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AUTOMATION SYSTEMS
IN SCIENTIFIC RESEARCH AND INDUSTRY

Fast Digital Meter of the Phase Difference between the Ion Beam and Accelerating Voltage Signals

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Abstract—A fast meter of the phase difference of two arbitrarily shaped signals at a frequency of 0.2 to 6 MHz is proposed. The device allows measuring the phase difference for the first harmonic with an error of not more than 1° within $\sim$20 μs. The signal frequency and amplitude may vary at a speed of up to 20 MHz/s and 40 dB/sec, respectively. Basic signal processing and phase calculation are implemented digitally in a field programmable gate array. The electronics design features are presented, the signal processing methods are described, and the meter parameters and the results obtained on the physical facility are given.

Keywords: digital signal processing, phase measurement, quadrature detection, synchronous detection.

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INTRODUCTION

The problem of measuring the phase difference of two signals is widely known in different areas of technology and scientific research. In particular, this problem is solved during operation of all heavy-particle accelerators when it is required to measure the phase difference between the high accelerating voltage and the first harmonic of the ion beam signal. In these cases, the measurement is complicated by the fact that the frequency of the accelerating voltage and the signal amplitude vary during the acceleration cycle at a sufficiently high rate. The problem can be solved if both signals are converted into digital form and subjected to a field programmable gate array (FPGA).

We formulate the problem on the example of the signal phase difference meter for the NICA booster complex (Dubna, Moskovskaya oblast') [1]. Thus, it is necessary to measure the phase difference between the sinusoidal accelerating voltage and the first harmonic of the ion beam signal from a broadband current sensor [2] for an ion acceleration cycle lasting about 2 s. The shape of the beam signal is shown in Fig. 1. The ion beam consists of four clusters rotating in the booster ring with a rotation period T_0. During the acceleration cycle, the frequency varies from 0.5 to 6 MHz, the signal amplitude increases by about an order of magnitude, and the total signal amplitude ranges from 50 μV to 10 mV. The phase measurement error should be no more than 1°, and the minimum measurement time should not exceed 20 μs. In addition to the average phase of the signals of all four clusters for the period T_0, it is necessary to measure the phases of the individual clusters with an error of not more than 5°. This problem was successfully solved by applying the synchronous detection method [3] implemented in digital form. Two orthogonal reference voltages are generated on the basis of the accelerating voltage signal and are then used for quadrature synchronous detection of the beam signal.

The aim of this work is to create a device that measures the phase difference of two signals with the required accuracy in a large range of amplitudes and frequencies of the signals under study.

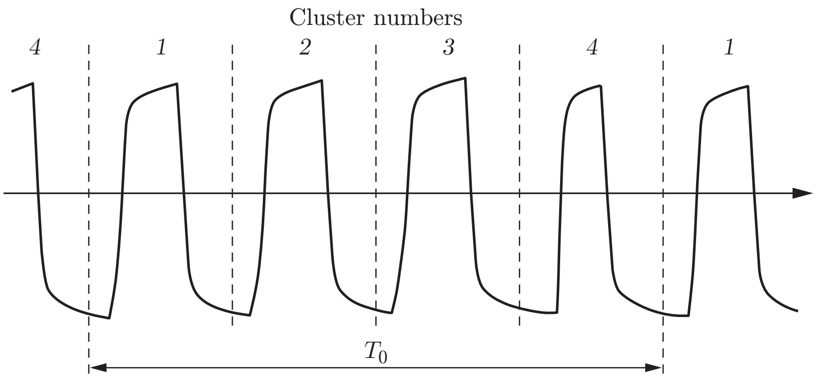

Fig. 1.

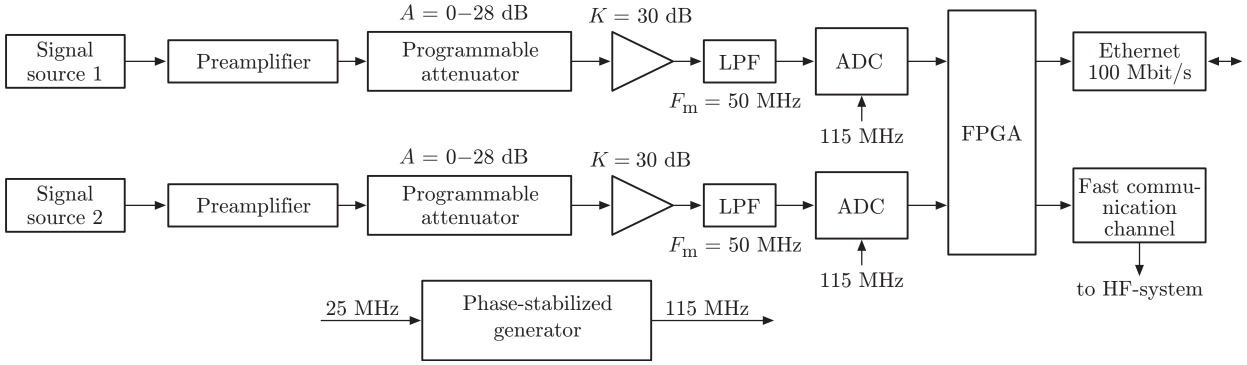

Fig. 2.

