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30 GHz Regenerative Frequency Divide-by-3

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***Summary* — We report the performance of a 30 GHz to 10 GHz regenerative frequency divider. The proposed divider design incorporates the conventional Miller regenerative frequency divider (divide-by-2) with an additional regenerative path. We achieve output referred phase modulation (PM) noise of $\mathscr{L}$(10 Hz) = −130 dBc/Hz and frequency stability of less than 1×10^{-15} at a 1-second averaging period for the proposed divider. We further improve the flicker PM performance of this divider by implementing a parallel amplifier configuration and achieve an output referred phase noise of $\mathscr{L}$(10 Hz) = −138 dBc/Hz and $\mathscr{L}$(10 kHz) = −162 dBc/Hz. We also present simulation results of the closed-loop PM and amplitude modulation (AM) noise performance of a regenerative divide-by-2 circuit.**

Keywords—frequency stability; regenerative divider; parallel-amplifier; phase noise

I. INTRODUCTION

Frequency dividers are important building blocks for frequency synthesis. Most frequency divider designs utilize digital technology. Digital dividers support wideband operation, are self-starting, and smaller in size but suffer from relatively high phase modulation (PM) noise. The analog regenerative frequency dividers (RFD) typically outperform the digital designs in terms of phase noise but are relatively narrowband, difficult to optimize for phase noise, and may not be self-starting under all conditions [1]–[8].

In this paper, we describe the design, implementation, phase noise, and time-domain performance of a low-phase noise 30 GHz divide-by-3 RFD.

II. PROPOSED DIVIDER SCHEME

A schematic diagram of the regenerative divide-by-3 is shown in Fig. 1. It comprises a regenerative divide-by-2 with an additional regenerative frequency mixing path. The output frequency ν_1 of the divide-by-2 is mixed with the input frequency ν_3 at Mixer1. The difference frequency ($\nu_2 = \nu_3 - \nu_1$) is selected using a bandpass filter and becomes the input for the regenerative divide-by-2 divider. For the divider to operate, the Barkhausen criteria needs to be satisfied. It states that the loop gain must be unity and that the total phase shift around the loop must be an integer multiple of 2π. Unlike a single-loop conventional Miller regenerative divider [1], which can be self-starting with thermal noise, our two-loop design requires an auxiliary signal to start the oscillation. In theory, it should be able to self-start under correct loop gain and phase conditions, but these conditions are harder to satisfy due to the double-loop nature of the system. To make this divider auto-start without needing an external signal we used a configuration where the auxiliary 10 GHz signal is provided by means of a digital divider that uses the 30 GHz input as shown in Fig. 1. We coupled out a portion of the input signal, divided the frequency by 3, and after required amplification fed the signal to the injection port via a coaxial switch. With this switch, we momentarily injected the 10 GHz signal to kick start the oscillation.

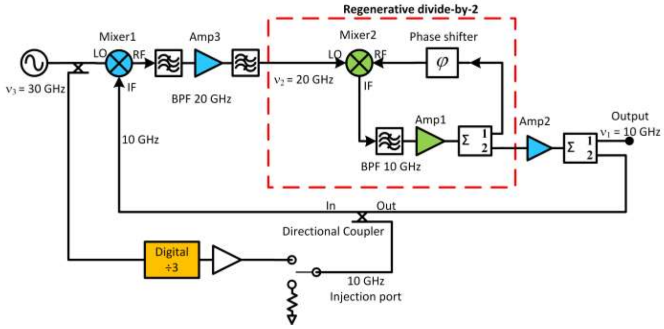

Fig. 1. Schematic diagram of the analog regenerative frequency divider (÷3) with auto-start configuration.

We compared the phase noise of the proposed analog regenerative divider in Fig. 1 with a commercial digital divider (*Microchip Prescaler - UXN40M7KE) and a custom-built hybrid frequency divider as shown in Fig. 2. In the hybrid divider configuration, the regenerative divide-by-2 of Fig. 1 is replaced with a digital divide-by-2. The 30 GHz signal is frequency mixed with the regenerated 10 GHz signal in the loop to generate 20 GHz. This 20 GHz signal is then divided by 2 to produce 10 GHz. Under the correct loop conditions, it results in a sustained oscillation and produces an output at 10 GHz which is one-third of the input frequency at 30 GHz. In contrast to the proposed analog ÷3 RFD, the hybrid divider is self-starting. In RFD, the regeneration initially starts from noise in the loop.

