Evaluation of the uncertainty on phase noise for optoelectronic oscillators

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ABSTRACT

In this paper, we give an estimate of the uncertainty associated with the phase noise measured for an optoelectronic oscillator. This uncertainty is better than 2 dB at 2 sigma.

KEYWORDS

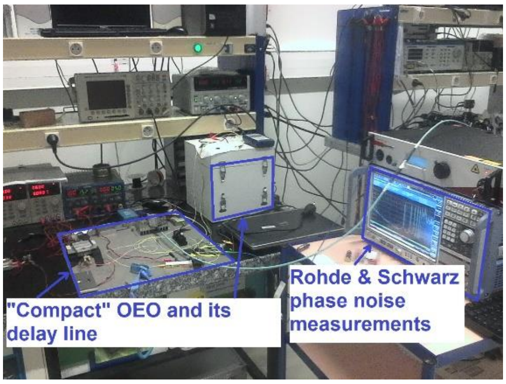
Optoelectronic oscillator; microwave signal; uncertainty; uncertainty analysis; error; noise.

1. INTRODUCTION

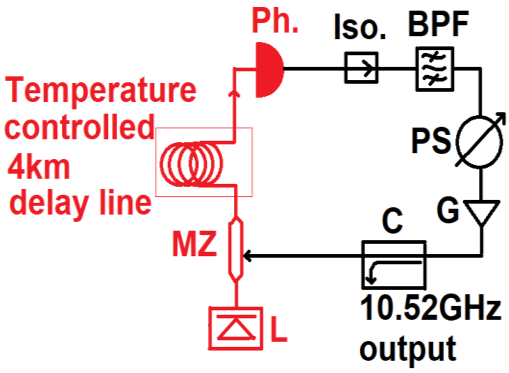
It is interesting to be interested in the problem of the veracity of the given values when the phase noise spectrum of an optoelectronic oscillator (OEO) is determined using methods based either on a phase noise measurement with a commercial system, or with an opto-electronic bench system developed in the laboratory.
Optoelectronic oscillators are still subjects of work currently and very recently. There are several examples in the literature [1 – 3].
It is necessary to measure the performance of this oscillator and, above all, to assess the uncertainty associated with this level of performance. For the evaluation of the uncertainties associated with the measured phase noise levels, we based our work on a modern method of calculation, which is recommended by the International Bureau ofWeights and Measures (BIPM). All of the measurements were subject to uncertainty, and a measurement result was complete only when the associated uncertainty accompanied a statement. The Joint Committee for Guides in Metrology (JCGM) is associated with BIPM. Note that JCGM is an organization from BIPM that prepared the "Guide to the Expression of Uncertainty in Measurement" (GUM). We used this guide for the evaluation of uncertainty, in order to maintain the correct standards.

2. MATERIALS AND METHODS

It is important to clearly define what we are measuring. First, we started by specifying what type of device under test (DUT) to characterize. Our goal was to be able to know the uncertainty on the validity of the results of the measurements on an oscillator, which is compact in the long term. For the sake of better understanding, it was easier to develop a DUT on the table in a laboratory. The goal was not so much to focus on the development of compactness at this stage, but rather to master the different elements of the DUT. When we had the DUT working well on the table, it was time to move on to the next step, which was the characterization of this DUT in terms of phase noise. To measure the noise performance of the DUT, we had two possibilities. We had a commercial bench and a bench made in the laboratory. Both of these measuring instruments had advantages and disadvantages. To begin with, on the one hand, the commercial bench was much easier to use for the operator in charge of the measurements. This commercial bench also made it possible to measure the noise quite far from the carrier, as will be seen later in this paper. On the other hand, the sensitivity of this bench was limited in terms of the measurable noise floor. Regarding the bench produced in the laboratory, it had the advantage of having a measurement noise floor significantly lower than the commercial bench. However, it did not allow measurements with an offset far enough from the carrier, and the use of this bench required more dexterity for the operator in charge of the measurements and more measurement time.



