Microwave Regenerative Frequency Dividers with Low Phase Noise

Eva S. Ferre-Pikal, *Member, IEEE*, and Fred L. Walls, *Senior Member, IEEE*

***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 $\mathcal{L}(10\text{ Hz}) = -134$ dB below the carrier in a 1 Hz bandwidth (dBc/Hz) and $\mathcal{L}(10\text{ MHz}) = -166$ dBc/Hz, and the PM noise of the 39.8 GHz to 19.9 GHz divider pair was $\mathcal{L}(10\text{ Hz}) = -122$ dBc/Hz and $\mathcal{L}(10\text{ MHz}) = -167$ dBc/Hz.**

I. INTRODUCTION

IN THIS paper[1] 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 by mixer and amplifier 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.

II. 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 $\nu_{\text{in}}/2$ when one of the input ports of the mixer is driven with a signal at a frequency ν_{in} [1]–[4]. Fig. 1 shows a block diagram of a regenerative halver. A more general regenerative circuit for dividing by $N+1$ would include a frequency multiplier ($\times N$) between the power splitter and the RF port of the mixer [3], [4]. Usually there are frequency bands in which the divider is unstable [5]; the divider should be carefully designed to avoid operation in these regions.

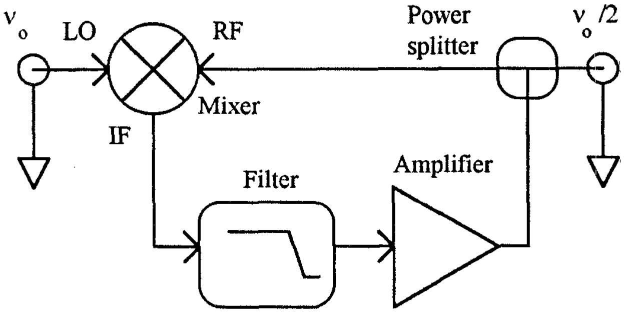

Fig. 1. Block diagram of a regenerative frequency halver.

In an ideal mixer, the IF signal is equal to the multiplication of the RF signal and the LO signal. 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 PM noise of the frequency halver is [4]:

$$S_\phi(f)_{\text{div2}} = \frac{\sum S_\phi(f)_{\text{comp}}}{4}, \tag{1}$$

where $S_\phi(f)_{\text{comp}}$ refers to the PM noise of the loop components (mixer, amplifier, and power splitter) and $S_\phi(f)_{\text{div2}}$ is the PM noise of the halver. 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:

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

where G_m is the phase gain of the mixer. For an ideal mixer, $G_m = -1$, and (2) becomes (1). Rubiola *et al.* [2] 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.

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. When the 3 dB bandwidth of the amplifier is higher than the image frequency ($3\nu_{\text{in}}/2$), (2) needs to be adjusted to:

$$S_\phi(f)_{\text{div2}} = \left(\frac{1}{1-G_m}\right)^2 (S_{\phi,1/f}(f)_{\text{mix}} + S_{\phi,1/f}(f)_{\text{amp}} + 2S_{\phi,\text{thermal}}(f)_{\text{amp}}), \tag{3}$$

Manuscript received February 27, 1998; accepted July 6, 1998.

The authors are with the National Institute of Standards and Technology, Boulder, CO 80303 (e-mail: walls@boulder.nist.gov).

[1] This work was first published as E. S. Ferre-Pikal and F. L. Walls, "Microwave regenerative dividers with low phase noise," *IEEE MTT-S Int. Microwave Symp. Digest*, 1998, pp. 1447–1450.

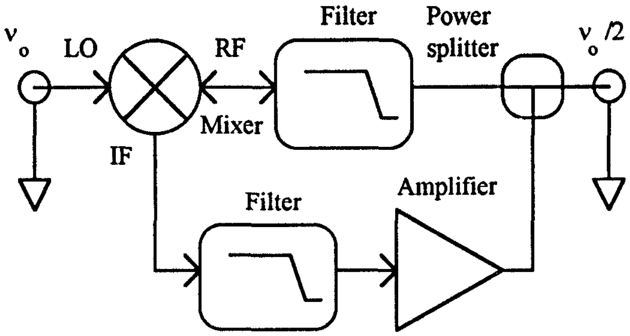

Fig. 2. Block diagram of a regenerative frequency halver with image rejection filter.

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 (3) the thermal noise of the amplifier is multiplied by two because thermal noise generated about the image frequency mixes with the input signal ν_{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 (2).

III. 39.8 GHz TO 19.9 GHz REGENERATIVE DIVIDERS

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 standard commercial devices. 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. Fig. 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].

