Proceedings of German Microwave Conference (GeMiC 2006), Karlsruhe, March 28-30, 2006. Session 3a-1

# Systematic Measurements for Testing the Influence of an Internal Noise Source on the Phase Noise of an Oscillator

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***Short Abstract*** **— Based on a novel theory of phase noise of resonator oscillators, the influence of an internal noise source on the phase noise behavior of a differential-amplifier oscillator is measured for different feedback parameters and compared to simulation using modern CAD software. The results will constitute the basis for a further development of the novel theory.**

***Keywords - phase noise; oscillators; feedback; spectrum; noise***

## I. INTRODUCTION

Generation of sinusoidal signals with low phase noise is and will remain an important objective for a large number of applications. There are many publications available dealing with the analysis of the spectral purity of signals produced by certain types of oscillators [1]. There exist also publications on the systematic and non-linear theory of sinusoidal oscillations [2]-[4]. These publications are highly instructive for those having a thorough background in very special fields of mathematics, as for instance the theory of non-linear differential equations and of the evaluation of nonlinearly processed stochastic processes. Due to their high specialization, though, they are not easily readable for the practitioner, and it is often not easy to see the link between the spectral properties of diverse noise sources in the oscillator circuitry and the phase-noise that is finally produced. In a recent paper [5] of one of the authors, a theory of oscillators has been developed that is based on standard mathematics of modern engineering curricula. In order to test the theory, systematic measurements have been performed. This paper will demonstrate first steps towards the validation of the theory.

To that aim, an oscillator circuit with a relatively simple non-linearity has been developed, where additional noise sources might be included on purpose. With these, measurements have been performed to cast a new light on the following questions:

- Can the phase noise be minimized by variation of feedback parameters?
- How do the feedback parameters influence the phase noise spectrum?
- How does the external noise source influence the phase noise spectrum?
- How good do measured results agree with standard CAD simulation?

## II. THE OSCILLATOR AND THE NOISE SOURCE

The oscillator was designed using a differential amplifier, which provides a relatively simple nonlinearity in the non-saturated case. In saturated operation, it provides another, more complex non-linearity, which makes possible a comparison of results for different non-linearities. In order to study the influence of feedback parameters on the phase noise and the nonlinear behavior, the oscillator circuit has been designed such that the feedback parameters might be adjusted. Additionally, two controllable current sources have been included, the control voltage of which might be a noise- source.

### *A. The differential oscillator*

The differential oscillator topology is shown in Fig.1. Two dual-type NPN BFE520 transistors are forming a differential amplifier. The collector resistance $R_{coll}$ allows an adjusment for the loop gain of the oscillator. The collector voltage $U_{coll}$ is decoupled via a bypass-capacitor to a subsequent emitter-follower stage. The LC-resonance circuit is placed in the feedback branch between the emitter follower and the differential amplifier. The current sources Isrc1 and Isrc2 are simple current mirrors to provide a constant current of 5mA thru the differential amplifier and the emitter-follower. The

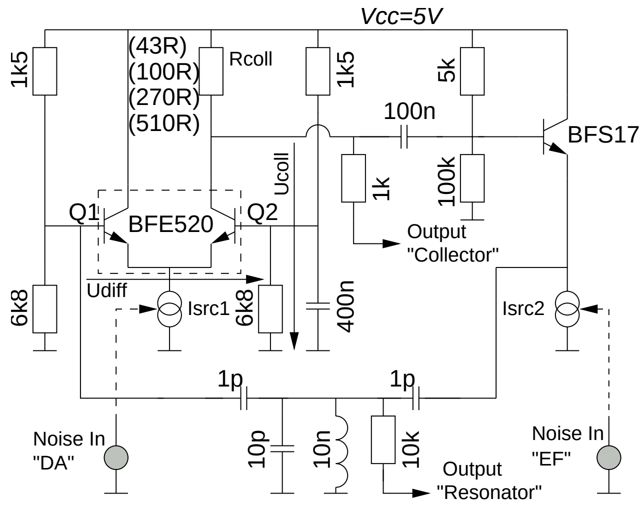


Figure 1. Differential amplifier topology with LC-resonator.

