LOW PM NOISE REGENERATIVE DIVIDERS[*]

E.S. Ferre-Pikal and F.L. Walls

National Institute of Standards and Technology
325 Broadway, Boulder CO 80303

Abstract - This paper describes the various contributions to the PM noise added by an oscillating regenerative divide-by-two circuit (halver). Two circuits are investigated: a 100 MHz to 50 MHz divider and a 18.4 GHz to 9.2 GHz divider. Several configurations of the 100 MHz to 50 MHz divider were studied. It was found that the broadband noise floor is determined by the thermal noise of the amplifier. We found that the thermal noise of the amplifier at the image frequency (3/2) v_o, unless eliminated, contributes to the thermal noise of the divider and thus increases the broadband noise by 3 dB. A PM noise performance of $\mathcal{L}(f) = 10^{-14.4}/f + 10^{-17.9}$ was ultimately achieved using a medium drive power mixer. PM noise measurements of the 18.4 GHz to 9.2 GHz divider show that the broadband noise is $\mathcal{L}(10\text{ MHz}) = -168$ dB below the carrier in a 1 Hz bandwidth (dBc/Hz), probably limited by the measurement system noise. A close-in noise of $\mathcal{L}(10\text{ Hz}) = -136$ dBc/Hz and $\mathcal{L}(10\text{ kHz}) = -157$ dBc/Hz was achieved. This design could easily be extended to 40 GHz and beyond, limited only by the availability of the mixer.

Introduction

In this paper we report the PM noise of two regenerative divide-by-two circuits: a 100 MHz to 50 MHz divider and a 18.4 GHz to 9.2 GHz divider. The contributions of the mixer and amplifier noise to the total noise are investigated.

Regenerative (or Miller) dividers use positive feedback to generate an output signal equal to $v_{in}/(N+1)$, where v_{in} is the frequency of the input

signal and N is an integer [1-4]. The block diagram of such a divider is given in Fig. 1. The input signal of frequency v_o goes into the LO port of the mixer. If the gain around loop 1 (IF port - bandpass filter - amplifier - splitter - multiplier - RF port - IF port) at a frequency of $v_o/(N+1)$ is greater than 1, self-sustained oscillation at that frequency is achieved, creating a divide-by-(N+1) circuit. The bandpass filter is used to reject the image frequency $\left(\dfrac{2N+1}{N+1}\right)v_o$. If no multiplier is included in the loop, the frequency is divided by two. Regenerative dividers are potentially very low noise circuits. Driscoll reported excellent PM noise for divide-by-two circuits at an input frequency of 160 MHz [3].
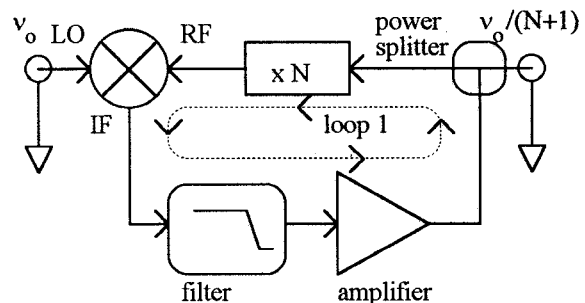

Figure 1. Block diagram of a regenerative divider.

In an ideal divider, where the frequency of the output signal at the mixer is the result of the sum and difference of the frequencies of the two input ports, the phase noise of the divider is given by [4]:

$$S_\phi(f)_{div} = \frac{\sum S_\phi(f)_{comp}}{N^2}, \qquad (1)$$

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where $S_\phi(f)_{comp}$ refers to the PM noise of the loop components (mixer, amplifier, and multiplier) and $S_\phi(f)_{div}$ is the PM noise of the divider. In a divide-by-two circuit the PM noise of the loop components is divided by four.