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. The measurement system for the amplifiers was similar to the system shown in Fig. 3, but with the amplifiers in place of the dividers. The measurement system for the mixers is shown in Fig. 5. In this system, the mixer under test was used as a detector in a PM noise measurements system, and the noise floor of the system was measured. Low noise amplifiers were used in the measurement system, and thus the measured low

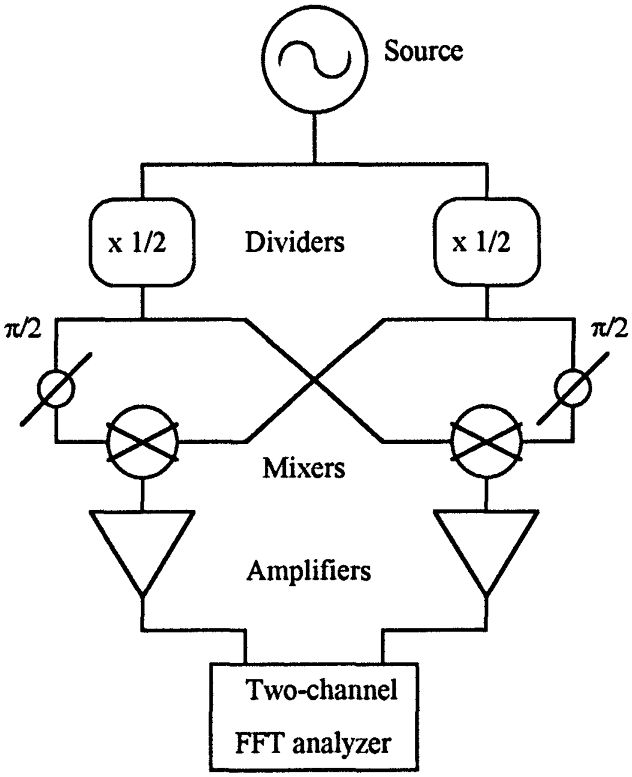

Fig. 3. Block diagram of system used to measure the PM noise in the dividers.

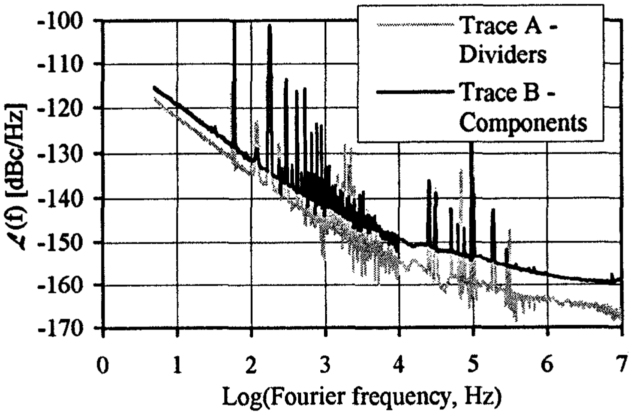

Fig. 4. Output PM noise for 39.8 GHz to 19.9 GHz divider pair and for components at $\nu_{\text{in}} = 21.2$ GHz.

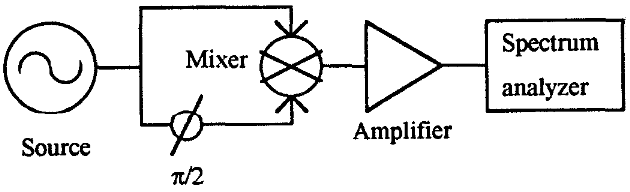

Fig. 5. Block diagram of system used to measure the PM noise of the mixers at 10.6 GHz and 21.2 GHz.

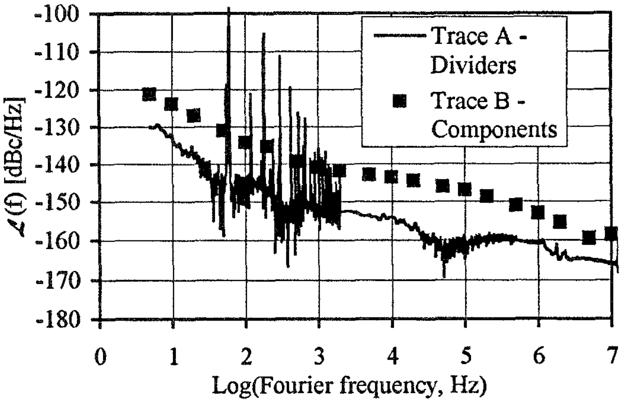

Fig. 6. Output PM noise for 18.4 GHz to 9.2 GHz divider pair and for components at $\nu_{\text{in}} = 10.6$ GHz.

frequency $1/f$ noise was due to mixer noise. These measurements were made at a carrier frequency of 21.2 GHz. The measured noise of 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. This indicates a reduction of 3 to 6 dB in component noise when placed in the regenerative halver in agreement with (2). The theoretical broadband noise of the divider pair assuming an ideal mixer can be computed from the thermal noise of the amplifier, using:

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

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.

IV. 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. 6 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. 6 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 at Fourier frequencies ≤ 1 MHz, 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. The theoretical thermal noise of the divider pair, computed using (4) and $P_o = 18$ dBm, $F = 5$ dB, and $G = 20$ dB, is −173 dBc/Hz.

