State-of-the-Art RF Signal Generation From Optical Frequency Division

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***Abstract*—We present the design of a novel, ultralow-phase-noise frequency synthesizer implemented with extremely-low-noise regenerative frequency dividers. This synthesizer generates eight outputs, viz. 1.6 GHz, 320 MHz, 160 MHz, 80 MHz, 40 MHz, 20 MHz, 10 MHz and 5 MHz for an 8 GHz input frequency. The residual single-sideband (SSB) phase noises of the synthesizer at 5 and 10 MHz outputs at 1 Hz offset from the carrier are −150 and −145 dBc/Hz, respectively, which are unprecedented phase noise levels.**

We also report the lowest values of phase noise to date for 5 and 10 MHz RF signals achieved with our synthesizer by dividing an 8 GHz signal generated from an ultra-stable optical-comb-based frequency division. The absolute SSB phase noises achieved for 5 and 10 MHz signals at 1 Hz offset are −150 and −143 dBc/Hz, respectively; at 100 kHz offset, they are −177 and −174 dBc/Hz, respectively. The phase noise of the 5 MHz signal corresponds to a frequency stability of approximately 7.6×10^{-15} at 1 s averaging time for a measurement bandwidth (BW) of 500 Hz, and the integrated timing jitter over 100 kHz BW is 20 fs.

I. Introduction

Low-noise microwave and RF oscillators are needed for applications such as radar [1], surveillance [2], private communications, global-navigation satellite services such as the Global Positioning System (GPS) [3], atomic-fountain clocks [4], phase noise metrology, and calibration [5], [6]. State-of-the-art phase noise performance at a few widely used frequencies of the RF spectrum, such as 5, 10, and 100 MHz, is currently achieved with quartz crystal oscillators [7]–[9]. A different approach to generating ultralow-noise signals is to divide the frequency of an oscillator operating at higher microwave frequencies. Several emerging and existing technologies that produce these ultralow-phase-noise microwave and RF signals generate them either from the optical-comb-based frequency division of a cavity-stabilized laser [10]–[13], or from a cryocooled sapphire microwave oscillator [14], [15]. Frequency division by N theoretically reduces the signal phase noise by N^2. Therefore, by dividing an ultralow-noise microwave signal that has SSB phase noise $\mathcal{L}(1\ \text{Hz}) = -104$ dBc/Hz at 10 GHz [11], a very-low-noise RF signal can potentially be generated. An ideal division of this signal should produce $\mathcal{L}(1\ \text{Hz}) = -170$ dBc/Hz at 5 MHz. Although this ideal phase noise level may be below that of the best current technology, such ultralow-noise levels could enable future applications in precision timing, navigation, or sensing. Moreover, it is important to test and understand the absolute limits of the best optical and electronic frequency division [15].

Electronic frequency dividers are important building blocks used in a wide variety of microwave and RF system designs. One form of divider, the regenerative frequency divider (RFD), is particularly useful for trying to achieve the lowest phase noise frequency synthesis [16]–[20]. RFDs can attain residual phase noise lower than that of other analog and digital configurations [21].

In this paper, we describe the design and implementation of an ultralow-phase-noise frequency synthesizer for generation of low-noise RF signals. We report the lowest values of phase noise to date for 5 and 10 MHz RF signals. These signals are obtained by dividing an ultralow-phase-noise 8 GHz microwave signal by use of digital dividers and state-of-the-art analog RFDs [20]. The 8 GHz signal is generated from a cavity-stabilized laser via a Ti:sapphire-based optical frequency divider (OFD) [11]. Section II describes the design and architecture of the synthesizer and briefly discusses the working principles of an OFD and RFD. In Section III, the techniques for residual and absolute phase noise measurements are discussed. The results of the residual phase noise of the entire frequency synthesizer and the absolute phase noise of two synthesized signals at 5 and 10 MHz are reported. Estimated Allan deviation and jitter for these signals are also provided in this section. Finally, some concluding remarks are presented in Section IV.

II. Description of the Frequency Synthesizer

Our implementation of a frequency synthesizer comprises an OFD and a combination of digital dividers and analog RFDs, as shown in Fig. 1. The input signal at 8 GHz is generated from a cavity-stabilized, self-referenced, 1-GHz Ti:sapphire mode-locked laser [11]. The first two stages of the synthesizer are digital dividers and the remaining six are RFDs. Custom-built mixers are used in the final three frequency division stages. This synthesizer generates eight outputs, viz., 1.6 GHz, 320 MHz, 160 MHz, 80 MHz, 40 MHz, 20 MHz, 10 MHz, and 5 MHz when an 8 GHz signal is applied at the input. The synthesizer operates