In real dividers, the output signal of the mixer (at the frequency of $v_o/(N+1)$) is the result of several mixing combinations. In addition, if the two input signals to the mixer have large harmonics, these will also mix and contribute to the output signal of the mixer. Rubiola et al. [5] showed that a more general equation for the PM noise of a regenerative divide-by-two circuit is

$$S_\phi(f)_{div2} = \left(\frac{1}{1-G_m}\right)^2 \sum S_\phi(f)_{comp}, \qquad (2)$$

where G_m is the phase gain of the mixer and $S_\phi(f)_{comp}$ is the PM noise of the loop components. For an ideal mixer, $G_m = -1$ and the noise in the components is reduced by 6 dB [5]. Rubiola et al. found that the PM noise of regenerative divide-by-two circuits change considerably when G_m is varied by varying the phase shift in the loop of the divider [5]. One of their suggested design schemes is to reduce the harmonics in the loop as much as possible, making G_m very close to -1. In this paper we study several configurations in which the harmonic content varies, and the resulting PM noise is investigated.

100 MHz to 50 MHz Regenerative Dividers

Several configurations of 100 MHz to 50 MHz regenerative dividers were built and tested. In all the configurations, the mixer operated in compression and the amplifier operated in the linear region. The first configuration is shown in Fig. 2. A medium power mixer and an amplifier with 15 dB gain were used in the configuration. For an input power of 8.5 dB relative to 1 mW (dBm) at a carrier frequency of 100 MHz, the resulting output power at 50 MHz was approximately 14.5 dBm.
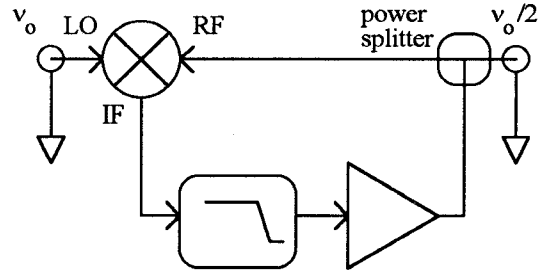

Figure 2. 100 MHz to 50 MHz regenerative divider - configuration 1.

Figure 3 shows the system used to measure the PM noise in a pair of dividers. In this system a 100 MHz source drives a pair of dividers. The output signals of the dividers are split and fed into a two channel, cross-correlation PM noise measurement system [7,8].
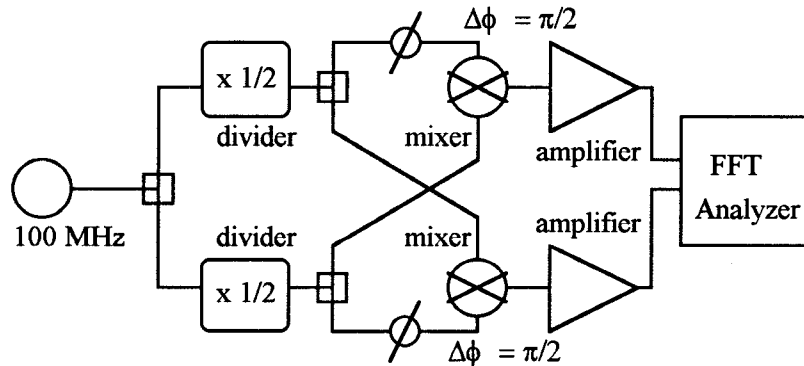

Figure 3. PM noise measurement system for a pair of dividers.

