Frequency Synthesis from Cryogenic Sapphire Oscillator

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Abstract—**In this paper we present several configurations enabling to obtain a low-noise 5 MHz signal from the 100 MHz delivered by the frequency synthesis of a Cryogenic Sapphire Oscillator. The residual single-sideband phase noise of several dividers is reported. Especially the noise of a custom built regenerative divider has been measured to be around $\mathcal{L}_{5MHz}(1 Hz) = -145$ dBc/Hz. This performance is sufficient to measure the residual phase noise of an ultra-stable quartz crystal resonator using a carrier suppression system.**

I. INTRODUCTION

The FEMTO-ST Institute, Besançon, France and the French space agency (CNES), Toulouse, France investigate the origins of noise in bulk acoustic wave resonators for several years [1]. To characterize ultra-stable resonators, the carrier suppression technique is used to measure the inherent phase noise of the DUT. The traditional method is based on a setup made with two arms in which two nearly identical resonators are inserted. When the two arms are equilibrated the noise of the driving source is rejected [2], [3]. Eventually 3 dB are subtracted from the measured noise assuming the two resonators are identical. This assumption may not be true especially when dealing with state-of-the-art resonators. In this way it is interesting to search to develop a new tool able to characterize only one resonator. In this case, the key point is the phase noise of driving source, which should be very low. At 5 MHz, the power spectral density (PSD) of phase fluctuations of the best quartz crystal resonators is expected to approach -140 dBc/Hz at 1 Hz from the carrier.

The development of Cryogenic Sapphire Oscillators based on whispering gallery mode sapphire resonator has allowed an improvement of 1 to 2 orders of magnitude in terms of frequency stability, between one and several thousand seconds of integration time, compared to the hydrogen maser [4], [5]. The state-of-the-art of such a source in terms of frequency stability is around 6.10^{-16} at 1s of integration time [5]-[9]. Other technologies are able to produce ultra-low-noise microwave signals, like optical-comb-based frequency division of a cavity-stabilized laser [11]-[13].

In this paper, we present the preliminary results on a new frequency division chain delivering a 5 MHz signal from the 100 MHz coming from the frequency synthesis of a CSO [4].

The limit imposed by commercial dividers is shown. A better result has been obtained by using a custom regenerative divider (RD) in the last division stage. Further investigations are proposed in order to improve these results.

II. FREQUENCY SYNTHESIS

A. Cryogenic Sapphire Oscillator source

The CSO has been described in [14]. It generates an ultra-stable signal near 10 GHz achieving in the best configuration a fractional frequency stability of $4.5x10^{-16}$ at 1 s. Three almost identical CSOs have been recently implemented in the lab in the frame of the Oscillator IMP project. Each of them is complemented with a low noise frequency synthesis delivering a 100 MHz signal [15]. The phase noise measured by beating two synthetized 100 MHz signals is presented in Fig. 1.
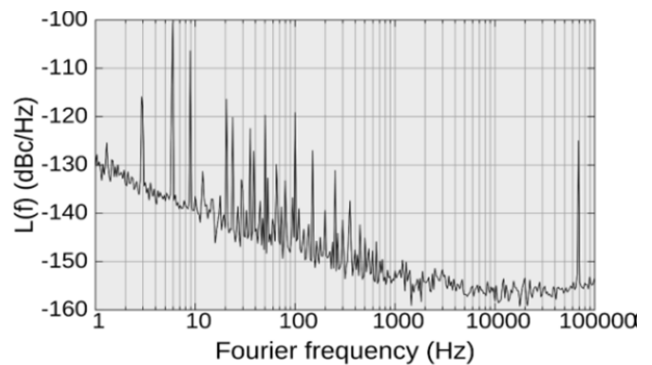

Fig. 1. Absolute phase noise of the 100 MHz signal delivered by the CSO synthesis chain. This result has been obtained by beating two nearly identical sources. The phase noise of one unit is assumed to be 3 dB lower.

