Low phase noise optical delay line optoelectronic oscillator uncertainty evaluation

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ABSTRACT

In this paper, we present the operation of an optoelectronic oscillator. We look at the evaluation of the uncertainty associated with the measurement of the phase noise of the signal emitted by this oscillator. Uncertainty on the phase noise measured for a low phase noise compact optical delay line optoelectronic oscillator is evaluated as ±1.5 dB at 2 σ.

KEYWORDS

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

1. INTRODUCTION

Several Optoelectronic oscillators (OEO) were designed as referenced [1 – 3]. A compact optical delay line OEO is designed to fit in a small volume that can be as less as 1 liter. Its source is a 1.55 μm wavelength laser. There are also a modulator, an optical fiber consisted in a delay line, a photodetector, a 8.2 – 12.4 GHz microwave amplifier and also a driving coupler. In addition, elements of this OEO must be less sensitive to mechanical and environmental perturbations. The delivered signal is especially evaluated for its frequency stability. Measurement of phase noise is carried out using a special bench [4] and we follow a modern approach for estimating its uncertainty [5], following previous works performed on oscillators [6, 7].

2. MATERIALS AND METHODS

This work is mainly based on reference [4]. We describe here the Device Under Test (DUT). It is a relatively compact OEO. One litter is typically the volume for onboard as seen in this reference [8]. The compactness of the delay lines could be achieved by packaging a coil of fiber, as is already done for instance for gyroscopes [9]. The compactness lead to other necessities, like the control of the sensitivity to electromagnetism perturbations (EMC), which, in the case of an OEO, should be less impacted due to the optical aspect of a large part of the oscillation loop. Amplifiers and electrical components may be sensitive to EMC. Optical fiber des not need to be temperature controlled as laser is stabilized of by a feedback loop [10]. OEO designed on the table in the lab delivers an output signal of 5 dBm at 10.5 GHz. It is constituted a RIO laser, model ORION driven by a 125 mA signal. Modulator is with an 11 GHz bandwidth, then, a 4 km optical fiber delay line, and a DSC40S Discovery photo-detector. In the electrical part of the loop of the oscillator, there is 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 1. To adjust the gain of the microwave amplifier in the OEO oscillation loop, we proceed with a vector network analyser (VNA).
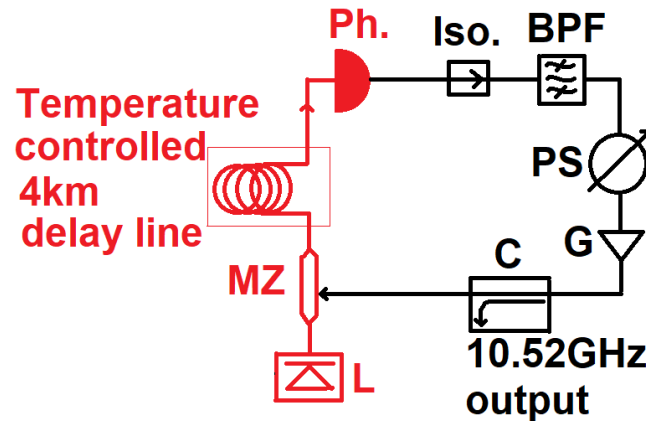

Fig. 1. OEO: Optical and electrical elements are drawn in red and black colors, respectively. L—laser; MZ—Mach Zehnder modulator; Ph—photodetector; Iso—isolator; BPF—band pass filter; PS—phase shifter; G—microwave low noise amplifier; C—coupler.

This OEO is given in Figure 1. Here, we have a photography of the OEO and the measurement bench, which served to characterize it. It is necessary to carry out this gain adjustment by working in an open loop. It is 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 [11]. We need 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 [12]. The results are shown in section "Result on the measurement of a known frequency synthesizer". Figure 2 shows the setup of this measurement.
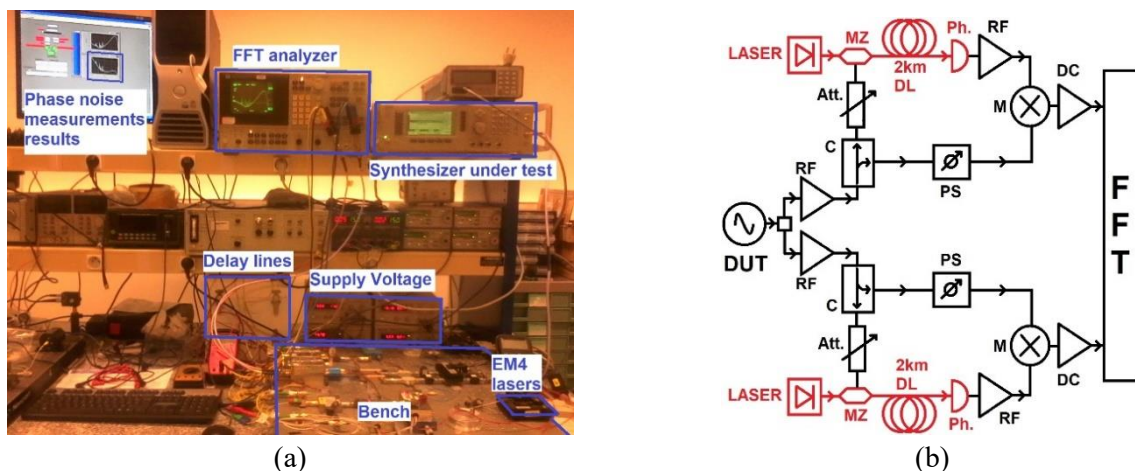
| (a) | (b) |

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. It is taken close to the carrier with a negative slope of S'(f) versus the Fourier frequency noted f. 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 [13, 14]. Here another work about uncertainty calculation [15]. Sources of uncertainties were discussed [16]. Several phase noise measurement techniques were investigated [17]. We proceed similarly for uncertainty calculation like in the case of a purely microwave setup [6] or for optic bench [18]. The uncertainty is given accordingly to main guideline of the Bureau International des Poids et Mesures (BIPM) in the guide "Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement" [19]. Actually, we followed a modern approach to express uncertainty in measurement [5, 7, 20 – 23]. 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: $u_c = \sqrt{(A^2 + BR^2 + BL^2)}$ (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 u_c, is better than $\sqrt{(0.69^2 + 0.20^2)}$ 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 = ±1.5 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 relatively compact OEO for its phase noise. The signal delivered at 10.5 GHz presents a relatively good performance in terms of phase noise, with a minimum of −145 dBc/Hz at 3×10^4 Hz from the carrier. The associated uncertainty is better than ±1.5 dB at 2 σ. This result is encouraging for an OEO produced on a table, and which, can potentially be re-arranged into a compact prototype that fits in a volume of one litter.

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