Ultra Low Phase Noise Sapphire—SiGe HBT Oscillator

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***Abstract*—A state of the art C band oscillator is presented. It is based on a high Q WGM sapphire resonator and on a low residual phase noise SiGe HBT amplifier. A two oscillator experiment performed on this system has revealed a phase noise level of −133 dBc/Hz at 1 kHz offset from the 4.85 GHz carrier, which is the best published phase noise result for a single loop, free running microwave oscillator.**

***Index Terms*—Bipolar transistor, microwave oscillator, phase noise, sapphire resonator, SiGe.**

I. Introduction

THE design of ultra low phase noise microwave oscillators is a challenging field of research with numerous potential applications. These sources can be included in phase noise measurement systems, as part of high quality down converters. They can also be part of very sensitive radar systems or used together with an atomic reference. The work presented in this paper is focused to this last field of applications. The goal is to generate a signal with a better short term stability than the best quartz-based microwave references in order to drive a cesium clock. This also requires a good medium term stability for the oscillator, which is impossible to get using ambient temperature sapphire resonators because of the strong sapphire permittivity dependence on temperature. The final system will require a temperature compensated resonator, an efficient temperature control, and it will be probably designed to work at cryogenic temperatures (where the Q factor of the resonator is also increased).

The aim of this paper is to present an intermediate result obtained on a 300 K single loop sapphire oscillator which is at least 20 dB better than what was previously published on similar oscillators [1]–[3]. Only the oscillators designed with a stabilization circuit using an interferometric technique [4] have demonstrated a better performance than this oscillator, at least for offset frequencies well within the stabilization loop bandwidth.

II. Oscillator Design

The interest in SiGe transistors for the design of low phase noise oscillators has been demonstrated on classical dielectric resonator oscillators (DRO) at various microwave frequencies. At 4.7 GHz, particularly, a phase noise lower than −110 dBc/Hz at 1 kHz offset has been obtained on a DRO featuring a moderate loaded Q factor ($Q_L = 4000$) [5], [6]. This result is about 20 dB better than what can be obtained with FET oscillators. At higher frequencies, the performance of these devices is still good, but the results obtained on 10 GHz oscillators [5], [6] have shown a degradation of the phase noise performance which was greater than expected from the natural frequency multiplication factor (6 dB in this case). This was probably due to the HBT gain, which was much better at 4.7 GHz than at 10 GHz, thus allowing the choice of a low phase noise oscillator topology [7], while keeping enough gain to start an oscillation on a resonator with not too strong coupling factors. Therefore, a frequency close to half the cesium frequency has been chosen in our application. The cesium frequency (9.192… GHz) will then be easily obtained from this source by using a low residual noise multiplier by two and adding a low phase noise RF signal in order to compensate for the small remaining frequency difference.

The resonator used is a monocrystalline sapphire rod featuring a fifth-order whispering gallery mode (WGM) resonance at 4.85 GHz. At this frequency, the sapphire resonator is still of moderate size (5 cm in diameter) and the dielectric losses are very low. The measured unloaded Q factor of the resonator is 290 000. Such a resonator sustains a high density of resonant modes, and a mode selection scheme must be implemented to prevent any parasitic oscillation on an unwanted mode. To this purpose, another resonator in series with the sapphire resonator is used. This resonator is a strongly coupled dielectric resonator featuring a loaded Q of about 1000. When tuned at the same frequency as the sapphire, it efficiently prevents any parasitic oscillation at the cost of a losses increase of about 1.5 dB. Other solutions may involve the direct filtering of the modes in the sapphire cavity [8].

Two experiments were then performed with two SiGe amplifiers using transistors from two different manufacturers. The best result presented here has been obtained with the device featuring the lowest gain (but the best residual phase noise), which implies a strong coupling of the sapphire resonator. Finally, the total losses in the loop are close to 6 dB, and the loaded Q factor of the resonator is about 60 000. This loaded Q is measured on the two series connected resonators (sapphire + filtering cavity).