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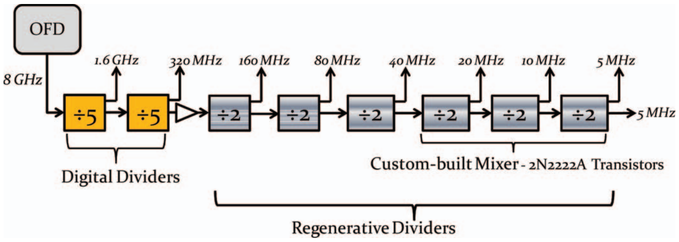

Fig. 1. Block diagram of the frequency synthesizer. OFD = optical frequency divider.

at input powers ranging from −5 dBm to +10 dBm, and the output power of synthesized signals ranges between +12 dBm and +14 dBm. A digital divider at the input is beneficial because it reduces the amplitude-modulated (AM) noise of the 8 GHz signal. One major advantage of this design over other low-noise synthesis schemes [14], [15] is that there is no requirement for a phase-locked loop (PLL).

A. Optical Frequency Divider

An ultra-stable 8 GHz signal for our synthesizer is generated from an optical frequency comb, as shown in Fig. 2(a). The frequency comb is a mode-locked Ti:sapphire ring laser that produces a femtosecond pulse train at a repetition rate of 1 ns, or a comb of optical frequencies with a frequency spacing f_r of 1 GHz. The frequency comb spectrum is stabilized by phase-locking the nth comb element to an optical reference v_{opt} [22], [23] while simultaneously stabilizing the laser offset frequency, f_o [10]. This transfers the stability of the optical reference to the comb mode spacing $f_r = (v_{opt} - f_o)/n$, where n is an integer of the order of 10^5 to 10^6. When these pulses are detected by the photodetector, it produces a comb of microwave frequencies with 1 GHz spacing within the photodetector bandwidth. The desired 8 GHz comb-tooth frequency is selected with a band-pass filter. For reference, the phase noise of this signal is shown in Fig. 2(b).

B. Regenerative Frequency Divider (RFD)

Fig. 3(a) provides the basic block diagram of a regenerative divide-by-2 circuit, which consists of a mixer, amplifier, phase shifter, and low-pass filters. A regenerative divide-by-2 multiplies the input signal (ν_0) with the feedback signal ($\nu_0/2$) from the mixer. This produces sum ($3\nu_0/2$) and difference ($\nu_0/2$) frequencies at the output of the mixer. A low-pass filter (LPF) after the mixer removes the undesired sum frequency, and the $\nu_0/2$ frequency is amplified and fed back into the mixer. A second LPF after the loop amplifier removes the thermal noise generated by the amplifier at $3\nu_0/2$ [18]. The output-referred double-sideband (DSB) residual phase noise of the divider is given by [18], [19]

$$S_\varphi(f)_{\mathrm{Div}} = \frac{\sum S_\varphi(f)_{\mathrm{comp}}}{N^2}\,\mathrm{rad}^2/\mathrm{Hz}, \quad (1)$$

where $S_\varphi(f)_{\mathrm{comp}}$ is the DSB phase noise of the loop components and N is equal to 2.

In an RFD, the dominant sources of noise are the mixer and the loop amplifier. Improving the noise of these components can dramatically improve the performance of the RFD. Our design uses a custom-built mixer in the last three RFD stages of the synthesizer. It is a double-balanced mixer (DBM), in which the diode ring is formed by connecting the collector and base of four 2N2222A bipolar junction transistors, as shown in Fig. 3(b) [24]. The low flicker ($1/f$) noise of the 2N2222A transistor makes it a very good candidate to be used as a nonlinear element of a DBM. Our previous work has shown that this design has lower $1/f$ noise than most commercially available DBMs for phase detection at 5 MHz [25]. The improved noise performance of this custom-built mixer translates directly to the superior noise performance of the RFD