(a)

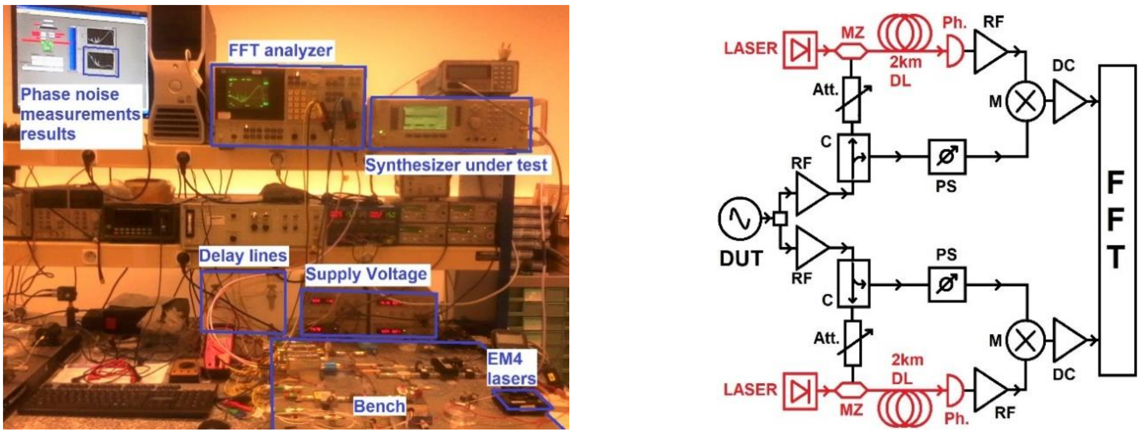


(b)

Fig. 1. (a) Photo of the optoelectronic oscillator and the phase noise measurement commercial bench. (b) Optoelectronic oscillator (OEO): Optical and electrical elements are drawn in red and black colors, respectively. L—laser; MZ—Mach Zehnder modulator; Ph—photodetector; Iso—isolator; BPF—band pass filter; PS—phase shifter; G—microwave low noise amplifier; C—coupler.

This work is largely inspired by [4]. We describe here the DUT to be characterized. This DUT was an OEO undergoing miniaturization. For miniaturization for this type of OEO, we aimed to place it in conditions where, in the long term, the oscillator could fit in a volume of one liter. One liter is typically the volume that an on-board oscillator should have [5]. If this oscillator had a delay line, this goal of miniaturization would be too ambitious. However, the compactness of the element comprising the delay lines could be achieved by packaging a coil of fiber, as is done for gyroscopes [6]. For the other building blocks of the delay line based OEO, compactness was ensured with patient 3D work on the OEO by interweaving the various components like the laser, modulator, and amplifiers, and providing compact power supply boards. The procedure followed here in the laboratory was not focused on compactness at this stage of the study. The compactness led to other constraints, such as the need to control the sensitivity of electromagnetism (EMC), which, in the case of an OEO, would be less impacted thanks to the optical aspect of a large part of the oscillation loop. Amplifiers and electrical components, on the other hand, are sensitive to EMC. It was not necessary to control the optical fiber through temperature, nor the possible stabilization of the laser by a feedback loop [7].
For the OEO on the table, it delivered an output signal of 5 dBm at 10.52 GHz. It constituted a laser from RIO, model ORION driven by a 125 mA signal. Then, we had a modulator with an 11 GHz bandwidth, a 4 km optical fiber delay line, and a DSC40S Discovery photo-detector. In the electrical part of the loop, we had a 54 dB gain amplifier for the microwave signal, an X-band filter, an ARRA passive phase shifter, and a buffer amplifier (AML812-1901) at the lateral arm of a microwave coupler in order to extract the output microwave signal. The OEO is represented in Figure 1b.
To adjust the gain of the microwave amplifier in the OEO oscillation loop, we proceeded with the help of a vector network analyser (VNA).
This OEO is clearly visible in Figure 1. Here, we have a photograph of the OEO and the measurement bench, which served to characterize it. It was necessary to carry out this gain adjustment by working in an open loop. For a more general case, it was easy to understand that the losses in the delay lines and all of the optical devices also needed to be compensated in order to ensure the continuity of the oscillation phenomenon over time [8]. For the general case of the oscillator, other losses can occur. Simply, the propagation of an electrical signal in

