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Ultra-Low-Noise Regenerative Frequency Divider

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***Abstract*—We designed ultra-low-noise regenerative divide-by-2 circuits that operate at input frequencies of 10, 20, and 40 MHz. We achieved output-referred single-sideband residual phase noise equal to −164 dBc/Hz at 10 Hz offset and estimated residual Allan deviation, $\sigma_y(\tau)$ less than $3 \times 10^{-15}\tau^{-1}$ for a single divider, which is, to our knowledge, the lowest noise of any divider ever reported at these frequencies. To measure such a low noise, we also built a cross-spectrum measurement system that has a noise floor of −175 dBc/Hz at 10 Hz offset from the carrier frequency. The low noise of the divider and the measurement system are achieved by using custom-built mixers/phase detectors that use 2N2222A bipolar junction transistors (BJTs) in a conventional double-balanced diode ring.**

I. Introduction

Frequency dividers are important building blocks used in a wide variety of microwave and radio-frequency system designs. One form of divider, the regenerative frequency divider, is very useful in low-phase-noise frequency synthesis [1]–[4]. These types of dividers can achieve lower residual phase noise than other analog and digital divider configurations [5]. There are several emerging technologies that produce ultra-low-phase-noise microwave signals generated either from the optical comb-based division of a cavity-stabilized laser [6], or from a cryocooled sapphire microwave oscillator [7], [8]. Frequency division by N reduces the signal phase noise by N^2. Therefore, by dividing an ultra-low-noise microwave signal that has single-sideband (SSB) phase noise, $\mathcal{L}(f)$, equal to −104 dBc/Hz at 10 GHz [6], a very-low-noise radio-frequency signal can be generated. An ideal division of this signal should produce −170 dBc/Hz at 5 MHz. Although 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 describe a regenerative divide-by-2 circuit operating at input frequencies of 10, 20, and 40 MHz that has the lowest residual phase noise ever reported. This divider is designed with a custom-built mixer [9], and we achieve SSB output-referred phase noise, $\mathcal{L}(10\text{ Hz}) \le -164$ dBc/Hz.

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, phase shifter, and low-pass filters. A regenerative frequency divider 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) is used after the mixer to remove the undesired sum frequency, and the $\nu_0/2$ 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 $3\nu_0/2$ [3]. The phase noise of the divider is given by [3], [4]

$$\mathcal{L}(f)_{\text{Div}} = \sum \mathcal{L}(f)_{\text{comp}}/N^2, \qquad (1)$$

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

Our design uses a custom-built mixer. It is a double-balanced mixer (DBM) with four 2N2222A bipolar junction transistors in the diode ring [9]. The collector and base of each transistor are connected together to form a diode ring, as shown in the mixer block of Fig. 1. Compared with many commercially available DBMs used for phase detection at 5 MHz, this design performs among the best [10]. The loop amplifier 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 a regenerative divider, the loop gain is limited by the mixer, the amplifier, or both. In our divider design, it is the mixer that operates in compression and thus limits the loop gain.

III. Experimental Results

To start, we built three prototype regenerative divide-by-2 circuits that operate at an input frequency of 10 MHz. The output power for these dividers is approximately +12 dBm. The phase noise of a single divider, the device under test (DUT), is measured against two similar reference dividers in a cross-spectrum measurement system [11], as shown in Fig. 2. In this system, the phase noise of the reference dividers, phase detectors (PD), and IF amplifiers are reduced by $\sqrt{m}$, where m is the number of averages in the fast Fourier transform (FFT) analyzer. The custom PDs are constructed with the same transistors used in the dividers.