Trace A in Fig. 4 shows the measured PM noise for a pair of dividers in this configuration. The continuous line in the plot is a fit to the measured values given by $\mathcal{L}(f)_{pair} = 10^{-13.65} + 10^{-17.4}$. The measured broadband noise is approximately $\mathcal{L}(f) = -174$ dB below the carrier in a 1 Hz bandwidth (dBc/Hz) and is mainly due to the thermal PM noise of the loop amplifier. In this configuration the contribution of the amplifier noise to the total broadband noise of the divider is given by

$$\mathcal{L}(f) = \left(\frac{1}{4}\right) 2\mathcal{L}(f)_{thermal,amp} = \frac{1}{2}\left(\frac{kTFG}{2P_o}\right), \qquad (3)$$

where k is Boltzmann's constant, T is the temperature in kelvins, F is the noise factor of the amplifier, G is the gain of the amplifier, and P_o is the output power of the amplifier. The thermal noise of the amplifier is multiplied by two because in this configuration the amplifier thermal noise extends to frequencies about 150 MHz (the image frequency, $(3/2)\ v_o$). This noise around 150 MHz mixes with the input signal and results in additional thermal noise at 50 MHz. The thermal noise is therefore doubled. Using a noise factor of 4 dB, and $P_o = 18$ dBm in Eq. (3), the contribution of the amplifier thermal noise to the divider thermal noise is -179 dBc/Hz for one divider or -176 dBc/Hz for a pair. If the broadband noise of the mixer and the noise in the pads of the measurement system are added, the total computed broadband noise is -178 dBc/Hz per divider or -175 dBc/Hz for the pair. This number agrees with the measured thermal noise (-174 dBc/Hz).
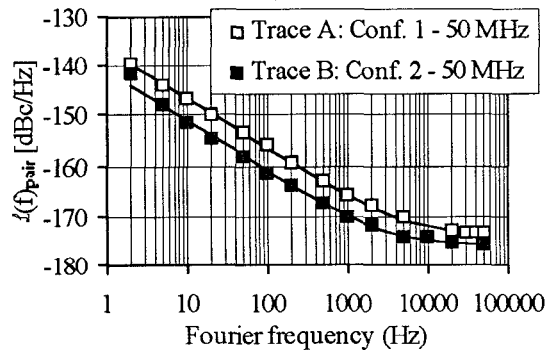
A second configuration, shown in Fig. 5 was also tested. In this configuration a lowpass filter is added between the power splitter and the RF port of the mixer. The filter was added to eliminate the contribution of the image frequency to the thermal noise of the divider and to further attenuate the unwanted harmonics in the loop. Trace B in Fig. 4 shows the measured PM noise for a pair of such dividers. The fit to the measured values, shown as a continuous line, is $\mathcal{L}(f) = 10^{-14.1}/f + 10^{-17.6}$. The measured broadband PM noise is approximately $\mathcal{L}(50 \text{ kHz}) \cong -176$ dBc/Hz. The contribution of the amplifier thermal noise to the broadband noise of the divider can be computed using

$$\mathcal{L}(f)_{thermal,div} = \left(\frac{1}{4}\right)\mathcal{L}(f)_{themal,amp} = \frac{kTFG}{8P_o}. \qquad (4)$$

Equation (4) yields $\mathcal{L}(f)$thermal = -179 dBc/Hz for a pair of dividers. When the broadband noise of the mixer and the attenuators in the PM noise measurement system are added, the total broadband noise for a pair of dividers is -177 dBc/Hz. This number is very close to the measured thermal noise (-176 dBc/Hz). The close-in noise of the dividers follows a 1/f power law, with $\mathcal{L}(10 \text{ Hz}) \cong -151.5$ dBc/Hz. The flicker noise is 4 dB less than the noise of the previous dividers. This improvement in the flicker noise could be due to the reduction of harmonics in the loop [5]. In the circuit in Fig. 5, the harmonics are reduced further by the addition of the extra filter, therefore the PM noise in this configuration should approximately follow Eq. 2.

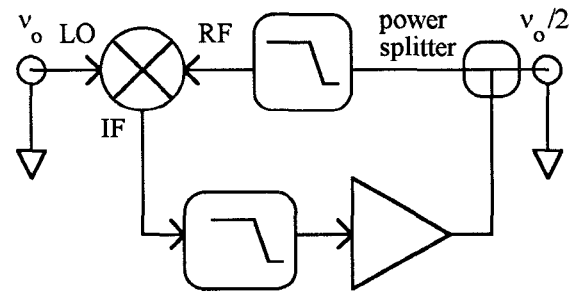Figure 4. PM noise of the 100 MHz to 50 MHz dividers in Figs. 2 & 5.