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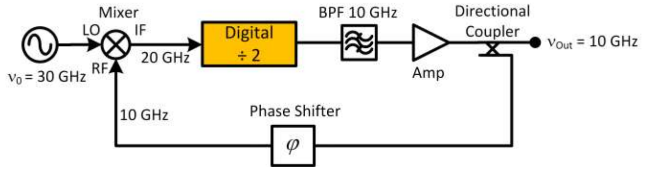


Fig. 2. Schematic diagram of a hybrid frequency divider (÷3).

III. PHASE NOISE MESUREMENT METHOD

For the residual phase noise measurement of the dividers, we used the two-channel cross-spectrum technique [8], [9]. The block diagram of the experimental setup is shown in Fig. 3. This method measures the combined noise of the two dividers. We used an AM/PM modulator to calibrate the phase detector sensitivity. The modulator was also used to optimize the measurement system for minimum AM sensitivity.

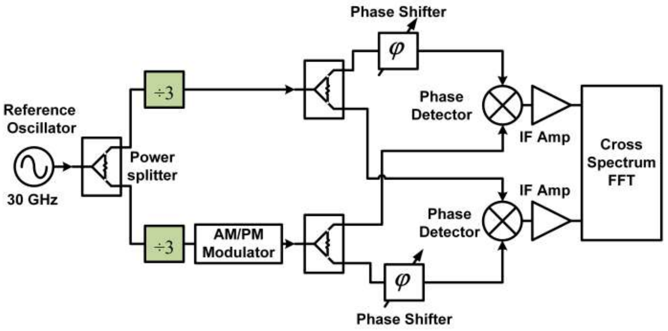


Fig. 3. Schematic diagram of the experimental setup for the residual phase noise measurements for a pair of frequency dividers. FFT – Fast Fourier Transform, AM – Amplitude modulation, and PM – Phase modulation.

IV. RESULTS

A. Phase Noise

The phase noise was measured for both ÷2 and ÷3 dividers for an input frequency of 20 GHz and 30 GHz, respectively. For the phase noise results provided in this paper, we assumed that the noise contributions of two quasi-identical dividers are equal, and we subtracted 3 dB from the measured noise to represent the noise of a single divider.

The output referred noise at 10 GHz for a single 20 GHz ÷2 is shown in Fig. 4 for both the digital divider and RFD. It illustrates that the RFD outperforms the digital divider at all offset frequencies from the carrier. Similarly, the phase noise of the 30 GHz ÷3 RFD was measured and shown in Fig. 5. Also shown is the phase noise of a single digital divider (*Microchip Prescaler-UXN40M7KE) and hybrid divider for comparison. The phase noise of the proposed RFD is lower than both the digital and hybrid dividers and significantly lower at higher offset frequencies. In our hybrid divider design, the dominant source of the noise was the digital ÷2 circuit. Typically, in a regenerative divider, the phase noise of the loop components reduces under correct phase conditions [2], [5], [6]. We see the effect of this in Fig. 5 where the phase noise of the hybrid divider is at least 5 dB to 6 dB lower than a fully digital divider.

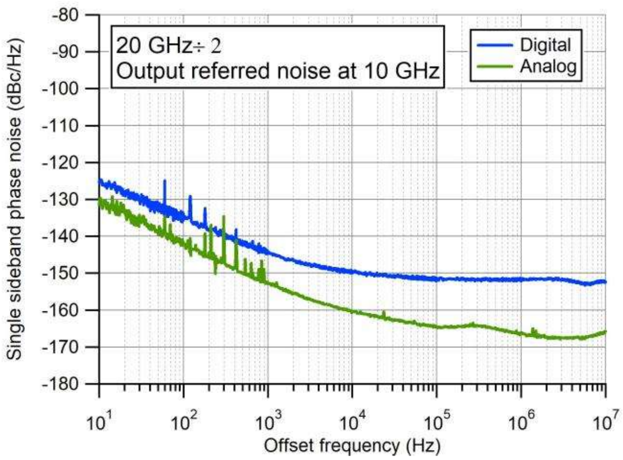


Fig. 4. Output referred residual phase noise of a single digital, and analog frequency dividers (÷2) at 10 GHz.