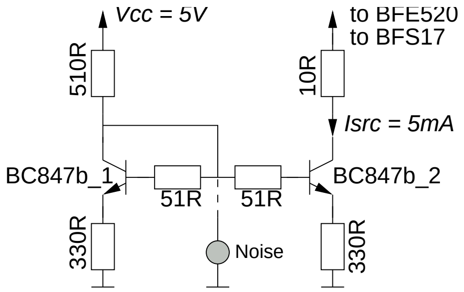


Figure 4. Current sources Isrc1,Isrc2 with voltage noise source

topoloy of the current sources is shown in Fig.2. The external noise source is connected to the base resistors of the current source transistors and the noise voltage is transformed into a noise current in the collector of BC847b_2. Fig.3 shows the nonlinear DC transfer function of the differential amplifier for different values of $R_{coll}$. Up to a resistance value of 330Ω, transistors Q1 and Q2 are working in their active forward region. For larger values of $R_{coll}$, Q2 is working in the saturated region, where both the base-emitter and the base-collector diode are forward biased. The circuit is assembled in SMD technology on a 0.5mm FR4 substrate material. For the passive components a 0603/0805 package size is used. The active devices are simulated using standard Gummel-Poon models as implemented in ADS2004A. The 1/*f*-noise model parameters are not included in the model and therefore not simulated.

## *B. The external noise source*

The noise source is shown in Fig. 4. It provides a constant, white noise spectral density over a frequency range from DC to 20MHz with an adjustable output voltage. The noise voltage is generated by a Zener-diode. It is coupled to an active 8[th]-order Butterworth filter as shown in Fig. 5. The spectral noise voltage density at the output of the filter can be adjusted in a dynamic range from $-20$ dBμV/$\sqrt{\text{Hz}}$ to +29 dBμV/$\sqrt{\text{Hz}}$. The noise source is capable to drive loads down to 50Ω. Typical noise spectra are shown in Fig.6. They are compared to the noise-floor of the measurement equipment.

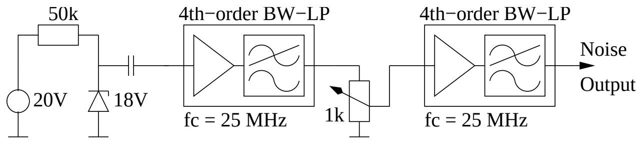


Figure 2. Noise source topology with zener diode

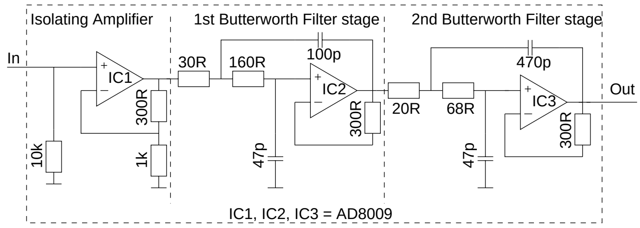


Figure 3. 4[th] order active low-pass butterworth filter circuit topology

## III. Measurement and Simulation Results

For the measurements, a HP8565EC spectrum analyzer and a MITEQ AU-1261 low-noise preamplifier were used. The phase noise was measured with the phase noise utility, implemented in the HP8565EC. For the ±5V supply for both the noise source and the oscillator, two HPE3610A DC power supplies were used.

## *A. Measurements without external noise source*

The large signal simulation and measurement results without external noise source for $R_{coll}$=100Ω, are compared in Tab.1. The simulated oscillation frequency is 40MHz above the

TABLE I. Simulation and Measurement Results without External Soise Source

| Results for $R_{coll}$=100Ω | *HB Simulation* | *TRAN Simulation* | *Measurement Results* |
|---|---|---|---|
| DC current $I_{src1/2}$ (mA) | 5.11 | | 5.1 |
| Frequency $f_0$ (MHz) | 463.8 | 463.4 | 423 |
| Power $P_{Coll@50\Omega}$ (dBm) | -30.1 | -31.9 | -33.3 |
| PHN@10kHz (dBc/Hz) | -99.7 | not sim.[a] | -100 |

a. Large signal phase noise simulation for transient simulation not available in ADS2004.

