PHASE NOISE OF X-BAND REGENERATIVE FREQUENCY DIVIDERS

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Abstract

This paper evaluates the design and implementation of experimental low noise regenerative divide-by-two (LNRD) dividers having low phase noise at the output frequency of 4.5GHz. The noise measurements of the 9GHz to 4.5GHz LNRD shows close-in flicker-of-phase noise of $\mathcal{L}$(1kHz) = -155 dBc/Hz and broadband thermal noise floor of $\mathcal{L}$(1MHz) = -170 dBc/Hz. For the design of the regenerative dividers, several MMIC amplifiers have been evaluated and their phase noise performance compared. The dividers have also been used in the generation of low noise 4.5GHz microwave signals. The LNRD design was easily extended for the design of a 4.5GHz to 2.25GHz LNRD which is currently under construction.

Introduction

With the recent advent of microwave signal sources with exceptional phase noise a need has arisen for frequency dividers which divide both the microwave source frequency and its noise whilst preserving the sine wave nature of the original signal. In particular, low phase noise frequency dividers are required to translate the spectrally pure signals of X-band sapphire oscillators [1-3] to lower frequencies with minimum phase noise degradation. This provides C- and S-band sources with phase noise superior to that which can be achieved by multiplication of the best quartz or SAW devices [10-12] both close to and far from the carrier.

In our research we have chosen to concentrate on regenerative dividers, as first described by Miller in 1939 [4] and further investigated by Kroupa [5], Driscoll [6], Ferre-Pikal and Walls [7], and others [8, 9]. From the work of those authors it is apparent that regenerative dividers can fulfil the need for narrow-band, analog frequency division, reducing the phase noise sidebands of the carrier during the division process by up to the 6 dB theoretical limit.

Two 9.0GHz to 4.5GHz divide-by-2 prototype LNRD modules have been designed, built and tested. Testing and analysis of the completed LNRDs included residual phase noise measurement (and comparison with device noise), an examination of the LNRD output harmonic content, and the measurement of the phase noise of two 4.5GHz sources based on 9GHz sapphire oscillators with LNRDs.

To complete the paper, comparisons are made between (i) the phase noise of the LNRD and static dividers (prescalers), and (ii) the resultant performance of the LNRD-based 4.5GHz sources against alternative signal generation schemes.

Regenerative Divider Design

Figure 1 shows the general block diagram of the prototype low noise regenerative divider.

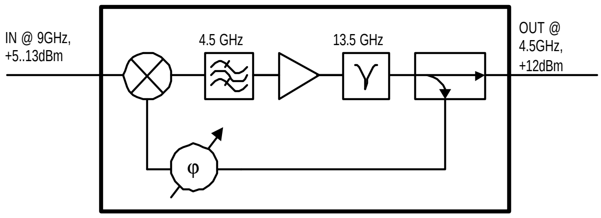

Figure 1. Block diagram of the prototype LNRD.

The LNRD was designed using a low noise mixer and cascaded MMIC amplifiers to satisfy loop gain requirements. A triple-balanced mixer was selected to satisfy the bandwidth demand of 4.5GHz IF output. The filters, phase shifter and power splitters have been designed as microstrip. Edge-coupled notch filters at the input and output of the amplifier module were included to reduce the image frequency at $3f_{in}/2$ by more than 30dB within the loop, and a 4.5GHz bandpass filter was included to prevent spurious oscillation. A phase shift element was included to allow adjustment of the loop phase condition to provide good output power and stability.

The most critical parameter in the design is the selection of the amplifiers, and considerable effort was made to characterise different types of MMIC amplifiers in terms of gain, output power and phase noise. Several types of MMIC amplifiers have been tested including the new generation amplifiers based on SiGe and InGaP/GaAs process technology. Also, careful attention has been made on the design of the cascaded loop amplifier within the divider.

Phase Noise of MMIC Amplifiers

Various MMIC amplifiers from different manufacturers have been examined, including Si Bipolar, GaAs HBT, SiGe HBT and InGaP/GaAs HBT process technology, which are all based on a Darlington pair topology. The parameters of a selection of the amplifiers tested at 4.5GHz have been tabulated in Table 1.

Table 1. Gain and output power of single-stage amplifiers at 4.5GHz.

