Oleksandra HOTRA[1], Andriy SAMILA[2], Leonid POLITANSKY[2]

Lublin University of Technology, Poland (1), Yuriy Fedkovych Chernivtsi National University, Ukraine (2)

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Synthesis of the configuration structure of digital receiver of NQR radiospectrometer

Abstract. *Analysis of methods for demodulation of free induction decay signal that are suitable for use in pulsed nuclear quadruple resonance radiospectrometers was performed. The structure and MATLAB Simulink model of the receive path of radiospectrometer was synthesized, in which the Software Defined Radio technology was chosen for the implementation of a quadrature detector with a filtration and quadrature reflection suppression system. The application of the principle of direct digitization of the signal made it possible to significantly reduce the length of the analog portion of the receiver, and, consequently, reduce the noise of the useful signal and the level of out-of-band higher order spectral components.*

Streszczenie. *Przeprowadzono analizę metod demodulacji sygnału zaniku indukcji swobodnej, które są odpowiednie do stosowania w impulsowych radiospektrometrach jądrowego rezonansu kwadrupolowego. Opracowano strukturę i model ścieżki odbiorczej radiospektromeru w środowisku MATLAB Simulink, w którym do realizacji kwadraturowego detektora z układem filtracji i tłumienia odbicia kwadraturowego wybrano oprogramowanie Software Defined Radio. Zastosowanie zasady bezpośredniej cyfryzacji sygnału pozwoliło znacznie zmniejszyć długość analogowej części odbiornika, a w konsekwencji zmniejszyć szum sygnału użytecznego oraz poziom pozapasmowych składowych widmowych wyższych rzędów. (**Synteza struktury konfiguracji odbiornika cyfrowego radiospektromeru NQR**).*

Keywords: NQR, simulation model, quadrature detection, SDR, radiospectrometer, digital filters, Field - Programmable Gate Array.
Słowa kluczowe: spektroskopia jądrowego rezonansu kwadrupolowego (NQR), model symulacyjny, wykrywanie kwadratur, Radio programowalne (SDR), radiospektrometr, filtry cyfrowe, bezpośrednio programowalna macierz bramek (FPGA).

Introduction

The study of physical properties of substances using pulsed electromagnetic radiation has become widespread in optical and radio wave spectroscopy. Pulsed Fourier spectroscopy of nuclear quadrupole resonance (NQR) is based on powerful radio frequency excitation pulses and the use of highly sensitive equipment [1-3]. In response to the short broadband δ-pulse, this method ensures the excitation of all resonance frequencies of the NQR spectrum. The method of detecting free induction decay signals (FID) requires a thorough analysis, since its implementation governs the accuracy of visualization of complex resonance spectra, especially when it comes to multi-pulse experiments.

Recently, in the developed countries of the world, much work is in progress on the development of radiotechnical systems that are referred to collectively as Software Defined Radio (SDR) [4]. The essence of SDR technology is to use full digitization of the radio signal by high-speed analog-to-digital converter (ADC) with subsequent processing of the received data in digital form. In this case, the basic parameters of receivers and transmitters are determined by the software itself, rather than by the hardware configuration.

The purpose of this work is to synthesize the configuration structure of the receive path of the NQR radiospectrometer, in which the SDR technology is chosen for the implementation of the quadrature detector with the filtration system and the suppression of quadrature reflections.

Statement of the research task

It is known that in the pulsed NQR, the FID signals are detected by transferring the resonance spectrum of width Ω to the low frequency (LF) range by subtracting the reference frequency ω_0, which is close to the frequency of the resonating nucleus. The method for detecting FID signals which is partially considered in [5] requires a more thorough analysis, since its implementation governs the accuracy of visualization of complex resonance spectra, especially when it comes to multi-pulse experiments. The features of the Fourier transform create additional problems when selecting the reference frequency for the synchronous detector ω_0. At first glance, it is logical to set ω_0 in the center of the spectral range Ω (Fig. 1, a) and to use only one component of the signal $\omega_0 \pm \Omega/2$ for the Fourier transform. However, in this case, the positive and negative frequencies of the resulting spectrum will be inseparable [6].