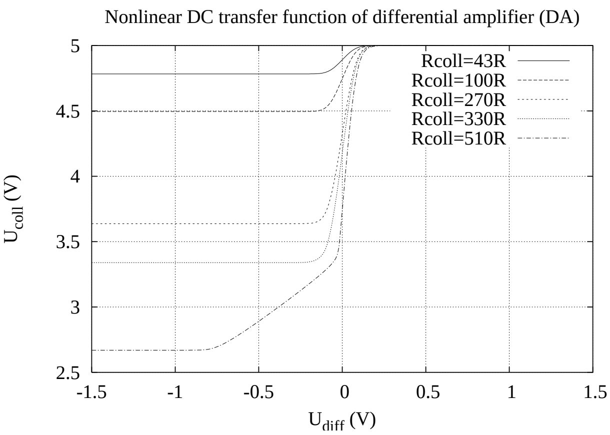


Figure 6. Simulated DC voltage transfer function with different values for *Rcoll*

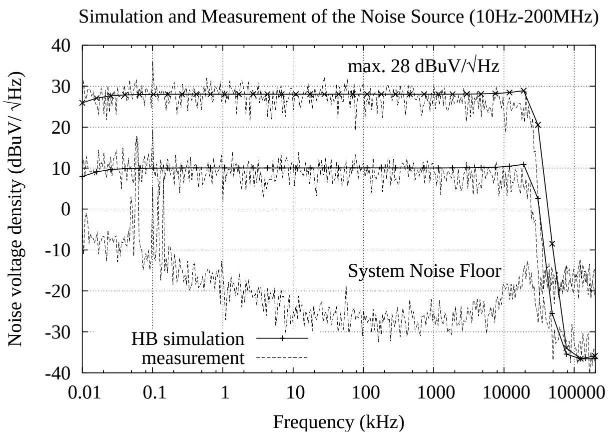


Figure 5. Low frequency noise source voltage density spectrum for different noise densities adjusted.

measured freqency, which is an accuracy of about 10%. For the collector power and the phase noise, the differences between simulation and measurement are very small. The power at the collector was measured without the preamplifier stage, directly with the 50Ω input of the spectrum analyzer. In Fig. 7 the simulated and measured results for the SSB (single side band) phase noise are shown. The phase noise measured with $R_{coll}$=100Ω is –100dBc/Hz at 10kHz offset. The lowest relative phase noise was measured with $R_{coll}$=270Ω for –103dBc/Hz at 10kHz offset. This measurement is not included in the diagram. As long as the transistor Q2 operates in its active forward region, the slope of the phase noise spectrum is –20dB/dec. If the transistor Q2 operates in its saturated region ($R_{coll}$=510Ω), the slope increases to –30dB/dec for offset frequencies below 20kHz. The simulated results are in the same range as the measured results. However, in the simulation, the minimum phase noise is obtained for $R_{coll}$=510Ω, and could even be minimized for higher values for $R_{coll}$. This could not be observed by measurement. The simulated slope with $R_{coll}$=43Ω, decreases for offset frequencies below 10kHz to –10dB/dec. This might be due to the missing 1/*f*-noise parameters in the transistor model. The 50kHz spurious responses in the phase noise spectrum are produced by the DC power supply. They occur only in the phase noise spectrum for $R_{coll}$=510Ω. The measured phase noise spectra at the collector output and at the resonator output are identical.

