ULTRA LOW PHASE NOISE MICROWAVE SiGe DEVICES AND OSCILLATORS

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Abstract **In this paper, an open loop phase noise measurement bench is used for the selection of SiGe transistors in a sapphire oscillator application. This oscillator has demonstrated a phase noise level of –133 dBc/Hz at 1 kHz offset (at ambient temperature) from a 4.85 GHz carrier frequency, for a loaded Q_L factor of 60,000.**

Introduction

Microwave sources are today challenging quartz crystal sources for some metrology applications in which a very high short term frequency stability is required. Cryogenic sapphire oscillators [1,2] are among these sources, the ones that feature the best phase noise performance. However, it is of strong interest to realize a reference source of this type with already high performance at ambient temperature, thus avoiding the cost and size of cryogenic equipment.

The resonator Q being fixed, the only solution to improve the source phase noise performance is to reduce the noise of the amplifier included in the oscillator loop. This can be done using a carrier rejection (or interferometric) noise suppression technique [3], but this technique, in spite of being very efficient, is rather complex and difficult to tune. Another approach is in the optimization of active device used in the amplifier. The optimization is performed both on the device itself (selection) and on its working conditions (RF and DC load).

It is well known that SiGe bipolar transistors are good candidates for low phase noise generation [4,5]. Typically, a phase noise improvement of 10 dB or more can be observed close to the carrier (10 kHz offset) on a SiGe HBT Dielectric Resonator Oscillator (DRO) compared to a GaAs FET DRO [6]. In this presentation, we will describe a residual phase noise measurement bench dedicated to the test and selection of very low phase noise transistors. Then, we will use these measurement results to realize a sapphire oscillator which features state of art performance at 295 K.

I. Residual phase noise measurement bench for devices selection

Selecting the appropriate device is one of the key of success in low phase noise design. An important tool of this purpose is an efficient noise measurement system, able to characterize the noise in nonlinear regime of a single device. Residual phase noise data are often preferred in this case to the data obtained from the measurement of an oscillator or from the measurement of the transistor baseband noise. Indeed, an oscillator is already a complex system, in which all the parameters (loop gain, loop phase shift...) are not easy to control. On the contrary, the baseband noise measurement is a too rough approach which does not provide any information on the noise conversion process from baseband to phase noise or on the effect of the device nonlinearities on this conversion process.

The measurement bench is depicted in Figure 1. It allows residual phase noise characterization in the microwave range (1-18 GHz) of transistors and other devices such as amplifiers, mixers, frequency dividers and multipliers [7 to 11]. A noise floor of –180 dBrad/Hz at 10 kHz can be observed at 3.5 GHz in Figure 2.

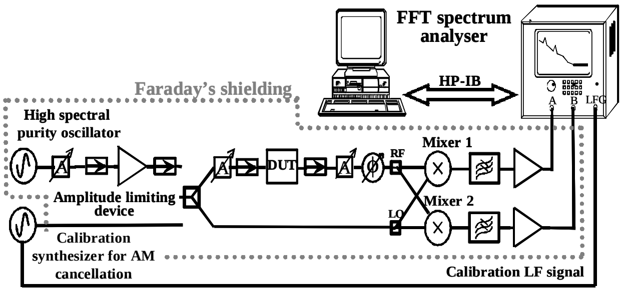

Figure 1 : Open loop phase noise measurement set-up

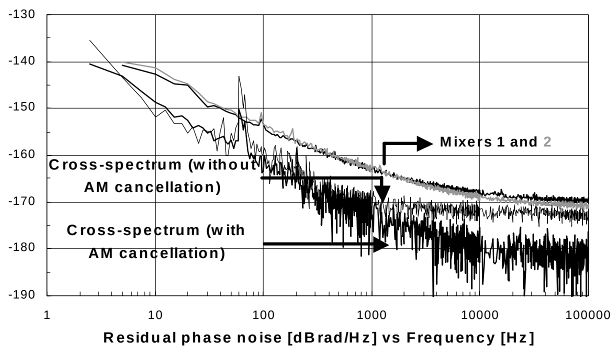

Figure 2 : Residual phase noise floor measurement system on each mixer and using cross-correlation configuration. (avg. 200)

Some special techniques must be implemented due to the low noise levels that have to be measured. We use a cross-correlation technique [12], which is based on a cross spectrum measurement on two identical mixers. It allows a substantial improvement of the experiment noise floor by eliminating the uncorrelated noise contributions of the two mixers (see Figure 2). But the phase detector noise is not the only challenge in this experimental setup. The source noise can also be a limiting element of the measurement. Its phase noise is theoretically suppressed with a good balance between the two phase detectors arms (no electrical delay).