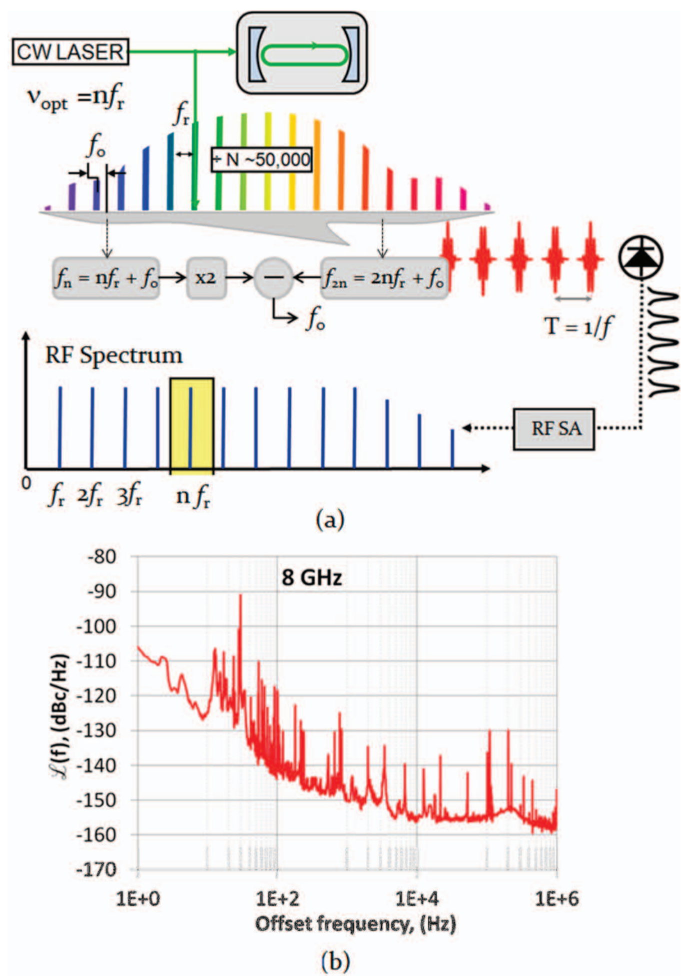

Fig. 2. (a) Schematic of mode-locked Ti:sapphire based optical frequency divider (OFD). RF SA = radio frequency spectrum analyzer. (b) Phase noise of 8-GHz comb-tooth.

TABLE I. List of Components Used in The Frequency Synthesizer.

Component	Manufacturer, model number	Output frequency
Divide-by-5	Hittite Microwave, HMC-C069	1.6 GHz
Divide-by-5	Hittite Microwave, HMC394LP4	320 MHz
Divide-by-2	Wenzel Associates Inc., LNRD7-320-10-15	160 MHz
Divide-by-2	Custom regenerative divider Mixer – Mini-circuits, ADE-1MH	80 MHz, 40 MHz
Divide-by-2	Amplifier–RFMD, RF2312 Custom regenerative divider Mixer–Custom mixer made with 2N2222A transistors in a diode ring Amplifier–RFMD, RF2312	20 MHz, 10 MHz, 5 MHz

over previous designs [20]. The loop amplifier in the RFD is a commercially available low-noise amplifier. The gain, noise figure (NF), and output power at the 1 dB compression point of the amplifier are 15 dB, 4 dB, and 20 dBm, respectively. In an RFD, the loop gain is limited by either the mixer, the amplifier, or both. In our divider design, the mixer operates in compression and thus limits the loop gain. Table I provides the list of components used in our frequency synthesizer (Fig. 1).

III. Measurement Techniques and Results

A. Residual Phase Noise of Digital and Analog Dividers

To obtain the lowest possible phase noise for the synthesizer, we built various regenerative divide-by-2 circuits to evaluate for lowest noise performance. These RFDs operate at an input frequency of 10 to 160 MHz. Commercial dividers are used for frequencies higher than 160 MHz (See Table I). To measure the noise of a single divider, we make phase noise measurements between the divider under test (DUT) and two independent, but like, dividers. This technique, known as a cross-spectrum phase noise measurement system, is shown in Fig. 4 [26]. The phase shifters establish phase-quadrature (90°) between two signals at the phase detector (PD) inputs. The output of each PD after amplification is analyzed with a two-channel cross-correlation fast-Fourier-transform (FFT) spectrum analyzer. Each PD produces voltage fluctuations that represent a joint contribution of uncorrelated phase fluctuations of the DUT and the reference divider. Computing the cross-spectral density of voltage fluctuations between two channels improves spectral resolution of noise measurements by reducing the effect of uncorrelated noise sources in each channel by $\sqrt{m}$, where m is the number of averages of the FFT. This technique reduces the noise floor of the measurement system to a level sufficiently low that the phase noise of DUT can be measured accurately.

Table II summarizes the residual phase noise of the dividers and the estimated absolute phase noise of eight synthesized signals. An approximate fit to the measured output-referred DSB residual phase noise of the divider is given by

$$S_\varphi(f)_{\mathrm{Div}} = b_1 f^{-1} + b_0 \ \mathrm{rad}^2/\mathrm{Hz}, \tag{2}$$

where b_1 and b_0 are, respectively, the coefficients for flicker phase and white phase noise. The SSB phase noise in decibels can then be written as

$$\begin{aligned}\mathcal{L}(f)_{\mathrm{Div}} &= 10\log\left[\frac{1}{2}S_\varphi(f)_{\mathrm{Div}}\right]\\ &= 10\log\left(\frac{b_1}{2}f^{-1} + \frac{b_0}{2}\right) \ \mathrm{dBc/Hz}.\end{aligned} \tag{3}$$