At 100 MHz the phase noise of one unit is -133 dBc/Hz at 1 Hz offset from the carrier. It should be mentionned that this performance is limited by the noise of the frequency dividers implemented in the frequency synthesis chain, initially designed to get a fractional frequency stability of $3x10^{-15}$, thus practically one order of magnitude higher than the current CSO performance. The phase noise of the CSO 10 GHz signal has been measured: $\mathcal{L}_{10GHz}(1 Hz) = -100$ dBc/Hz [7]. For an ideal 100 MHz frequency synthesis the expected phase noise is

-140 dBc/Hz. These numbers demonstrate that there is some margin (7 dB) to improve the current system.

The simplest way to get a 5 MHz signal from a 100 MHz source is to use a chain of several dividers reaching the appropriate ratio, i.e. 20. This simple design is shown in Fig. 2.
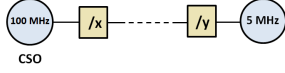

Fig. 2.   Simple cascade of several frequency dividers in order to get 5 MHz.

For an ideal division by ratio N, the phase noise is expected to be divided by N^2. The single sideband PSD of the input and output signals are thus related by:

$$\mathcal{L}_{5MHz}(f) = \mathcal{L}_{100MHz}(f) - 20 \cdot \log(\frac{100}{5})$$

Assuming the input signal with $\mathcal{L}_{100MHz}(1\ Hz) = $ -133 dBc/Hz, a noise-free synthesis is expected to deliver a 5 MHz output signal such as $\mathcal{L}_{100MHz}(1\ Hz) = $ -159 dBc/Hz. Unfortunately such theoretical limit cannot be practically reached due to the phase noise of the RF components (dividers, amplifiers) entering in the design of the frequency synthesis. The aim of this work is to evaluate the limit achievable with a simple solution based as much as possible on commercially available frequency dividers.

B. Commercial frequency dividers

We tested several commercial frequency dividers that could be implemented in the first stage of our frequency division chain. The measurement principle we implemented is represented in Fig.3.
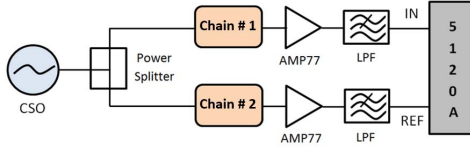

Fig. 3.   Measurement system configuration for commercial dividers.

The setup is based on a digital cross-correlation PM-noise measurement system (Symmetricom-5120A Microsemi Corporation). The power of the CSO 100 MHz signal is divided in two arms consisting in two identical divider chains.

Different combinations have been tested. The measurement results are presented in section III (see Fig. 8). One of the most convenient divider is the HMC705 (Hittite Microwave, Analog Devices). The division ratio of the HMC705 can be set between 1 to 17, and thus can constitute the first stage of the frequency division chain.

C. Regenerative Frequency Divider

The regenerative frequency divider (RD) is known for its very low phase noise. The RD principle presented in Fig. 4 can be extended in a wide frequency range [17]-[20].
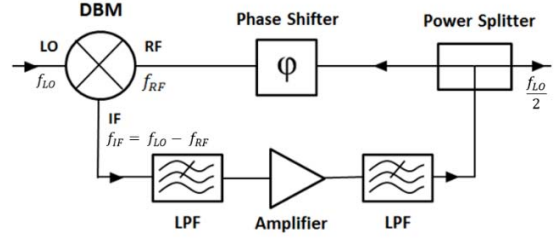

Fig. 4.   Block diagram of a frequency regenerative divider by 2.