Often, for detection of FID signals another method is used which lies in arrangement of frequency ω_0 at one of the edges of spectral range Ω (Fig. 1, b) [7]. Although in this case all detected signals will have the same sign (for example, choose the band $\omega_0+\Omega$), but the effect of resonance conditions derangement will result in nonuniform excitation and a decrease in the signal-to-noise ratio. Moreover, additional noise from the opposite with respect to ω_0 spectral band $\omega_0-\Omega$ during synchronous detection will be added to the noise in the operating band $\omega_0+\Omega$. One of the solutions to this problem is the formation of separate frequencies for excitation and detection of resonance, which is often a technically challenging task [8]. Another option is to apply a quadrature detection of FID which allows an increase in the signal-to-noise ratio by a factor of $\sqrt{2}$ [9].

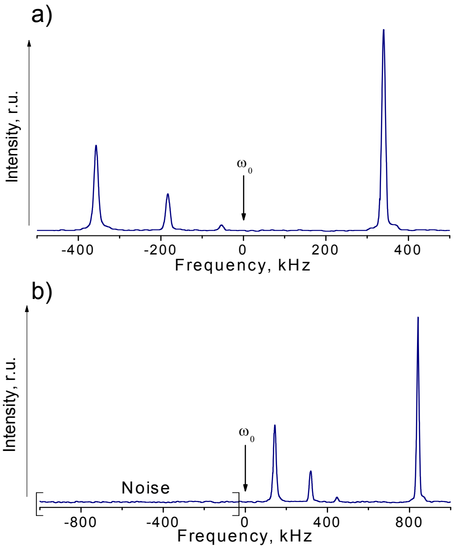

Fig. 1. Selection of reference frequency ω_0 of synchronous detector during pulsed excitation of NQR: a – in the centre of range Ω, b – at the edge of range Ω

Apart from increasing sensitivity, the use of quadrature detection imposes some restrictions. The main problem is that the suppression of unnecessary peaks when adding two signals will occur only under the condition of exact equality of their amplitudes and phase difference of 90°. In reality, the implementation of these conditions is practically impossible, therefore, in the spectra there are small residual signals - quadrature reflections [6]. The amplitude of the latter does not exceed 1% of the main signal, so they are harmful only when measuring weak peaks on the background of relatively intense.

In [10], the authors considered the development of a frequency synthesizer and a pulse train driver for a nuclear quadruple resonance spectrometer. Structure configuration of the direct frequency synthesizer (DDS) and the pulse train driver was carried out using the technology of optimizing the resources of the programmable crystal. As a result, about 50% of hardware resources in the field-programmable gate array (FPGA) are not yet involved. The principle of building a configuration structure, which ensures the implementation of SDR with direct digitization of the signal and its integration on the basis of the remaining free hardware resources of FPGA is considered below.

Simulation modeling of the receive path of radiospectrometer developed on the principle of direct digitization of a signal

DEVELOPMENT OF MATLAB SIMULINK MODEL

Fig. 2 shows a model of a high-frequency (HF) receiver of pulsed NQR spectrometer in which the SDR technology is chosen for the implementation of a quadrature detector with a system of filtration and suppression of quadrature reflections. The receiver is based on the principle of Digital Down-Converter (DDC), which significantly reduced the length of its analogue path, and therefore reduced the noise of the FID signal and the asymmetry of detected signal parameters. The experimental model of the receiver involves a high-speed 12-bit ADC AD9230BCPZ (rate of conversion 170 MSPS) which is used to digitize the response signal in the range of resonance frequencies 1 - 50 MHz [11, 12].

To simulate the receive path of the spectrometer, in MATLAB Simulink a test radio signal was synthesized, representing a carrier oscillation at 30 MHz with an envelope in the form of a sum of two harmonics - 400 kHz and 800 kHz In this case, the band radio signal

$$s(t)=a(t)\cos\left(\Phi(t)\right)=a(t)\cos\left(\omega_0 t+\varphi(t)\right)$$

is a real part of a complex signal $z(t)$ [13]:

$$z(t)=a(t)\cos\left(\omega_0 t+\varphi(t)\right)+j\cdot a(t)\sin\left(\omega_0 t+\varphi(t)\right)=$$
$$=z_m(t)\exp(j\omega_0 t),$$

where a complex envelope equals:

$$z_m(t)=a(t)\exp\left(j\cdot\varphi(t)\right)=$$
$$=a(t)\cos\left(\varphi(t)\right)+j\cdot a(t)\sin\left(\varphi(t)\right)=$$
$$=I(t)+jQ(t).$$

