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Demonstration of a Sub-Sampling Phase Lock Loop Based Microwave Source for Reducing Dick Effect in Atomic Clocks *

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We demonstrate a simple scheme of 6.835 GHz microwave source based on the sub-sampling phase lock loop (PLL). A dielectric resonant oscillator of 6.8 GHz is directly phase locked to an ultra-low phase noise 100 MHz oven controlled crystal oscillator (OCXO) utilizing the sub-sampling PLL. Then the 6.8 GHz is mixed with 35 MHz from an direct digital synthesizer (DDS) which is also referenced to the 100 MHZ OCXO to generate the final 6.835 GHz signal. Benefiting from the sub-sampling PLL, the processes of frequency multiplication, which are usually necessary in the development of a microwave source, are greatly simplified. The architecture of the microwave source is pretty simple. Correspondingly, its power consumption and cost are low. The absolute phase noises of the 6.835 GHz output signal are −47 dBc/Hz, −77 dBc/Hz, −104 dBc/Hz and −121 dBc/Hz at 1 Hz, 10 Hz, 100 Hz and 1 kHz offset frequencies, respectively. The frequency stability limited by the phase noise through the Dick effect is theoretically estimated to be better than $5.0 \times 10^{-14}\tau^{1/2}$ when it is used as the local oscillator of the Rb atomic clocks. This low phase noise microwave source can also be used in other experiments of precision measurement physics.

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Low phase noise microwave sources are generally used in the physical experiments of Raman atomic interferometer,[1] testing local position invariance,[2] precision atomic spectroscopy measurement,[3] atomic spin squeezing,[4] and atomic clocks.[5−12] The phase noise of the microwave source is one of the key factors to limit the precision of those measurements.

Among the atomic clocks, the Rb atomic clocks are widely used in the fields of telecommunications, global navigation satellite systems (GNSS) and industrial applications because of its superior characteristics of high frequency stability, low power consumption, and small volume.[13−15] In recent years with widespread applications promoted by GNSS, the frequency stability of the Rb atomic clocks has been greatly improved. The short-term frequency stability of the Rb atomic clocks operated in a continuous optically pump mode has been better than $2.5 \times 10^{-13}\tau^{-1/2}$.[16,17] A pulsed optically pumped (POP) Rb atomic clock with short-term frequency stability of $1.7 \times 10^{-13}\tau^{-1/2}$ has been reported.[18]

However, for the Rb atomic clocks operated in the mode of continuous optically pumping or POP, the absolute phase noises of local oscillator are still one of the main limitations for improving their short-term frequency stabilities.[19−21] For the continuous interrogation atomic clocks, the frequency modulation noise at even harmonics of modulation frequencies would limit its short-term frequency stability via the intermodulation effect.[19] For the POP clocks, its short-term frequency stability would be limited by the absolute phase noise of the local oscillator through the Dick effect.[20,22,23] The short-term frequency stability limited by the frequency noise of the local oscillator can be expressed as[24]

$$\sigma_y^{\mathrm{LO}}(\tau) = \left\{ \sum_{k=1}^{\infty} \mathrm{sinc}^2\left(k\pi \frac{T}{T_{\mathrm{C}}}\right) S_y^{\mathrm{LO}}(kf_{\mathrm{C}}) \right\}^{1/2} \tau^{-1/2}, \quad (1)$$

where $S_y^{\mathrm{LO}}(kf_{\mathrm{C}}) = (kf_{\mathrm{C}})^2/\nu_0^2 \cdot S_\varphi^{\mathrm{LO}}(kf_{\mathrm{C}})$ is the power spectral density of the microwave source fractional frequency fluctuation, $S_\varphi^{\mathrm{LO}}(kf_{\mathrm{C}})$ is the power spectral density of phase noise, ν_0 is the carrier frequency, $f_{\mathrm{C}} = 1/T_{\mathrm{C}}$, and T_{C} is the duration of the atomic clock cycle. In our case, f_{C} is 100 Hz. The phase noise at the offset frequency range of 100 Hz to 1 kHz is the leading limit to the short-term frequency stability. Therefore, it is beneficial to develop a microwave source with low phase noise at these offset frequencies to improve the short-term frequency stability of Rb atomic clocks,

The phase noise of the microwave source could be considerably improved by the ultra-stable laser[25,26] or cryogenic sapphire oscillator (CSO) based microwave generators.[27−29] Nevertheless, for the compact Rb clocks used in the GNSS or industry applications, it is not realistic to use these complex, expensive and bulky systems. Thus, it will still remain a well-adapted solution to develop the ultra-low noise OCXO based microwave source, and there have been several reports on developing microwave sources for atomic clocks.[7−12] In most of these schemes, to phase lock a dielectric resonant oscillator (DRO), the