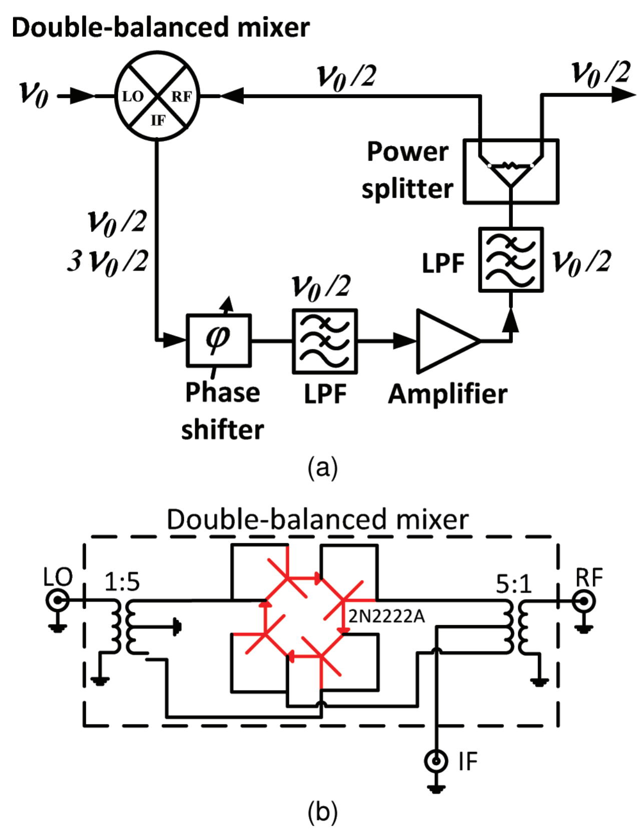

Fig. 3. (a) Block diagram of the regenerative frequency divide-by-2. (b) The custom-built double-balanced mixer. The diode ring is constructed by connecting the collector and base of four 2N2222A bipolar junction transistors.

TABLE II. Estimation of Absolute Phase Noise of the Synthesized Signals.

Divider stage i	Output frequency (MHz)	Division ratio (N)	Fit to the measured output-referred SSB residual phase noise of a single divider $\mathcal{L}(f)_{\mathrm{Div}} = 10\log\left(\frac{b_1}{2}f^{-1} + \frac{b_0}{2}\right)$, (dBc/Hz): $10\log(b_1/2)$ (dB)	$10\log(b_0/2)$ (dB)	Estimated SSB absolute phase noise of synthesized signal $\mathcal{L}(1\text{ Hz})_{\mathrm{abs}}$ (dBc/Hz)
1	1600	5	−123	−154	−118
2	320	5	−123	−154	−123
3	160	2	−138	−170	−128
4	80	2	−142	−179	−133
5	40	2	−142	−178	−138
6	20	2	−153	−178	−143
7	10	2	−153	−178	−148
8	5	2	−153	−178	−150

The values of the coefficients b_1 and b_0 for individual dividers are presented in columns 4 and 5 of Table II. For each custom-built RFD, the loop delay and input power to the mixer and loop amplifier are optimized for achieving the lowest phase noise at the divider output [17]. The residual noise of these RFDs for output frequencies below 20 MHz is approximately equal to −153 and −178 dBc/Hz at 1 Hz and 100 kHz offset frequencies. This $1/f$ noise level achieved with our custom-built dividers using 2N2222A transistors is 10 to 15 dB better than any commercial divider available at these frequencies [20], [27].

Once the residual noise of each individual divider is measured, we can estimate the absolute phase noise of the eight synthesized signals, as indicated in Fig. 1. If $S_\varphi(f)_{\mathrm{Div}_i}$ is the output-referred DSB residual phase noise of the ith divider, then the DSB absolute noise, $S_\varphi(f)_{\mathrm{abs}_i}$, of the ith synthesized signal is given by

$$S_\varphi(f)_{\mathrm{abs}_i} = \frac{S_\varphi(f)_{\mathrm{abs}_{i-1}}}{N_i^2} + S_\varphi(f)_{\mathrm{Div}_i}\mathrm{rad}^2/\mathrm{Hz}. \quad (4)$$

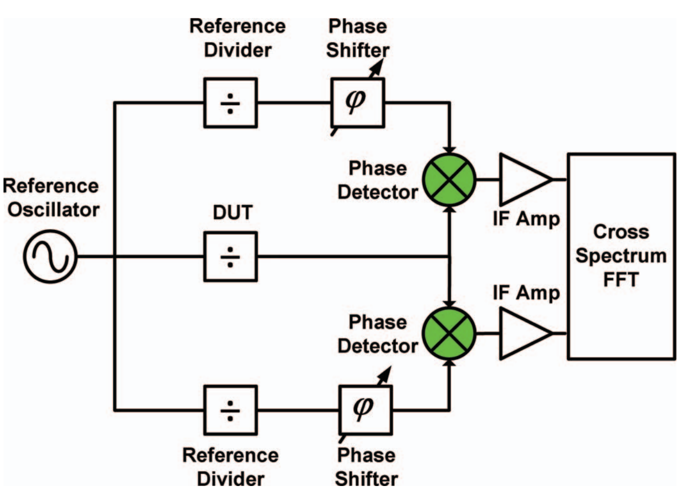

Fig. 4. Experimental set-up for the divider phase noise measurement. DUT = divider under test; IF AMP = intermediate frequency amplifier; FFT = fast Fourier transform.