The concept of quadrature modulation lies in multiplication of complex envelope $z_m(t)$ by complex frequency $\exp(j\omega_0 t)$. The finite equation for the synthesis of radio signal [13] is the following:

$$s(t)=\mathrm{Re}\left[z(t)\right]=I(t)\cos(\omega_0 t)-Q(t)\sin(\omega_0 t)\,. \tag{1}$$

As can be seen from Fig. 2, the receiving channel of the spectrometer consists of analog and digital paths. The functional elements of the analog channel are amplification modules “Amp1”, interface modules “Amp2” and a bandpass filter “BPF”. The latter serves to suppress parasitic signals outside the band of spectrometer operating frequencies. A link with a digital path is an ADC block which simulates the work of a 12-bit ADC at a sampling frequency of 170 MHz.

The digital path of the receiver ensures complex envelope extraction of radio signal $z_m(t)$ by multiplying radio signal (1) by $\exp(-j\omega_0 t)$, which provides transfer of the spectrum to the region of zero frequencies. The detection process will generate a following signal:

$$z_d(t)=s(t)\exp(-j\omega_0 t)=A(t)+jB(t)\,,$$

with complex components:

$$\begin{aligned}A(t)&=\frac{1}{2}I(t)+\frac{1}{2}I(t)\cos(2\omega_0 t)-\frac{1}{2}Q(t)\sin(2\omega_0 t),\\ B(t)&=\frac{1}{2}Q(t)-\frac{1}{2}Q(t)\cos(2\omega_0 t)-\frac{1}{2}I(t)\sin(2\omega_0 t).\end{aligned} \tag{2}$$