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100 MHz OCXO is usually frequency multiplied to 6.8 GHz (for the Rb atomic clocks) or 9.2 GHz (for the Cs atomic clocks) with a non-linear transmission line (NLTL) or a step recovery diode (SRD), and then mixed with the output signal of the DRO to generate an intermediate frequency signal which is further phase locked to a DDS with the reference signal also provided by the OCXO. In that way the output frequency of the DRO will be indirectly phase locked to the 100 MHz of OCXO. In this process, our previous work shows that the additional phase noise of the NLTL is greatly affected by its operation parameters such as the input power, the input and output impedances.[10] To suppress the additional phase noise of the NLTL, the architecture of the schemes would be very complex, bulky, and expensive for optimizing the operation parameters of the NLTL. To simplify the structure, François *et al.* designed a simple microwave source with a 1.6 GHz custom-designed frequency multiplication module, but the subsequent frequency division and multiplication are still needed. Therefore, the structure of the source is still quite complicated.[11] In this Letter, we demonstrate a simple scheme of a 6.835 GHz low phase noise microwave source based on the sub-sampling PLL for Rb atomic clock. With the help of the sub-sampling PLL technique, which is usually used in the radio-frequency and radar engineering,[30,31] the structure of the synthesizer can be greatly simplified. The absolute phase noise is slightly better than the result in Refs. [8-10]. The microwave frequency synthesizer developed here can also be used in the experiments of the other physical experiments of precision measurement.

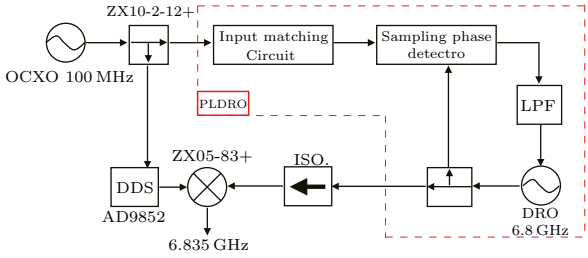

Fig. 1. The architecture of the microwave source. The part enclosed in the red dashed line is the phase locked DRO, labelled as PLDRO.

The architecture of the microwave source is shown in Fig. 1. The 100 MHz signal from the OCXO (Beijing Institute of Radio Metrology and Measurement, ZF550) is divided into two arms via a power splitter (Mini-Circuits, ZX10-2-12+). The first arm 100 MHz signal is used as the reference signal for an AD9852 chip based home-made DDS, which is used to achieve functions of frequency modulation and scanning. The DDS is controlled through serial communication with a computer. The second arm 100 MHz signal is used to phase lock the 6.8 GHz DRO utilizing a sub-sampling PLL. With the help of the sub-sampling PLL technique, the DRO is directly phase locked to the 100 MHz OCXO. The microwave frequency multiplication and mixing process are greatly simplified. The phase locked DRO is labelled as PLDRO. The 6.8 GHz output signal of the PLDRO goes through a microwave isolator (Fairview, FMIR1021), which is used to prevent the microwave signal from being reflected back into the PLDRO. The output signal of the PLDRO is then mixed (Mini-Circuits, ZX05-83+) with the 34.68 MHz output signal of the DDS to generate the final 6.835 GHz output signal. Compared to the previous works on the development of microwave source, the structure of the source of Fig. 1 is much simpler. Correspondingly, the power consumption and the cost of the source are considerably decreased as some necessary frequency-multiplier modules are omitted in this scheme.[7,8,10,11]

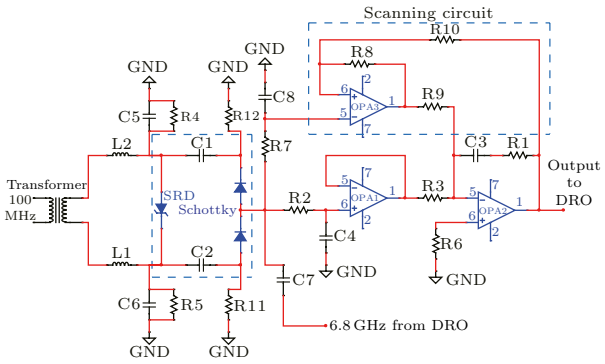

Fig. 2. The detailed schematic of the sub-sampling PLL.

The detailed schematic of the sub-sampling PLL is shown in Fig. 2. The sampling phase detector is the key component of the PLL. The sampling phase detector mainly consists of an SRD and a pair of Schottky diodes. The maximum frequency of the phase detector can reach 18 GHz. The input impedance of the SRD is usually about 4–10 Ω, and the output impedance of the 100 MHz OCXO is usually 50 Ω. Thus, we design an input matching circuit to match impedances between them, which is realized by a transformer. In addition to matching impedance, the transformer is also used to convert unipolar pulses into symmetrical pulses. The loop pass filter (LPF) of the sub-sampling PLL is realized by a positive proportional-integral (PI) circuit. A voltage follower behind the sampling phase detector is designed to serve functions of isolation and impedance matching between the sampling phase detector and the LPF, and also as a low pass filter to suppress the high-frequency noise of the PLL. The scanning circuit is designed to improve the capture bandwidth of the PLL and to shorten the time of phase locking. The volume of the developed PLDRO is only slightly larger than that of a microwave amplifier. The whole volume of the microwave source is largely reduced.

