A Dedicated Microwave Frequency Synthesizer for the Rubidium Atomic Clock

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***Abstract*—The phase noise of the microwave synthesizer is one of the considerable limitations on the short-term stability of microwave atomic clocks through Dick effect. We present a dedicated microwave frequency synthesizer at 6.834 GHz in place of the commercial microwave signal generator. A phase-locked loop (PLL)-based direct digital synthesizer (DDS) generates a 134 MHz signal, which is mixed with a 6.7 GHz signal output from a phase-locked dielectric resonant oscillator (PDRO), to deliver a 6.834 GHz signal to the rubidium atomic sample for microwave interrogation. We measured the phase noise behavior of the 6.834 GHz signal to be -91 dBc/Hz and -122 dBc/Hz at 100 Hz and 1 kHz offset frequencies, respectively, which induced an instability contribution of 5.5×10^{-14} at 1s averaging time to the clock. The dedicated microwave frequency synthesizer helps to improve the compactness and low-consumption of the engineering rubidium atomic clocks.**

***Keywords*—frequency synthesis, rubidium atomic clock, PLL, DDS.**

I. INTRODUCTION

With the development of semiconductor diode lasers and fast-gated electronics, the cell-based pulsed optically pumped (POP) rubidium atomic clocks with optical-microwave double resonance (DR) scheme have attracted much attention these years. Thanks to simple architecture, compact size and a comparable level of frequency stability to passive hydrogen maser, rubidium atomic clocks are suitable candidates for space atomic frequency standards and are widely used in satellite navigation systems. According to previous research results, the short-term stabilities of the rubidium atomic clocks are demonstrated in the range of $1\sim3\times10^{-13}$, with long-term stabilities at the level of 10^{-15} [1]-[4].

For the POP rubidium atomic clock in optical-microwave DR regime, the performances of optical source and microwave source are especially crucial for optical pumping and driving the microwave resonance to interrogate the rubidium ground-state hyperfine clock transition. The laser source was built and described in [5]. In this work, we focus on the microwave frequency synthesizer for the POP rubidium atomic clock, which is characterized by simple architecture and low noise.

On the road to our engineering prototype of the POP rubidium atomic clocks, an dedicated microwave frequency synthesizer will take the place of the commercial microwave signal generator for further compactness and low power consumption. Meanwhile, we notice that the phase noise of the local oscillator (LO) is one of the considerable limitations on the clock short-term stability through Dick effect [6], [7], which promotes the research into the low phase noise microwave synthesizer for the rubidium atomic clock. An improved synthesis chain at 6.834GHz given in [1] utilized a step recovery diode (SRD) on the basis of the scheme proposed in [8], whose phase noise brought an clock instability at the level of 7×10^{-14}. A ultra-low phase noise 6.834GHz microwave frequency synthesizer for Rb vapor cell atomic clocks was presented in [9], which resulted in an instability contribution of 2×10^{-14} to the Rb clock. A microwave source based on the sub-sampling phase-locked loop (PLL) illustrated in [10] limited the clock frequency stability via the phase noise to be 5×10^{-14}.

II. DESIGN AND IMPLEMENTATION

The microwave frequency synthesizer in this study for the rubidium atomic clock generates a microwave frequency signal around 6.834682GHz in the range of ±10kHz, referring to the 10MHz standard frequency from the LO. The clock transition signal is obtained by detecting the resonance in the microwave cavity between the the output microwave frequency and the Rb ground-state hyperfine transition frequency. In order to improve the clock frequency stability, the performance requirements of the microwave synthesizer, listed in the second column of Table I, especially phase noise, are the focuses in the design and implementation of the frequency synthesis chain. The widely-used direct digital frequency synthesizer (DDS) has a distinct advantage of small frequency step with digitally fast tuning but is accompanied by the shortcomings of various spurs and low-output frequency [11], [12]. Another common frequency-synthesis method, the PLL features high -bandwidth and -frequency output, but the minimum frequency step, the resulting phase noise and switching speed are comparatively unsatisfactory [13], [14]. Accordingly, the frequency synthesis scheme proposed by tradeoff in Fig. 1 combines the DDS and PLL, which conduces to low spur levels and phase noise, and wideband outputs along with high frequency resolution and fast frequency switching.