Figure 5. 100 MHz to 50 MHz regenerative divider - configuration 2.

To further examine the PM noise reduction in these two configuration a phase modulator was added at the input of the amplifier in the circuits in

Figs. 2 and 5. Phase modulation noise was added at ± 20 kHz from the signal. This noise addition simulated flicker noise in the amplifier, since the added noise was dependent on the input power to the amplifier. The noise sidebands were measured for closed loop (CL) configuration (divider) and for open loop (OL) configuration (Fig. 6). For the circuit in Fig. 2, the ± 20 kHz noise sidebands on the CL configuration were 3-4 dB lower than in the OL configuration. For the circuit in Fig. 5, the ± 20 kHz noise sidebands in the CL configuration were 6 dB lower than in the OL configuration. Different noise reductions were observed in the two configurations. This agrees with the 1/f PM noise results. The modulator was also added to the input of the divider. The resulting sidebands at the output of the divider were 6 dB lower than the injected sidebands as expected.
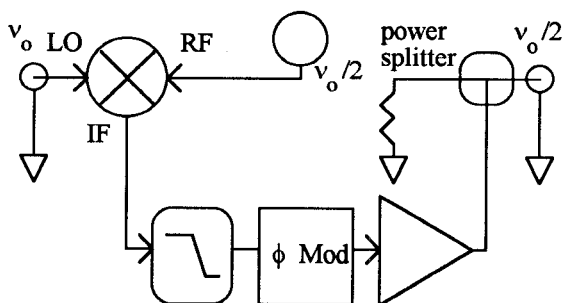

Figure 6. PM noise addition in open loop configuration.

The flicker noise of the amplifiers used in the dividers was approximately $\mathcal{L}(10\ \text{Hz}) = -154\ \text{dBc/Hz}$ at a carrier frequency of 50 MHz. Using the PM noise from the circuit in Fig. 5 and a reduction of 6 dB in the component noise, this yields a PM noise of $\mathcal{L}(10\ \text{Hz}) = -157\ \text{dBc/Hz}$ for a pair of dividers. This is approximately 5 dB lower than the measured noise in this circuit, therefore the close-in noise is mostly limited by mixer noise.

A third configuration of a regenerative divide-by-two circuit, shown in Fig. 7, was also built and tested. In this configuration a lowpass filter was placed between the power splitter and the mixer's RF port, and another lowpass filter was placed at the output of the power splitter. For an input power of 7.5 dBm, the output power of the dividers was approximately 15.8 dBm. Trace A in Fig. 8 shows

the PM noise of a pair of dividers of this configuration. The fit to the measure data (continuous line) is $\mathcal{L}(f) = 10^{-13.3}/f + 10^{-17.1}$. Both the flicker and the thermal noise are about 3 dB higher than in the dividers of Fig. 2 (configuration 1). This might be due to several reasons. First, the input signal to the amplifier contains large harmonic distortion and thus intermodulation products are created by the amplifier, which probably degrade the PM noise of the amplifier. Second, the harmonic content of the signal into the RF port of the mixer is higher than in the configuration 1. In addition, it is possible that the amplifier is slightly compressed.
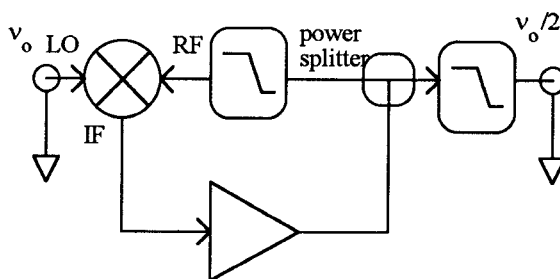