Device Type	Process Technology	Gain (dB)	P1dB (dBm)
HP MSA-0886	Si Bipolar	8	+9
Mini-Circuits ERA-5SM	GaAs HBT	14	+15
Stanford Microdevices SGA-4186	SiGe HBT	7.5	+9.5
Stanford Microdevices NGA-489	InGaP/GaAs HBT	13	+15

The phase noise of the amplifiers have been measured using a standard phase noise bridge set-up (see Figure 2). The measurements have been performed with the amplifier in saturation, which is the operating condition in the LNRD. The results are shown in Figure 3 and have been tabulated below in Table 2.

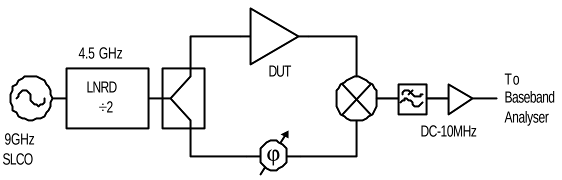

Figure 2. Amplifier phase noise measurement setup.

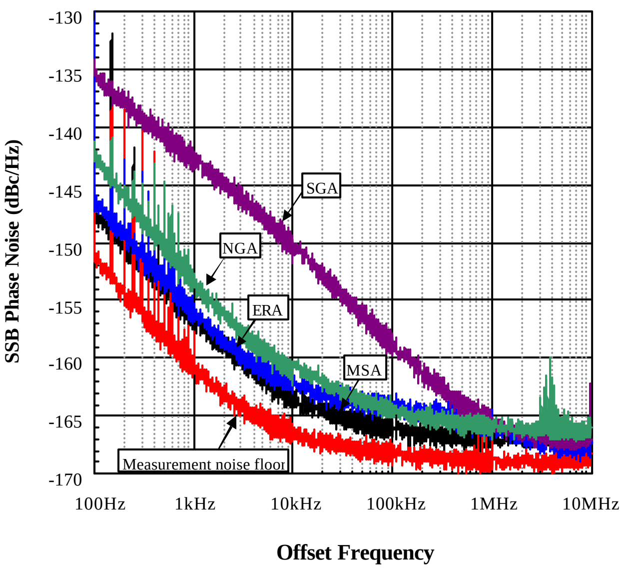

Figure 3. Measured phase noise of single-stage MMIC amplifiers at 4.5GHz

Table 2. Phase noise performance of single-stage MMIC amplifiers at 4.5GHz (measurement noise floor not removed).

Device Type	$\mathcal{L}$ (100Hz) dBc/Hz	$\mathcal{L}$ (1kHz) dBc/Hz	$\mathcal{L}$ (10kHz) dBc/Hz	$\mathcal{L}$ (100kHz) dBc/Hz
MSA-0886	-147	-156	-163	-166
ERA-5SM	-146	-156	-162	-164
SGA-4186	-135	-143	-150	-159
NGA-489	-142	-153	-161	-164

As can be seen in Figure 3, the noise power varies as 1/f flicker from 100Hz to 3kHz for ERA, MSA and NGA. However, SGA has a higher noise power and has a 1/f noise signature from 100Hz to 300kHz. The thermal noise floor of the amplifiers was measured as less than -166 dBc/Hz.

In addition, the variations of the phase noise of the amplifiers have been measured for different input levels. The variations observed were within ±1dB, which was within the measurement inaccuracies.

Phase Noise Theory of Regenerative Dividers

It is known that the phase modulation (PM) noise of an optimised regenerative divide-by-2 divider is given by

$$L_{RD}(f) = \frac{\sum L_{dev}(f)}{4} \qquad \textbf{Eq. 1}$$

where $L_{RD}(f)$ and $L_{dev}(f)$ refer to the SSB phase noise power spectral density of the divider, and the devices within the divider loop, respectively [5]. Rubiola et al [9] have explained that this limit may only be achieved with careful setting of the phase shift around the divider loop, at the expense of output power and possibly stability.

This PM noise can be attributed mainly to the mixer and amplifier noise within the loop. As a result, Eq. 1 can be written as :

$$L_{LNRD}(f) = \frac{1}{4}[L^{1/f}_{mixer}(f) + L^{1/f}_{amp}(f) + L^{thermal}_{mixer}(f) + L^{thermal}_{amp}(f)] \qquad \textbf{Eq. 2}$$

where the first and second terms are flicker noise of the mixer and amplifier respectively, the third term is the thermal noise (conversion loss) of the mixer, and the last term is the thermal noise floor (noise figure) of the amplifier. If the flicker noise of the mixer is assumed to be less than the amplifier, then the close-to-the-carrier phase noise of the optimised divider can be represented by the phase noise of the active amplifier in the loop divided by 4.

