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Residual Phase Noise Measurements of the Input Section in a Receiver

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Abstract

If not designed properly, the input section of an analog down-converter can introduce phase noise that can prevail over other noise sources in the system. In the paper we present residual phase noise measurements of a simplified input section of a classical receiver that is composed of various commercially available mixers and driven by an LO amplifier.

Introduction

A classical design approach for receivers operating at microwave frequencies is to down-convert the detected signal to some intermediate frequency before digitizing the signal. The final design of a receiver is chosen depending on performances, which can be described by various parameters. The most important ones are broad-band noise power, close-in noise power, nonlinearity, spurious free dynamic range, temperature stability, isolation between channels (for multiple channels systems), power consumption and price. The main parameter this paper will be investigating is the close-in phase noise of the receiver's input section. We are interested in measurements of residual phase noise up to 100 kHz away from the 1.3GHz carrier. Figure 1 shows a simplified prototype of the receiver's input section that has been constructed for applications in high energy physics

[1]. For this particular application for instance, the demands for phase stability are approximately 0.01° of integrated RMS phase noise. We start by identifying the main noise contributors.

Mixer and Amplifier Noises

The following paragraph is a short overview of microwave mixer and amplifier noises and the reader should refer to literature listed at the end of the paper for more detailed reading. According to [2] there are three types of noises generated in a mixer. Shot noise, thermal noise and flicker noise. Shot noise is caused by carriers passing through the PN junction in a diode. The thermal noise is caused by the series resistance in the mixer [3,4]. Flicker noise is related to surface-state density of the material and it is not an issue at higher frequencies [5]. There are various parameters that define mixer noise performances and can be set by the designer. Among the most important are the LO power and the VSWR of the mixer ports.

The LO power has no effect on thermal noise, since the series impedance does not change with power. On the other hand, in most mixers shot noise changes with LO power and it is correlated over the whole band. This means that there will be a certain increase in the noise floor due to mixing of these coherent components. This increase in noise floor can be avoided if proper filtering is used. The noise figure of a mixer decreases with an increase in LO till a certain point [2].

Noise figure of the mixer depends also on matching [2, 6, 7]. Using the wave representation of noises (as carried out in [8]) it can be shown that the noise figure is a function of the reflection coefficient. An obvious approach to solve this problem is to have the mixer ports properly matched. Mixer matching can be achieved by using amplifiers, circulators or passive matching as suggested in [6, 9].

The output signal-to-noise ratio of a mixer depends also on the sensitivity of the mixer. The sensitivity or the mixer slope, defines the output DC voltage in volts at the IF port per one radian of change in phase between the RF and LO ports. In literature [6] it is shown how mixer sensitivity changes with LO power and matching on the IF port. In general a capacitive load on the IF improves mixer sensitivity. However, this also causes a decrease in IF bandwidth.

The other source of noises in the input section of the receiver is the microwave amplifier. We decided to use the amplifier on the LO port since mixers usually demand relatively high LO power for linear and low noise operation. A detailed study of close-in noises added by a microwave amplifier is presented in [10]. Besides broad-band noise, amplifiers exhibit close-in flicker noise, which is usually not given in manufacturer's datasheet. This close-in phase noise generated by the amplifier is up-converted to the LO carrier that is being amplified, which is then transmitted to the IF port through the mixing process. The level of flicker noise close to the carrier that is generated by the amplifier depends on the input power to the amplifier. A more linear amplifier will decrease flicker noise as shown in [10].

Measuring Method

The measuring method for residual phase noise measurements that was used in this paper is presented in various text books and studied in various articles like [4, 6]. Figure 2 shows a block diagram of the measurement setup.