### *B. Measurements with external noise source*

The measurement and characterization procedure of the oscillator with the external noise source was as follows. For each of the four collector resistor values $R_{coll}$=43/100/270/510Ω, the "right-sided" SSB phase noise spectrum from 500Hz–50MHz offset frequency and the carrier spectrum in a 100MHz bandwidth were measured, both at the collector output and at the resonator output, for external noise voltage densities of 10dBμV/$\sqrt{\text{Hz}}$ and 25dBμV/$\sqrt{\text{Hz}}$, with noise input at the differential amplifier current source $I_{SRC1}$ (noise in "DA") and at the emitter follower current source $I_{SRC2}$ (noise in "EF"). This procedure results in 64 measured spectra which cannot be presented completely in this paper. Therefore, some selected and representative measurements will be discussed. The complete set of measurements might be found in [6].

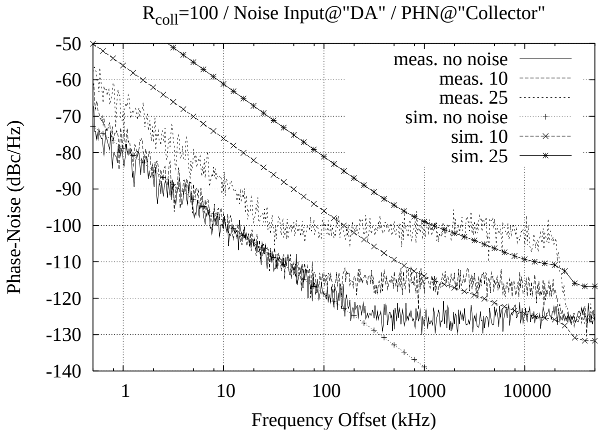


Figure 7. Simulated and measured phase noise spectrum for different noise voltage densities. Collector resistance $R_{coll}$=100Ω.

The simulated and measured phase noise spectra at the collector, with external noise input at "DA", are shown for $R_{coll}$=100/510Ω in Fig. 8 and Fig. 9 respectively. The limited bandwidth of the noise source might be observed at 25MHz frequency offset. As it was expected, with increasing noise voltage density the phase noise is also increasing. For $R_{coll}$=510Ω, the –30dB/dec slope is changed into –20dB/dec. The simulated phase noise is in the range of the measured phase noise only for $R_{coll}$=270/510Ω. For $R_{coll}$=43/100Ω the simulated phase noise quantity and shape differs substantially from measurement.

A comparison of measured noise spectra at the collector with different resistor values, for an input voltage noise density of 25dBμV/$\sqrt{\text{Hz}}$ at "DA" is shown in Fig. 10. The influence of the external noise source on the phase noise is worst for $R_{coll}$=43Ω and best for $R_{coll}$=100Ω. For $R_{coll}$=100/510Ω, two regions in the phase noise spectra can be distinguished clearly: A –20dB/dec region close to the carrier and a constant (white) noise region up to 25MHz offset frequency. The corner frequency between those two regions depends on the value for