However the rejection of its amplitude noise (AM noise) is more difficult. There are two ways in which this noise can be detected [13]. Firstly, by using an imperfectly balanced mixer or, secondly, in a direct manner by the device under test in non-linear regime. We propose two solutions to these problems :

AM cancellation technique

In order to minimize the detection of the AM noise, the first solution lies in the implementation of a systematic refinement of the mixer quadrature condition. The goal is to search for conditions where not only the phase detection is maximum but also, and above all, where the AM detection is minimum (the two extrema do not necessarily coincide). When this minimum AM detection is reached, a possible diminution of the phase detection coefficient K_ϕ is evaluated using the FM modulation.

The impact of this procedure on the noise floor is shown in Figure 2. The AM noise of the source, a 3.5 GHz dielectric resonator oscillator (DRO) from MITEQ Co., is detected by the mixer in quadrature mode, but this parasitic detection is then efficiently reduced by the proposed AM cancellation technique.

Source AM noise and its reduction

Even if the previously described procedure is implemented, it has no effect on the conversion of the source amplitude fluctuations by the DUT itself. Indeed, if a non-linear device is characterized, an AM-to-PM conversion process may occur. In this case, the source amplitude fluctuations are converted into phase fluctuations and detected by the experiment set-up just like true phase fluctuations. The DUT phase noise is thus artificially increased, and in a way which is hard to detect unless the DUT noise and the source AM noise feature very different spectral signatures. The only solution to this problem is in the reduction of the source AM noise. This can be done firstly by selecting an oscillator with a low AM noise level, such as a DRO instead of a synthesizer (see Figure 3). However, when testing very low noise nonlinear devices, this source selection can be insufficient. To overcome this problem, a device similar to the low phase noise DUT is used as an amplitude limiter, in order to reduce the AM noise of the source. The MITEQ DRO is thus cascaded with a limiting amplifier stage made of an Infineon BFP620 SiGe bipolar device. Although this transistor features a phase noise a few dB higher than the DUT investigated (a SiGe Semiconductor LPNT32 HBT) in Figure 5, it has the advantage of a very high small signal gain of 12 dB onto a 50 Ω load at 3.5 GHz.

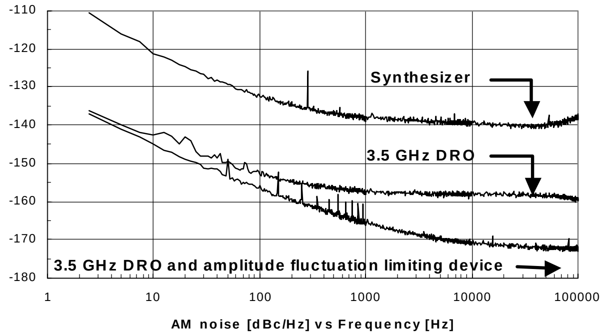

Figure 3 : AM noise at 3.5 GHz of different sources (avg. 200)

Finally, using the DRO followed by the SiGe device at the optimum point leads to an impressive 15 dB reduction of the source AM noise, as shown in Figure 3. This new source, which features an AM noise level lower than –170 dBc/Hz at 10 kHz from the 3.5 GHz carrier, is probably the quieter microwave source ever published (to our knowledge) with respect to the AM noise.

II. Residual phase noise of microwave SiGe HBT

The new source is then used in the measurement bench to characterize different SiGe transistors and particularly a very low noise device, an SiGe HBT from SiGe Semiconductor. This device is a large emitter area transistor (4*0.8*32 µm²), featuring a high S_{21} of 8.5 dB at 3.5 GHz, and dedicated to applications in this low microwave range [14]. The measurement of the 3.5 GHz residual phase noise of this device, loaded into 50 Ω loads, is depicted in Figure 4. The effect of the AM noise cancellation techniques presented previously is clearly seen on this example. Without these techniques, the device phase noise could not be measured, even if the noise floor of the cross correlation based setup is lower than the DUT phase noise level.