The low noise RF signal is first split into two branches. One of the branches is delayed for 90° and the two signals are mixed with a mixer. The low noise amplifier on the IF port of the mixer increases the dynamic range of the measuring method. The output is measured with a scope or a spectrum analyzer. In formal representation the mixing process presented in Figure 2 equals to:

$$A\cdot\sin(\omega_c t+\Delta\varphi_{gen})\cdot\cos(\omega_c t+\Delta\varphi_{gen}+\Delta\varphi_{amp+mixer})\approx\frac{A}{2}\sin(\Delta\varphi_{amp+mixer})\propto\Delta\varphi_{amp+mixer} \qquad (1)$$

Where ω_c is the frequency of the carrier, $\Delta\varphi_{gen}$ is the phase noise added by the signal generator, A is the product of both amplitudes and $\Delta\varphi_{amp+mixer}$ is the residual phase noise added by the input section of the receiver, i.e. by the amplifier and the mixer. The term representing the second harmonic is canceled out, since the phase noise is observed at base-band. We also assumed small angles approximation to obtain the last expression on the RHS of equation (1). Amplitude noise, that could be included in (1) as an additional amplitude modulation term, is neglected since the mixer is driven close to saturation. In order to correctly translate phase deviation in equivalent amplitude deviation, the sensitivity (slope) of the mixer has to be measured. One of the possible ways to measure the slope is by applying slightly different frequencies (by ~100 kHz) on the RF an LO ports of the mixer. With a scope one can measure a change in voltage over a time (phase) interval. The observed time interval has to be small compared (e.g. 1/100) to the period of the signal for accurate slope measurements. As shown in [6] the mixer sensitivity is a function of frequency. For accurate measurements it is therefore necessary to repeat the slope measurement for each offset frequency.

When measuring phase noise with the setup shown in Figure 2, it is important to reduce the amplitude noise as much as possible. Filtering and driving a balanced mixer in saturation will help to reduce the amplitude noise power. It is also important to have a good match on all the ports of the mixer, which can be achieved with isolators. At the same time this guarantees better isolation between splitter ports. At last but not at least, the cables of the measurement setup should be kept as short as possible.

As a measurement method check we measured the close-in phase noise of the signal source at 1.3GHz. The measured values over a 10MHz bandwidth are given in Figure 3. Measurements show that due to the measuring method the noise of the generator is subtracted out. Consequently a lower noise floor than the one presented in Figure 3 is measured. This is discussed in the following section.

Measurement Results

Using the measuring technique described in the previous section, measurements using level 7, level 13, level 10 and level 17 mixers were carried out. The MMIC amplifier (HMC481 from Hittite [11]) in the LO branch was the same in all cases (except for the measurement with the active mixer). By varying the attenuation at the output of the amplifier we achieved various power levels that were needed for each particular mixer. Figure 4 shows relative noise floor of phase noise measurement results in dBc/Hz. Besides passive mixers manufactured by Mini Circuits [12], we also measured one active mixer from Hittite [13]. As mentioned at the beginning of the paper, the measured close-in phase noise is supposed to be generated in both, the LO amplifier and the mixer. In order to check which of the two is adding more noise, the amplifier was moved in front of the splitter. In this way the phase perturbation of the amplifier is canceled out by the measuring method. The results of this test are represented with the black curve in Figure

4. It is obvious that the major part of the noise is introduced by the amplifier. Measurements of various mixers in the same configuration as shown in Figure 1 show that different passive mixers with the same LO amplifier port exhibit same flicker noise performances. This is another proof that the measured noise is dominated by the LO amplifier contribution. The green curve in Figure 4 shows the noise floor of the active mixer [13]. Although the test setup is kept the same (except for the LO amplifier) the active mixer exhibits higher phase noise over a band from 100 Hz to 10 kHz.

The RMS jitter is an often used measure for the close-in phase noise. It equals to the integral of double (the measured values are SSB) the values measured in Figure 4 over the bandwidth of interest. Table 1 summarizes the integrated RMS phase/time perturbation for some measurement configurations presented in Figure 4. The integrated bandwidth is from 100 Hz to 100 kHz.

Nonlinearity Measurements of Mixers

In our applications the mixer is the input device to the receiver. According to Figure 4 the best choice for the input mixer would be a level 7 mixer since it needs the lowest LO power. However, other issues like linearity have to be considered. As mentioned in one of the sections in this paper, the LO power defines the linearity of the mixer. In a matter of fact it is expected for a low level mixer to have poor linearity performances.

Measurements show that in practice there are exceptions to this rule. Figures 5-7 show linearity measurements for various commercially available mixers. It is interesting to notice that for instance the level 13 mixer starts compressing at lower input power than the level 10 mixer. Measurements of the second harmonic in Figure 6 and third harmonic in Figure 7 gives a more detailed insight into the linearity issues of various mixers. Again, measurements show that for example the second harmonic of the level 10 mixer can be compared at certain operating points to the linearity of a level 17 mixer. On the other hand, the third harmonic of the level 10 mixer is much higher than the third harmonic generated by a level 7 mixer at specific input power values. It is worth noting that curves presented in Figures 5-7 depend on LO power. It is therefore necessary for the designer to carry out extensive measurements before choosing a mixer and setting the operating point.

