

# Ultra-low-noise Regenerative Frequency Divider for High-Spectral-Purity RF Signal Generation

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**Abstract**—We implement an ultra-low-noise frequency divider chain from 8 GHz to 5 MHz that utilizes custom-built regenerative frequency divide-by-2 circuits. The single-sideband (SSB) residual phase-noise of this regenerative divider at 5 MHz output is -163 dBc/Hz at 10 Hz offset frequency. This level is achieved with custom-built mixers that use 2N2222A bipolar junction transistors in a conventional double-balanced diode ring. We report absolute phase-noise of radio-frequency (RF) signals at 10 MHz and 5 MHz obtained by dividing an 8 GHz signal generated from ultra-stable optical comb-based frequency division. The absolute SSB phase-noise for a 10 MHz and 5 MHz signal at 1 Hz offset is -143 dBc/Hz and -150 dBc/Hz, and at 100 kHz offset is -174 dBc/Hz and -177 dBc/Hz, respectively.

## I. INTRODUCTION

Frequency dividers are important building blocks used in a wide variety of microwave and radio-frequency (RF) system designs. One form of divider, the regenerative frequency divider, is very useful in low-phase-noise frequency synthesis [1-4]. These dividers can achieve lower residual phase-noise than other analog and digital dividers [5]. There are several emerging technologies that produce ultra-low phase-noise microwave and RF signals generated either from the optical comb-based division of a cavity-stabilized laser [6-8], or from a cryo-cooled sapphire microwave oscillator [9, 10]. Frequency division by  $N$  reduces the signal phase-noise by  $N^2$ . Therefore, by dividing an ultra-low-noise microwave signal that has SSB phase-noise,  $\mathcal{L}(f)$ , equal to -104 dBc/Hz at 10 GHz [7], a very-low-noise RF signal can potentially be generated. An ideal division of this signal should produce -170 dBc/Hz at 5 MHz. While this ideal phase-noise level may be below that of the best current technology, such ultra-low-noise levels could enable future applications in precision timing or navigation. Moreover, it is important to test and understand the absolute limits of optical and electronic frequency division.

In this paper, we begin by briefly describing a regenerative divide-by-2 circuit. This divider is designed with a custom-built mixer [11, 12], and we achieved  $\mathcal{L}(10 \text{ Hz})$  equal to -163 dBc/Hz, when the divider operates at input frequencies of 40 MHz and lower.

We also describe the design and implementation of an ultra-low noise frequency synthesizer (or divider chain) for generation of low-noise RF signals. These signals are

obtained by dividing an ultra-low phase-noise 8 GHz microwave signal with a combination of digital and analog regenerative dividers. The 8 GHz signal is generated via optical-comb frequency division [7].

## II. DESCRIPTION OF THE REGENERATIVE DIVIDER

The basic block diagram of a regenerative divider is shown in Fig. 1. It consists of a mixer, amplifier, low-pass filter and phase shifter. A regenerative frequency divider multiplies the input signal ( $f_{in}$ ) with the feedback signal ( $f_{in}/2$ ) from the mixer. This produces sum ( $3f_{in}/2$ ) and difference ( $f_{in}/2$ ) frequencies at the output of the mixer. A low-pass filter (LPF) is used after the mixer to remove the undesired sum frequency, and the  $f_{in}/2$  frequency is amplified and fed back into the mixer. A second LPF is used after the loop amplifier to remove the thermal noise generated by the amplifier at  $3f_{in}/2$  [3]. The phase-noise of the divider is given by [3, 4]

$$\mathcal{L}(f)_{Div} = \sum \mathcal{L}(f)_{comp} / N^2,$$

where  $\mathcal{L}(f)_{comp}$  is the phase noise of the loop components.

Our design uses a custom-built mixer. It is a double-balanced mixer with four 2N2222A bipolar junction transistors in the diode ring. The collector and base of each transistor are tied together to form a diode ring, as shown in the mixer block of Fig. 1. The loop amplifier is a commercially available low-noise amplifier. The gain, noise figure and output power at the 1 dB compression point of the amplifier are 15 dB, 4 dB and 20 dBm, respectively. In a regenerative divider, either the mixer or the amplifier, or both, need to operate in compression. In our divider design, it is the mixer that limits the loop gain. The residual flicker phase-noise of the mixer and the amplifier chosen for the divider are roughly equal.

