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An electro-optic system implementing an accurate phase measurement method for sinewave signals

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Abstract – **This paper deals with a preliminary design of an electro-optic system for accurately measuring the phase of sinewave signals output by generators up to 100MHz. In particular, a short description of the measurement method and an envisioned application, namely the characterization of waveform recorders, is provided. In the paper, an initial selection of the commercially-available instruments, which are suitable for implementing the proposed electro-optic system and the chosen specifications, are shown. To estimate the repeatability of the phase measurements according to the main characteristics of the chosen equipment, a simulator was implemented and its description is available in the paper. According to the simulation, a maximum standard deviation of 0.028° can be achieved at 100 MHz.**

I. INTRODUCTION

The calibration of waveform recorders (e.g., oscilloscopes) requires the utilization of well characterized (i.e., reference) signals at their input in order to obtain an accurate estimation of their frequency response [1]. According to the chosen type of reference signal, the utilized techniques, which are available in the literature, can be classified as [2]: (i) pulse-based and (ii) swept-frequency based. The former one takes the advantage of frequency combs and multisine signals, however, it exhibits low accuracy in the estimation of the phase response at high frequencies (e.g., GHz range). The latter technique exhibits very good accuracy in estimating the magnitude response, while cannot be adopted for phase response because the knowledge of the input phase of the test sinusoidal signal is extremely difficult to be obtain with the methods described in the literature and with the currently available instrumentation [3]. Furthermore, due to the increasing analog bandwidth of the waveform recorders available on the market, as stated in [3], it is not possible to find a measurement method that is capable of covering a wide range of frequencies while also maintaining a low value of the phase measurement uncertainty.

In [4], a method for measuring the phase spectrum of the output of a sinusoidal frequency source is described for the calibration of an electroshock weapon characterization system. An electroshock weapon characterization system consists of a long-epoch (e.g., 12s) and 200 MHz analog bandwidth for the waveform recorder to acquire both high voltage and current waveforms, simultaneously [4]. Preliminary hardware implementations of the phase measurement method [4] were described in [1] and [5]. In particular, a proof of concept was proposed in [1] with an arbitrary waveform generator, an oscilloscope and an universal digital counter.
An experimental assessment of the phase measurement repeatability in terms of standard deviation for sinewave frequencies ranging from 100 Hz to 10 MHz was published in [1]. The reported results exhibit maximum standard deviations of 0.009° for both 100 Hz and 10 MHz, [1]. However, this implementation is limited to characterize only arbitrary waveform generators with two output channels synchronized to each other and to a maximum sinewave frequency of 10 MHz.

In this paper, a preliminary design of an electro-optic system that implements the method proposed in [4] is described. This implementation aims to increase the maximum sinewave frequency (i.e., to 100 MHz) that can be analyzed respect to the electrical hardware implementations, which were demonstrated in literature as achieving a maximum working frequency range of 10 MHz, [1], [5]. In particular, the proposed implementation has been simulated by means of the OptiSystem [10] software and MATLAB tools and the assessment of the phase standard deviation is provided for 100 MHz.

The paper is structured as follows. Section ii. describes the phase measurement method. A description of the electro-optic phase measurement system for implementing the adopted phase measurement method is provided in Section iii.. In Section iv., a simulator of the system implemented with OptiSystem and MATLAB tools is described and the obtained simulation results in terms of standard deviation of the phase estimates are discussed. The last Section concludes the paper.

