# MICROWAVE REGENERATIVE DIVIDERS WITH LOW PHASE NOISE[*]

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Abstract - We demonstrate regenerative divide-by-two (halver) circuits with very low phase modulation (PM) noise at input frequencies of 18.4 GHz and 39.8 GHz. The PM noise of the 18.4 to 9.2 GHz divider pair was $\mathscr{L}(10\ \text{Hz}) = -134$ dB below the carrier in a 1 Hz bandwidth (dBc/Hz) and $\mathscr{L}(10\ \text{MHz}) = -166$ dBc/Hz, and the PM noise of the 39.8 GHz to 19.9 GHz divider pair was $\mathscr{L}(10\ \text{Hz}) = -122$ dBc/Hz and $\mathscr{L}(10\ \text{MHz}) = -167$ dBc/Hz.

## Introduction

In this paper we present experimental phase modulation (PM) noise results for regenerative divide-by-two (halver) circuits at microwave frequencies. Regenerative dividers are relatively simple circuits that can work at very high frequencies, limited only by mixer availability. Low PM noise has been demonstrated for these dividers at frequencies in the MHz range [1,2], but we are not aware of any PM noise results at frequencies above 10 GHz. For this reason we investigated the PM noise of two regenerative halver circuits: a 18.4 GHz to 9.2 GHz divider and a 39.8 GHz to 19.9 GHz divider.

## PM Noise in Regenerative Halver Circuits

Regenerative halvers use a mixer, a bandpass filter, and an amplifier in a closed-loop configuration to create oscillations at a frequency $\nu_{in}/2$ when one of the input ports of the mixer is driven with a signal at a frequency $\nu_{in}$ [1-4]. See Fig. 1. A more general

regenerative circuit for dividing by N+1 would include a frequency multiplier (x N) between the power splitter and the RF port of the mixer [3-4]. Usually there are frequency bands where the divider is unstable [5]; the divider should be carefully designed to avoid operation in these regions.
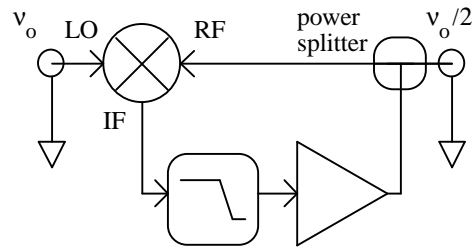


Figure 1. Block diagram of a regenerative divider.

In an ideal mixer, the IF signal is equal to the multiplication of the RF signal and the LO signals. The frequency components of the IF signal are $\nu_{RF} \pm \nu_{LO}$. If such a mixer is used in a regenerative halver circuit, the phase modulation (PM) noise of the frequency halver is given by [4]:

$$S_\phi(f)_{\text{div}} = \frac{\sum S_\phi(f)_{\text{comp}}}{4}, \qquad (1)$$

where $S_\phi(f)_{\text{comp}}$ refers to the PM noise of the loop components (mixer, amplifier, and power splitter) and $S_\phi(f)_{\text{div}}$ is the PM noise of the divider. In a halver circuit the PM noise of the loop components is thus reduced by a factor of 4.

In actual mixers, the frequency components of the output signal of the mixer are the result of several mixing combinations. Furthermore, the input signals at the LO and RF ports usually have harmonics, which also contribute to the frequency components of the mixer's output. Rubiola, et al. [2] showed that when such a mixer is considered, the PM noise of a regenerative halver is given by

$$S_\phi(f)_{\text{div}2} = \left(\frac{1}{1-G_m}\right)^2 \sum S_\phi(f)_{\text{comp}} \quad (2)$$

where $G_m$ is the phase gain of the mixer. For an ideal mixer, $G_m = -1$ and Eq. (2) becomes Eq. (1). Rubiola et al. found that the PM noise of regenerative halver circuits changes considerably when $G_m$ is varied by varying the phase shift in the loop of the divider [2].

The flicker noise of regenerative halvers is the result of flicker noise in the mixer and flicker noise in the amplifier, and the broadband noise is due to the thermal noise of the amplifier. We have found that, when the 3 dB bandwidth of the amplifier is higher than the image frequency ($3\nu_{\text{in}}/2$), Eq. (2) needs to be adjusted to

$$S_\phi(f)_{\text{div}2} = \left(\frac{1}{1-G_m}\right)^2 [S_{\phi,1/f}(f)_{\text{mix}} \quad (3)$$
$$+ S_{\phi,1/f}(f)_{\text{amp}} + 2S_{\phi,\text{thermal}}(f)_{\text{amp}}],$$

where $S_{\phi,1/f}(f)_{\text{mix}}$ is the flicker noise of the mixer, $S_{\phi,1/f}(f)_{\text{amp}}$ is the flicker noise of the amplifier and $S_{\phi,\text{thermal}}(f)_{\text{amp}}$ is the thermal noise of the amplifier. In Eq. (3) the thermal noise of the amplifier is multiplied by 2 since thermal noise generated about the image frequency mixes with the input signal $\nu_{\text{in}}$ and generates additional broadband noise at a frequency of $\nu_{\text{in}}/2$. When the 3 dB bandwidth of the amplifier is smaller than the image frequency or when an extra filter is added to