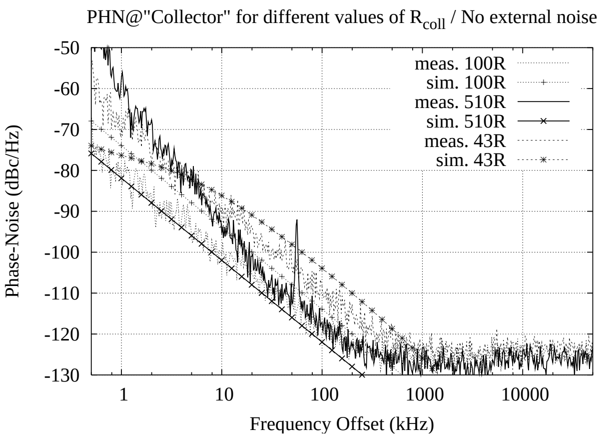


Figure 9. Phase noise without external noise for Rcoll=43/100/510Ω

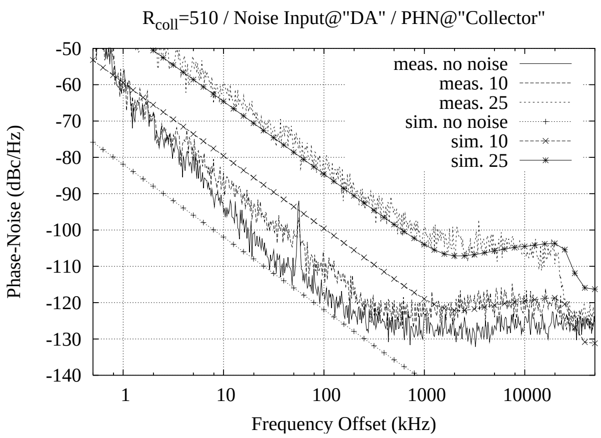


Figure 8. Simulated and measured phase noise spectrum for different noise voltage densities. Collector resistance $R_{coll}$=510Ω.

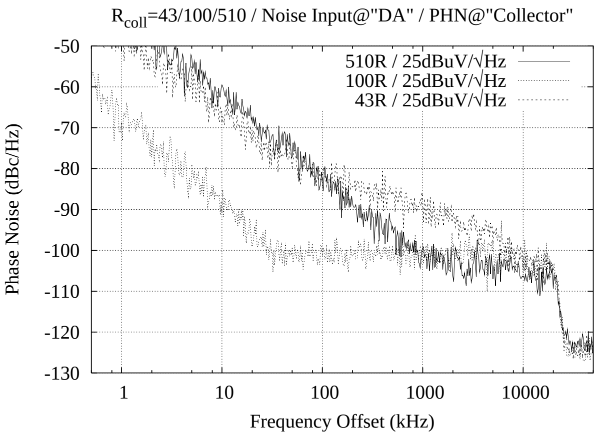


Figure 13. Measured phase noise for $R_{coll}$=43/100/510Ω with a noise voltage density 25dBuV/√Hz at noise input "DA".

$R_{coll}$. It is important to mention, that the LC-resonance circuit is not changed and is the same for all measurements. A comparison for an input voltage noise density of 25dBμV/$\sqrt{Hz}$ at "EF" is shown in Fig. 11. The influence of the external noise source on the phase noise is worst for $R_{coll}$=510Ω and best for $R_{coll}$=100Ω. The measured phase noise for $R_{coll}$=100Ω below 20kHz offset frequency is identically to the measurement results for noise input at "DA". A white noise region, as in Fig. 10 with band limitation to 25MHz, could not be observed. As can be seen in Fig. 12 the high-to-low and low-to-high transition between the maximum and minimum voltage, is slow for $R_{coll}$=43Ω and faster for $R_{coll}$=100Ω and $R_{coll}$=510Ω. For $R_{coll}$=100Ω the high state has a flat shape, without peaks or overshoots, as it is for $R_{coll}$=510Ω. According to [3], this indicates a low sensitivity of the oscillator steady state signal, against impulse distortions. In this experiment, the value $R_{coll}$=100Ω is the best choice for minimum influence of the external noise source. It was also found that for offset frequencies from 500Hz-1MHz the measured phase noise shape and quantity is the same at the resonator and the collector output. For larger offset frequencies (1MHz-50MHz) the measured phase noise at the resonator is smaller than at the collector. This behaviour might be seen in the measured carrier spectra from Fig. 13 and Fig. 14.

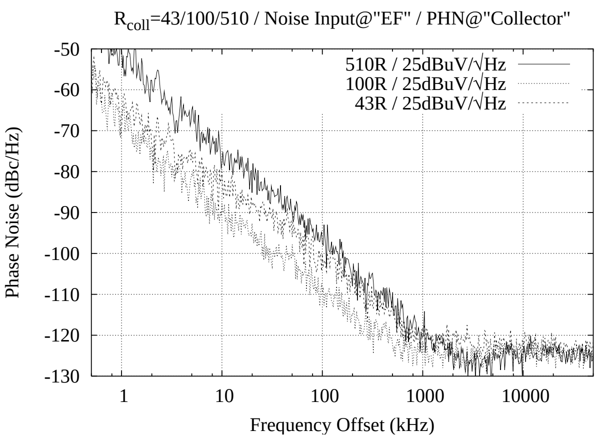


Figure 12. Measured phase noise for $R_{coll}$=43/100/510Ω with a noise voltage density 25dBuV/√Hz at noise input "EF".