II. PHASE MEASUREMENT METHOD

In the following, the phase measurement method from [1] is shortly described. As depicted in Fig. 1, in order to measure the phase of a sinewave signal with the method described in [1], the following functional blocks are utilized: (i) pulse source, (ii) pulse delay, (iii) pulse selector,

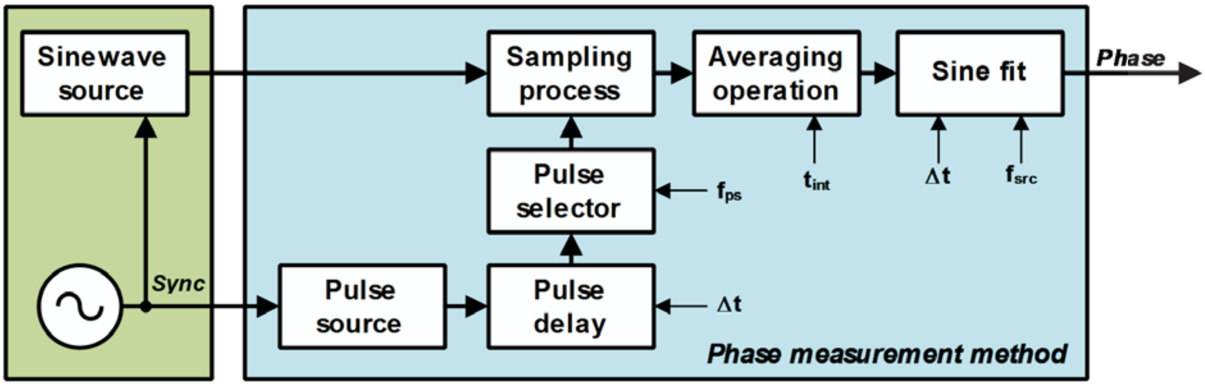

Fig. 1. General overview of the phase measurement method [1].

(iv) sampling process, (v) averaging operation, and (vi) the sine fit.

The sinewave source under test provides a signal synchronized with an external clock (i.e., Sync). This synchronization signal is also utilized by the pulse source to provide a pulse train signal working at the same frequency of the Sync signal. The pulse train signal is then delayed according to an imposed Δt by the pulse delay block. The delayed pulse train signal drives a pulse selector that allows to reduce the frequency of the pulse train signal according to the desired f_{ps} value. In particular, the pulse train signal must have a frequency that is an integer sub-multiple of the sinewave frequency (i.e., f_{src}). The sampling process provides a measurement of the sinewave amplitude at the instant defined by the pulse train signal. Because the frequency of the pulse train signal is an integer sub-multiple of f_{src}, the amplitude measurements are provided at the desired pulse train rate and, therefore, it refers to the same sinewave phase. An averaging operation is performed on the amplitude measurements obtained at Δt. The averaging operation is performed to reduce the effect of noise on the variability of the amplitude measurements. When at least three amplitude measurements at three different Δt delays along the sinewave period are obtained, the 3-parameter sine fit interpolating algorithm is applied for estimating the sinewave phase according to its frequency f_{src}.

The main uncertainty sources affecting the phase measurement method are: (i) the jitter on the pulse train signal defining the sampling instants, (ii) the noise affecting the amplitude measurements, and (iii) the synchronization error between the pulse train and the sinewave. An influence quantity of the phase measurement is the clock drift of the external clock that directly affects the synchronization between the pulse train and the sinewave under test. The effect of the random jitter and noise on the phase measurement accuracy can be reduced by increasing the number of amplitude measurements utilized in the averaging operation (i.e., both random variables are assumed to be Gaussian distributed with zero mean). However, the required time for a single measurement of a phase increases with the number of samples applied to the averaging operation. As a consequence, the effect of the synchronization error increases too, with an effect of reducing the measurement repeatability.

III. THE ELECTRO-OPTIC PHASE MEASUREMENT SYSTEM

An implementation of the phase measurement method based on electro-optic components is depicted in Fig. 2. The synchronization signal (i.e., Sync) provided by the sinewave generator is used for generating an optical pulse train. This optical train is produced by means of an electrical pulse generator that provides to a Mach Zehnder Modulator (MZM) driver a pulse train synchronous with the Sync signal and having its repetition rate at an integer sub-multiple of f_{src}. Furthermore, the pulse generator is controlled by a control unit for introducing a delay on the electrical pulse train signal to sample the sinewave in different instants of its period. The MZM provides as output an optical pulse train at the wavelength of 1550nm (wavelength of the continuous wave laser) with a pulse located at the instants defined by the electrical pulse train.

