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Measurements to reveal Phase-Noise producing Mechanisms in Resonator-Oscillators

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ABSTRACT

During the last decades, several theoretical models describing phase noise of oscillator signals have been established. Verification of these models has mainly been done by computer simulations. However, what is still missing is a rigorous *experimental* validation of diverse aspects of these models. This is not an easy job, since internal noise sources of the measurement equipment superimpose the effects to be measured. Therefore, a novel measurement method is introduced. Relatively strong, additional noise-sources are deliberately included into oscillator circuits. Controlling the power and the spectrum of these sources allows to clearly identifying the effects of these sources to the spectrum of the oscillator's output signal. This paper shows typical measurement results and their interpretations. It turns out that at least for the oscillator under test, modeling with simple additive noise might not be sufficient. Rather, multiplicative noise must also be taken into account. The consequence is that the output of oscillators might not only be affected by phase noise but also by amplitude noise. Under these circumstances, models that explicitly exclude amplitude noise in oscillators might need completion.

Keywords: Phase-Noise, amplitude-noise, multiplicative noise, oscillators, noise spectra

1. INTRODUCTION

Phase noise in oscillator-signals is a well-known phenomenon that limits the quality of a variety of measurements. Therefore, many publications have either addressed the theory of how phase-noise is produced or what had to be done in order to reduce phase-noise in oscillator-signals.

Theories might be categorized roughly into four groups. The first one is dealing with a theoretical description of noise spectra. Its protagonist is Leeson[1]. Other authors like Hajimiri and Lee[2,3,4] introduced amplitude- and phase-impulse transfer characteristics in order to explain the spectra of oscillator signals. The strongly theoretically based Munich-school is going back to Kärtner[5,6], where phase-space-trajectories are evaluated in order to predict the oscillator behavior. Publications of Demir[7] might be seen as a consequent improvement of the Munich-models. Still other authors are introducing a combination of large-signal- and small-signal-models and harmonic balance[8].

Verification of the advanced theoretical models is not a simple task, since the aim is to produce oscillators with low phase-noise. Therefore, it is difficult to separate the effects coming from the device under test from those effects being produced by the measurement equipment. In this paper, a novel method for measuring and identifying the effects of noise sources in an oscillator will be introduced.

2. METHODOLOGY

Any theoretical model on oscillator phase-noise assumes that there are several independent sources of noise in the oscillator. They differ in how these sources influence the oscillator output in the steady state.

The main idea of the novel model is to include into the oscillator circuit at least one additional, physical source of noise at a position in the circuit, where also an intrinsic noise source is assumed to be. By varying the additional noise power

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and making it much larger than the power of the intrinsic source, the influence of this source might directly be seen in the output spectrum of the oscillator.

By repeating this experiment with noise sources at different positions in the oscillator circuit, it might be seen how noise sources at different positions in the circuit influence the phase-noise behavior of the oscillator. It appears thus to be possible to review the validity of several models of phase-noise in oscillator signals.

This method was first introduced by this author[9]. Its application using advanced measurement equipment is demonstrated in this paper.

3. EXPERIMENTAL SETUP

The novel method has been applied to a transmission-type resonator-oscillator with parallel-parallel-feedback. Its principal structure is shown in the block circuit diagram following Fig. 1.

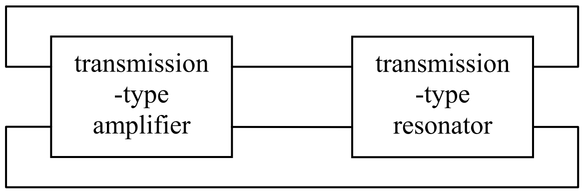

Fig. 1. Block-circuit diagram of the used transmission-type resonator-oscillator with parallel-parallel-feedback.

The schematic of the oscillator is shown in Fig. 2. Its amplifier consists of a differential amplifier with an emitter follower as output stage. Since shot noise is assumed to be a major cause for noise production in the amplifier, the current sources in the differential amplifier and the emitter follower are designed as voltage-controllable sources. Inputting a noise voltage at one of the control inputs then superimposes the intrinsic shot noise of these stages. In order to be able to control the gain of the amplifier independently from the current produced by current source VCCS2, resistor R1 (and thus its resistance value) could be exchanged.