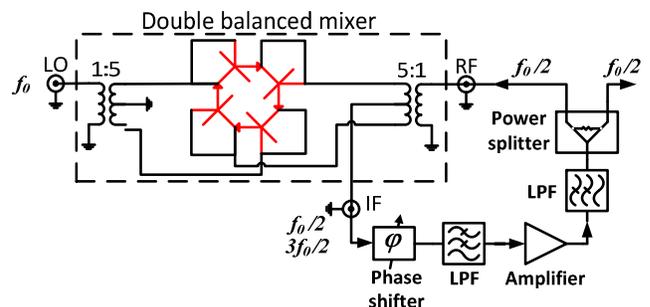


Figure 1. Block diagram of a regenerative divider. The diode ring in this double-balanced mixer is constructed by use of transistors with the collector input tied to the base.

### III. RESIDUAL PHASE-NOISE AND ALLAN DEVIATION OF THE REGENERATIVE DIVIDER

To start, we construct regenerative divide-by-2 circuits that operate at input frequencies of 20 MHz and 10 MHz and measure the residual phase-noise. In order to measure the noise of a single regenerative divider as a device under test (DUT), we build three similar dividers. A cross-spectrum measurement system [13] is designed with the same custom-built mixers implemented as phase detectors. The experimental set-up is shown in Fig. 2, and the noise floor of the measurement system is shown in Fig. 3.

The loop phase and amplitude of the DUT are optimized for the lowest noise [2]. The residual output referred phase-noise of a single divider,  $L(10 \text{ Hz})$ , is approximately equal to  $-163 \text{ dBc/Hz}$ , as shown in Fig. 3. Its  $1/f$  noise level is almost 10 dB better than any commercial regenerative divider available at these frequencies.

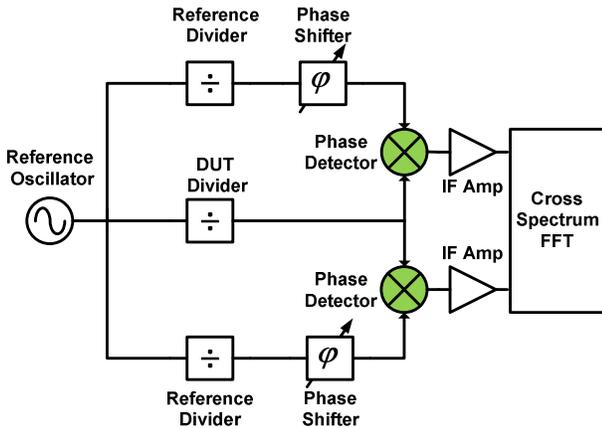


Figure 2. Experimental set-up for the divider phase noise measurement. IF AMP- Intermediate Frequency Amplifier, FFT - Fast Fourier Transform.

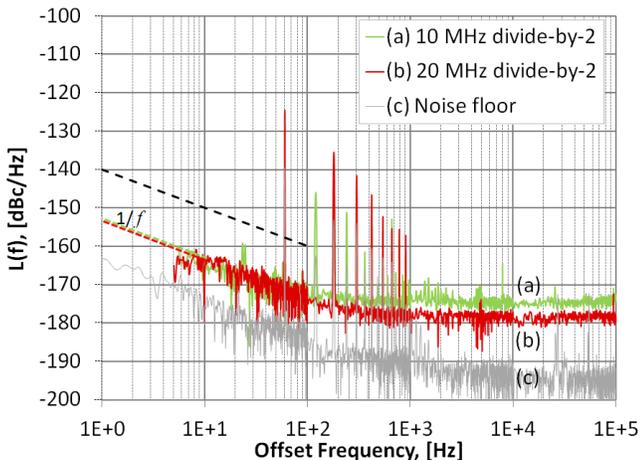


Figure 3. Single-sideband output referred phase-noise of the regenerative divider. (a) 10 MHz divide-by-2 (b) 20 MHz divide-by-2 (c) Noise floor. Dashed line is the typical noise of commercial regenerative dividers.

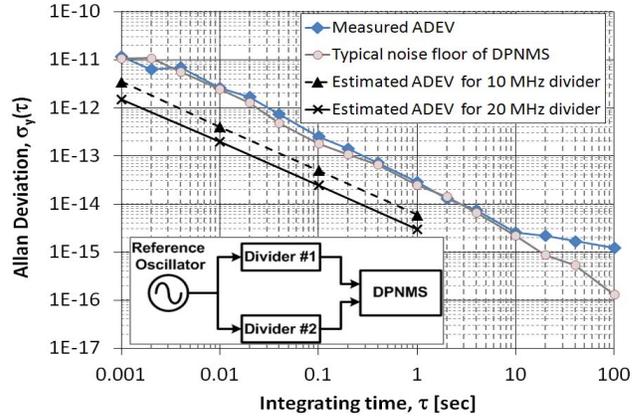


Figure 4. Residual Allan deviation (ADEV) of 10 MHz and 20 MHz divide-by-2 circuits. The estimated ADEV is mapped from the measured phase noise. The inset shows the set-up for measuring  $\sigma_y(\tau)$  of a pair of dividers. DPNMS - Digital Phase-Noise Measurement System.