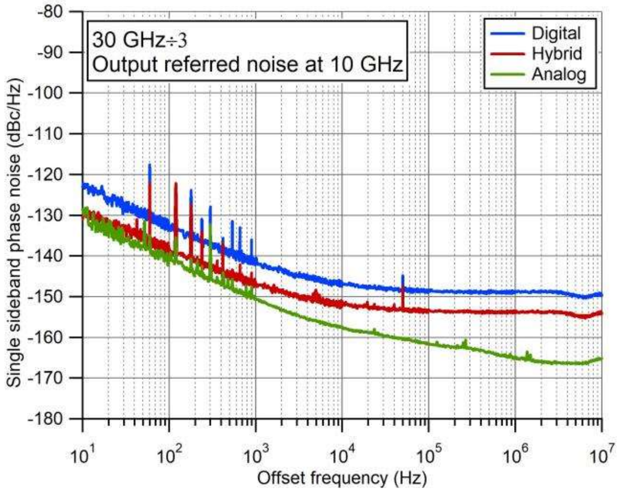


Fig. 5. Output referred residual phase noise of a single digital, analog, and hybrid frequency dividers (÷3) at 10 GHz.

B. Frequency Stability

Additionally, we measured the frequency stability of the regenerative dividers using the measurement scheme shown in Fig. 6a. The 30 GHz signal was first divided by 3 using the proposed regenerative divider and then divided by 100 with a commercial digital divider. The frequency stability was measured at 100 MHz using the *Symmetricom 5125A time-domain analyzer. We achieved a residual Allan deviation of 1×10^{-15} at a 1 second averaging period and approximately 2.2×10^{-18} at 100,000 seconds, as illustrated in Fig. 6b. The 1-second stability was limited by the measurement system's noise floor. The result in Fig. 6b is the combined performance of the RFDs and digital dividers. Assuming equal and uncorrelated noise for the dividers, the residual Allan deviation of a single divider chain will be lower by a factor of $\sqrt{2}$ [9]. The frequency stability measurements were conducted at room temperature of $20.5 \pm 3\ ^{\circ}$C.

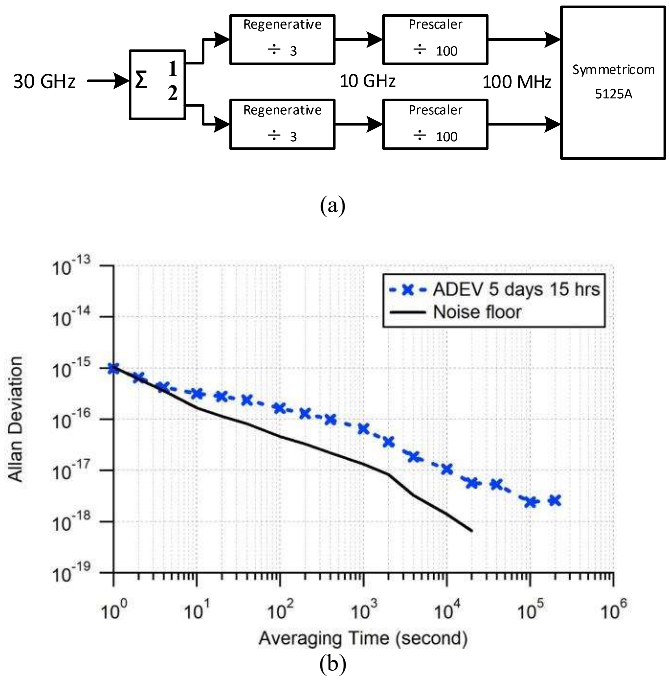


Fig. 6. (a) Schematic diagram of the measurement set-up. (b) Residual Allan deviation of a pair of analog plus digital dividers. Input Frequency = 30 GHz, Total division ratio, N = 300, and output frequency = 100 MHz.

C. Parallel Amplifier Configuration for Improving Phase Noise

The performance of the proposed RFD as shown in Fig. 4 and Fig. 5 (green curve) was limited by the phase noise of the loop amplifiers. It is known that the parallel amplifier configuration improves the flicker noise [10], so we used this approach. However, we decided to simplify our ÷3 RFD circuit. First, we removed 'Amp2', and reduced some of the losses in the loop by removing the two 20 GHz bandpass filters (BPFs). We also reconfigured 'Mixer1' such that the 20 GHz signal was now generated at the IF port instead of the RF port. Since the IF port of the mixer has a lower bandwidth than the LO and RF ports, it naturally provided the filtration that we were getting from the BPFs.