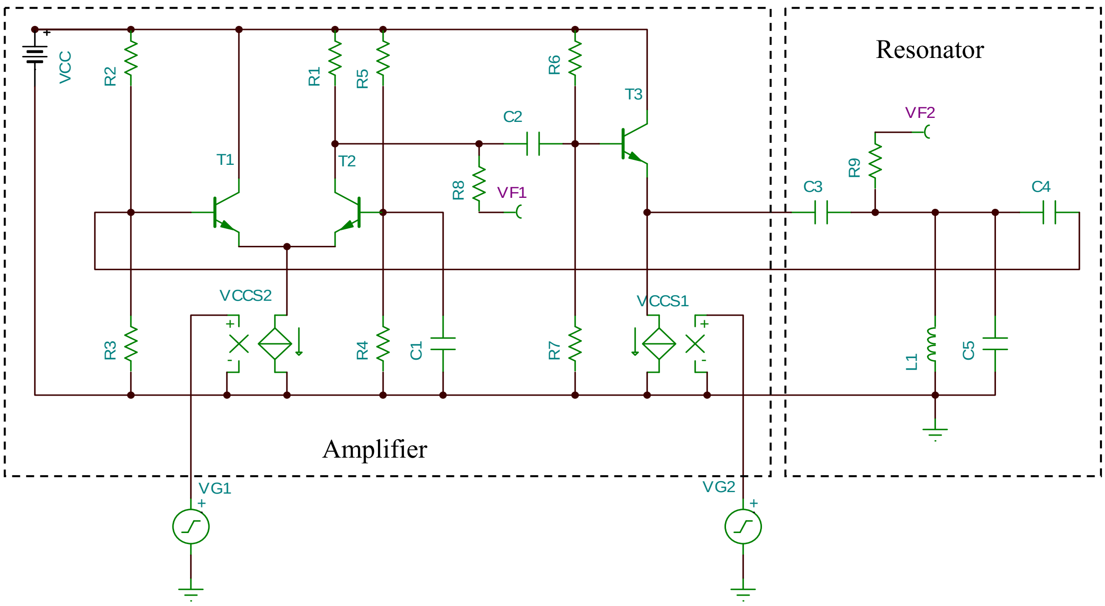

Fig. 2. Schematic of the oscillator for demonstration of the novel method. Voltage sources VG1 and VG2 might be used to externally input additional noise by controlling current sources VCCS1 and VCCS2.

The resonance frequency of the oscillator was designed to be approximately 423 MHz. An external noise source has been designed with a white spectrum between 10 Hz and 20 Mhz. Its output noise density is scalable up to 28 dBµV/√Hz. Above 20 MHz, the spectral power density decreases rapidly with increasing frequency (see Fig. 3).

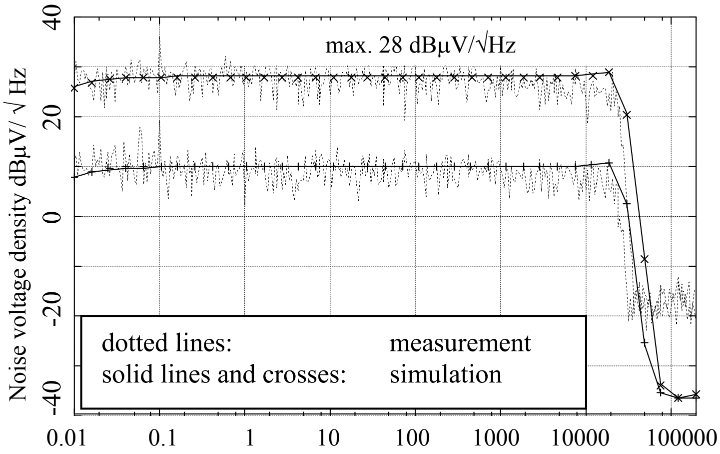

Fig. 3. Noise voltage density of noise source for controlling the two current sources in the oscillator under test. A maximum density of 28 dBµV//√Hz can be achieved, which is shown in the upper curve. Noise voltage density might be controlled. For demonstration, a density of 10 dBµV//√Hz is shown in the lower curve. (Design and measurement see Hoffmann and Weiss[9]).