Concerning the amplifier phase noise performance, it is essential to select a device with a low $1/f$ noise and to use it properly. The transistor involved in this experiment has been designed by SiGe Semiconductor, Inc. in order to feature a low residual phase noise in this frequency range. It is a relatively large device ($4^{*}0.8^{*}32\ \mu m^2$) with a very low equivalent input

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voltage noise floor of about 0.5 nV/$\sqrt{\text{Hz}}$ and a corner $1/f$ noise frequency of about 1 kHz (data measured on a nonoscillating device). To obtain a good performance with this device, it is also necessary to filter the base-emitter junction current noise, which is generally the main cause of phase fluctuations in bipolar transistors oscillators [9]. A capacitive filtering technique, such as the one used in previously published papers [5], [6], is of no interest here because the goal is to get good performance not only far from the carrier but also very close to the carrier (down to 1 Hz offset, if the oscillator has to be associated with a cesium reference). Therefore, a new low impedance bias network has been designed for the bipolar oscillator (patent pending). A detailed study of the transistors residual phase noise and gain performance will be presented in a separate paper.

Finally, the amplifier and the resonator are associated in a feedback loop and the signal is extracted from a 10 dB coupler. Because the phase noise of such an oscillator was expected to be much lower than any existing reference at this frequency, two identical oscillators have been built.

III. Oscillator Metrology and Results

The two oscillators signals, respectively at 4.866 GHz and 4.849 GHz, are mixed and the beat 17 MHz signal is analyzed using an HP phase noise measurement system. The reference synthesiser (HP8662A) is used at 170 MHz together with a frequency divider of 10 in order to reduce its phase noise floor which was prohibitive at 17 MHz otherwise. This measurement setup is depicted in Fig. 1. The microwave part of the experiment (the two oscillators loops and the mixer) is build on a vibration isolated table. However, no temperature control is used for the resonators.

The result of the phase noise measurement is shown in Fig. 2. Considering that this noise is the addition of the two oscillators' uncorrelated noises, 3 dB must be subtracted from this curve to get the noise of a single oscillator. This leads to a single sideband phase noise level of −133 dBc/Hz at 1 kHz offset, and probably close to −160 dBc/Hz at 10 kHz offset. The noise increase from the ideal $1/f$ curve between 1 Hz and 10 Hz is probably due to a contribution of the HP8662A noise. The noise of this 170 MHz source has, indeed, been measured in an experiment involving two HP8662A synthesisers. 20 dB have been subtracted to this spectrum (to take into account the division ratio of 10), and a comparison has been done with the curve plotted in Fig. 2. The noise level has been found to be very close to the one measured in the sapphire experiment at 1 Hz offset, 3 dB below at 10 Hz and more than 10 dB below at 100 Hz and 1 kHz offset. For the upper range of offset frequencies (10 kHz to 100 kHz), the white noise floor of Fig. 2 is due to the frequency divider noise. Another possible contribution to the phase noise at the lower offset frequencies could be the temperature fluctuations of the resonator. Therefore, further investigations could take benefit of a temperature control of the resonators and, above all, of an higher frequency division ratio of the synthesiser signal.

In order to compare this result to previously published ones, we have plotted in Fig. 3 different phase noise levels obtained on RF and microwave oscillators at 1 kHz offset frequency. The interest of this offset frequency for comparison purpose lies in the following two assertions: 1) the measurement is easier at 1 kHz than at higher offset frequencies, where the noise floor has to be very low, or than at lower offset frequencies where