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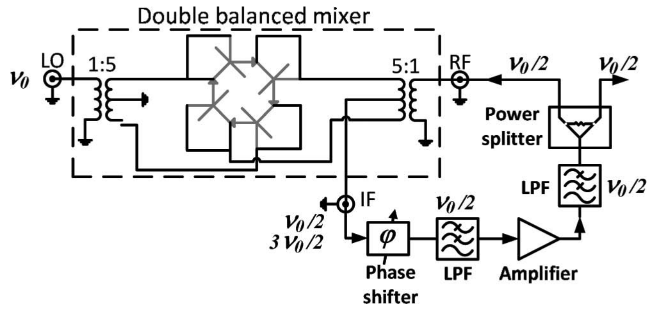

Fig. 1. Block diagram of the regenerative divider: The diode ring in this double-balanced mixer is constructed using transistors with the collector input connected to the base. $\nu_0 = 10$, 20, or 40 MHz.

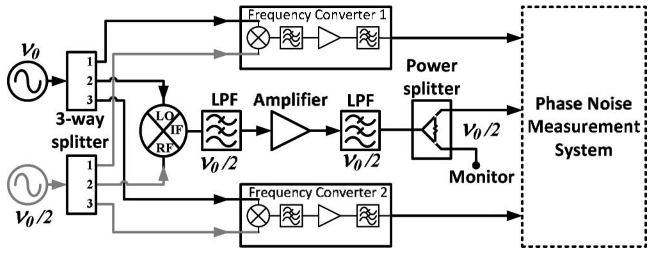

Fig. 3. Configuration for the mixer and amplifier noise measurement under open-loop condition: The phase noise measurement system is the same as that shown in Fig. 2.

In a regenerative frequency divider, the dominant sources of noise are the loop amplifier and the mixer. The noise of the entire feedback chain, comprising the mixer, amplifier, and filters, is measured under an open-loop configuration that replicates the closed-loop operating conditions, as shown in Fig. 3. The local oscillator (LO) and reference frequency (RF) ports of the mixer are kept at 10 and 5 MHz, respectively for this measurement. Inside frequency converter blocks 1 and 2, the mixers, filters, and amplifiers are arranged in a manner similar to that of the DUT's open-loop feedback circuit, shown in the middle of Fig. 3. The noise contribution of two oscillators and frequency converters 1 and 2 cancels out in the cross-spectrum measurement system. Trace A of Fig. 4 shows the combined component noise. The close-to-carrier flicker-noise is due to almost equal contributions from the mixer and the amplifier. However, the thermal noise is dominated solely by the amplifier, and it agrees to within 1 dB of what is expected from the input power and NF of the amplifier. The feedback loop is then closed and the phase noise of the divider is measured. The loop phase delay is optimized for the lowest noise [2] and $\mathcal{L}(10\ \text{Hz}) = -164$ dBc/Hz is achieved for a single divider at 5 MHz as shown in Trace B of Fig. 4. This value is almost 6 dB lower than the components' noise expected from (1), except at offset frequencies lower than 20 Hz. This disagreement is due to thermal fluctuations and vibration disturbances of the laboratory environment. Trace C shows the noise floor of the measurement system.

Similar tests are repeated for 20- and 40-MHz divide-by-2 circuits. Identical mixers and amplifiers are used, only the LPFs are replaced to provide appropriate cut-off values. The measured phase noise results are given in Table I; the performance of each divider is very similar and agrees well with the theory.

To get an idea of the divider's performance in timing applications, the estimated residual Allan deviation, $\sigma_y(\tau)$ of a single divider is calculated from phase noise. For 1 ms $< \tau <$ 1 s, $\sigma_y(\tau)$ is approximately $2.6 \times 10^{-15}/\tau$, $1.2 \times 10^{-15}/\tau$, and $6 \times 10^{-16}/\tau$ for 10-, 20-, and 40-MHz dividers, respectively. A measurement bandwidth of 500 Hz is used for the calculation of Allan deviation.