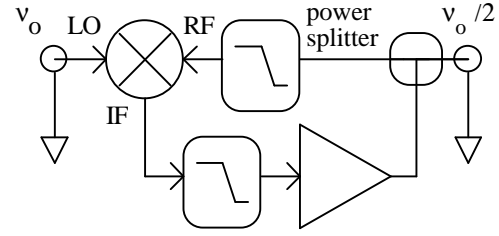the frequency halver as in Fig. 2, the PM noise is given by Eq. (2).



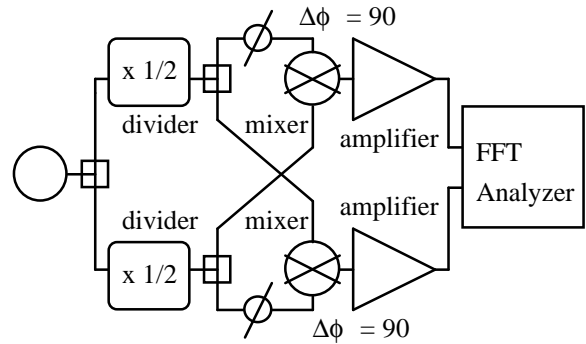Figure 2. Block diagram of frequency halver with image rejection filter.



Figure 3. Block diagram of the PM measurement system used.

### 39.8 GHz to 19.9 GHz Regenerative Divider

A pair of 39.8 GHz to 19.9 GHz regenerative dividers of the type in Fig. 1 were built and tested. A bandpass filter between the splitter and the RF port of the mixer was not included because the amplifier gain at the image frequency was small. The mixers, amplifiers, and filters used in our circuits were all commercial devices with low PM noise. The output power of the dividers was 9.5 dB relative to 1 mW (dBm), and the gain of the amplifying stage was 20 dB. Figure 3 shows the cross-correlation PM noise measurement system used to obtain the PM noise of the divider pair [6]. In this system, the PM noise of the PM detectors is reduced as $\sqrt{N}$, where N is the number of samples in the measurement. A

PM/AM noise calibration standard was used to calibrate the gain of the system [7].
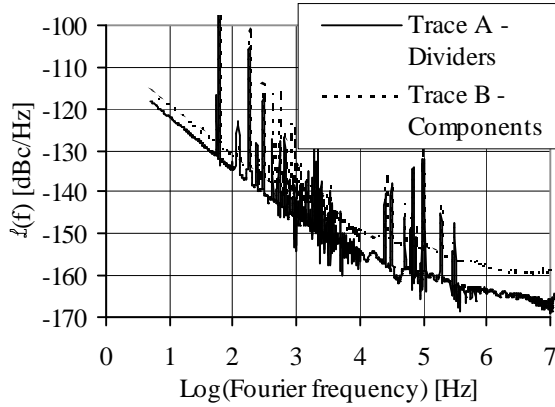


Figure 4. PM noise for 39.8 GHz to 19.9 GHz divider pair and for components at $\nu_{in} = 21.2$ GHz.

Trace A in Fig. 4 shows the output PM noise for the 39.8 GHz to 19.9 GHz divider pair. The measured low frequency PM noise was approximately $\mathcal{L}(10 \text{ Hz}) = -122$ dB below the carrier in a 1 Hz bandwidth (dBc/Hz) for the pair, and the PM noise at 10 MHz from the carrier was $\mathcal{L}(10 \text{ MHz}) = -167$ dBc/Hz for the pair. We also measured the PM noise added by the amplifiers and mixers used in the halver circuits. These measurements were made at a carrier frequency of 21.2 GHz. The noise added by the amplifiers was approximately 8 dB higher than the mixer noise for frequencies below 100 kHz. Trace B in Fig. 4 shows the total PM noise of the amplifiers and mixers used in the dividers. This trace includes noise of two amplifiers and two mixers. At Fourier frequencies lower than 1 kHz the components noise is approximately 3 dB higher than the dividers PM noise. At higher frequencies the components noise is approximately 6 dB higher than the noise in the divider pair. These measurements indicate a reduction of 3 to 6 dB in component noise when placed in the regenerative halver in agreement with Eq. (2). The theoretical broadband noise of the divider