The estimated absolute phase noise of the synthesized signals is given in column 6 of Table II for an 8 GHz input signal with $\mathcal{L}(1\text{ Hz}) = -106$ dBc/Hz.

An ideal division by 1600 should reduce the noise by 64 dB, and we should achieve −170 dBc/Hz for 5 MHz at a 1 Hz offset. From Table II, it is clear that because of the electronic noise limits it is not possible to achieve this noise level with the technologies currently available at RF frequencies and implemented in this setup. Further, combining the residual phase noise of each divider with (4) indicates that for any oscillator at 8 GHz with $\mathcal{L}(1\text{ Hz}) \leq -96$ dBc/Hz, a SSB noise level of −150 dBc/Hz at 5 MHz can be achieved if a frequency synthesizer is built from these dividers.

B. Residual Phase Noise of the Frequency Synthesizer

We built two identical synthesizers similar to that illustrated in Fig. 1. A common 8 GHz input signal from a commercial signal generator is applied to both synthesizers and the residual noise is measured at the output of each stage. A cross-spectrum measurement system as shown in Fig. 5 is used; this configuration measures the phase noise of a pair of synthesizers, unlike the configuration in Fig. 4, which measures the noise of a single divider. An image of the prototype of two synthesizers and the measurement setup is shown in Fig. 6. The residual noise of a pair of frequency synthesizers at different outputs is shown in Fig. 7. In the case of ideal frequency division by N, the phase noise of a signal decreases by N^2 or $20\log(N)$ in decibels. Thus, for a division by 2, a 6 dB reduction in noise is expected if the signal noise at the input of the divider is not affected by the divider noise. Fig. 7 shows that there is a 6 dB reduction in noise for most divider stages. However, the noise at 10 MHz output is higher than anticipated, although the measured residual noise of the divider itself is $\mathcal{L}(1\text{ Hz}) = -153$ dBc/Hz (Table II). This may be caused by interaction of this dividing stage with the pre- and post-dividing stages.

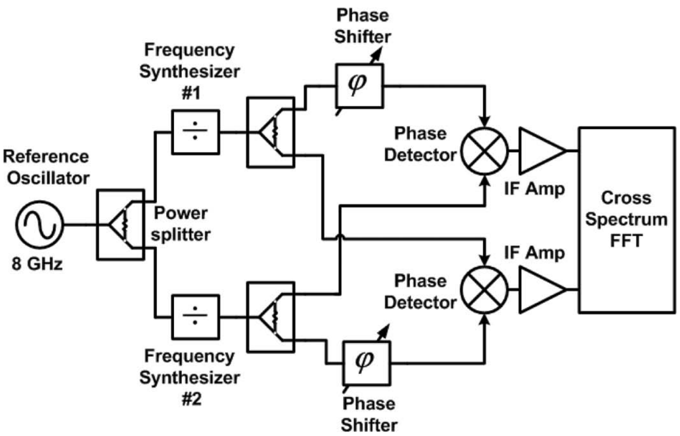

Fig. 5. Experimental setup for the residual phase noise measurements for a pair of frequency synthesizers.

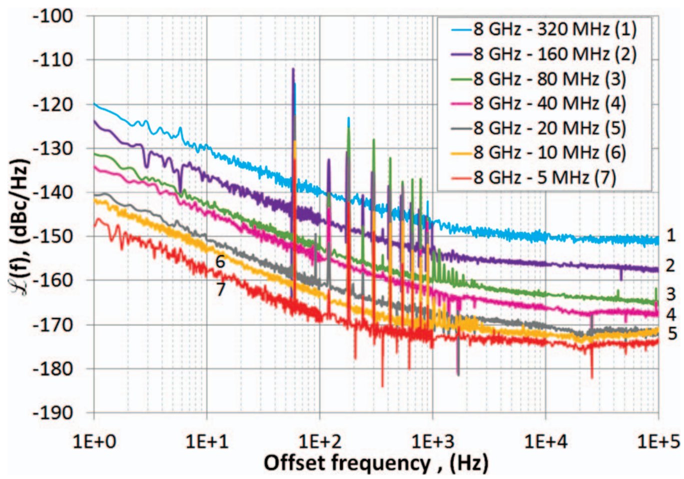

Fig. 7. Residual single-sideband phase noise of a pair of synthesizers at different output frequencies for 8 GHz input. For several stages, the phase noise slope between 1 and 10 Hz offsets is 1 to 2 dB steeper than $1/f$. This is due to thermal fluctuations and vibration disturbances of the laboratory environment.