This divider uses a mixer, an amplifier, some low-pass filters and a phase shifter in a closed loop configuration. The input signal of the divider f_{LO} is mixed with the RF signal f_{RF}. The IF signal contains two frequencies:

$$f_{IF} = f_{LO} \pm f_{RF} \tag{1}$$

The sum frequency is suppressed by a first low-pass filter (LPF). The closed loop condition imposes:

$$f_{IF} = f_{RF} \tag{2}$$

Combining equations 1 and 2 leads to an output signal frequency equals to $\frac{f_{LO}}{2}$. The second low pass filter is used to remove the broadband noise due to the thermal noise of the amplifier [18]-[20]. The built mixer is a well-proven double balanced mixer with a diode ring composed of four 2N2222A [21]. The transistors behave as diodes since the base is shorted to the collector. The principle of such a mixer is given in Fig. 5.
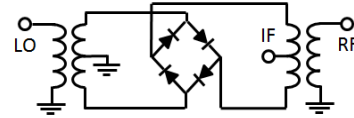

Fig. 5.   Principle of a double balanced mixer with a diode ring. Our mixer is composed of four 2N2222A transistors acting as diodes.

The amplifier is used to ensure an open loop gain superior to 1. The phase condition, which is close to 2π like in an oscillator, is set by a phase shifter. The regeneration starts due to the thermal noise inside the loop [17], [18]. The amplifier is a low-noise AMP77 (Mini-Circuits). Its low level gain is 15 dB and its output power at the 1 dB compression point is around 18 dBm at 5 MHz. In the RD loop the amplifier saturates [18], [22]. The output signal power is +12 dBm.

In order to measure the phase noise of the RD, we modified the previous set-up as shown in Fig. 6. The 100 MHz signal from the CSO is frequency divided by 10 with a HMC705 before the power splitter. The noise of this divider is subtracted out in the test system leaving the phase noise of the regenerative dividers.
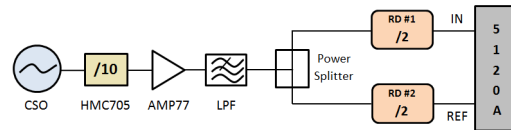

Fig. 6.   Block diagram of the measurement system for regenerative dividers.

The residual PM noise of a pair of RD is shown in Fig. 7. In this configuration, the divider pair reached -142 dBc/Hz at 1 Hz offset from the carrier. Both dividers have the same scheme and same components; therefore it is possible to subtract 3 dB from the measured phase noise to determine the contribution of each divider. Thus, each of our dividers shows an estimated residual phase noise of

$$\mathscr{L}_{5MHz}(1\ Hz) = -145\ dBc/Hz$$

and $\mathscr{L}_{5MHz}(10\ kHz) = -175\ dBc/Hz$.

The phase optimization in the loop of the divider and the tuning of the maximum output amplitude will decrease this phase noise [18].
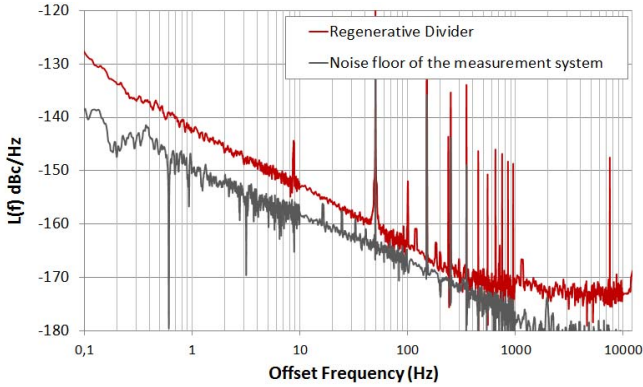

Fig. 7. Residual single-sideband phase noise of two frequency regenerative dividers at 5 MHz output for a 10 MHz input.

A phase noise of $\mathscr{L}_{5MHz}(1\ Hz) = -145\ dBc/Hz$ allows to measure quartz resonators whose frequency stability in the Allan deviation is $\sigma_y(\tau) = 4.7\times10^{-14}$.