a circuit is not done without loss. We can therefore see that a certain number of losses must be compensated. Many other elements will generate losses of electrical or optical signal power in an oscillation loop. Filters, circulators, attenuators, isolators, power lines, phase shifters, and connectors also help to attenuate the signal strength in the oscillation loop. With knowledge of the reflectance at each point in the open loop oscillator circuit, we could verify the correct impedance match. This good adaptation is fundamental to avoid losses by reflection. When an oscillation circuit is correctly matched, i.e., adapted in impedance, if we are talking about an oscillator of the electric type, we can therefore look at the open loop with the transmission factor. One port of the VNA measured the received power level, and on another port, the analyzer delivered a transmitted power level. The difference in dB between the two power levels emitted and received corresponded precisely to what was missing, in terms of loss in the open loop of the oscillator under construction. The work then consisted of adding amplification elements in the loop. We inserted one or more amplifiers, taking the precaution to add insulators or filters if necessary. We needed to know the reflectance of each amplifier, as well as the noise factor, especially at the start of the amplification chain. Figure 1a shows a picture of the OEO during measurements and Figure 1b describes the OEO. As mentioned previously, there are two ways to evaluate the performance of the DUT in terms of phase noise. Prior to the measurement, we calibrated the two systems with a commercial frequency synthesizer (Anritsu/Wiltron 69000B) with a declared phase noise of −105 dBc/Hz at 10 kHz of a 10 GHz carrier [9]. The results are shown in section "Result on the measurement of a known frequency synthesizer". Figure 2 shows the setup of this measurement.



(a) (b)

Fig. 2. (a) Photo of the phase noise measurement bench developed at the laboratory while measuring the phase noise of a synthesizer under test. (b) Schematic view of phase noise measurement bench system using a double optical delay line. Optical elements and electrical elements are respectively drawn in red and black colors. DUT—device under test; MZ—Mach–Zenher modulator; DL—delay line; Ph—photodetector; M—mixer; DC—DC amplifier; RF—microwave amplifier; Att.—attenuator; C—directive coupler; PS—phase shifter; FFT—fast Fourier transform analyzer.

3. UNCERTAINTY ESTIMATION

Investigating the uncertainty calculation is an old challenge of scientists working on phase noise. It firstly concerns the knowledge of the experimentally determined phase noise close to the carrier with a negative slope of S'(f) versus the Fourier frequency noted f, and secondly, it concerns the determination of the ground noise f0 far from the carrier, mostly dependent from the power inside the loop with an approximation of kT/P, where k is the Boltzmann constant, T is the temperature, and P is the power. FredWalls and his colleagues from NIST described the principle of phase noise and its calculation [10, 11]. In 2010, Won Kyu Lee from Korea explained their work concerning uncertainty calculation [12]. In 2013, sources of uncertainties in an uncertainty evaluation were discussed by Shinya Yanagimachi and his colleagues from Japan [13]. Several phase noise measurement techniques were investigated by Ulrich L. Rohde and Ajay K. Poddar from Germany in 2013 [14]. For the uncertainty calculation, we proceeded similarly to the determination of the uncertainty for a purely microwave setup [15]. The uncertainty was calculated according to the main guideline delivered by the Bureau International des Poids et Mesures (BIPM) in the guide "Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement" [16]. Actually, we followed a modern approach to express uncertainty in measurement [17 - 22]. The uncertainty in the results of a measurement consist of several components, which may be listed as two categories according to the way in which their numerical value is estimated.