The optical pulse train is then utilized as an optical input to a second MZM (i.e., included in the sampler processing block, see Fig. 2). This second MZM acts as an optical sampler for the optical signal output by the first MZM. The resulting optical signal at the sampler's output is again an optical pulse train having the amplitude modulated by the sinewave. Because the electrical pulse train signal is synchronized with the sinewave, the resulting optical pulse train at the sampler's output will present an optical energy proportional to the sinewave amplitude at the set delay values. Finally, the sampler's output is then converted in an electrical signal by means of a high-bandwidth photodiode (PD).

The electrical signal from the PD is acquired by a data acquisition (DAQ) system that performs a coherent sam-

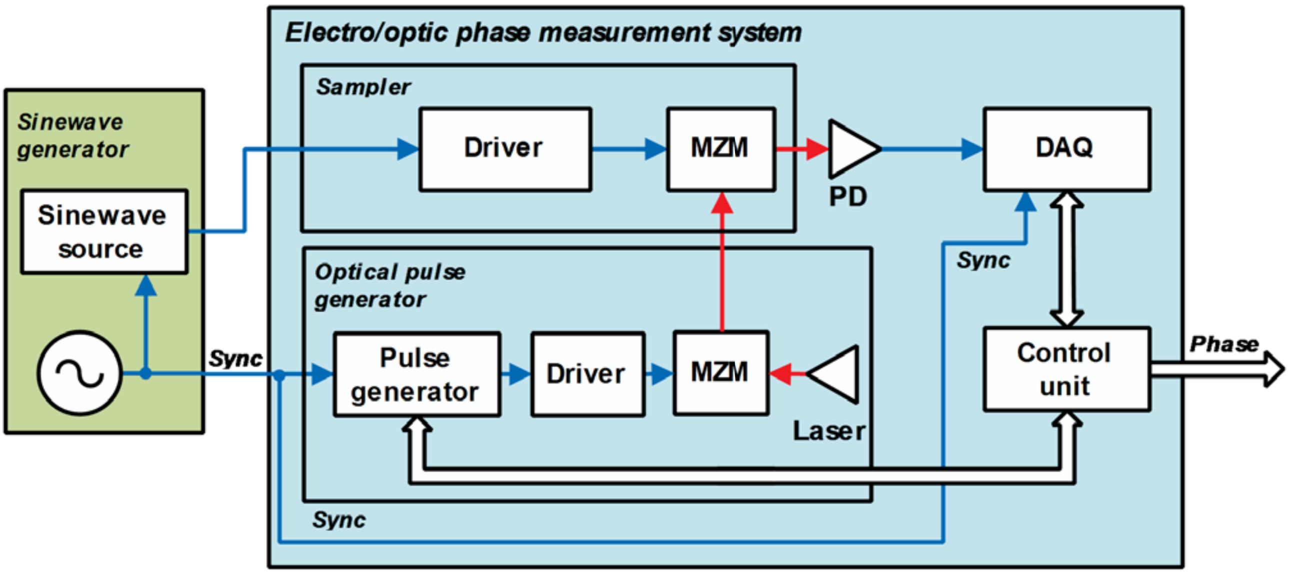

Fig. 2. The proposed electro/optic PMS.