PRINCIPLE OF OPERATION OF THE SIGNAL PHASE DIFFERENCE METER

A functional diagram of the meter is shown in Fig. 2. Signals from sources *1* and *2* (S_1 and S_2) are fed to two identical channels, in which, after amplification and filtering, they are converted into digital form using a 14-bit ADC and transmitted to the FPGA. As the main electronics unit is located at a distance of tens of yards from the signal sources, the effect of noise on the connecting cables can be reduced by placing low-noise preamplifiers near the signal sources. The transmission coefficients of the channels can be programmed in the range of 28 dB, which extends the dynamic range of input signals. The low-pass filter (LPF) with a band of ~50 MHz limits the input signal band to the Nyquist frequency. All digital signal processing and phase calculation are carried out in an Altera Cyclone-3 FPGA [4]. The results of real-time measurements are transmitted via a fast communication channel and recorded in the computer memory, where they can be read through a special data port.

SIGNAL PROCESSING ALGORITHM

The FPGA structure is shown in Fig. 3. The basis of the phase measurement process is quadrature synchronous detection. For the reference signal S_2, an orthogonal component $S_{2\mathrm{ort}}$ is specifies. This component is formed when the signal S_2 passes through a chain of registers, and the entry into each subsequent register is recorded with a delay equal to the clock frequency of the FPGA (~8.7 ns). The component $S_{2\mathrm{ort}}$ is created on the basis of signals S_{2i} and S_{2j} taken from the outputs of registers i and j, for which the quantity $E = \int\limits_0^T S_2 S_{2\mathrm{ort}} dt$ changes sign when passing through zero (T is the signal period). $S_{2\mathrm{ort}}$ is calculated using linear interpolation.

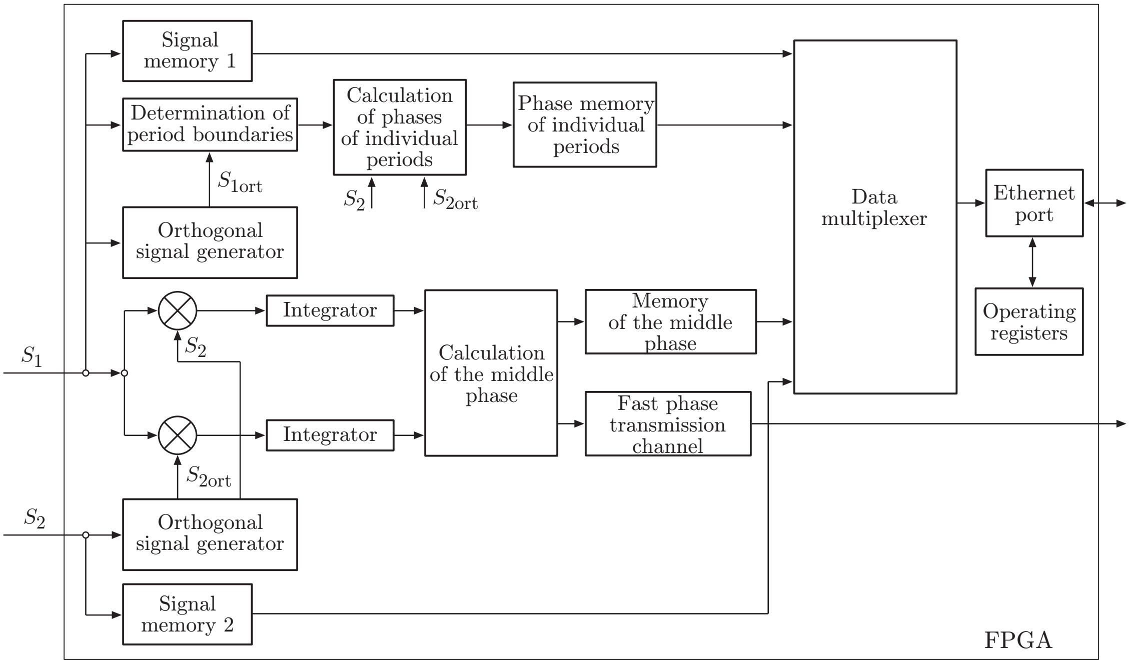

Fig. 3.