Figure 7. 100 MHz to 50 MHz regenerative divider - configuration 3.
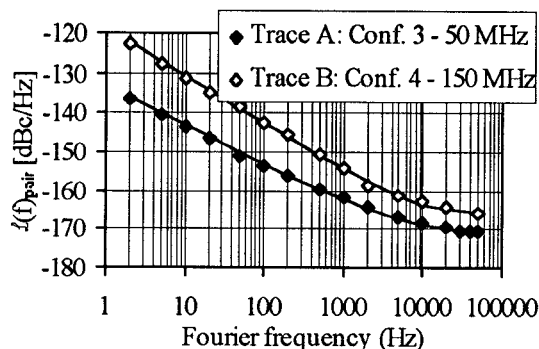

Figure 8. PM noise of configurations 3 and 4 of regenerative dividers.

The PM noise at $v_o = (3/2)v_{in}$ was also investigated. One way to achieve an output signal of frequency $(3/2)v_{in}$ is to use the circuit in Fig. 7 and substitute the output lowpass filter for a bandbass filter centered at $(3/2)v_{in}$, 150 MHz in this case. Using Kroupa's approach [4], the predicted PM noise of the 150 MHz signal is

481

$$S_\phi(f)_{150MHz} = \left(\frac{3}{2}\right)^2 S_\phi(f)_{in} + S_\phi(f)_{mixer}$$
$$+ S_\phi(f)_{amp,150MHz} + \frac{S_\phi(f)_{amp,50MHz}}{4}, \tag{5}$$

where $S_\phi(f)_{150\ MHz}$ is the PM noise of the 150 MHz output signal, $S_\phi(f)_{in}$ is the PM noise of the 100 MHz input signal, $S_\phi(f)_{amp,150\ MHz}$ is the PM noise of the amplifier for a carrier frequency of 150 MHz and $S_\phi(f)_{amp,50\ MHz}$ is the PM noise of the amplifier for a carrier frequency of 50 MHz. The total PM noise of the 150 MHz output includes the PM noise of the input signal multiplied by $(3/2)^2$ plus the PM noise of the mixer, plus the PM noise of the amplifier at a carrier signal frequency of 150 MHz plus the PM noise of the amplifier at a carrier frequency of 50 MHz multiplied by $(1/2)^2$.

To obtain an output signal of frequency 150 MHz we used a lowpass filter with a cutoff frequency (f_c) of 155 MHz at the output of the power splitter followed by a highpass filter with $f_c = 120$ MHz. The total loss across the filters was approximately 3 dB. For an input power of 8.5 dBm the output power obtained was approximately 8.7 dBm. Trace B in Fig. 8 shows the PM noise of the 150 MHz output signal of such a circuit. The fit to the measured values (shown as a continuous line) is $10^{-11.85}/f^{1.2} + 10^{-16.65}$. The close in PM noise is 10 to 13 dB higher than the PM noise of the equivalent circuit at 50 MHz, probably due to PM noise of the amplifier at a carrier frequency of 150 MHz. The broadband noise extracted from the fit is $\mathcal{L}_{thermal,\ pair}$ = -166.5 dBc/Hz, approximately 4.5 dB higher than the thermal noise of the equivalent circuit at 50 MHz. This difference is due to the difference in amplifier output power levels between the two circuits.

