of the Keysight 8257D signal generator. 8257D produces an FM-modulated signal, which scans the transition frequency 70 times per second, with 140 Hz amplitude. DDS divides the frequency of the 100 MHz from VCO by 10. The obtained 10 MHz signal from the DDS is connected to a 10 MHz reference input of 8257D. The signal detected by the photodiode and the 70 Hz modulation signal from 8257D is connected to an SRS SR830 lock-in amplifier to obtain the derivative of the DROR resonance that is indicated in Fig 3. To lock the repetition rate of the fiber laser to the DROR resonance, the derivative of the resonance signal is connected to SRS SIM960 PID controller. The output of the PID controller is amplified by a high-voltage amplifier and applied to the fiber phase shifter inside the fiber laser cavity.

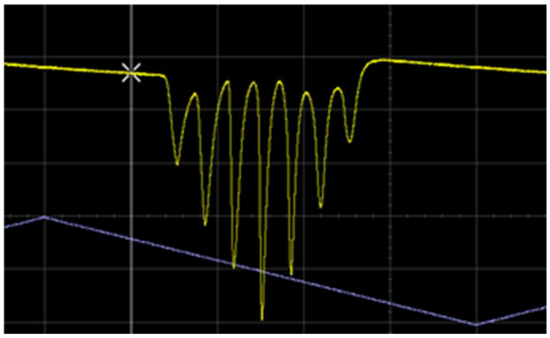

Fig 3. The oscilloscope image of the detected DROR resonance.

The stability of the stabilized VCO to the repetition rate of mode-locked femtosecond fiber laser is characterized by Allan deviation plots measured using Microsemi 5125A, which is referenced to an H-maser is shown in Fig 4. The frequency stability of the photonic-based Rb atomic clock is $3x10^{-12}$@1 s and decreased to $2.5x10^{-13}$@400 s and $7.1x10^{-13}$@$10^4$ s. The results obtained belong to a study whose optimization studies have not yet been completed, and it is assumed that frequency stability will be improved when optimization studies are performed.

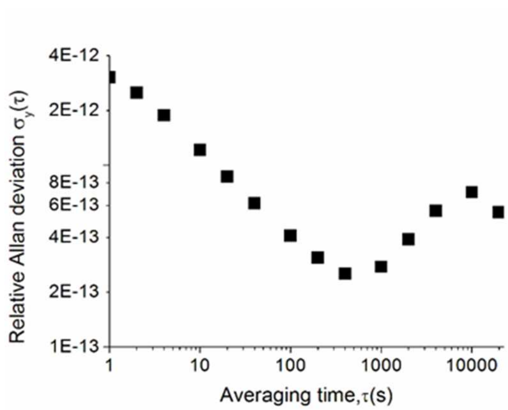


Fig 4. The Allan deviation of the low phase noise photonic-based Rb Atomic Frequency Standard.

The phase noise of VCO measured by Agilent E5052B signal Source analyzer and is shown in Fig 5. The measured phase noise shows that there are many noise spurs are thought to be caused by signal dividers, amplifiers, a large number of filters, and attenuators were used in the installation of the clock system. By simplifying the system and using lower noise components, the phase noise of the clocks will be reduced.

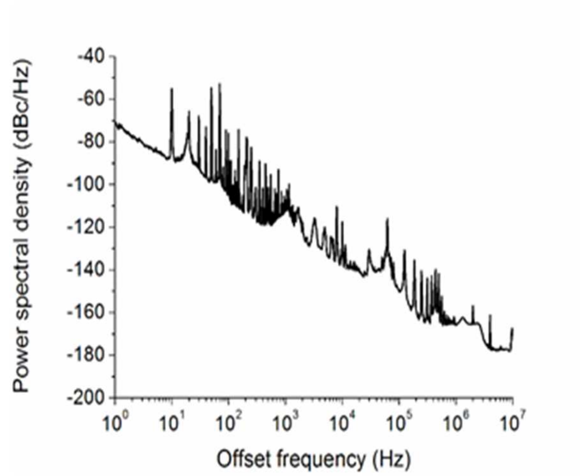


Fig 5. The phase noise of VCO.