III. PRELIMINARY RESULTS OF FREQUENCY SYNTHESIS

The phase noise of the tested configurations is shown in Fig. 8. The noise floor of the measurement system is at least 15 dB lower than those of the measured devices. Supplementary RF amplifiers are required to inject the signals in the 5120A with the appropriate power level.
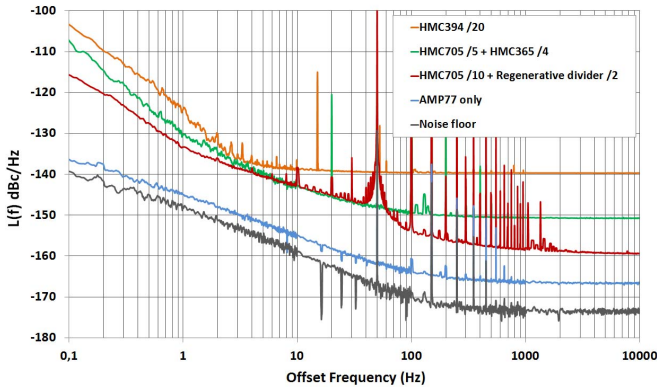

Fig. 8. Residual single-sideband phase noise of several frequency dividers configurations at 5 MHz output for a 100 MHz input.

The noise of a pair of AMP77 amplifiers has been thus also measured. It appears close to the noise floor of the measurement system and at least 10 dB below the divider noise. Although they are easy to use and offer many division combinations, the commercial dividers are clearly too noisy. The best result is a HMC705 with a division ration of 10 followed by a RD. In this case HMC705 noise limits the general performance. The residual and the estimated absolute phase noises are summarized in Table I.

TABLE I. NOISE RESULTS OF SEVERAL CONFIGURATIONS OF CASCADED COMMERCIAL DIVIDERS

Input frequency	*100 MHz*		
Cascaded dividers	*Division ratios*	*Estimated absolute phase noise ; $\mathscr{L}(1\ Hz)\ dBc/Hz$*	*Equivalent flicker noise (ADEV, $\sigma_y(\tau)$)*
HMC394	20	-128	2.3×10^{-13}
HMC705 ; HMC365	5 ; 4	-133	1.3×10^{-13}
HMC705 ; RD	10 ; 2	-137	1.2×10^{-13}

The best noise value at 1 Hz is -137 dBc/Hz. In term of fractional frequency stability, this is equivalent to a flicker noise floor in the Allan deviation: $\sigma_y(\tau) = \mathbf{1.2\times10^{-13}}$. This preliminary result has been obtained with a very simple configuration and can be improved. Indeed it has already been proven that a succession of several regenerative dividers is a suitable way to provide an ultra-low-noise frequency synthesizer [23]. With a chain of dividers-by-2, it is not possible to get 5 MHz from a 100 MHz signal. The input signal has to start from a divisible by 5×2^n frequency, e.g. 80 MHz. In order to use such frequencies the initial frequency synthesis (from 10 GHz to 100 MHz) will be adapted by modifying the frequency of the Dielectric Resonator Oscillator [15].

IV. CONCLUSION

In this paper, different dividers are reported to get 5 MHz from the 100 MHz signal of a Cryogenic Sapphire Oscillator. The residual phase noise has been measured for different configurations of cascaded commercial dividers. The lowest estimated phase noise has been shown at $\mathscr{L}(1\ Hz) = -137\ dBc/Hz$. This is why only regenerative dividers are going to be used. Indeed such dividers (with a ratio of 2) shown an absolute phase noise of $\mathscr{L}(1\ Hz) = -145\ dBc/Hz$, which is still perfectible but very likely the best choice in term of dividers.

The necessity to start from 100 MHz was the main reason of using commercially available dividers. Some of them present interesting low phase noise performances [6], but they are still not enough to get a state-of-art synthesized signal at 5 MHz.

Further work will involve the improvement of the general frequency synthesizer absolute phase noise. The optimization of the noise of frequency regenerative dividers is the first objective. Moreover the global performance of the frequency synthesizer is still improvable because some digital dividers are present in the first stage of the division, from 10 GHz to 100 MHz. The possibility to replace them by regenerative dividers could significantly reduce the phase noise.

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