Figure 9 shows a divider configuration that has two output frequencies: $v_o/2$ and $(3/2)v_o$. In this configuration the $(3/2)v_o$ signal is obtained from the mixer IF port after some filtering and amplification. The rest of the circuit is similar to the divider in Fig. 5, which yielded the best PM noise at $v_o/2$ (50 MHz). This configuration should yield better PM noise at the image frequency since the harmonics in the system are kept small, and the input signal to the amplifier has low harmonics.
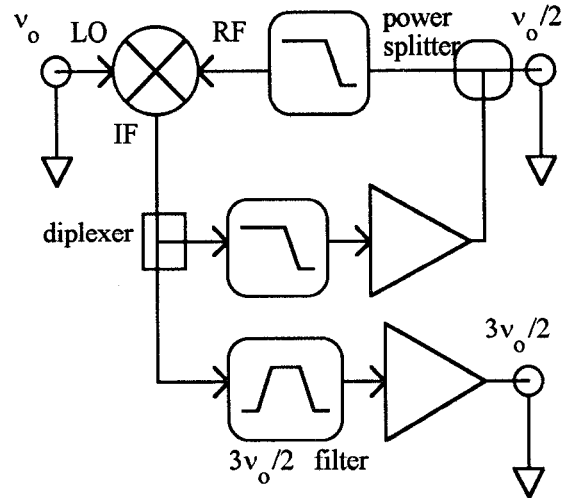

Figure 9. Regenerative divider with two output frequencies: $v_o/2$ and $(3/2)v_o$.

AM Noise Measurements in 100 MHz to 50 MHz Dividers

In regenerative dividers either the mixer or the loop amplifier (or both) are in saturation. It is therefore expected that these dividers cause some reduction in the AM noise of the source that is used to drive them. We made several AM measurements to investigate this possibility. Fig. 10 shows the system used to make the AM measurements. A 100 MHz source is used to drive a divide-by-two circuit. The divider used in these measurements was the circuit in Fig. 5. The output of the divider is split and each channel is fed into an AM detector. The output of the detectors are fed into an FFT signal analyzer. Trace A in Fig. 11 shows the AM noise of the source at 100 MHz while trace B shows the AM noise of the divided signal (at 50 MHz). Trace B is higher than Trace A, indicating that the noise added by the divider contributes to the total noise, and thus no improvement in the AM noise of the carrier can be seen. We repeated the same measurements using a signal generator to drive the divider. The signal generator was approximately 7 dB noisier (close-in) than the previous source. Nevertheless no clear reduction in the AM noise of the source was observed. It is possible that the mixer in the divider was not driven hard enough to obtain a reduction in the AM noise.
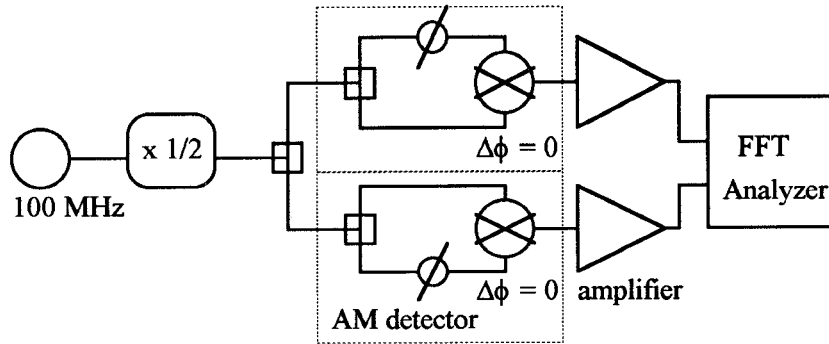
482

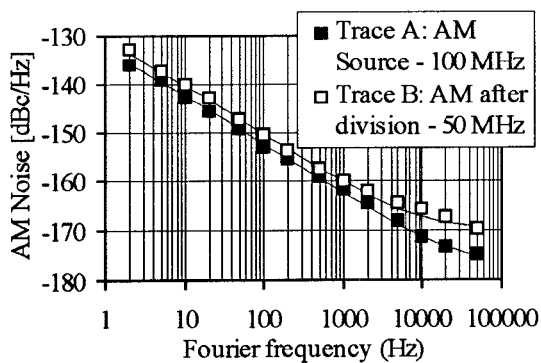Figure 10. System used to measure AM noise of divider.

Figure 11. AM Noise measurement on source and divider.