The SiGe transistor performance is then compared to other SiGe devices, measured in the same way, in Figure 5. All the devices feature a very good phase noise performance. There is actually a trade off to be made between phase noise and gain performance. The noisier device is the one that features the best gain performance. However, in our application, the gain performance provided by the LPNT32 devices was sufficient and we have selected this device for further designs. Such a phase noise performance could have not be reached without an appropriate noise minimization technique at the transistor level. The main noise source in these devices is the base-emitter current noise source. Previous works have shown that this can be realized with a high value capacitance on the base-emitter junction [5,15].

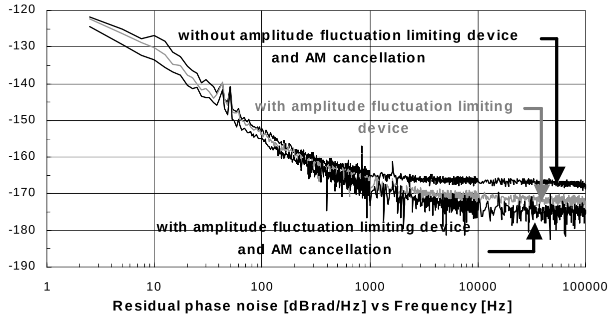

Figure 4 : Residual phase noise of a SiGe Semiconductor LPNT32 bipolar transistor in compression configuration at P_{IN}(3.5 GHz)=3 dBm. Transistor bias network high impedance with a filtering capacitance on base-emitter junction. (avg. 200)

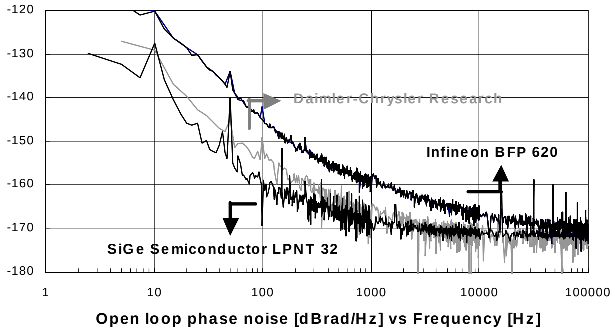

Figure 5 : Open loop phase noise of different SiGe HBT at P_{IN}(3.5 GHz)=0 dBm. Transistor bias network high impedance with a filtering capacitance on base-emitter junction. (avg. 200)

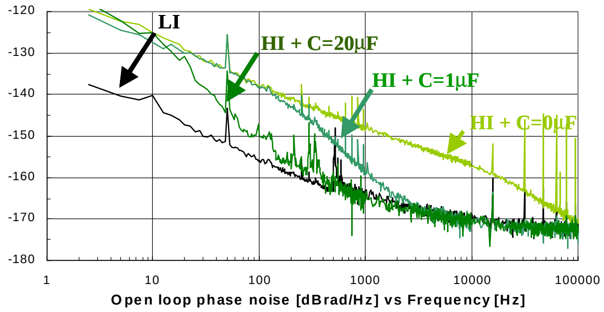

Figure 6 : Open loop phase noise of the LPNT32 device in different bias network configuration at P_{IN}(3.5 GHz)=0 dBm. HBT bias : I_C=10 mA, V_{CE}=2 V (avg. 200)

Figure 6 illustrates the effect of the bias network on the residual phase noise of the SiGe HBT. The possible bias network configurations are : low impedance (LI) and high impedance bias network (HI) with different capacitance's value in parallel on the emitter-base junction. The best performance is achieved with the low impedance bias network. Considering the excellent residual phase noise level of this transistor, -171 dBrad/Hz at 10 kHz offset and –143 dBrad/Hz at 10 Hz, a very low phase noise oscillator dedicated to metrology applications can be designed.

III. Application : sapphire / SiGe oscillator

The goal was then to realize with this device a microwave source better than the best quartz based oscillators. This work is part of the PHARAO program leaded by the French national space agency (CNES).