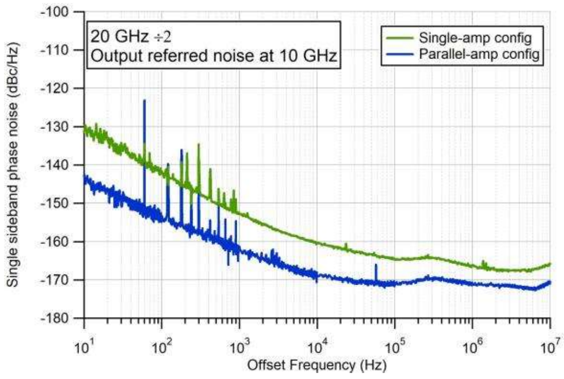


Fig. 7. Output referred phase noise at 10 GHz of a single RFD ÷2 using the parallel amplifier. The amplifiers for the parallel-amp and the single-amp configurations were of different types.

Once the divider circuit was simplified, we replaced 'Amp1' in Fig. 1 with a commercial parallel amplifier with following specifications: Frequency range = 8 GHz to 12 GHz, Gain = 17 B, Noise Figure (NF) = 8 dB, 1 dB compression point (P1dB) = +21 dBm, and $\mathscr{L}(1\text{ Hz}) \approx -132$ dBc/Hz.

This amplifier lowered the noise of the regenerative divide-by-2 (ν_2 = 20 GHz) by more than 13 dB at a 10 Hz offset frequency, as shown in Fig. 7. Unfortunately, this parallel amplifier works only in the X-band frequency range and thus cannot be used to replace 'Amp3' for the amplification of 20 GHz signal. Therefore, we built an array of 4-parallel amplifiers (Fig. 8) to overcome this limitation. We used amplifiers from *Qorvo, Model number CMD274 and achieved a gain of 5 dB and P1dB equal to +11 dBm at 20 GHz. The low gain may be due to the substrate losses and the power splitter not being rated at 20 GHz. For the same parallel amplifier, we achieved a gain of 14.5 dB and P1 dB > +20 dBm at 10 GHz.

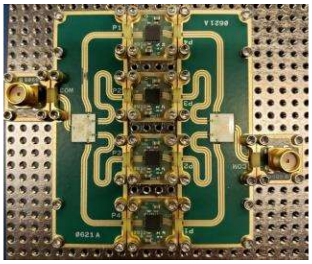


Fig. 8. Photograph of the custom-built low-noise 4-parallel amplifier array.

Once both 'Amp1' and 'Amp3' were replaced with these parallel amplifiers, the close-to-the-carrier phase noise of the regenerative divide-by-3 circuit improved. We attained single-sideband phase noise, $\mathscr{L}(10\text{ Hz}) = -138$ dBc/Hz and $\mathscr{L}(10\text{ kHz}) = -162$ dBc/Hz as shown in Fig. 9. This phase noise level is almost 15 dB lower than the noise of the digital divide-by-3 described earlier. Furthermore, the amplifiers used for the parallel amplifier and single amplifier configurations were of different types. Therefore, the observed improvement in the flicker phase noise is not the expected 6 dB.