Conclusions

The residual phase noise introduced by a generic receiver's front-end was measured. For the down-conversion different commercially available mixers were used. Measurements show that the major contributor to the close-in phase noise of the simplified input stage (Figure 1) is the LO amplifier. From the close-in phase noise point of view, it is sometimes better to use a passive mixer with an external LO amplifier, rather than an active mixer with an integrated LO amplifier. In the circumstances presented in this paper, mixer type has no effect on the relative noise floor measurements. As a consequence, the most appropriate mixer for a specific system should be chosen according to other parameters. In this paper we investigated linearity. As expected, measurements in Figures 5-7 show that in average level 17 mixers, along with the active mixer, exhibit best linearity performance. However, at some working points a level 13 or even a level 10 mixer can produce lower second or third harmonics than a level 17 mixer. Depending on the design, linearity and close-in phase noise characteristics of the receiver’s front-end can be optimized by choosing the most appropriate mixer and amplifier. As an example we set our phase perturbation requirements to 0.01° RMS and RF port input power to +9dBm. For this particular application a mixer like HMC483MS8G (see Table 1) can not be used. According to measurements presented in Figures 6-8 the SYM-25DLHM would be a good choice.

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References

[1] U. Mavric, B. Chase, ”Analog Receiver and Transmitter Design for the ILC Main LINAC LLRF Control System,” *IEEE Eurocon07, Warsaw, Poland, September 2007*

[2] S.A. Mass, *Microwave Mixers – Second Edition*, Artech House, Norwood, MA, 1993

[3] M. W. Muterspaugh et al., “Single Balanced Mixer Output Filter,” *United States Patent – 5,034,994, July, 1991*

[4] F.L. Walls, et al., ”Extending the Range and Accuracy of Phase Noise Measurements”, Proceedings of the 42nd Annual Symposium on Frequency Control, pp. 432-441, June, 1998

[5] B.C. Henderson, “Mixers in Microwave Systems: Part 1,” *Watkins-Johnson Company Tech-Notes*, vol. 17, No.1, January, 1990

[6] F.L. Walls, et al., “Accurate Measurements of Spectral Density of Phase Noise in Devices,“ *31st Annual Symposium on Frequency Control*, pp. 335-343, 1977

[7] P. Will, “Reactive Loads – The Big Mixer Menace,” *Microwave*, pp. 38-42, April 1971

[8] P. Penfield, “Wave Representation of Amplifier Noise,” *IRE Transactions on Circuit Theory*, Vol.9, Issue 1, pp. 84-86, March, 1962

[9] “Doubly-Balanced Mixer Termination,” *US patent 4,601,063*, July, 1986

[10] A. Hati, et al., ”Merits of PM Noise Measurements Over Noise Figure: A Study at Microwave Frequencies, “ *IEEE Transactions on ultrasonics, ferroelectrics, and frequency control*, Vol. 53, No.10, pp.1889-1894, October 2006

[11] http://www.hittite.com/product_info/product_specs/amplifiers/hmc481mp86.pdf

[12] http://www.minicircuits.com/

[13] http://www.hittite.com/product_info/product_specs/mixers/hmc483ms8g.pdf

[14] http://www.psi.au.com

[15] http://www.wenzel.com

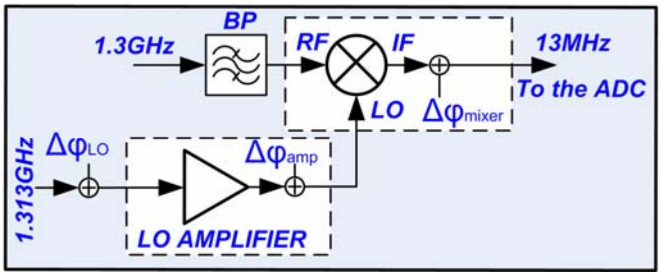

Figure 1: Block diagram of the receiver's analog front-end used in high energy physics for control of electromagnetic fields in superconducting RF cavities.