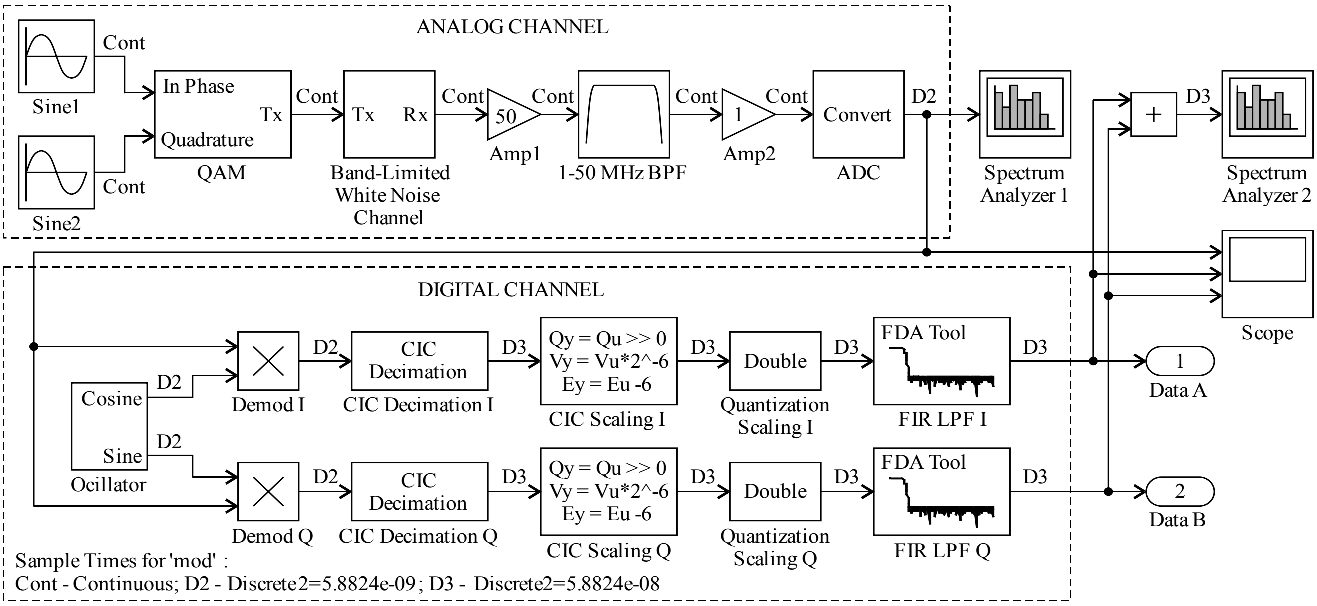

Fig. 2. Simulation model of the proposed receiver of NQR spectrometer

The process of digital processing of the demodulated components (2) of the FID signal lies in reducing their sampling rate (decimation) and filtering from the components of double frequency $2\omega_0$. Signals received from the outputs of "demod" multipliers still have a high sampling rate (170 MHz). To construct the resonance spectra of NQR with a maximum width of the spectral band Ω equal to 1 MHz, it is sufficient to have a value which is an order of magnitude lower, so in the digital path of the SDR receiver, 5-cascade integral comb filters with an infinite impulse response (CIC Decimation modules in Fig. 2) are used, which provide a reduction of the sampling rate to 17 MHz. However, as a result of operation of CIC filters, the bit capacity of the output signals increases due to the reduction of their bandwidth, therefore, in the simulation model of the receiver, Quantization Scaling modules are introduced for artificial limitation of the bit capacity to 16 bits [12].

Fig. 3 shows frequency characteristics obtained in MATLAB for CIC and compensating FIR filters.

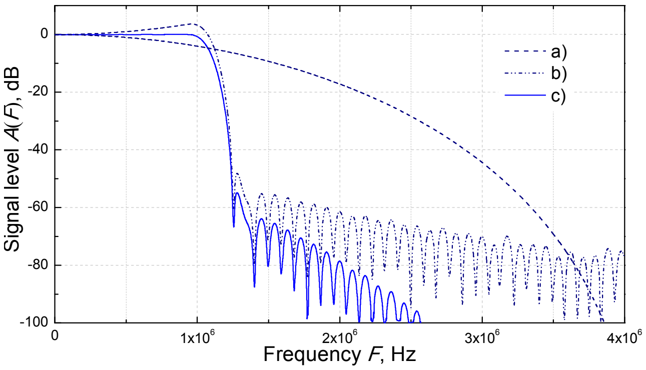

Fig. 3. Results of simulation of frequency characteristics of digital filters: a – CIC, b – compensating FIR, c – total characteristic

Unfortunately, CIC filters have a rather steep amplitude-frequency response, which goes down to 0 when approaching the sampling frequency. The curvature of frequency response is compensated by "FIR Low Pass Filter" modules that are nonrecursive filters with a finite impulse response.

The output signal and transmission characteristic of compensating filter are represented by the dependencies:

$$y(n) = \sum_{k=0}^{N-1} h(k)x(n-k),$$

$$H(z) = \sum_{k=0}^{N-1} h(k)z^{-k},$$

where $x(n)$ is input influence, $h(k)$ are impulse response coefficients, N is the number of filter coefficients.

SYNTHESIS OF SDR CONFIGURATION STRUCTURE AND RESEARCH ON ITS CHARACTERISTICS

The concept of proposed model realization on the basis of DSP libraries System Toolbox and FDATool makes possible its efficient implementation on the basis of field-programmable gate arrays. In this case, the FPGA of Intel (Altera) or Xilinx are effective, since CAD systems of their configuration structures are closely integrated with MATLAB.

The SDR configuration structure of spectrometer receiver developed in Altera Quartus II Web Edition Software for FPGA EP4CE15E22C8 is shown in Fig. 4 [14].

The structure of pulse former proposed in [10] already has a DDS, the output signal of which will be used as the reference for spectrum transfer. In order to implement the digital quadrature detection, another transcoding table is added to the DDS configuration structure for the function $y = \cos(x)$. The reference signals are sent to the inputs of the "mult1", where they are multiplied with the information signal. Since ADC data and DDS reference signals are 12-bit, we obtain a 24-bit number as a result of multiplication. The operation of multiplication will lead to transferring of signal spectrum to LF. In this case, further work with the digital signal, which is sampled by 170 million samples per second, is no longer appropriate and it is necessary to carry out resampling to a lower frequency. Before this operation, LPF is required. In the SDR configuration structure (Fig. 4), a CIC filter is used that provides a 10-fold reduction of the sampling rate.