The architecture of the synthesizer shown in Fig. 1 consists of the PLL, the DDS, the phase-locked dielectric resonant oscillator (PDRO), the input and output signal conditioning part and the control part. Among them, the DDS outputs 134MHz; and the PDRO generates 6.7GHz starting from the

10MHz standard frequency by tenfold multiplication to the intermediate 100MHz, and then multiplied by 67. The 6.834GHz microwave is obtained by mixing the 134MHz and the 6.7GHz signals. Therefore, the implementation of design scheme is based on the synthesis of 134MHz and 6.7GHz.

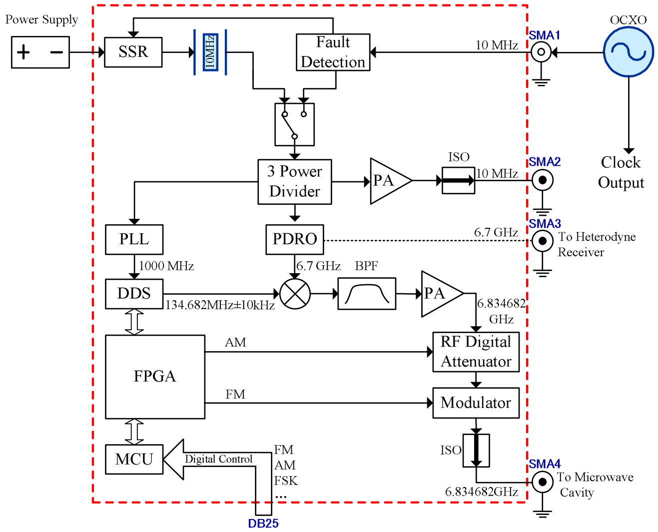
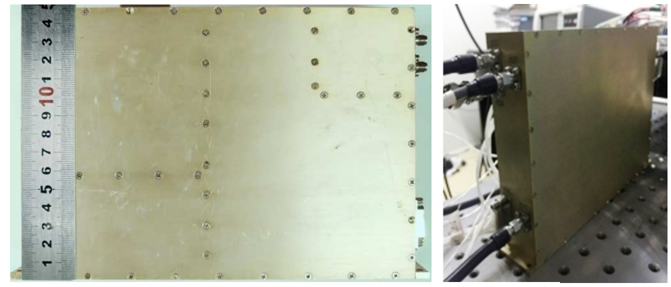


Fig. 1. Architecture of the frequency synthesizer for the rubidium atomic clocks in the red dashed line.

The Oven Controlled Crystal Oscillator (OCXO) is monitored by the fault detection circuits, which deliver TTL(transistor-transistor logic) control signals to SSR (solid-state relay) and the electronic switches, to allow a hot switch between the internally integrated 10MHz crystal oscillator and the external OCXO under continuous operation. When the OCXO is running, the power supply of the internal 10MHz crystal oscillator will be shut off by the SSR and switch the reference source to the external OCXO by the electronic switches, or else the synthesizer takes the internal 10MHz crystal oscillator as reference. The 10MHz reference signal is split into three parts by the power divider. One is output after amplification and isolation. And the other two take part in the microwave frequency synthesis as the reference of the PLL and the PDRO, with phase locked both to the 10MHz standard frequency signal. The PLL outputs a 1000MHz frequency modulated continuous wave (FMCW) to be fed into the DDS as its clock frequency signal. The DDS under control of the FPGA generates a specified frequency in the range of 134.682MHz±10kHz, which is mixed with the 6.7GHz from the PDRO through the double balanced frequency mixer. After being filtered and amplified, a certain microwave frequency signal in the range of 6.834682GHz±10kHz with 50mHz resolution can be obtained, which is power-tuned and frequency-modulated by the digital attenuator and modulator, respectively, both controlled by the FPGA. Under the precise digital control, the power of the output microwave signals covers a range of -50~0dBm, with 0.1dBm resolution.

The top-view and side-view photograph of the 6.834GHz synthesizer with a volume of about 1.28 liters (214×150×40mm) are presented in Fig. 2(a) and Fig. 2(b), respectively, which is enclosed in the permalloy box for shielding from the external magnetic fields. The four SMA (sub-miniature version A) interfaces in the side of the box are provided for input and output such as 10MHz standard frequency for experiments and measurements, 6.7GHz which can be fed into the heterodyne receiver in the case of the microwave detection, 6.8GHz for microwave interrogation. A 25-pin D-Sub connectors (DB25) is used for power supply and digital control signals.