Further, the thermal noise floor of the divider is set by the conversion loss of the mixer, the noise figure of the amplifier, and the available power to the RF port of the mixer. However, the mixer thermal performance can be ignored if the power input to the amplifier and the amplifier's noise figure are known (since the mixer's conversion loss is already accounted for in the calculation of amplifier input power). Accordingly, the SSB broadband thermal noise of the divider is given by Eq. 3:

$$L_{RD}^{thermal}(f) = \frac{1}{4} L_{amp}^{thermal}(f) = \frac{1}{4} \frac{kTF_{amp}}{2P_{amp,in}} \qquad \textbf{Eq. 3}$$

Given T = 300K, k =1.38x10^{-23} J/K, and the values for the cascaded amplifier $P_{amp,in}$ = -2dBm and F_{amp} = 6dB, the thermal noise floor is calculated as -175 dBc/Hz.

Regenerative Divider Performance

Two LNRD prototypes, having +12dBm output power, have been designed and tested. The operating bandwidth of the divider is ±50 MHz (input), which is mainly determined by the bandwidth of the loop filter and the fixed phase shifter within the total loop. Each LNRD module is housed in an aluminium enclosure 130 x 90 x 20mm, and operates +12 to 15 volts dc at 100mA. Input power range is +5 to +13dBm.

Divider Output Spectrum

A low-pass microstrip filter at the coupler output (not shown in Figure 1), reduces the 4.5GHz harmonics (mainly 2nd, 3rd and 4th) to –60dBc. The output spectrum of the LNRD driven by a 9.0GHz sapphire oscillator is shown in Figure 4, and the measured harmonics are listed in Table 3.

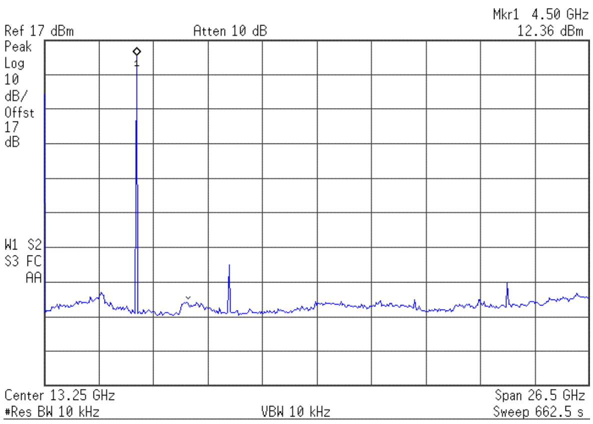

Figure 4. Output spectrum of a 4.5GHz LNRD after a 9GHz sapphire oscillator.

Table 3. 4.5GHz LNRD output harmonics.

Harmonic Number	Frequency GHz	Harmonic Amplitude
1	4.5	+12.4 dBm
2	9.0	-59.8 dBc
3	13.5	-69.8 dBc
4	18.0	-66.1 dBc
5	22.5	-64.7 dBc

Divider Residual Phase Noise

Residual phase noise measurements have been performed by comparing the two divider prototypes when driven by a single 9GHz low noise oscillator, as in Figure 5. The results are shown in Figure 6.

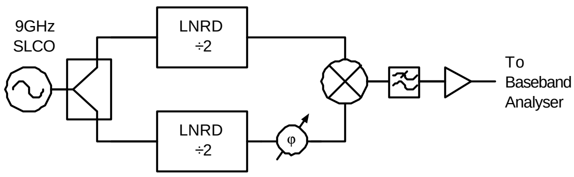

Figure 5. Residual phase noise measurement setup.

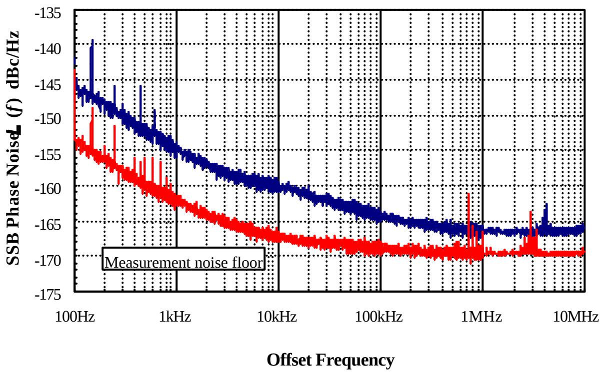

Figure 6. Residual phase noise of the regenerative divider.