At the final two stages, the residual noises at 1 Hz offset for a pair of synthesizers are −147 and −143 dBc/Hz for 5 and 10 MHz, respectively. Note that the phase noises of two digital dividers ($\div$ 5) in the synthesizer are equal (Table II). The second divider prevents the ideal noise reduction by N^2 (or 14 dB) and thus affects the performance of the entire synthesizer.

C. Frequency Stability of the Synthesizer

The residual Allan deviation, $\sigma_y(\tau)$, of a pair of synthesizers is measured at 5 MHz. The measurement setup is shown in the inset of Fig. 8. The measured $\sigma_y(\tau)$ of the synthesizers is below the noise floor of the best commercial time-domain measurement system [28] for an integration time $\tau < 10$ s. For comparison, $\sigma_y(\tau)$ is calculated from the residual frequency-domain measurements of Fig. 7 for $0.1 \text{ s} < \tau < 1$ s. The $\sigma_y(1 \text{ s})$ is estimated to be approximately 1.1×10^{-14} at the final output at 5 MHz for a pair of synthesizers, and the long-term stability at 1000 s is measured to be less than 1×10^{-15} for a measurement BW of 500 Hz. Under the assumption of equal and uncorrelated noise for the synthesizers, the result of Fig. 8 will be lower by a factor of $\sqrt{2}$ for a single divider, i.e., $\sigma_y(1 \text{ s}) = 7.6 \times 10^{-15}$.

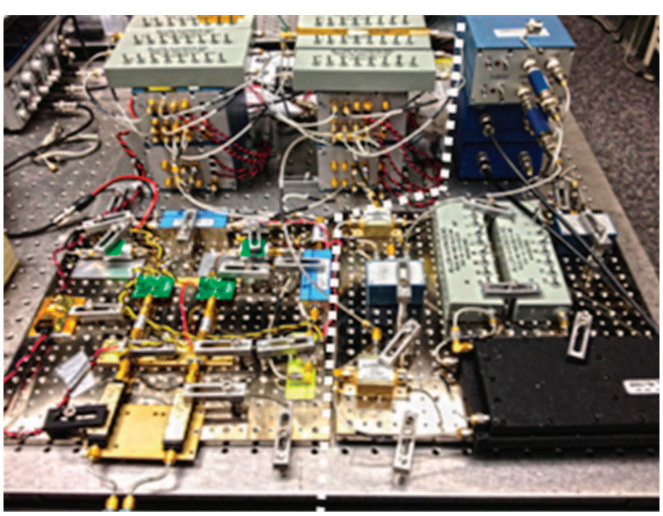

Fig. 6. Photograph of a pair of frequency synthesizers (left of the dashed line) and the measurement set-up (right of the dashed line).

D. Absolute Phase Noise Measurement

Absolute phase noise measurement includes the 8 GHz source noise. The 8 GHz signals for each synthesizer are generated from two similar but independent OFDs, each phase-locked to its own independent cavity-stabilized laser [22], [23]. The two-channel cross-spectrum analog phase noise measurement system is shown in Fig. 5. Usually, for an analog phase noise measurement of two oscillators, a PLL is required to keep two signals in phase quadrature [5]. However, in this case, the 8 GHz signals are so stable that once phase quadrature at 5 MHz has been set with a mechanical phase shifter, they remain in quadrature for 15 min (the entire measurement duration), thus eliminating the need for a PLL. The results of the absolute noise are shown in Figs. 9(a) and 9(b).

For one synthesizer, we achieve $\mathcal{L}(1 \text{ Hz}) = -150$ and −143 dBc/Hz and $\mathcal{L}(100 \text{ kHz}) = -177$ and −174 dBc/Hz, at 5 MHz and 10 MHz, respectively. These phase noise values correspond to a frequency stability of 7.6×10^{-15} at 1 s averaging time for a measurement BW of 500 Hz. The integrated timing jitter over 100 kHz bandwidth is 20 fs, an unprecedented jitter result at these carrier frequencies. The noise of the 5 MHz signal coincides with, and is limited entirely by the residual noise of the synthesizer. It also agrees with the estimated value given in Table II. However, for the 10 MHz case, the absolute close-to-carrier noise is a few decibels higher that the residual noise indicated by the black dashed line. This is due to the ground-loop effects that could not be completely mitigated for such sensitive measurements. The close-to-carrier phase noise and short-term instability at these frequencies