Oscillator and noise source had been designed and characterized by H. Weiss[10] in 2006. Meanwhile, advanced measuring equipment (agilent signal source analyzer E5052A) is available, which allows for more significant and meaningful measured results.

4. RESULTS AND THEIR INTERPRETATION

Before measuring phase noise, the spectrum of the oscillator was measured with a bandwidth of approximately 100 Hz. 16 measurements were used to find an averaged, smoothed curve. Fig. 4 shows the spectra for two different values of

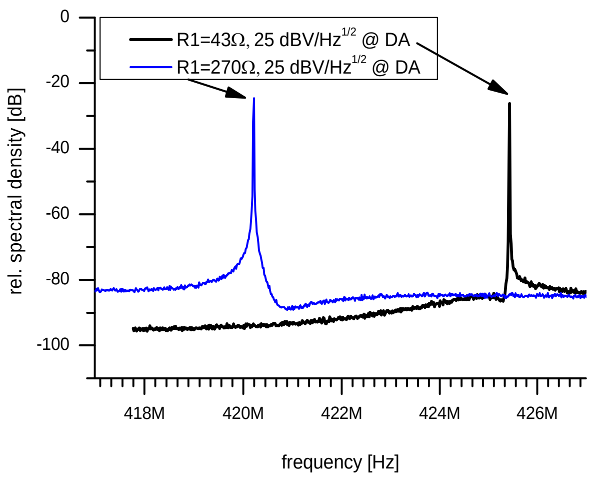

Fig. 4. Relative spectral densities at output of oscillator for R1=43Ω and R1=270Ω. White noise with a density of 25 dBµV//√Hz was added to the current source at the differential amplifier.

the voltage gain of the amplifier in the oscillator. This was achieved by changing the collector resistance R1 in the differential amplifier (see Fig. 1Fig. 2). For both measurements, the additional noise source at the differential amplifier was set to a value of 25 dbμV/√Hz.

Spectra are not symmetric. Since a purely amplitude modulated signal or a purely phase-modulated signal would have a symmetric amplitude spectrum, the only explanation is that there must be a spectrum that is phase modulated as well as amplitude modulated at the same time!

Phase noise spectra are thus only delivering half of the necessary information, since these are eliminating the influences of amplitude fluctuations.

All following measurements are measurements of phase noise, which have been found by using the quadrature receiver that is built-in in the measurement equipment. Amplitude information and phase information are thus found as orthogonal pieces of information. Therefore, phase noise spectra are symmetrical around the carrier. Phase noise measurements are thus only giving the spectrum with respect to the absolute value of the frequency-offset from the nominal oscillation frequency.

A first question to be solved was how the spectrum of the output signal would be changed by varying the average power of the two noise sources built in into the oscillator.

Fig. 5 shows the phase noise spectrum with parameter R1 = 43 Ω, i.e. the voltage gain of the differential amplifier is relatively small. For that reason, the nonlinear behavior of the amplifier in the oscillator might be described by a skew-symmetric input-output characteristic.

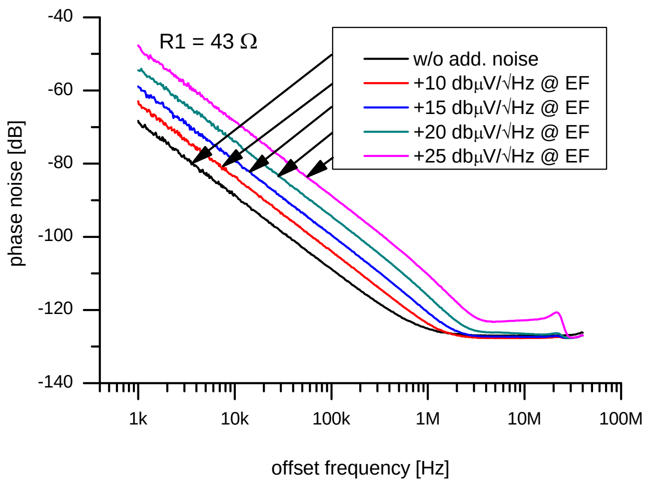

Fig. 5. Phase noise spectrum with additional noise from the current source at the emitter follower. R1 = 43 Ω.