We measured the absolute phase noises of the main output signals at carrier frequencies of 100 MHz, 35 MHz, 6.8 GHz and 6.835 GHz with a phase noise analyzer (R&S FSWP26 with option 61) using cross-correlation techniques to enhance sensitivity. The measured phase noises of the signals and phase noise floor of the FSWP26 are shown in Fig. 3. The phase

noise floor of the FSWP26 with option B61 is provided by FSWP26 datasheet. The data from the datasheet is only given under the condition of the cross-correlation factor being one ($X_{\rm corr}$=1). However, the noise floor can be further lowered with increasing $X_{\rm corr}$ as $5\log(X_{\rm corr})$. In the actual measurement, $X_{\rm corr}$ and the bandwidth are set as 50 and 3%, respectively. Thus the measurement results will not be limited by the phase noise floor of the FSWP26. The absolute phase noise of the OCXO 100 MHz has a slight bump at the offset frequencies around 100 kHz, which is inherent from the custom-made free running OCXO. The phase noise of the 6.8 GHz signal of the PLDRO at offset frequencies smaller than 100 Hz is deteriorated by an idealized $20\log N$. At offset frequencies larger than 100 Hz, especially at the offset frequency of locking bandwidth, the phase noise is maximum deteriorated by an additional 5 dB. This is because the absolute phase noise of free running DRO at small offset frequencies is quite poor. The locking bandwidth of PLL is about 150 kHz. Thus the gain within the servo loop bandwidth is not enough. As a consequence, the phase noise, especially at the offset frequencies near the locking bandwidth, cannot be sufficiently suppressed. Even with this limitation, the phase noise performances are still slightly better than the results of the scheme based on the NLTL or SRD. The improvement probably result from the better impedance match compared to the NLTL or SRD based scheme. The phase noise of the 6.835 GHz output signal is the same as the phase noise of the PLDRO. The phase noise of the DDS 35 MHz signal is excellent, which does not limit the phase noise of the 6.835 GHz output signal. The absolute phase noise performances of this work compared with that in several previous works are listed in Table 1. From the formula (1), using the absolute phase noise of the 6.835 GHz output signal, it can be calculated that the short-term frequency stability of the atomic clock is estimated to be better than $5.0\times10^{-14}\tau^{1/2}$.

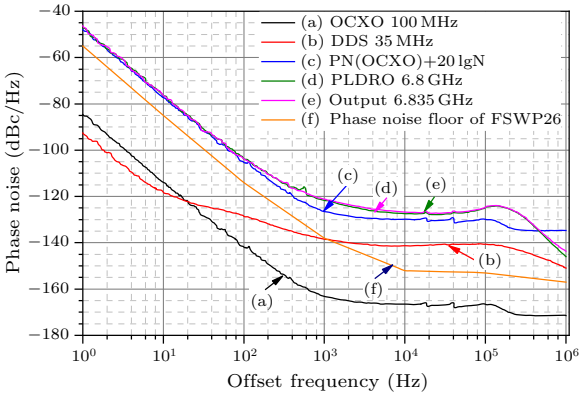

Fig. 3. The absolute phase noises of the main output signals in the microwave source. The carrier frequencies are at (a) 100 MHz of the OCXO, (b) 35 MHz of the DDS, and (c) 6.8 GHz deteriorated by idealized $20\log N$ from 100 MHz OCXO, (d) 6.8 GHz of the PLDRO, (e) 6.835 GHz output signal, (f) phase noise floor of the FSWP26 at carrier frequency of 7 GHz.

Table 1. The phase noise performances of several related works.

Offset frequency (Hz)	100	1 k	10 k	100 k	1 M
Ref. [8]	−102.5	−118.2	−121.7	−122.3	−136.6
Ref. [9]	−90.2	−113.2	−123.7	−126.3	
Ref. [10]	−95.6	−119.6	−122.3	−123.1	−140.6
This work	−103.7	−121.2	−126.7	−124.3	−143.6

In conclusion, we have demonstrated a simple low phase noise 6.835 GHz microwave source based on the technique of sub-sampling PLL, with the associated low power consumption and cost. The absolute phase noises of the 6.835 GHz output signal are measured to be −47 dBc/Hz, −77 dBc/Hz, −104 dBc/Hz and −121 dBc/Hz at 1 Hz, 10 Hz, 100 Hz and 1 kHz offset frequencies, respectively. When it is used as the local oscillator of the Rb atomic clocks, the short-term frequency stability limit of the Rb atomic clocks due to the absolute phase noise via the intermodulation or the Dick effect is theoretically estimated to be better than $5.0\times10^{-14}\tau^{1/2}$. Although we only develop a microwave source for Rb atomic clocks in this work, the same scheme can be easily adopted to use for Cs atomic clocks by simply changing the output frequencies of the PLDRO and DDS. The microwave source can also be used in the experiments of the Raman atomic interferometers or gyroscopes and other experiments of fundamental physical measurement. Limited by the phase noise of the DRO and gain and bandwidth of the PLL, the phase noise performance of the source realized via this method would not expect to reach the performance of the ultra-stable laser or CSO based source.

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