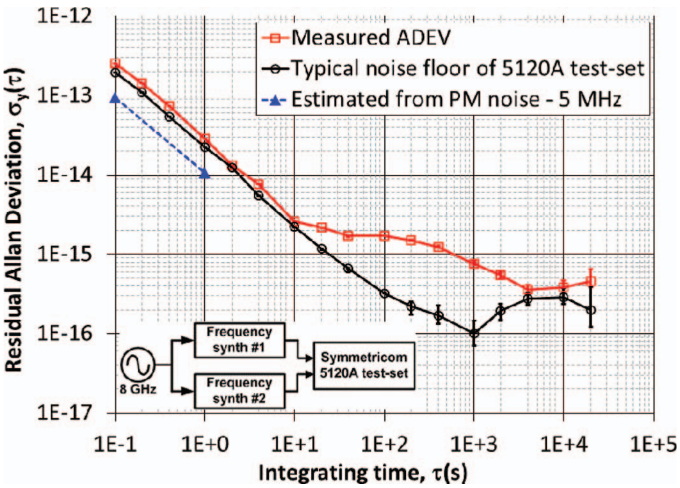

Fig. 8. Residual Allan deviation (ADEV) for a pair of synthesizers at 5 MHz output. The estimated ADEV is mapped from the measured residual phase noise. For a single synthesizer, the ADEV will be lower by a factor of $\sqrt{2}$. The synthesizer stability measurements after 2000 s are most likely limited by the temperature sensitivity of the 5120A measurement system. Measurement BW = 500 Hz.

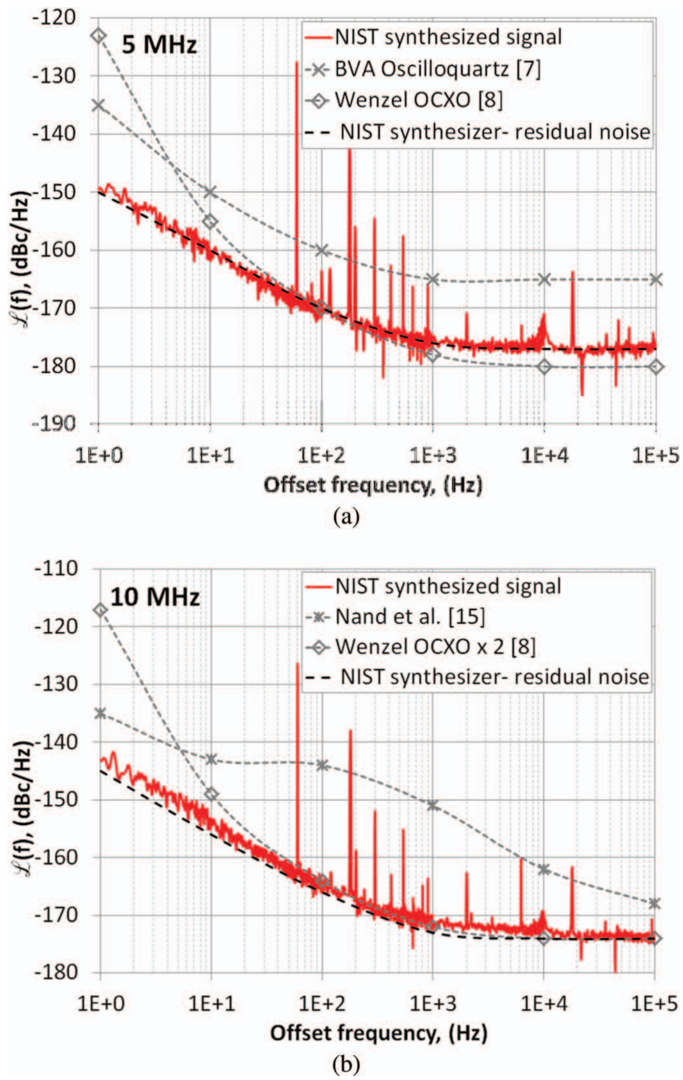

Fig. 9. Absolute phase noise of one synthesizer (grassy plots) measured at (a) 5 MHz and (b) 10 MHz outputs. For comparison, the phase noise of a few state-of-the art oscillators is shown. OCXO = oven controlled crystal oscillator, BVA = Boîtier à Vieillissement Amélioré. The number of fast Fourier transform (FFT) averages m chosen for each decade of frequency span (first decade is 1 to 10 Hz) are respectively 100, 200, 500, 1000, and 1000. The noise contribution of each synthesizer is almost equal; therefore, in the cross-spectrum measurement (Fig. 5) we observed only 3 to 5 dB improvement. The noise floor of the measurement system at 5 and 10 MHz (not shown here) for the same number of m is at least 10 to 15 dB lower.