To get an idea of the divider's performance in timing applications, the residual Allan deviation,  $\sigma_y(\tau)$  of a pair of dividers is measured at 10 MHz and 5 MHz with a digital phase-noise measurement system that computes the Allan deviation [14]. The measurement set-up is shown in the inset of Fig. 4. The measured  $\sigma_y(\tau)$  of both dividers is lower than the noise floor of the measurement system for an integration time  $\tau < 10 \text{ s}$ . For  $1 \text{ ms} < \tau < 1 \text{ s}$ ,  $\sigma_y(\tau)$  mapped from the residual phase-noise of Fig. 3 is shown. The  $\sigma_y(\tau)$  at 0.1 s is estimated to be  $5 \times 10^{-14}$  for a 10 MHz divider and  $3 \times 10^{-14}$  for a 20 MHz divider, as shown in Fig. 4.

### IV. DESIGN AND IMPLEMENTATION OF AN ULTRA-LOW NOISE FREQUENCY SYNTHESIZER

The block diagram of a frequency synthesizer based on optical frequency comb divider (OFC) and a combination of digital and analog regenerative dividers is shown in Fig. 5. The input signal at 8 GHz is generated from a cavity-stabilized, self-referenced, 1 GHz Ti:sapphire mode-locked laser [7]. The first two stages of the synthesizer are digital dividers and the remaining six dividers are regenerative. The custom-built mixers are used in the final three 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. Several other frequencies can be generated by mixing two signals; for example, a 100 MHz signal can be obtained by mixing 80 MHz and 20 MHz. The synthesizer operates at input powers anywhere between  $-5 \text{ dBm}$  and  $+10 \text{ dBm}$  and the output power level of all stages is approximately 11 dBm. An advantage of having a digital divider at the input is that it reduces the amplitude-modulated (AM) noise of the 8 GHz signal.

We built two identical divider chains similar to that shown in Fig. 5 and measured the residual phase-noise of the entire chain at 10 MHz and 5 MHz outputs. The results are shown in Fig. 6 in dotted lines. The SSB residual noise at 1 Hz offset is  $-150 \text{ dBc/Hz}$  and  $-146 \text{ dBc/Hz}$ .