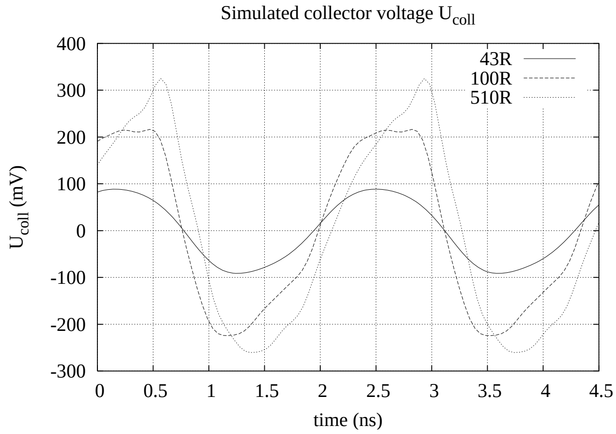


Figure 11. Collector voltage time domain signal $U_{coll}$ obtained from HB simulation.

The simulated and measured carrier spectra at the collector output and at the resonator output are shown in Fig. 13 and Fig. 14 respectively. The carrier spectra were measured without external noise and for a noise density of 10dBuV/$\sqrt{Hz}$ and 25dBuV/$\sqrt{Hz}$. The spectra for $R_{coll}$=270Ω are chosen, because some effects might be seen more clearly with this resistance. The effects are more or less present for all other resistance values. The LC-resonator values in the simulation were changed, in order to achive the same oscillation frequency, as in the measured spectra. This simplifies the comparison between simulated and measured spectra. The differences between the simulated power, spectrum and phase noise for the different LC-resonator values are neglectable small. The spectra are simulated using the harmonic balance mixer noise simulation. The spectrum at the collector output (Fig. 13) shows a virtually white noise power spectrum for offset frequencies up to ±20MHz, whereas the spectrum at the resonator in Fig. 14 is a filtered version of the collector spectra. The shape of the simulated spectra correspond to the measurements, but the quantity and the noise floor do not fit

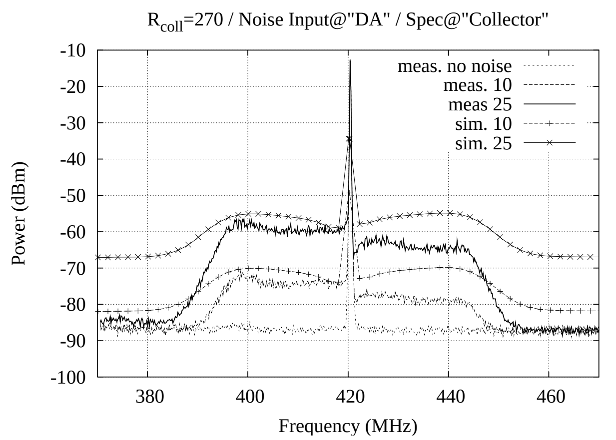


Figure 10. Simulated and measured spectrum at the "collector output" in a 100MHz frequency band around the carrier.

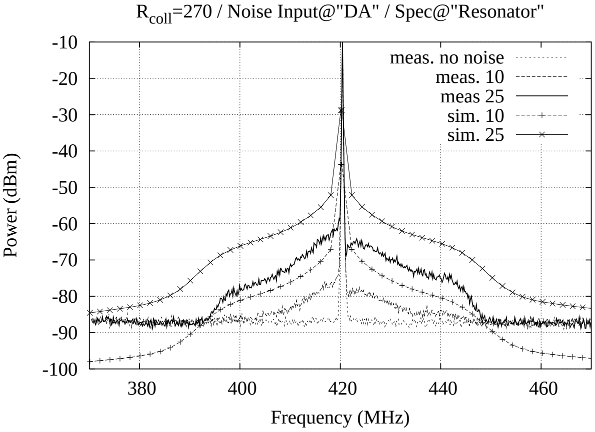


Figure 16. Simulated and measured spectrum at the “resonator output” in a 100MHz frequency band around the carrier.

very well to the measurements, especially not for the resonator output. Another finding is the asymmetric spectra around the carrier. The “left-sided” power spectra is 5dB higher than the “right-sided” spectra. Close to the carrier, there is a “kink” in the “right-sided” spectra. The simulated spectra are symmetric around the carrier. Therefore different quantities and spectra for phase noise might be measured, if either the “right-sided” or the “left-sided” spectrum is defined as SSB phase noise.