IV. CONCLUSION

We report an ultra-low-noise regenerative frequency divider. The divider is tested at three frequencies—10, 20, and 40 MHz—and we achieve SSB output-referred phase-noise, $\mathcal{L}(10\ \text{Hz}) \leq -164$ dBc/Hz and $\sigma_y(\tau)$ less than $3 \times 10^{-15}/\tau$. To our knowledge, this is the lowest phase noise,

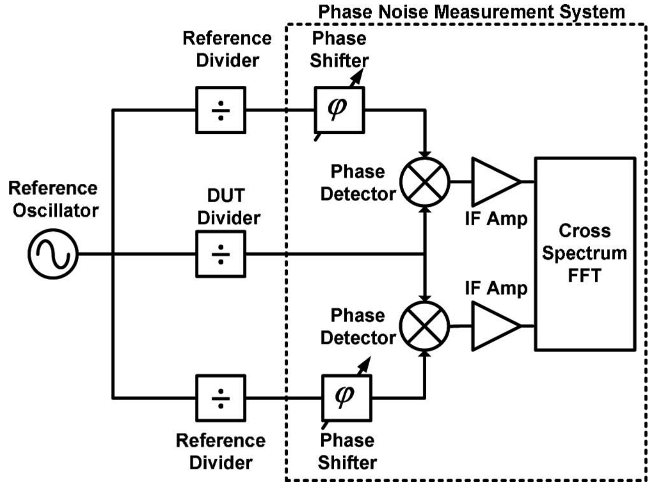

Fig. 2. Experimental setup for the divider phase noise measurement. IF Amp = intermediate frequency amplifier; FFT = fast Fourier transform.

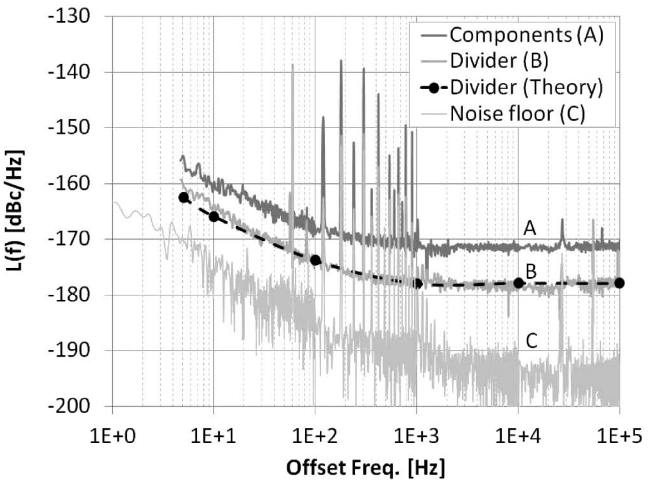

Fig. 4. Single-sideband residual phase noise at 5 MHz: Trace A = combined component noise; Trace B = output-referred noise of a 10-MHz divide-by-2 circuit; Trace C = noise floor of the measurement system.

TABLE I. Output-Referred Residual Phase Noise of Divide-by-2 Circuits.

Offset frequency [Hz]	$\mathcal{L}(f)$ [dBc/Hz] at $\nu_0/2$		
	$\nu_0 = 10$ MHz	$\nu_0 = 20$ MHz	$\nu_0 = 40$ MHz
10	−164	−164	−165
100	−174	−174	−175
1000	−178	−179	−178
10000	−178	−179	−178
100000	−178	−179	−178

and corresponding $\sigma_y(\tau)$, ever reported at these carrier frequencies. Although these regenerative dividers are robust, the phase noise close-to-carrier offset frequencies for these measurements show correlations to the environment. Vibration and temperature fluctuations are beginning to disturb the prototype setup during the long averaging time necessary for cross-correlation measurements. Isolation from environmental effects may lead to slightly improved results close to the carrier.

Currently, we are building a divider chain to divide the microwave signal from an optical comb divider [6], [12] to 5 MHz. We expect to achieve $\mathcal{L}$(10 Hz) of approximately −160 dBc/Hz at the final output stage of the chain.

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