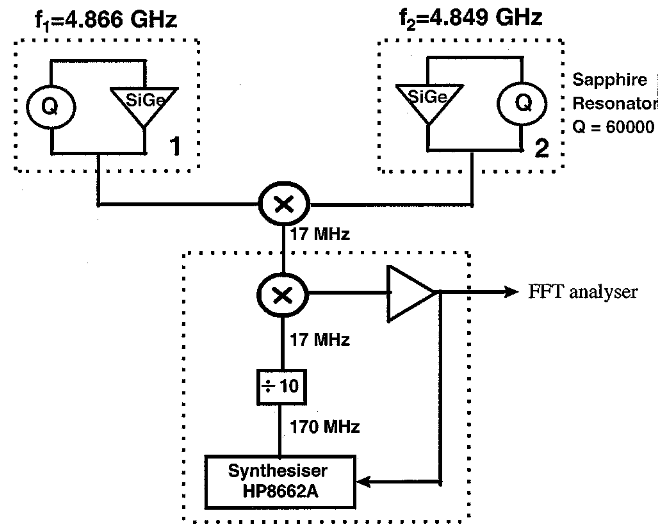

Fig. 1. Two oscillators phase noise measurement setup.

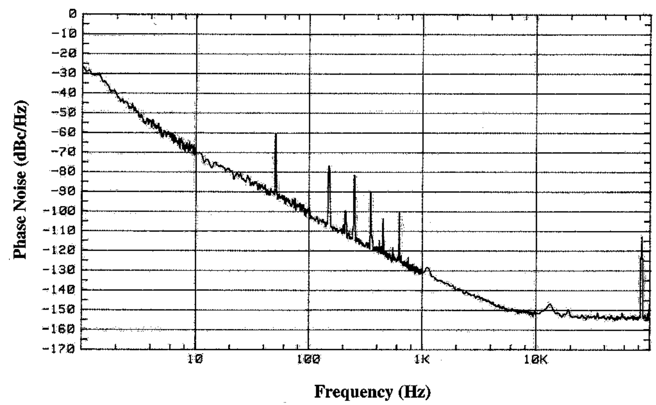

Fig. 2. Single sideband phase noise of the beat 17 MHz signal. The phase noise of a single 4.85 GHz oscillator can be estimated by substracting 3 dB to this curve.

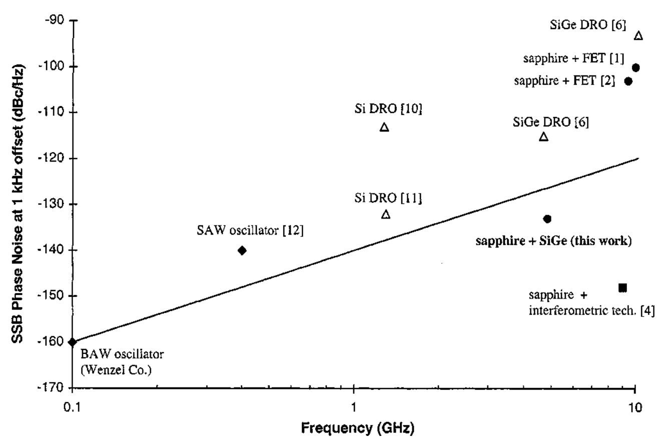

Fig. 3. Phase noise at 1 kHz offset frequency of some selected low phase noise sources in the RF and microwave range. The solid line represents the slope of the natural frequency multiplication of a given source (with no additive noise). The sapphire resonators (● and ■ in the figure) feature about ten times higher unloaded Q factors than the classical dielectric resonators (△ in the figure).

vibrations problems and temperature fluctuations are common; 2) 1 kHz is generally included in the fundamental $1/f$ frequency fluctuations region of the oscillator, which is directly related to the active device performance.

It is clear from Fig. 3 that the sapphire—SiGe oscillator is competitive with the best RF and microwave sources. Only the combination of a sapphire resonator and of an interferometric noise reduction technique is superior to this oscillator.

IV. Conclusion

An ultra low phase noise microwave oscillator has been presented. This oscillator takes advantage of low phase noise SiGe devices and of a high Q sapphire resonator. Improvement of this oscillator is still expected in the future through the improvement of the WGM resonator mode filtering technique and/or of the amplifier gain and phase noise characteristics, which should be possible according to on-going simulation results.

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