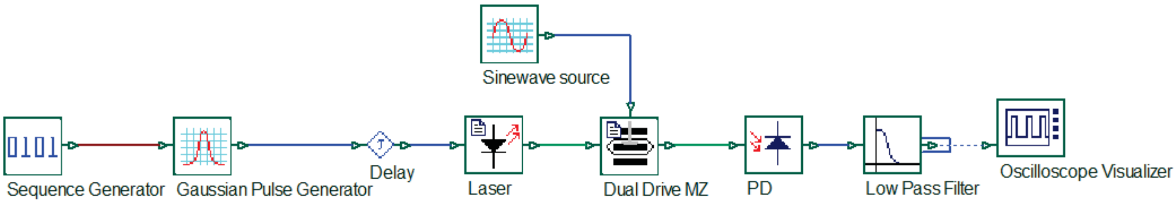

Fig. 3. The simulated OptiSystem diagram.

pling over several periods. From the acquired samples, a signal value is extracted and stored for further processing. The control unit imposes several delays to the pulse train signal to obtain measurements at several instants along the sinewave period. From the obtained measurements, by knowing the imposed delay and the sinewave frequency, the 3-parameter sine fit is applied to estimate the phase.

An initial analysis of the equipment available on the market that can be suitable for the implementation of the proposed system is described. As an optical pulse generator, the ModBox C-Band pulse by iXblue [6] could be a valid solution. It can be driven externally by an electrical trigger signal for generating an optical pulse train with a pulse repetition rate adjustable up to 20 MHz. The pulse duration (see [6]) can be controlled within the range of 100 ps to 25 ns and, furthermore, it is possible to introduce on the pulse train a delay respect to the trigger of up to 2.5 ns, guaranteeing a root-mean-square jitter of 10 ps. The nominal optical wavelength of the continuous wave laser is 1550 nm and the Relative Intensity Noise (RIN) is -140 dB/Hz, [6]. As a sampler, the MXLER-LN-20 MZM [7] embedding a specific driver for bias control by iXblue controller has been selected as a possible solution for this implementation. This MZM exhibits a nominal working bandwidth of 20 GHz, having an extinction ratio of 40 dB and a nominal insertion loss of 3.5 dB. At the output of the sampler block, the O2E-1201-MTRQ optical to electrical converter [8] has been chosen as a detector. It exhibits a conversion gain of 100 V/W at 1550 nm with a typical noise equivalent power of 39.7 pW/$\sqrt{Hz}$. For implementing the coherent sampling of the converted signal, the PicoScope 9302-25 [9] has been selected as a possible device. In particular, it exhibits an electrical working bandwidth of 25 GHz with a time-base ranging from 5 ps/div to 3.2 ms/div.

IV. SIMULATION TESTS

The proposed electro-optic system implementation has been simulated by means of the OptiSystem tool [10] (see Fig. 3). The assessment of its performance in terms of standard deviation of the phase measurements has been done in MATLAB. In particular, the optical pulse generator has been simulated by considering the Gaussian pulse generator library that provides an electrical output, which

Table 1. *The polynomial equation coefficients.*

Coefficient	Value	95% confidence bounds
p1	5.32×10^9	$[-2.61, 13.26] \times 10^9$
p2	-5.13×10^9	$[-12.29, 2.03] \times 10^9$
p3	2.11×10^9	$[-0.63, 4.86] \times 10^9$
p4	-0.49×10^9	$[-1.07, 0.01] \times 10^9$
p5	6.86×10^7	$[-0.65, 14.37] \times 10^7$
p6	-6.09×10^6	$[-12.10, -0.01] \times 10^6$
p7	3.38×10^5	$[0.42, 6.34] \times 10^5$
p8	-1.12×10^4	$[-1.97, -0.27] \times 10^4$
p9	211.3	$[83.38, 393.30]$
p10	2.46	$[-3.21, -1.71]$

is delayed through the electrical signal time Delay block. The delayed Gaussian pulse drives a laser block working at the wavelength of 1550 nm with a power of 20 mW. A dual drive MZM modulator was used to simulate the sampler block. In particular, the laser output is connected to its optical input, while the electrical input is driven by a sinewave signal having an amplitude of 1 V. The MZM is polarized with bias voltages of -2.8 V and -1.1 V, respectively. These two values of bias voltage have been demonstrated to guarantee the best linearity and sensitivity performance according to the absorption/phase MZM characteristic available in the simulator.