The spectrum is obviously falling with increasing offset frequency with a slope of −20 dB/decade in the vicinity of the carrier, if additional noise is fed into the current source at the emitter follower (EF). However, at about two to three MHz apart from the carrier, a white spectrum begins to dominate. This spectrum falls down sharply at about 20 MHz offset frequency, which demonstrates its direct relation to the fed-in noise.

With a parameter of R1 = 270 Ω, the situation changes slightly, since now the input-output characteristic of the amplifier in the oscillator begins to deviate from the skew-symmetric behavior. This is also seen in the measured curves.

Fig. 6 shows that the phase noise spectrum is first falling with −20 dB/decade as in the case before. However, at about one MHz apart from the carrier, the spectrum begins to change to one with a slope of about −10 dB/decade (offset 1/*f*-

noise), provided the additional noise is powerful enough. For less powerful additional noise, a superposition of white noise and offset 1/*f*-noise is seen.

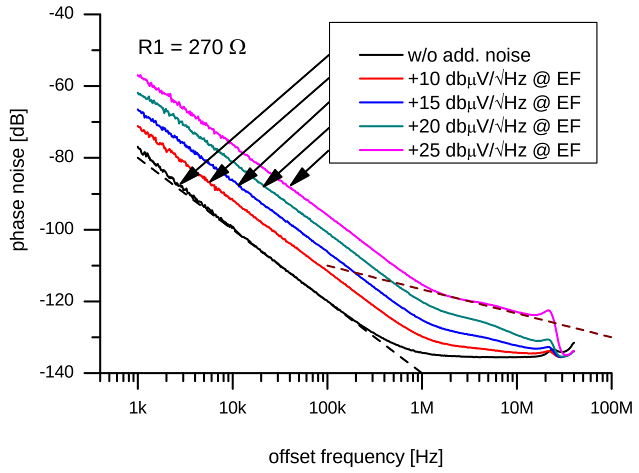

Fig. 6. Phase noise spectrum with additional noise from the current source at the emitter follower. R1 = 270 Ω. Dotted lines are tangents with slope −20 dB/decade and −10 dB/decade, respectively.

In the curve without additional noise, even a steeper slope as compared to −20 dB/decade is seen for very small offset frequencies. Since this does not occur in the cases of additional fed-in noise, it is concluded that this effect must be produced from a noise source at a different position in the circuitry.

In Fig. 7, the results of additional noise voltage density of 25 dBµV/√Hz at the emitter follower are shown for three different values of the collector resistance R1.

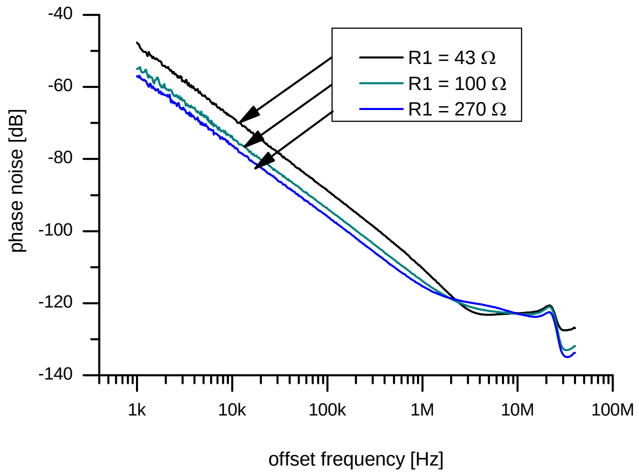

Fig. 7. Phase noise spectrum with additional noise from the current source at the emitter follower for different values of collector resistance (and thus slightly different nonlinear input-output characteristic of differential amplifier).