(a) (b)

Fig. 2. (a) Top view of the synthesizer. (b) Side view of the synthesizer.

III. EXPERIMENTAL MEASUREMENTS AND ANALYSES

The microwave frequency synthesizer has been employed in the frequency servo loop of our POP rubidium clock prototype to take the place of the previous microwave signal generator R&S SMF 100A. The spectra of the the output microwave frequency signals 6.8GHz and 6.7GHz starting from the LO (BVA-8607, Oscilloquartz Corp.) and through the synthesis chain in this work were measured by a signal analyzer (FSV13, R&S). Fig. 3(a) and Fig. 3(b) show the spectra of the 6.8GHz and 6.7GHz microwave signals, respectively.

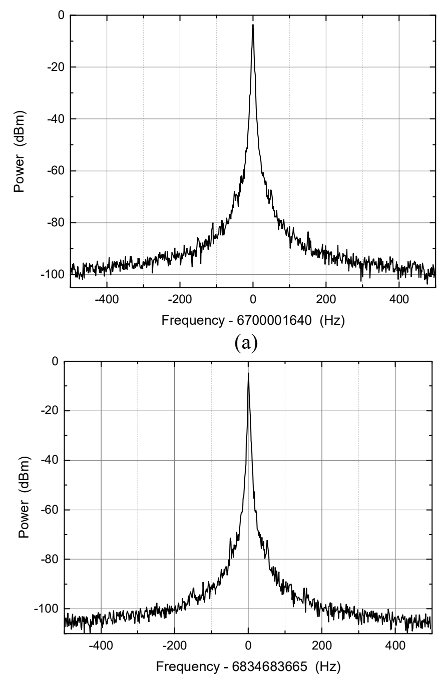


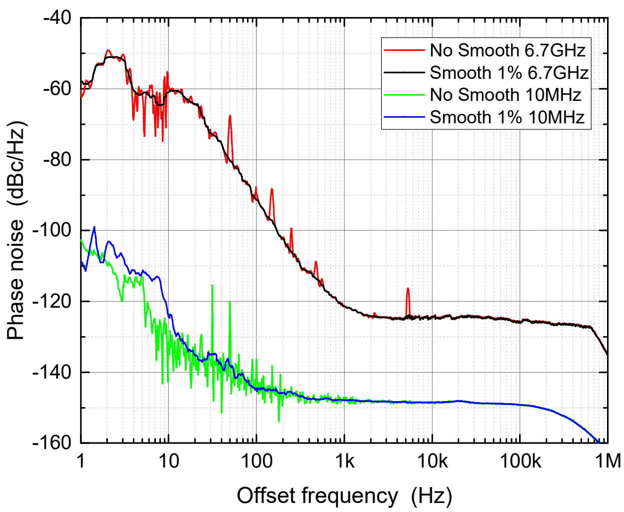
Fig. 3. (a) Spectrum of the synthesizer output 6.7GHz. (b) Spectrum of the synthesizer output 6.8GHz. RBW=1Hz, reference level 0dBm.

At 50Hz and its harmonics of the two spectra shown above, subtle spurs show symmetry with respect to the center frequency, which may arises from the power frequency magnetic field residual small interference.

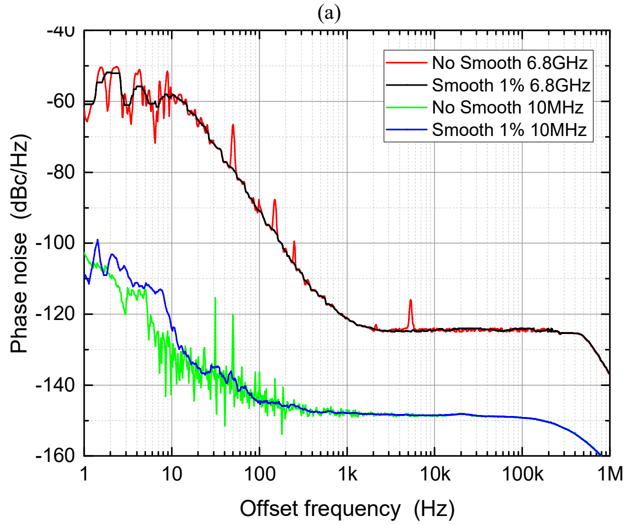
Moreover, an interesting performance characteristic of the frequency synthesizer is the phase noise. It induces one of the contributions to the clock short-term instability through Dick effect, which can be given by (1) [1], [15].