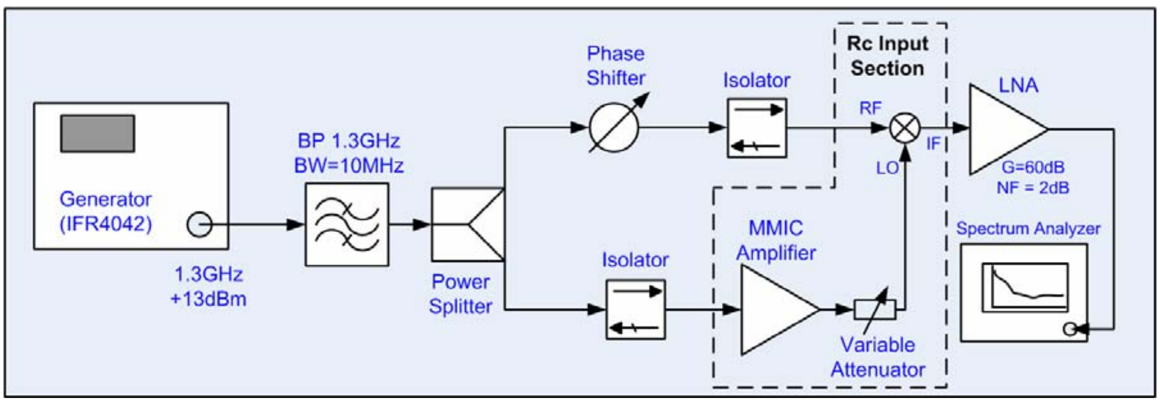

Figure 2: Residual phase noise measurements test setup.

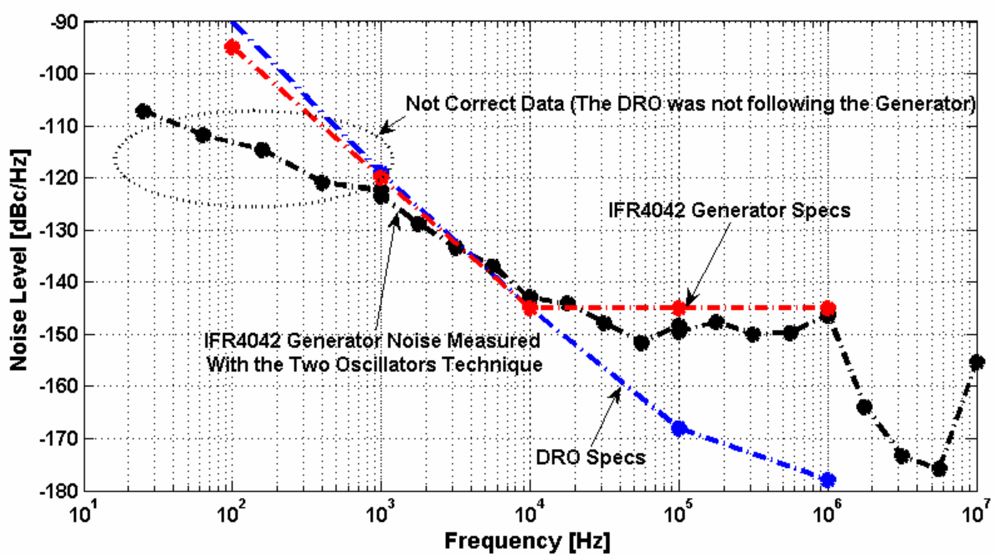

Figure 3: The generator noise in dBc/Hz (black) compared to the manufacturer's values (red) and compared to the specified phase noise values of the dielectric resonator oscillator (DRO [14]) in blue. The DRO was used for measuring the generator noise using the phase noise analyzer from Wenzel Associates, Inc. [15].