In comparison to these results, the next two figures show the effects of superposition of noise to the current source in the differential amplifier (DA).

These curves show that additional noise in the current source in the differential amplifier causes a significantly different spectrum. This time, already from 100 KHz offset frequency on, a different change in the spectrum is visible. First, the spectrum decreases with −20 dB/decade. Then, there appears a small range with about −10 dB/decade, another with further decrease in the absolute value of the slope and finally, the spectrum goes down with −20 dB/decade, again.

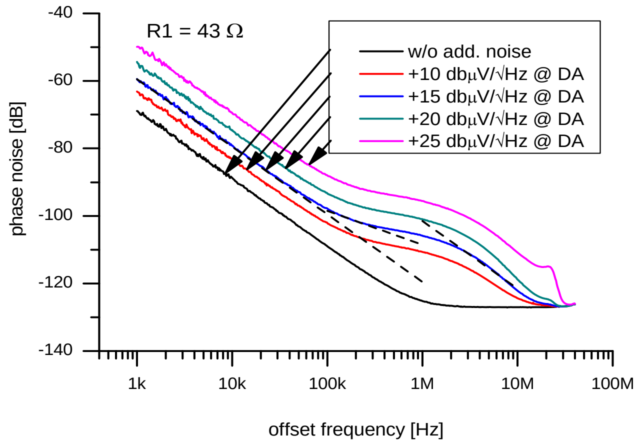

Fig. 8. Phase noise spectrum with additional noise from the current source at the differential amplifier. R1 = 43 Ω. Dotted lines are tangents with slopes −20 dB/decade and −10 dB/decade.

Since the non-linearity of the amplifier has not been changed in comparison to the situation as shown in Fig. 5, the additional noise must be processed differently. The most probable explanation would be that this time noise is acting multiplicatively rather than additively, since the input-output characteristic of the differential amplifier depends multiplicatively from the current of the current source in the differential amplifier.

As soon as the non-linearity changes, also the output spectrum of the oscillator changes. This is demonstrated by the next figure, where the collector resistance R1 equals 270 Ω, which means that the non-linear behavior of the differential amplifier is different as compared to the case R1 = 43 Ω. This is demonstrated in Fig. 9.

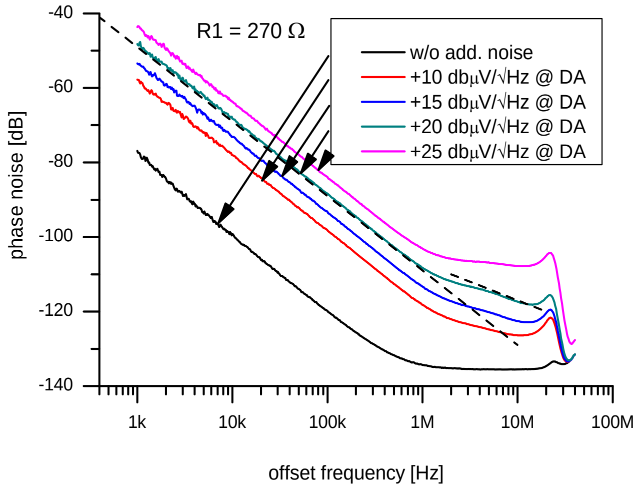

Fig. 9. Phase noise spectrum with additional noise from the current source at the differential amplifier. R1 = 270 Ω. The dotted lines have slopes of −20 db/decade or −10 db/decade for comparison.

5. CONCLUSIONS

The demonstrated measurements show that an interesting means has been found to reveal phase-noise-producing mechanisms in resonator oscillators. It could be given evidence that

- noise sources at different positions in the oscillator might influence the phase-noise spectrum in different ways,
- even slight changes in the amplifier–nonlinearity change the spectrum,
- additive and multiplicative noise must be distinguished,
- amplitude must not always be neglected.

In a next step, these measurements might be used to test different models of oscillator phase-noise. It appears, as if this method might also be applied to other classes of oscillators, as for instance relaxation-type oscillators or propagation-delay-type oscillators.

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