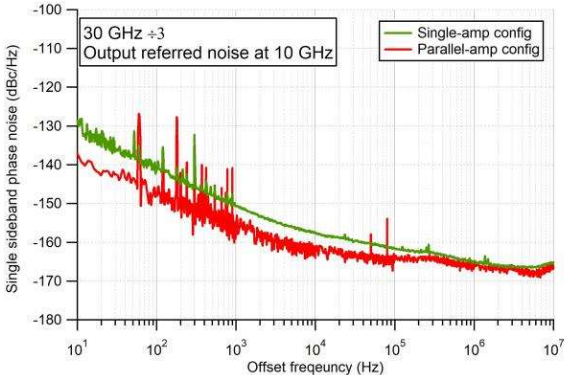
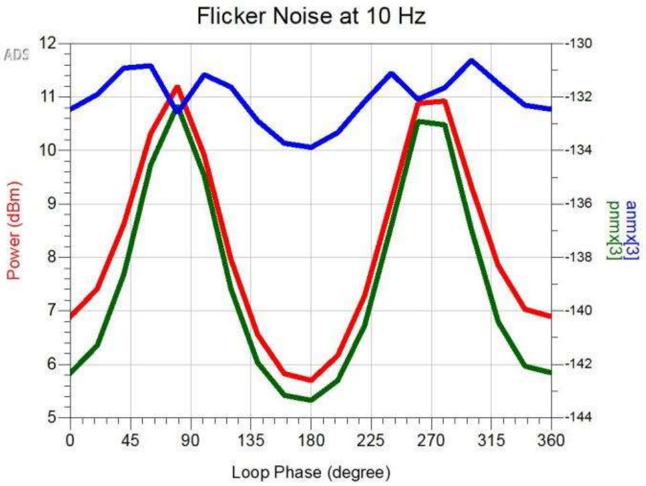


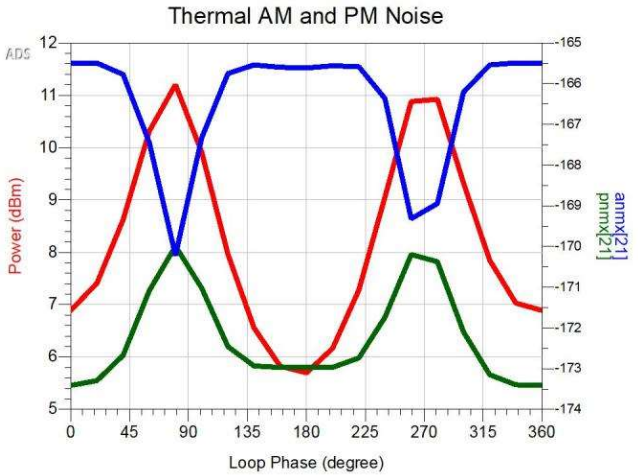
Fig. 9. Output referred phase noise at 10 GHz of a single RFD ÷3 using the parallel amplifiers. The single-amp configuration uses three loop amplifiers as in Fig. 1 whereas parallel-amp configuration uses two loop amplifiers.

V. SIMULATION STUDY

To understand and optimize the PM and AM noise performance of the dividers, we performed simulations of the RFDs at steady-state operation using the *Keysight Advanced Design System (ADS) using the circuit envelope simulation technique. The preliminary results for the ÷2 dividers are shown in Fig. 10. The simulation shows that both the flicker and thermal PM noise are lowest at the loop phase shift corresponding to the lowest output power. This same trend was also observed experimentally with the regenerative divide-by-2 circuit. For this simulation, we assumed the AM and PM noise of the loop components are equal.



(a)



(b)

Fig. 10. Simulation result showing the output power (red), AM noise (blue), PM noise (green) versus loop phase shift of RFD ÷2 circuit. (a) The top graph shows the 10 Hz intercept of AM and PM noise. (b) The bottom graph shows thermal AM and PM noise levels.

VI. CONCLUSIONS

We reported the performance of a 30 GHz regenerative divide-by-3 frequency divider. The proposed divider design uses an additional regenerative mixing path to the conventional Miller regenerative frequency divider (divide-by-2). With the initial prototype, we achieved output referred phase noise, $\mathscr{L}(10\ \text{Hz}) = -130$ dBc/Hz, and frequency stability of less than 1×10^{-15} at a 1-second averaging period for a single divider. We further improved the flicker phase noise performance of the divider by implementing an array of parallel amplifiers and reached $\mathscr{L}(10\ \text{Hz}) = -138$ dBc/Hz and $\mathscr{L}(10\ \text{kHz}) = -162$ dBc/Hz for the divide-by-3, and $\mathscr{L}(10\ \text{Hz}) = -143$ dBc/Hz and $\mathscr{L}(10\ \text{kHz}) = -169$ dBc/Hz for the divide-by-2 circuit. We also simulated the closed-loop phase and amplitude noise performance of the ÷2 RFD using ADS. The simulation showed that the PM noise is lowest at the loop phase shift corresponding to the lowest output power. This same correlation was also observed experimentally. We will extend our study to the ÷3 frequency divider in the future.

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