18.4 GHz to 9.2 GHz Regenerative Dividers

We also tested a 18.4 GHz to 9.2 GHz regenerative divider. This divider was similar to the one shown in Fig. 2 (but a bandpass filter was used instead of a lowpass filter). No bandpass filter between the splitter and the RF port of the mixer was included because the amplifier gain at 27.6 GHz (image frequency) was very small, approximately -20 dB. The amplifying stage consisted of three amplifiers of approximately 6.5 dB gain. For an input power of 9 dBm, the output power of the divider was 14.5 dBm. Trace A in Fig. 12 shows the measured PM noise of a single 18.4 GHz to 9.2 GHz divider. From the figure, the thermal noise of the divider is ≤ -168 dBc/Hz and the close-in PM noise is $\mathcal{L}$(10 Hz) = -136 dBc/Hz. The measured thermal noise is probably limited be AM noise in the

signal generator used to drive the dividers. The theoretical thermal noise can be computed using Eq. (4). The first amplifier dominates the thermal noise; therefore for F = 0 dB,

$$\mathcal{L}(f)_{thermal} = -177 dBm / Hz + 6.5 dB$$
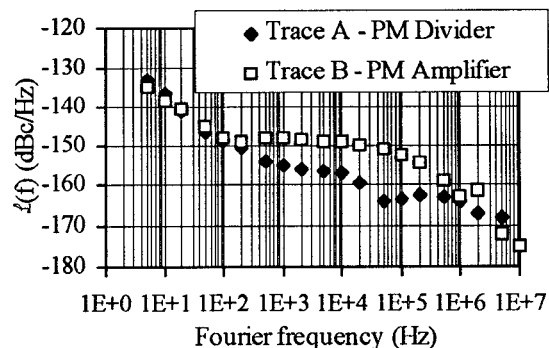$$- 6dBm - 6dB = -182.5dBc / Hz.$$

Figure 12. PM noise for 18.4 GHz to 9.2 GHz divider and for amplifier at 10.6 GHz.

The second amplifier will add about 1 dB to this result; therefore $\mathcal{L}(f)_{thermal} \cong$ -181.5 dBc/Hz. For a noise factor of 5 dB, the resulting thermal noise is -176.5 dBc/Hz. To investigate the origin of the close-in noise, the PM noise of an amplifier similar to those used in the dividers was measured at a carrier frequency of 10.6 GHz. Trace B in Fig. 12 shows the measured PM noise of the amplifier. At 10 Hz from the carrier, $\mathcal{L}$(10 Hz) $\cong$ -138 dBc/Hz. This corresponds to approximately -133 dBc/Hz for three cascaded amplifiers (as in the divider), and thus an equivalent noise of -139 dBc/Hz in a divider.

which is within 3 dB of the measured PM noise in the divider. This indicates that the close-in amplifier noise probably contributes to the close-in noise in the divider. Using amplifiers with lower close-in PM noise should improve the PM noise performance of the divider at low Fourier frequencies. The measured PM noise of the amplifier shows some excess noise at Fourier frequencies of 200 Hz - 200 kHz. This excess noise might be due to AM in the source used to drive the amplifier.

Conclusion

We have shown PM noise results for several regenerative dividers. The best performance of the 100 MHz to 50 MHz divider was achieved using a medium power mixer and an additional lowpass filter between the power splitter and the RF port of the mixer. This extra lowpass filter was included to eliminate the contribution of the image frequency thermal noise to the overall thermal noise of the divider. This improves the thermal noise of the divider by 3 dB. For this divider, the close-in noise had a 1/f power law and was approximately $\ell(10 \text{ Hz})$ = -154 dBc/Hz; the thermal noise was approximately -179 dBc/Hz. Regenerative dividers built at 18.4 GHz to 9.2 GHz also had very low PM noise. The measured broadband PM noise, probably limited by AM noise in the source of the measurement system was approximately -168 dBc/Hz. The close-in noise was $\ell(10 \text{ Hz}) \cong -136$ dBc/Hz.

Acknowledgments

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