Then the quadrature components of $F_{\sin}$ and $F_{\cos}$ of the signal S_1 are calculated:

$$F_{\sin} = \int_0^{nT} S_1 S_2 dt = \frac{nT}{2}\sin(\varphi_0), \tag{1}$$

$$F_{\cos} = \int_0^{nT} S_1 S_{2\mathrm{ort}} dt = \frac{nT}{2}\cos(\varphi_0), \tag{2}$$

where φ_0 is the phase difference between the first harmonics of S_1 and S_2 and n is the number of signal periods over which the integration is performed.

The value of n is chosen as the integral part of the ratio of T_{m} to T, where T_{m} is the specified time of one measurement (within 20–50 μs). Further, the phase difference φ_0 is found as the arctangent of the ratio $F_{\sin}/F_{\cos}$. The arctangent is calculated using the CORDIC iterative algorithm [5].

The phase difference for a single cluster, e.g., for cluster *2* (out of four) is found by the integration in Eqs. (1) and (2) during each signal period from each of the four periods. To find the cluster boundaries, we took the first signal harmonic and specified a component $S_{1\mathrm{ort}}$ orthogonal to it using the same algorithm as for $S_{2\mathrm{ort}}$. The cluster boundaries were defined as the points of intersection of the component $S_{1\mathrm{ort}}$ with the zero level.

The orthogonal components $S_{1\mathrm{ort}}$ and $S_{2\mathrm{ort}}$ are continuously calculated during the same time T_{m} as the phase difference. Thus, we monitor the signal frequency in the case of change in the latter during the measurement cycle.

MEASUREMENT ACCURACY

The measurement error of the mean phase difference (averaged over all clusters) is mainly determined by three factors:

— error in finding the orthogonal signal $S_{2\mathrm{ort}}$;

— amplitude noise of electronics in the channel of the signal S_1;

— temperature drift.

If the phase difference between the components S_2 and $S_{2\mathrm{ort}}$ differs by the value of $\Delta\varphi$, then the phase measurement error is approximately equal to $\Delta\varphi$. The error value $\Delta\varphi$ is determined mainly by the delay in the calculation of $S_{2\mathrm{ort}}$ during rapid change in the signal frequency. From the simulation results and

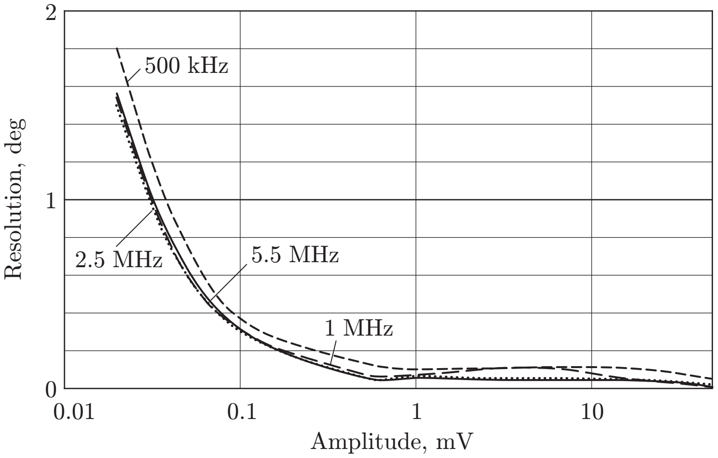

Fig. 4.

experimental testing, we can conclude that at a rate of change in the signal frequency of up to 20 MHz /s, the error $\Delta\varphi$ is smaller than ∼0.4°.

The effect of amplitude noises of the electronics in the channel of the signal S_1 was studied experimentally on a laboratory stand. The dependence of the mean square error of measurement (or resolution) on the signal amplitude is shown in Fig. 4. As can be seen from the figure, when the signal voltage is more than 30 μV, the resolution of the phase measurements is better than 1°.

These tests showed that, when the temperature changes from 25 to 45 45 °C, the measured difference of phases changes by less than 0.3°.

Thus, we can assume that, for the real amplitudes of the input signals, the maximum total error of the measured phase difference averaged over all clusters does not exceed 1°. Similar measurements performed for the phases of the individual clusters showed that the error in the measured phase difference is smaller than 4°.

CONCLUSIONS

The phase difference meter developed at the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, allows determining the phase differences of signals whose frequency and amplitude change at rates of up to 30 MHz/s and 40 dB/s, respectively, within a time of ∼20 μs with a measurement accuracy of more than 1°. This was achieved by carrying out the main amount of digital signal processing in the FPGA. The meter was successfully tested with a real ion beam on the Nuclotron facility in Dubna [6]. The dependences of beam phase on the phase of the accelerating HF voltage during the whole beam acceleration cycle were obtained.

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