V. CONCLUSION

To our knowledge, the results in this study 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 $\mathcal{L}(10\text{ Hz}) = -122$ dBc/Hz and $\mathcal{L}(10\text{ MHz}) = -167$ dBc/Hz. Another divider pair, operating at an input frequency of 18.4 GHz had a PM noise of $\mathcal{L}(10\text{ Hz}) = -134$ dBc/Hz and $\mathcal{L}(10\text{ MHz}) = -166$ 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 $\nu_{\text{in}}/(N+1)$ 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 $\mathcal{L}(1\text{ kHz}) \cong -156$ 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.

ACKNOWLEDGMENT

We thank M. M. Driscoll for fruitful discussions on the topic.

REFERENCES

[1] M. M. Driscoll, "Phase noise performance of analog frequency dividers," *Proc. 43rd Annu. Freq. Control Symp.*, 1989, pp. 342–348.

[2] E. Rubiola, M. Olivier, and J. Groslambert, "Phase noise of regenerative frequency dividers," *Proc. 5th Eur. Freq. Time Forum*, pp. 115–122, 1991.

[3] R. L. Miller, "Fractional frequency generators utilizing regenerative modulation," *Proc. IRE*, vol. 27, pp. 446–457, 1939.

[4] V. F. Kroupa, *Frequency Synthesis: Theory, Design & Applications*. New York: Wiley, 1973, pp. 62–63.

[5] R. G. Harrison, "Theory of regenerative frequency dividers using double-balanced mixers," *IEEE MTT-S Int. Microwave Symp. Digest*, 1989, pp. 459–462.

[6] W. F. Walls, "Cross-correlation phase noise measurements," *Proc. IEEE Freq. Contr. Symp.*, 1992, pp. 257–261.

[7] F. L. Walls, "Secondary standard for PM and AM noise at 5, 10, and 100 MHz," *IEEE Trans. Instrum. Meas.*, vol. 42, pp. 136–143, 1993.

[8] R. A. Woode, M. E. Tobar, E. N. Ivanov, and D. G. Blair, "An ultralow noise microwave oscillator based on a high-Q liquid nitrogen cooled sapphire resonator," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 43, pp. 936–941, 1996.

Eva S. Ferre-Pikal (S'96–M'96) was born in Ponce, Puerto Rico, on February 13, 1966. She received her B.S. degree in electrical engineering from the University of Puerto Rico, Mayaguez, in 1988. In 1989, she received her M.S. degree in electrical engineering from the University of Michigan, Ann Arbor. From 1988 to 1991 she worked for AT&T Bell Laboratories in Westminster, CO. She received her Ph.D. degree from the University of Colorado at Boulder in 1996. The main topic of her thesis was the up-conversion of low frequency noise into amplitude and phase noise in BJT amplifiers.

Dr. Ferre-Pikal currently is a National Research Council Postdoctoral Research Associate at the National Institute of Standards and Technology. Her research interests are phase and amplitude noise processes in oscillators, amplifiers, and other devices; and the design and applications of low noise devices.

Fred L. Walls (A'93–SM'94) was born in Portland, OR, on October 29, 1940. He received the B.S., M.S., and Ph.D. degrees in physics from the University of Washington, Seattle, in 1962, 1964, and 1970, respectively. His Ph.D. thesis was on the development of long-term storage and nondestructive detection techniques for electrons stored in Penning traps and the first measurements of the anomalous magnetic (g-2) moment of low energy electrons.

From 1970 to 1973 he was a Postdoctoral Fellow at the Joint Institute for Laboratory Astrophysics in Boulder, CO. This work focused on developing techniques for long-term storage and nondestructive detection of fragile atomic ions stored in Penning traps for low energy collision studies. Since 1973 he has been a staff member of the Time and Frequency Division of the National Institute of Standards and Technology, formerly the National Bureau of Standards, in Boulder. Currently he is Leader of the Phase Noise Measurement Group and is engaged in research and development of ultra-stable clocks, crystal-controlled oscillators with improved short- and long-term stability, low-noise microwave oscillators, frequency synthesis from RF to infrared, low-noise frequency stability measurement systems, and accurate phase and amplitude noise metrology.

He received the 1995 European "Time and Frequency" award from the Societe Francaise des Microtechniques et de Chromometrie "for outstanding work in ion storage physics, design and development of passive hydrogen masers, measurements of phase noise in passive resonators, very low noise electronics and phase noise metrology." He is the recipient of the 1995 IEEE Rabi award for "major contributions to the characterization of noise and other instabilities of local oscillators and their effects on atomic frequency standards". He also has received three silver medals from the U.S. Department of Commerce for fundamental advances in high resolution spectroscopy and frequency standards, the development of passive hydrogen masers, and the development and application of state-of-the-art standards and methods for spectral purity measurements in electronic systems. He has published more than 130 scientific papers and holds 5 patents.

Dr. Walls is a member of the American Physical Society, a senior member of the IEEE, a member of the Technical Program Committee of the IEEE Frequency Control Symposium, and a member of the Scientific Committee of the European Time and Frequency Forum.