pair assuming an ideal mixer can be computed from the thermal noise of the amplifier, using

$$\mathcal{L}(f)_{\text{thermal}} = 2 \frac{\mathcal{L}(f)_{\text{thermal,amp}}}{4} = \frac{kTFG}{4P_O}, \, (4)$$

where $\mathcal{L}(f)_{\text{thermal,amp}}$ is the thermal noise of the amplifier, 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. For a noise figure of 2 dB, G = 20 dB and $P_O = 13$ dBm, $\mathcal{L}(f)_{\text{thermal}}$ for the pair is -171 dBc/Hz, approximately 4 dB lower than the PM noise measured at 10 MHz.

### 18.4 GHz to 9.2 GHz Regenerative Dividers

The output power of the 18.4 GHz to 9.2 GHz dividers built was approximately 14 dBm. In these circuits the mixer was operating in compression, and the gain of the amplifying stage was approximately 20 dB. A bandpass filter between the splitter and the RF port of the mixer was not included because the amplifier gain at 27.6 GHz (image frequency) was very small, approximately - 20 dB. Trace A in Fig. 5 shows the output PM noise for a pair of 18.4 GHz to 9.2 GHz regenerative halvers. The measured low frequency component was $\mathcal{L}(10 \text{ Hz}) = -134$ dBc/Hz (for the pair), and the noise at 10 MHz from the carrier was $\mathcal{L}(10 \text{ MHz}) = -166$ dBc/Hz (for the pair). Trace B in Fig. 5 shows the total PM noise of the components used in the dividers (mixers and amplifiers). These measurements were made at a carrier frequency of 10.6 GHz. The components noise, dominated by amplifier noise, is approximately 10 dB higher than the dividers noise at Fourier frequencies below 10 kHz. This indicates either that there was a reduction of 10 dB in the components noise when used in the dividers or that the

measurements of the components noise were limited by the noise in the measurement system. At frequencies above 1 MHz, the difference is approximately 6 dB in agreement with Eq. (2). The theoretical thermal noise of the divider pair, computed using Eq. (4) is -175 dBc/Hz.
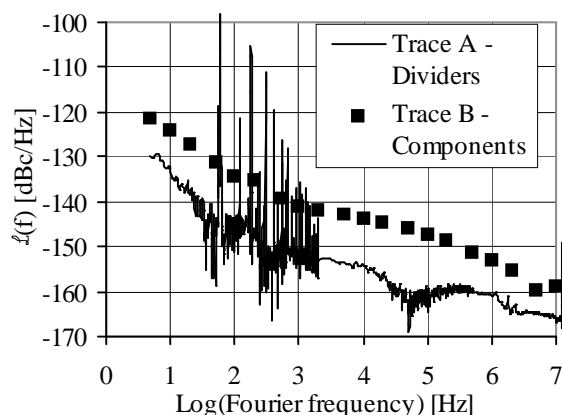


Figure 5. PM noise for 18.4 to 9.2 GHz dividers and for their components.

## Conclusion

To our knowledge, these results are the first to demonstrate low PM noise in regenerative halver circuits at input frequencies above 10 GHz. Our 39.8 to 19.9 GHz divider pair had a PM noise of $\mathcal{L}(10$ Hz$) = -122$ dBc/Hz and $\mathcal{L}(10$ MHz$) = -167$ dBc/Hz. Another divider pair, operating at a input frequency of 18.4 GHz had a PM noise of $\mathcal{L}(10$ Hz$) = -134$ dBc/Hz and $\mathcal{L}(10$ MHz$) = -166$ dBc/Hz. In both cases the divider PM noise, limited by amplifier PM noise, could be reduced by using lower noise amplifiers.

This approach can be extended to higher frequencies. The nonlinearity of the mixer or alternately a frequency multiplier could be used to generate harmonics of the IF. This results in an output frequency of $v_{in}/(N+1)$ where N is the multiplication factor [3]. For example, a mixer with RF and LO ports rated around 80 GHz, and with an IF port rated up to 10 GHz can be used along with a times-nine frequency multiplier to yield a regenerative prescaler that divides by 10.

With the constant improvement of PM noise in oscillators, the need of low noise devices for frequency synthesis is growing. Woode et al. [8] have recently demonstrated a 8.95 GHz oscillator with PM noise of $\mathcal{L}(1$ kHz$) \cong -156$ dBc/Hz. To synthesize lower frequencies from this oscillator without degrading the PM noise requires the use of low noise schemes such as regenerative dividers.

## References

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