generated from our frequency synthesizer are lower than those achieved with any other synthesizer or signal source. For comparison, the phase noise of two commercially available state-of-the-art oven-controlled crystal oscillators (OCXOs) at 5 MHz is shown in Fig. 9(a). The first oscillator is a high-stability Boîtier à Vieillissement Amélioré (BVA, improved-aging most advanced product) quartz oscillator [7] and the second oscillator is also an OCXO with ultralow thermal noise, designated as Wenzel OCXO [8]. The phase noises of these two oscillators are $\mathcal{L}(1\ \text{Hz}) = -135$ and -124 dBc/Hz, respectively, compared with -150 dBc/Hz for the NIST synthesized signal. Similar comparison of phase noise at 10 MHz is shown in Fig. 9(b), where the first signal is generated by multiplying the frequency of the Wenzel OCXO by 2 and the second 10 MHz signal is synthesized from a cryo-cooled sapphire microwave oscillator as reported by Nand *et al.* [15]. Figs. 9(a) and 9(b), respectively, indicate that at 1 Hz offset, the 5 and 10 MHz signals generated from NIST the synthesizer are at least 15 and 9 dB better than any reported signal source, either research or commercial.

The deleterious effect of amplitude-modulated (AM) noise leakage in the residual and absolute phase noise measurements [29] was carefully controlled and evaluated. The DSB AM noise of the divider output was measured to be $S_\alpha(f) = 10^{-13.3}f^{-1} + 10^{-16.7}$ at 5 MHz. The 2N2222A-based mixers used as PDs were evaluated for the AM-to-PM conversion. Over the entire range of the PD output voltage that does not saturate the IF amplifier, the 2N2222A-based PD showed a range of AM rejection between 28 and 50 dB. The interaction between correlated and anti-correlated noise sources in a cross-spectrum measurement can lead to underestimation of desired measured noise [30]. To avoid this effect, the same sign for the phase slope of both measurement PDs was selected. A Matlab simulation (The MathWorks Inc., Natick, MA) using the measured AM noise and the worst-case mixer AM rejection was performed and determined that the maximum errors resulting from AM leakage were +0.4 dB and −0.4 dB for positive and negative correlations, respectively.

IV. Conclusion and Discussion

We report the lowest values of phase noise to date for 5 and 10 MHz RF signals obtained by dividing an 8 GHz signal by means of a state-of-the-art frequency synthesizer. The 8 GHz signal is generated from a cavity-stabilized laser via Ti:sapphire-based OFD. The SSB absolute phase noises achieved for 5 and 10 MHz signals are $\mathcal{L}(1\ \text{Hz}) = -150$ and -143 dBc/Hz and $\mathcal{L}(100\ \text{kHz}) = -177$ and -174 dBc/Hz, respectively. This corresponds to a frequency stability of approximately 7.6×10^{-15} at 1 s averaging time and an integrated timing jitter of 20 fs over a 100 kHz bandwidth. This performance is entirely limited by the phase noise of the frequency dividers. The close-to-carrier phase noise and short-term instability at these frequencies generated from our frequency synthesizer are lower than those achieved with any other synthesizer or signal source.

This configuration of our synthesizer allows generation of many frequencies in addition to those already present in the chain. For example, by mixing the 80 MHz [$\mathcal{L}(1\ \text{Hz}) = -136$ dBc/Hz] and 20 MHz [$\mathcal{L}(1\ \text{Hz}) = -143$ dBc/Hz] outputs of our current system, the resulting 100 MHz signal will have phase noise at 1 Hz offset approximately equal to -135 dBc/Hz.

Further work will involve optimizing the noise of each stage of the frequency synthesizer. Currently, the noise of the second divide-by-5 stage (1.6 GHz divide-by-5) is limiting the noise of almost all following stages. We plan to replace this digital divider with a regenerative divide-by-5, thereby improving the overall performance of the synthesizer by at least a few decibels.

A fiber-based OFD with a 200 MHz repetition rate has shown scaled phase noise performance comparable to that of a Ti:sapphire-based OFD at 10 GHz [13]. In the future, we also plan to use Er:fiber-based OFDs for the generation of 5 and 10 MHz signals, instead of 8 GHz from Ti:sapphire-based OFD. However, it is unknown that at what RF frequency the flicker phase noise of the photodiodes [31]–[33] will dominate and limit the noise reduction from N^2. The optimal frequency of transition from optical division to analog regenerative division is dependent on the flicker noise performance of the photodiode and therefore must be studied further at these lower RF frequencies.

Acknowledgments

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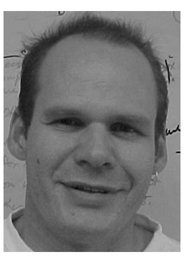

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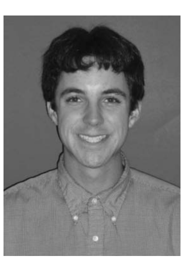

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Photographs and biographies of **Tara Fortier**, **Franklyn Quinlan**, **Jason DeSalvo**, and **Andrew Ludlow** were unavailable at time of publication.

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