## III. CONCLUSIONS

Double radio optical resonance was created by the photonic method. The detected resonance derivate was being used to stabilize the repetition frequency of the mode-locked fiber laser and the photonics-based Rb standard was realized. The preliminary experimental results related output frequency stability of low phase noise photonics-based Rb atomic frequency standard was measured $3x10^{-12}$, $2.5x10^{-13}$ and $7.1x10^{-13}$ at 1, 400, and $10^4$ s averaging times respectively. For offset frequencies above 500 Hz, phase noise of laser locked DRO oscillator which used as MW source in Rb frequency standard, was significantly improved when the VCO was locked to the fiber laser. The measured phase noise reaches -200 dBc/Hz for an offset frequency of 10 MHz, which is lower than the previous record-holders [8-9]. It is thought that the obtained frequency stability values will be improved by optimization studies.

## REFERENCES

[1] J. Millo, M. Abgrall,M. Lours,E. M. L. English, H. Jiang,
IV. Guéna, A. Clairon,M. E. Tobar, S. Bize, Y. Le Coq, and G. Santarelli, "Ultra- low noise microwave generation with fiber-based optical frequency comb and application to atomic fountain clock," Appl. Phys. Lett 94, 141105, 2009.

[2] S. Weyers, B. Lipphardt, and H. Schnatz,"Reaching the quantum limit in a fountain clock using a microwave oscillator phase locked to an ultra stable laser," PHYSICAL REVIEW A 79, 031803(R), 2009.

[3] W. Zhang, Z. Xu, M. Lours, R. Boudot, Y. Kersalé, A.N. Luiten, Y.Le Coq, and G. Santarelli, "Advanced noise reduction techniques for ultra-low phase noise optical-to-microwave division with femtosecond fiber combs,"IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 58, no. 5, May 2011.

[4] T. Hirayama, M. Yoshida, M. Nakazawa, K. Hagimoto, and T. Ikegami,"Mode-locked laser-type optical atomic clock with an optically pumped Cs gas cell," Optics Letters, Vol.32, pp.1241-1243, 2007.

[5] M.Y. Peng, A.Kalaydzhyan, and F.X. Kärtner,"Balanced optical-microwave phase detector for sub-femtosecond optical-RF synchronization," Optics Express, Vol.22, pp. 27102-27111, 2014.

[6] B. Oktem, C. Ülgüdür and F. Ömer Ilday, "Soliton-similariton fibre laser," Nature Photon. 4, 307, 2010.

[7] K. Jung, J. Shin and J. Kim, "Ultralow Phase Noise Microwave Generation From Mode-Locked Er-Fiber Lasers With Subfemtosecond Integrated Timing Jitter,"IEEE Photonics J. 5, 5500906. 2013.

[8] F. Quinlan, T. M. Fortier, H. Jiang, A. Hati, C. Nelson, Y. Fu, J. C. Campbell, and S. A. Diddams, "Exploiting shot noise correlations in the photodetection of ultrashort optical pulse trains," Nature Photon. 7, 290, 2013.

[9] D. Nicolodi, R. Bouchand, M. Lours, X. Xie, Y. Le Coq, M. Giunta, M. Lezius, W. Haensel, R. Holzwarth, P.-A. Tremblin, G. Santarelli, S. Datta, A. Joshi, C. Alexandre, IEEE International Frequency Control Symposium, 2016.

[10] T. Bandi, C. Affolderbach, C. Stefanucci, F. Merli, A. K. Skrivervik, and Gaetano Mileti," Compact High-Performance Continuous-Wave Double-Resonance Rubidium Standard With $1.4 \times 10^{-13}$ $\tau -1/2$ Stability," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 61, No. 11, pp.1769- 1777,2014.

[11] E.Şahin,"Frequency Stabilization of the Extended Cavity Diode Laser to the $^{87}Rb\text{-}D_2$ transition by using Zeeman Modulation Method", will be published at EFTF 2021 conference proceedings.