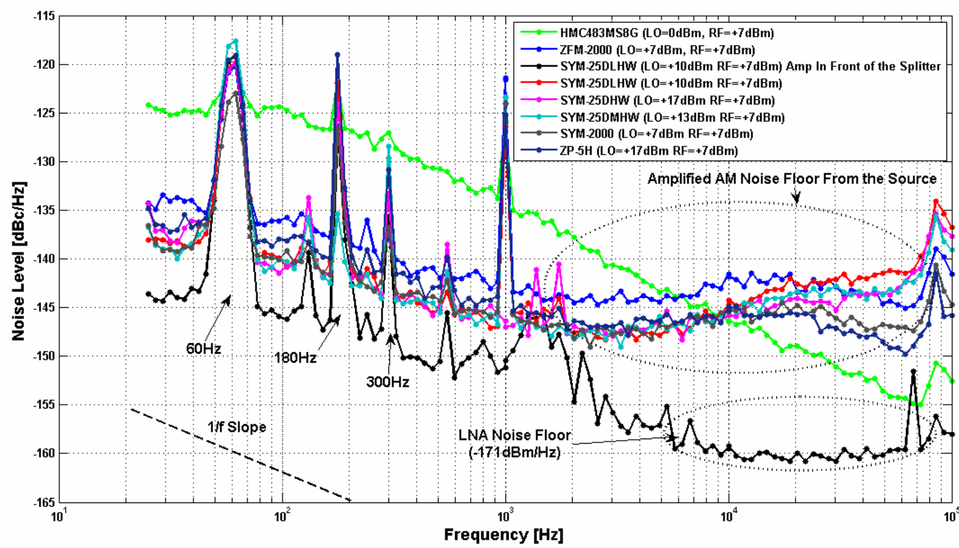

Figure 4: Measurements of Residual Phase Noise in the receiver's front end with various commercially available mixers.

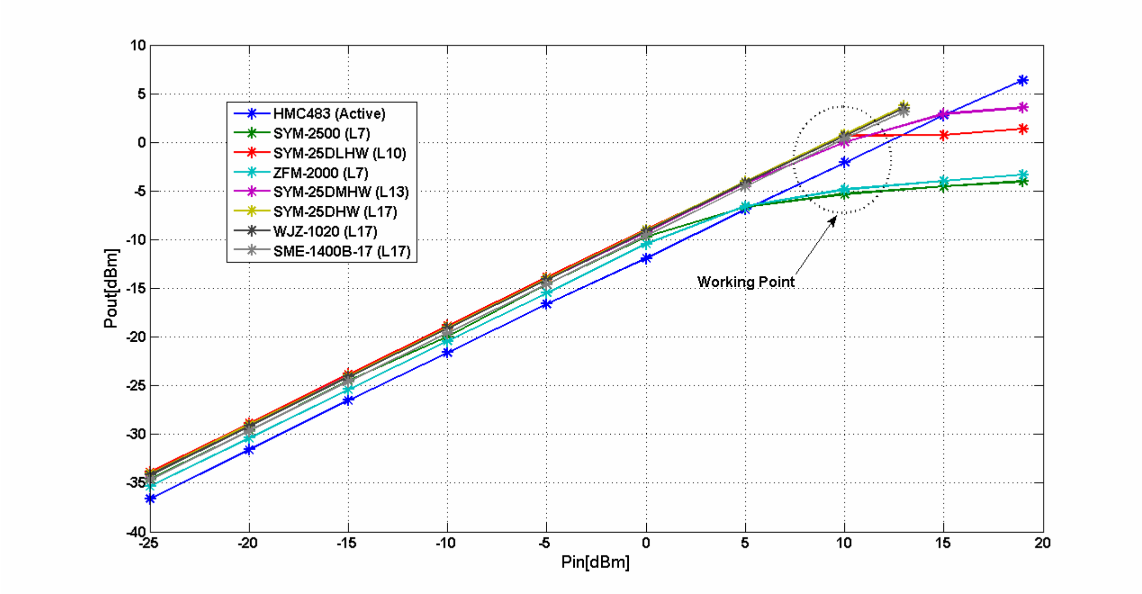

Figure 5: Output power of the carrier as function of input power on the RF port for various mixers.