Assuming equal contributions from each of the LNRDs, the measured phase noise at 100Hz, 1kHz and 10kHz was -146, -155 and -160 dBc/Hz respectively for a single divider. After consideration of the noise floor for large offsets, the thermal floor can be characterised as -170 dBc/Hz at offsets greater than 1MHz.

The measured results are approximately 5dB higher than theoretical results, both in the flicker and thermal regions. This is attributed to the phase setting in the LNRD loop, which was set to achieve maximum output power and good loop stability. This is consistent with the theory of [9] which indicates that the 'factor of 4' in Eq. 1 is for a divider optimised for phase noise, at the expense of considerable output power and potential stability problems.

However, the results satisfy the performance required for the LNRD to be used in a low noise 4.5GHz signal generator.

Comparison of LNRD and Static Prescalers

The performance of the LNRD can be compared with available high frequency static prescalers. The Si Bipolar, GaAs or SiGe static prescalers in the market do not meet the lowest noise limits that is required for design of low noise frequency sources at the frequency range of 4-5GHz. Their phase noise performance show $\mathcal{L}$(1kHz) above -145dBc/Hz, with broadband thermal noise floors above -150dBc/Hz. Table 4 shows the performance of typical static prescalers, based on typical data from the product datasheets. The LNRD shows better performance in comparison.

Table 4. Comparison of residual phase noise of LNRD with typical performance of prescalers from datasheets.

Device	Process Technology	$\mathcal{L}$ (100Hz)	$\mathcal{L}$ (1kHz)	$\mathcal{L}$ (100kHz)
			dBc/Hz	
Agilent IFD-53010 @ 4GHz in, ÷4	Si Bipolar	-136	-143	-145
Agilent HMMC-3102 @ 6GHz in, ÷2	GaAs HBT	-113	-133	-148
SiGe Microsystems D602 @ 5GHz in, ÷2	SiGe	-136	-145	-149
United Monolithic CND2049 @ 4GHz in, ÷2	GaAs FET	-128	-139	-148
PSI LNRD @ 9GHz, ÷2	Custom	-146	-155	-160

Oscillator Phase Noise Measurements

Two-oscillator phase noise measurements have been carried out to examine the performance of the dividers when used as part of a low noise frequency source. For these measurements, two prototype low noise frequency dividers (LNRD) have been attached to the output of two PSI 9.0GHz low noise sapphire oscillators (SBO-9.000-XPL and SLCO-9.000-ACS). The phase noise was measured using the two-oscillator PLL method, as shown in Figure 7.

As seen from the Figure 8, the measurements indicate a reduction of 6dB in the phase noise observed at 4.5GHz compared with 9GHz for offset frequency of 100Hz to 3kHz. It is clear that for offsets less than 3kHz the LNRD can be considered to add no excess noise , allowing phase noise reduction truly '20dB per decade'.

At higher offsets the thermal performance of the LNRDs limit the source noise, to -165 dBc/Hz at 100kHz offset. This is consistent with the measured residual noise.

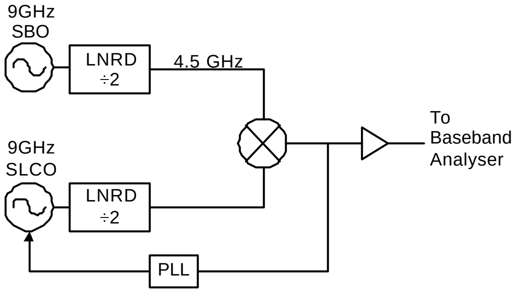

Figure 7. Two-oscillator PLL phase noise measurement setup for 4.5GHz (for 9GHz measurement, LNRDs were removed).

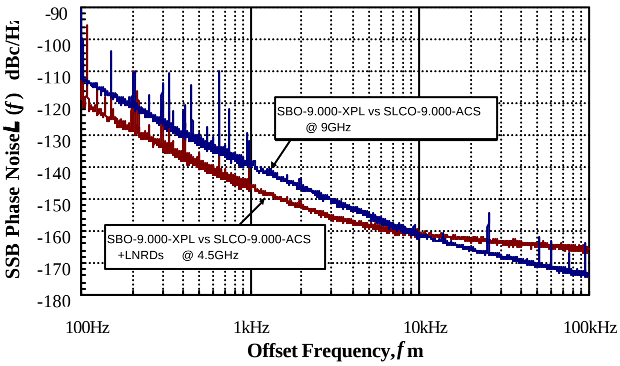

Figure 8. Comparison of two-oscillator phase noise at 9GHz and 4.5GHz.