$$\sigma_y^{LO}(\tau)=\left(\sum_{k=1}^{\infty}\text{sinc}^2\left(k\pi\frac{T}{Tc}\right)S_y^{LO}(kf_C)\right)^{1/2}\tau^{-1/2} \quad (1)$$

In our case, T_C represents the cycle duration of the clock ($f_C=1/T_C$), T is the Ramsey time, and $S_y^{LO}(f)$ is the PSD (power spectral density) of the microwave fractional frequency fluctuations, which can be obtained from the conversion relationship $S_y^{LO}(f)=(f/\nu_0)^2 S_\phi(f)$. In this equation, f is the Fourier frequency, ν_0 is the 6.8GHz microwave frequency output from the synthesizer, and $S_\phi(f)$ is the PSD of the phase noise. In our case, T_C is close to 5ms, and $T=3.3$ ms.



(a)



(b)

Fig. 4. (a) Phase noise at 6.700GHz and its reference 10MHz (output of the LO). (b) Phase noise at 6.834GHz and reference 10MHz. Unprocessed and smoothed by 1% phase noise behaviors of the RF (output of the synthesizer) are plotted in red and black, respectively; and unprocessed and smoothed by 1% phase noise behaviors of the reference 10MHz in green and blue.

The phase noise behaviors of the 6.83468GHz and 6.7GHz from the synthesizer in this work were measured by a phase noise analyzer (FSWP8, R&S), and shown in Fig. 4(a) and Fig. 4(b), respectively.

From (1) and the measured phase noises of the 6.83468GHz microwave frequency signal given in Fig. 4(b), the Dick effect contribution to the clock short-term instability can be calculated as $5.5\times10^{-14}\tau^{-1/2}$, which is conductive to guarantee the clock short-term stability at the level of 10^{-13} and is comparable with those of other laboratories [1], [9], [10] for the rubidium atomic clocks. Other relevant performance characteristics of the synthesizer are listed in the Table I. We can find that the measurement results meet the design requirements well.

TABLE I
MICROWAVE SYNTHESIZER PERFORMANCE CHARACTERISTICS

Characteristics	Requirements	MEASUREMENTS
Phase noise	< -70dBc/Hz @ 10Hz < -90dBc/Hz @ 100Hz < -110dBc/Hz @ 1kHz < -120dBc/Hz @ 10kHz	-60dBc/Hz @ 10Hz -92dBc/Hz @ 100Hz -122dBc/Hz @ 1kHz -125dBc/Hz @ 10kHz
Output Frequency	*Range:* 6.834682GHz±10kHz *Resolution:* 50mHz	6.8346726109~ 6.8346926109GHz 10mHz
Output Power	*Range:* -50dBm~0dBm *Resolution:* 0.1dBm	-50dBm~0dBm 0.1dBm
Isolation	30dB	~30dB
Switching Time	1 μs	500ns

IV. CONCLUSIONS

We have designed and implemented a dedicated microwave synthesizer based on the combination of the DDS and PLL techniques for the engineering prototype of the POP rubidium atomic clock. A 6.834GHz microwave frequency signal with 30dB output isolation and 1μs switching time for interrogating atoms is generated from the 10MHz LO and through the synthesis chain, whose power is tunable with 0.1dBm resolution and ranges from -50dBm to 0dBm. The phase noises of the output 6.8GHz signal were measured to be -92dBc/Hz at 100Hz, -122dBc/Hz at 1kHz and -125dBc/Hz at 10kHz, which resulted in a tolerable short-term instability contribution of $5.5\times10^{-14}\tau^{-1/2}$ to our clock. The low-noise home-made synthesizer with a small size (1.28L) is of great significance to the compact rubidium atomic clock.

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