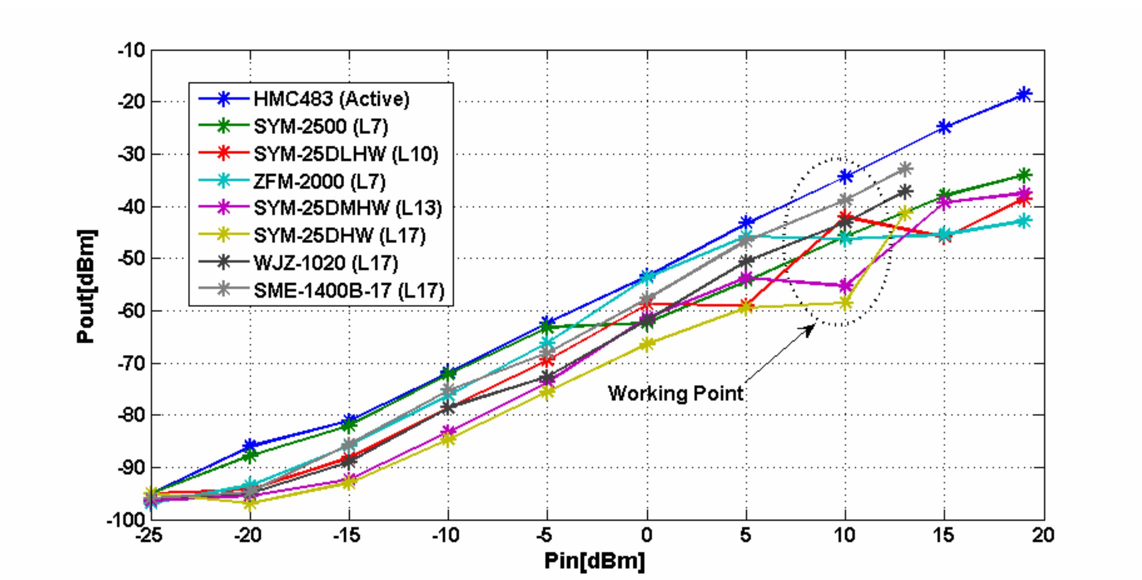

Figure 6: Power of the second harmonic at the IF port as function of input power on the RF port for various mixers.

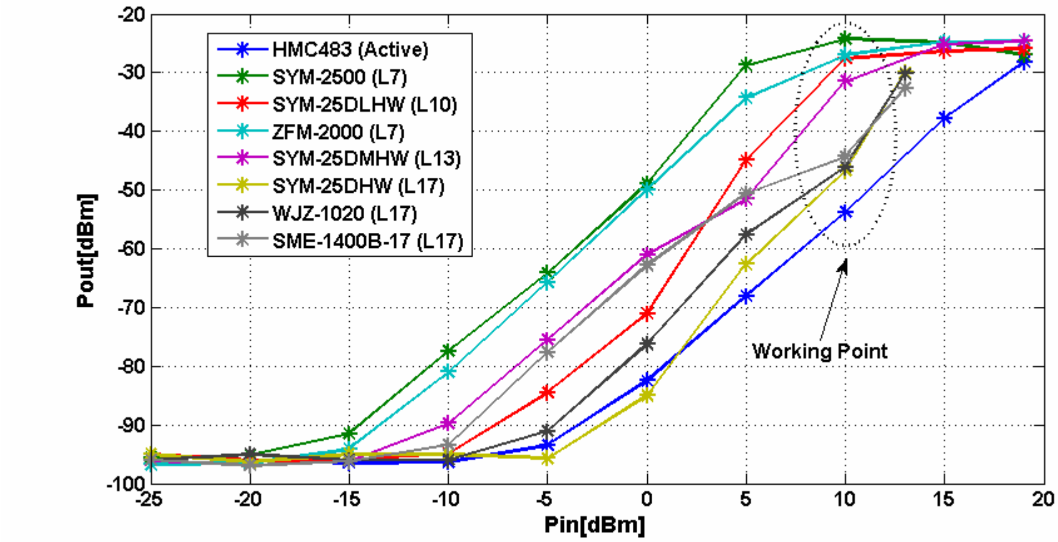

Figure 7: Power of the third harmonic at the IF port as function of input power on the RF port for various mixers.

Mixer	t_{jrms}*[fs]*	φ_{jrms}*[°]*
HMC483MS8G (Active)	2.4	1.1e-3
SYM25DLHW (L10)	1.6	7.8e-4
ZFM-2000 (L7)	1.7	8.1e-4
SYM25DHW(L17)	1.5	7.2e-4
SYM25DLHW Amp In Front of the Splitter	0.3	1.6e-4

Table 1: Time and amplitude jitter equivalents of the measured residual noises (Integrated from 100 Hz to 100 kHz).