### *C. Colpitts Oscillator for comparison purposes*

A Colpitts oscillator (Fig. 15) was designed for comparison purposes of the phase noise spectra. The transistor in the Colpitts oscillator is typically driven into saturation, when the oscillator is in a steady state. As can be seen in Fig. 16, the slope changes from –20dB/dec to –30dB/dec for offset frequencies below 10kHz, whereas the slope for the non-saturated differential oscillator is about –20dB/dec.

## IV. Conclusion

In this experiment a low frequency external noise source was used to measure the noise upconversion in an oscillator under different feedback parameters. It was shown, that for small offset frequencies (500Hz-1MHz) the phase noise is the same at the resonator and at the collector, but for larger offset frequencies (1MHz-50MHz) the phase noise spectrum at the resonator is a filtered version of the collector spectrum. The spectrum of the low frequency noise source is not symmetrically upconverted around the carrier. An optimum resistance value with $R_{coll}$=100Ω was found, for which the noise source influence is minimized.

As long as the transistors operate in the active forward region, the slope is –20dB/dec. Furthermore it was shown that an –30dB/dec slope region appears close to the carrier, in the phase noise spectrum, if one of the transistors is operating in the saturated region.

Thus, valuable conclusions might be found. One of them is that now evidence is given that white noise at certain points in the oscillator circuitry produces a phase-noise spectrum in a range near the carrier, and with –20dB/dec, if the used

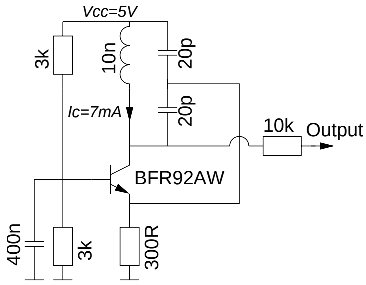


Figure 14. Colpitts oscillator ($f_0$=437 MHz) designed for phase noise comparison purposes (typically operating in saturated region).

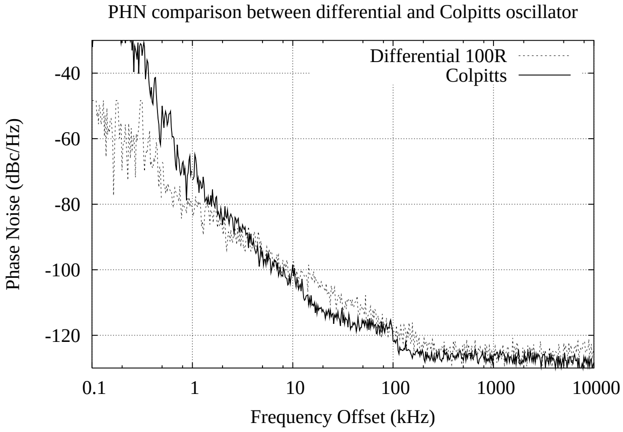


Figure 15. Measured phase noise spectrum for the Colpitts oscillator and the differential oscillator with $R_{coll}$=100Ω

nonlinearity is having an odd characteristic. It produces also a part of the spectrum that is white. If the nonlinearity changes symmetry such that also even parts of the characteristic are important, then a part of the phase noise spectrum close to the carrier, is produced that decreases with –30dB/dec. Therefore, there is evidence that in the used differential-amplifier-oscillator, the most important mechanism for phase noise is the upconversion of noise in the input circuitry of the amplifier by virtue of its nonlinear transfer characteristic, as it was assumed in [5].

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