The oscillator configuration is based on a parallel feedback topology. The resonator is a monocrystalline sapphire rod used on a 5th order Whispering Gallery Mode (WGM) resonance at 4.85 GHz. The measured unloaded and loaded factors, of the resonator are respectively about 290,000 and 60,000. Because the expected performance of the oscillator was much beyond the best available microwave synthesized reference sources, a two oscillators measurement has been performed. Therefore, two identical sapphire/SiGe oscillators have been realized at 4.866 GHz and 4.849 GHz. Their output signal is mixed to generate a 17 MHz beat frequency which is compared to a reference synthesizer (HP8662A) used at 170 MHz and divided by 10 in order to improve its phase noise performance at 17 MHz. The measured phase noise spectrum is plotted in Figure 7. Above 10 kHz offset frequency the observed spectrum is related to the synthesizer phase noise. Under 10 Hz offset frequency, the increase of the noise may be due to a thermal instability. The phase noise of a single 4.85 GHz oscillator can be estimated by subtracting 3 dB to this curve. The measured phase noise at 1 kHz is therefore –133 dBc/Hz and by extrapolation close to –160 dBc/Hz at 10 kHz offset.

This observed performance is close to state-of-the-art [16] and is compared in Figure 8 versus other published low phase noise oscillators at 295 K. Some RF quartz sources are shown in this figure. The result that could be obtained at microwave frequencies by multiplying these quartz sources is shown by dotted lines (with the assumption of no additive multiplier noise). It shows that the measured performance of our oscillator corresponds to the best single loop microwave oscillator at ambient temperature. The only other comparable source is the sapphire-interferometric oscillator previously reported in [3]. This oscillator, however, makes use of a complex noise cancellation circuit, which requires a fairly high volume and which may be difficult to tune.

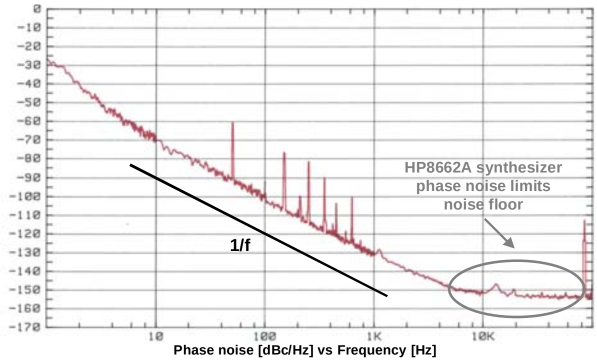

Figure 7: Single sideband phase noise of the 17 MHz beat signal between the two Sapphire / SiGe HBT microwave oscillators (4.866 GHz and 4.849 GHz)

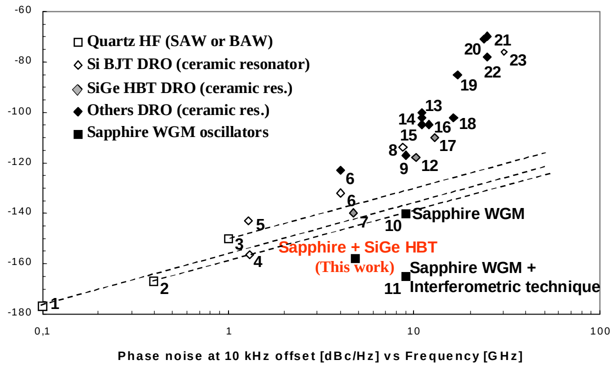

Figure 8: Phase noise comparison at 10 kHz offset with other state-of-the-art oscillators (Reference in Table 1).

1. 100 MHz oscillator, WENZEL, *commercial product*
2. 400 MHz oscillator, Z. Galani, IEEE-MTT Workshop, 1994
3. 1 GHz SAW oscillator, SAWTEK, *commercial product*
4. 1.28 GHz BJT DRO, E. C. Niehenke and P.A. Green, IEEE-MTT S, 1987
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Table 1: References used in the performance comparison.

Conclusion

A low residual phase noise measurement bench at microwave frequencies has allowed us to select a transistor featuring exceptional phase noise performance. This performance is reached not only by selecting the device, but also the devices operating conditions. The device is then used in sapphire microwave oscillator, which demonstrates the best phase noise performance ever published for a microwave single loop oscillator.

Reference

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