The output of MZM modulator is connected to a PD working at the nominal wavelength of 1550 nm and exhibiting an electrical bandwidth of 25 GHz. The PD current is converted into a voltage signal, therefore providing a conversion gain of 100 V/W. The voltage signal is connected to an oscilloscope visualizer block available in the OptiSystem libraries that is configured by means of a developed MATLAB script. In particular, this MATLAB script reads the acquired samples and finds the maximum in the record. A record contains a single optical pulse period. Furthermore, this MATLAB script allows imposing a delay to the electrical signal time delay block to perform the sampling operation of the sinewave signal in different instants. The 3-parameter sine fit algorithm was implemented in MATLAB and applied on the obtained maximum values according to the imposed delays and the sinewave frequency.

By considering the equipment analysis described in the previous section, in the simulations, the following non-idealities have been considered: (i) a random jitter of 10 ps impacting the delay stability of the optical pulse train, (ii) a RIN of -140 dB/Hz for the laser, and (iii) a noise equivalent power of 39.7 pW/$\sqrt{Hz}$ for the voltage signal at the output of the PD.

The simulations have been performed by considering a sinewave working at 100MHz. Future work will be intended to perform the analysis at 1 GHzand more, too.

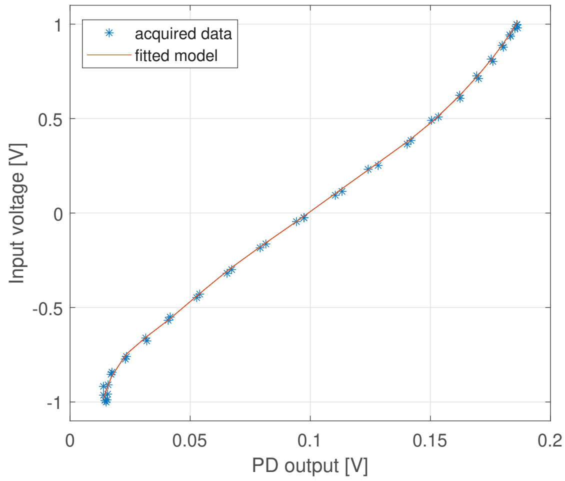

Fig. 4. MZM characteristic at sine-wave frequency of 100 MHz.

A. *The MZM-based sampler*

By considering as inputs the sinewave signal and the optical pulse train, and as output the maximum voltage provided by the PD, the MZM characteristic is nonlinear. This limits the utilization of this MZM as a sampler for the desired phase measurement system implementation. Thus, the theoretical nonlinear characteristic of the MZM needs to be firstly characterized by means of simulation analysis and then compensated before applying the 3-parameter sine fit to the signal data. To this aim, a MATLAB script has been implemented with the goal of measuring the maximum amplitude at the PD's output for several MZM input voltages. In particular, the MZM electrical input has been driven by a sinewave of 1 V as amplitude and having a phase ranging from 0 ° up to 360 °. The optical pulse train delay was set to 0 s and the maximum PD's output voltages for several imposed phases were evaluated.

In Fig. 4, the sinewave amplitude at 0 s for the different applied voltages is plotted against the maximum PD's output voltage. A polynomial equation has been estimated with the aim of compensating this nonlinear behavior. In Tab. 1, the obtained coefficients of the polynomial equation with the relative ranges at 95% of confidence level are reported. The obtained fitted equation exhibits a root mean square error of 0.018 V.

B. *Monte Carlo analyses*

For assessing the repeatability of the phase measurement against non-idealities (e.g., random jitter, RIN and noise equivalent power affecting the PD's output voltage), two Monte Carlo analyses have been conducted with 40 trials considering a sine fit applied on: (i) a single maximum PD voltage measurement at each imposed delay, and (ii) the average of 100 maximum PD measurements at each delay.