It is interesting to consider how the elementary terms are grouped together for the calculation of the final uncertainty. We can see that we are dealing with two main categories of elementary uncertainty terms. The first category of terms of uncertainty is called "type A". These terms are evaluated by statistical methods such as reproducibility, repeatability, special consideration about Fast Fourier Transform analysis, and the experimental standard deviation. The components in category A are characterized by the estimated variances. The second family of uncertainty contributions are evaluated by other means. They are called "type B", and because various components and temperature control, experience with or general knowledge of the behaviour and properties of relevant materials and instruments, manufacturer's specifications, data provided in calibration and other certificates (noted BR), their uncertainties assigned to reference data taken from handbooks. The components in category B should be characterized by quantities, which may be considered as approximations to the corresponding variances, the existence of which is assumed.

We are getting to the significant part about uncertainties. We must now examine each of the elementary terms. 4.1. Statistical Contributions

Repeatability (A1): It is the variation in measurements obtained by one person on the same item and under the same conditions. Repeatability conditions include the same measurement procedure, the same observer, and the same measuring instrument used under the same conditions, repetition over a short period of time, and at the same location. We automatically performed 4 to 10 measurements with the fast Fourier transform (FFT) analyzer. The elementary term of uncertainty for repeatability eRep was experimentally found to be equal to 0.3 dB for 4 measurements and 0.2 dB for 10 measurements at 1. Its probability distribution was normal (Gaussian). A1 was thus deduced with a 0.682 at 1 (where is the standard deviation).

Reproducibility (A2): Measurements are performed by the same operator. There are no changes caused by differences in the operator behavior. All components and devices are dedicated to the instrument and none of them are replaced. This term was selected as zero. Finally, statistical contribution can be considered as follows: A =p (SAi) (i).

We can list the different categories of elementary uncertainty terms in table 1.

Note that the individual contribution of each elementary terms strongly depends on the shape of their diffusion law. For the terms of types A, we logically have shapes according to the Gaussian law. However, this is not always true for other terms. For example, among the terms of type B, some will follow the normal distribution, others the triangular distribution. Uncertainty at a 1 σ interval of confidence is calculated as follows: uc = √ (A2 + BR2 + BL2) (ii)

According to Equation (i), it can then be considered that the whole statistical contribution is better than 0.69 dB. We deduce from (ii) that the uncertainty at 1 sigma, noted as uc, is better than √ (0.692 + 0.202) dB. Its leads to a global uncertainty of ±0.72 dB at 1 σ.

Table 1. Typical chart used for uncertainty evaluation

Uncertainty elementary terms	Designation
A-type example	Repeatability
A-type example	Reproducibility
A-type example	Uncertainty term due to the number of sample
Intermediary result on statistical elementary terms	$(\Sigma Ai^2)^{1/2}$
B-type first category	BR (related to Standards)
B-type second category	BL1
B-type second category	…
B-type second category	BLn
Intermediary result	ΣBLi
Total uncertainty estimated at 1 sigma	$(A^2+BR^2+BL^2)^{1/2}$

Table 1. Typical chart for estimation of the uncertainty

For convenience and to keep an operational uncertainty in case of the degradation or drift of any elementary terms of uncertainty, it is wise to degrade the global uncertainty. This is why we choose to keep U = ±2 dB at 2 σ for a common use of the phase noise optoelectronic instrument, instead of ±1.44 dB at 2 σ. This final uncertainty is defined at 2 σ, according to the empirical rule 68.27% at 1 σ is not enough, but 95.45% at 2 σ is more efficient for a normal distribution in statistics.

4. CONCLUSION

In conclusion of this paper, we can indicate that we have characterized the OEO in terms of phase noise. The signal delivered at 10.52 GHz with an output power of 5 dBm presents a relatively good performance in terms of phase noise, with a minimum of −145 dBc/Hz at 3 × 104 Hz from the carrier. The associated uncertainty is better than ±2 dB at 2 σ. This re-sult is encouraging for an OEO produced on a table, and which, can potentially be rear-ranged into a compact prototype that fits in a volume of one liter.

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