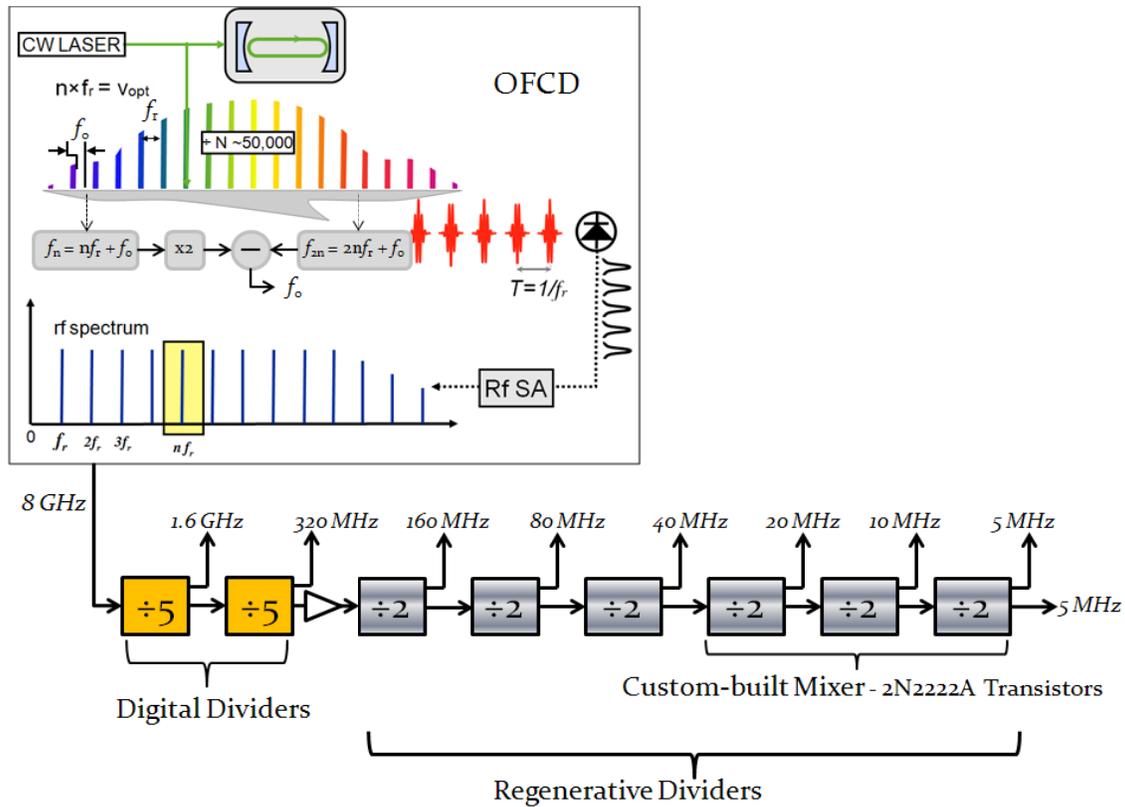


Figure 5. Block diagram of the frequency synthesizer. OFCD – Optical frequency comb divider.

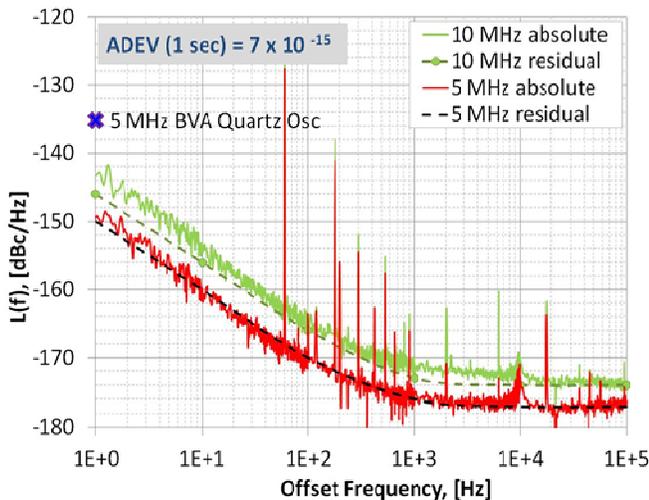


Figure 6. Absolute phase-noise of the synthesized signals at 5 MHz and 10 MHz. The dashed lines represent the residual phase-noise of the divider chain.

In addition to residual noise, the absolute phase-noise of the synthesized 5 MHz and 10 MHz signals is also measured. The 8 GHz signals for each divider chain are generated from two similar but independent OFCDs, each phase-locked to its own independent cavity-stabilized lasers [15, 16]. The results of the absolute noise are shown in Fig. 6. We achieve a SSB absolute phase-noise of  $L(1 \text{ Hz}) = -143 \text{ dBc/Hz}$  and  $-150 \text{ dBc/Hz}$  and  $L(100 \text{ kHz}) = -174 \text{ dBc/Hz}$  and  $-177 \text{ dBc/Hz}$  for

10 MHz and 5 MHz signals, respectively. This corresponds to a frequency stability of  $7 \times 10^{-15}$  at 1 s averaging time. The noise of the 5 MHz signal coincides with and is limited by the divider noise. However, in the 10 MHz case, the absolute noise close-to carrier is a few decibels higher than the residual noise indicated by the dashed line, due to unmitigated ground-loop effects. The close-to-carrier phase-noise and short-term instability at these frequencies generated from our frequency synthesizer are lower than that achieved with any other synthesizer or signal source. For comparison, the state-of-the-art high stability BVA<sup>1</sup> quartz oscillator at 5 MHz has phase-noise,  $L(1 \text{ Hz}) = -135 \text{ dBc/Hz}$  [17], almost 15 dB higher than the signal generated from optical division.

## V. CONCLUSION

We report an ultra-low-noise regenerative frequency divider. The low noise of the divider is achieved by use of custom-built mixers with 2N2222A bipolar junction transistors (BJTs) in a conventional double-balanced diode ring. We also report absolute phase-noise of RF signals at 10 MHz and 5 MHz obtained by dividing an 8 GHz signal generated from ultra-stable optical-comb-based frequency division. The SSB absolute phase-noise achieved for 10 MHz and 5 MHz signals is  $L(1 \text{ Hz}) = -143 \text{ dBc/Hz}$  and  $-150 \text{ dBc/Hz}$  and  $L(100 \text{ kHz}) = -174 \text{ dBc/Hz}$  and  $-177 \text{ dBc/Hz}$ , respectively. The close-to-carrier phase-noise and short-term

<sup>1</sup> Manufacturer is indicated for information. No endorsement is implied.

instability at these frequencies generated from our frequency synthesizer are lower than that achieved with any other synthesizer or signal source.

In the future, we would like to optimize the noise of each stage of the divider chain, package the entire divider chain in a rack-mount enclosure for improved long-term stability and environmental isolation.

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