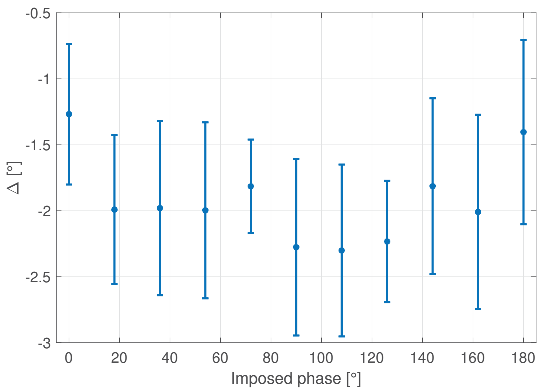

Fig. 5. Phase estimate error for imposed phases ranging from 0° to 180 °, with bars representing $3 \cdot \sigma$, considering a single PD measurements for each delay.

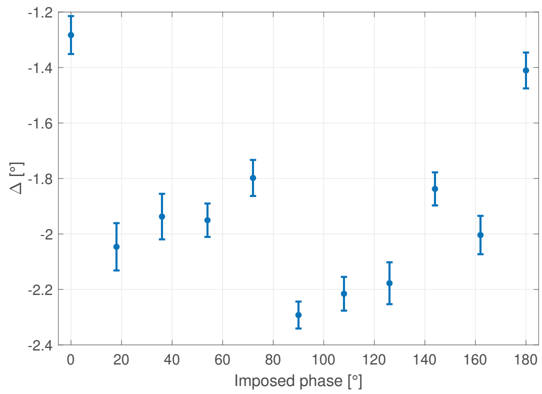

Fig. 6. Phase estimate error for imposed phases ranging from 0° to 180 °, with bars representing $3 \cdot \sigma$, considering the average of 100 PD measurements for each delay.

In this way, the fact that the averaging operation reduces the variability of the phase measurements is expected.

The obtained results by considering a single maximum PD voltage measurement are depicted in Fig. 5, as in terms of error between the provided phase estimate and the imposed one (i.e., $\Delta = \hat{\phi} - \phi$). For each imposed phase, 40 estimates are calculated and the error average together with the standard deviation σ are evaluated. In the graph, the bars represent $3 \cdot \sigma$. Among the imposed phases, the maximum obtained standard deviation is 0.25 °. As shown in Fig. 5, the phase estimates have an offset of around -2 ° and, being covered by their variability, a trend on the error averages is not clearly visible.

In Fig. 6, the obtained results by considering the average of 100 maximum voltage measurements for each time delay, before to perform sine fit, are shown. In this case, the maximum standard deviation is 0.028 °, i.e., as it was expected, about one order less than the one obtained by considering a single measurement. As in the previous case, the error offset is around -2 °, while an error trend is more visible. This trend can be minimized by considering a further compensation step.

V. CONCLUSION AND FUTURE WORK

In this paper, the architecture of an electro-optic system implementing an accurate measurement of the phase of sinewave signals up to 100 MHz was described. In particular, a first selection of the suitable instruments for its implementation was provided. According to the major uncertainty sources that may affect the accuracy of phase measurements, several Monte Carlo analyses were performed with the aim of assessing the standard deviation of the phase estimates. Furthermore, the compensation of the non-linearity of the chosen MZM was performed by means of simulations. This allowed correcting the sampling results from the sinewave signal with the optical pulse train. The obtained results expressed a maximum standard deviation of 0.028 ° at 100 MHz.

Future works will be focused on: (i) the assessment of the performance of the electro-optic system at 1 GHz and more, (ii) considering the clock drifts and synchronization error in the simulator, (iii) adopting in the simulator as absorption/phase characteristic a model closer to the real characteristic of the selected MZM, and (iv) a first implementation of the proposed system by means of hardware.

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