Table 5. Phase noise of 9.0 and 4.5GHz sources (assumes equal contributions from each sapphire oscillator/LNRD combination).

Offset Frequency	Phase Noise of 9.0GHz Source $\mathcal{L}(f)$ dBc/Hz	Phase Noise of 4.5GHz Source $\mathcal{L}(f)$ dBc/Hz
100Hz	-112	-120
1kHz	-139	-145
10kHz	-161	-161
100kHz	-173	-165

Comparison with Other Technologies

The 4.5GHz signal generated with an LNRD and a sapphire oscillator can be compared with alternative signal generation schemes. Common practice has been to multiply the output of quartz crystals (around 10 to 100MHz) or low noise SAW oscillators (~ 500MHz) to microwave frequencies. This technique increases the phase noise sidebands of the source oscillator by the multiplication factor (ie. increasing the phase noise by minimum 20 log N).

Figure 9 compares the measured phase noise of the sapphire oscillator/LNRD-based source with high quality quartz and SAW oscillators, assuming ideal (noiseless) multiplication. At 4.5 GHz the LNRD-based oscillator has the lowest phase noise from 100Hz to 100kHz.

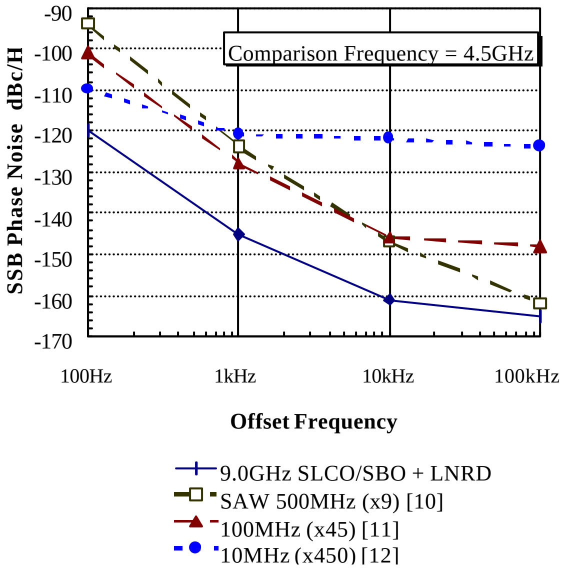

Figure 9. Comparison of various signal generation techniques, normalised to 4.5GHz output. Note that ideal '20 log N' multiplication has been assumed.

Conclusion and Future Work

The design of a low noise regenerative divide-by-two frequency divider has been shown. The LNRD has low phase noise at the output frequency of 4.5GHz. The residual noise measurements conducted showed close-in noise of L(1kHz) = -155 dBc/Hz and broad-band thermal noise floor of L(1MHz) = -170 dBc/Hz. The thermal noise floor was found to be limited by the amplifier's noise figure and phase tuning of the divider loop to maximise output power and stability. With further optimisation an improvement in the far-from-carrier noise floor of close to 5dB can be expected.

Several MMIC amplifiers were examined for suitability in the LNRD circuit. At 4.5GHz three amplifier types (based on three alternate process technologies) met the phase noise requirement for the LNRD, $L(f)$ less than -150 dBc/Hz at 1kHz offset.

Two 4.5GHz signal generators were produced with phase noise $L(f)$ = -145 dBc/Hz at 1kHz and -165 dBc/Hz at 100kHz offset. This results compares very favourably with other signal generation schemes, including multiplied quartz and SAW systems.

An LNRD with 4.5GHz input and 2.25GHz output has been designed following similar principles to the 9.0-4.5GHz units, with some minor modifications. The power splitters are implemented as drop-in commercial units, rather than microstrip couplers, due to size constraints. Preliminary modelling indicates that the residual phase noise of the 4.5-2.25 LNRD should be less than $L(f)$ = -156 @ 1kHz and -164 @ 10kHz offset frequency.

It is further planned to produce an LNRD from 2.25 to 1.125 GHz, to facilitate the production of a low phase noise microwave signal generator. With straight-forward mixing and switching plus a low noise UHF synthesiser, an ultra-low phase noise 0.1 to 18.0GHz signal source can be produced.

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