After the CIC filter, there is an FIR filter, which compensates the sloping frequency response. The FIR filter coefficients calculated in MATLAB FDATool. The module of the parallel binary adder "add1" serves to shift constant component of the data coming from the ADC output by the value equal to half the maximum amplitude of the information signal. The "pll1" module generates reference frequency signals: 170 MHz - for ADC, multipliers, adder and CIC filters; 17 MHz - for FIR filters operation.

As a result of computer parametric identification of information transformations in analogue-digital paths of the proposed SDR for the NQR pulse spectrometer, the voltage oscillograms (Fig. 5) and spectral characteristics (Fig. 6) of the quadrature components of the demodulated FID signal were obtained.

The high efficiency of digital quadrature detection with the use of direct signal digitization technology is also confirmed by the low content of the dual frequency components in the spectrum of the receiver output signal. In particular, with a sampling frequency of 17 MHz and a cutoff frequency of the compensating LPF of 1 MHz, the level of side and out-of-band emissions in the effective bandwidth of the SDR is not more than -100 dB.

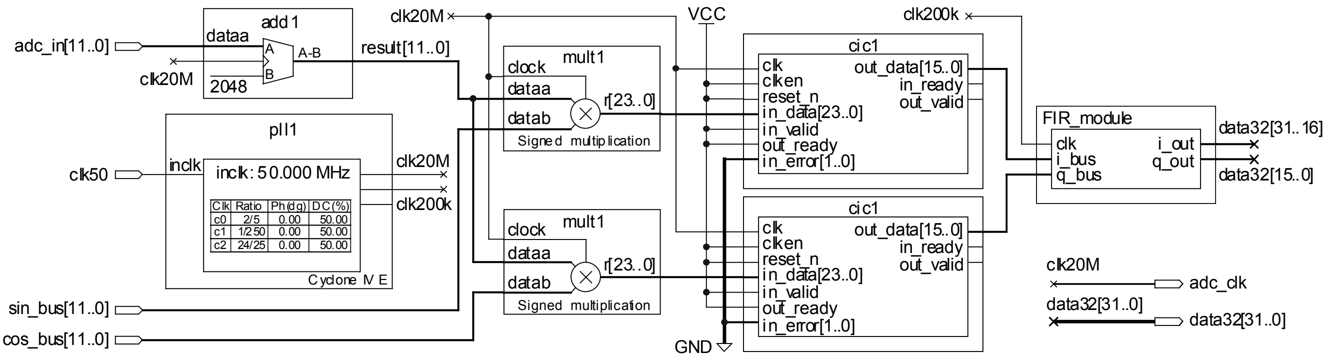

Fig. 4. SDR configuration structure in Altera Quartus II Web Edition Software

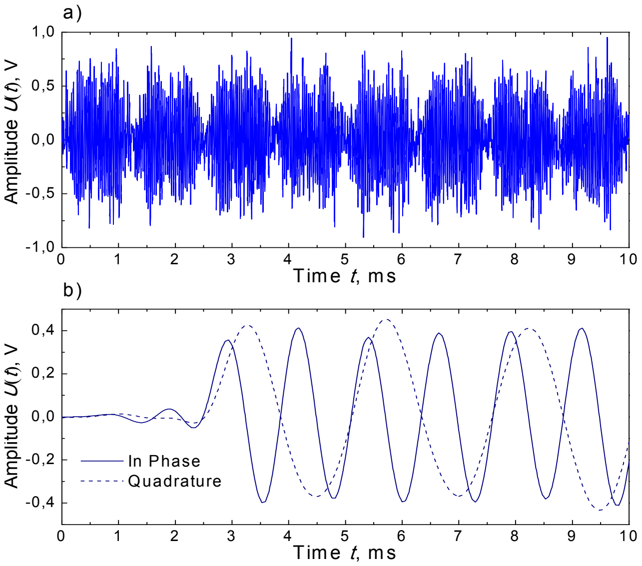

Fig. 5. Voltage oscillograms in the paths of proposed receiver: a – modulated oscillation, b – demodulated components of the QAM signal

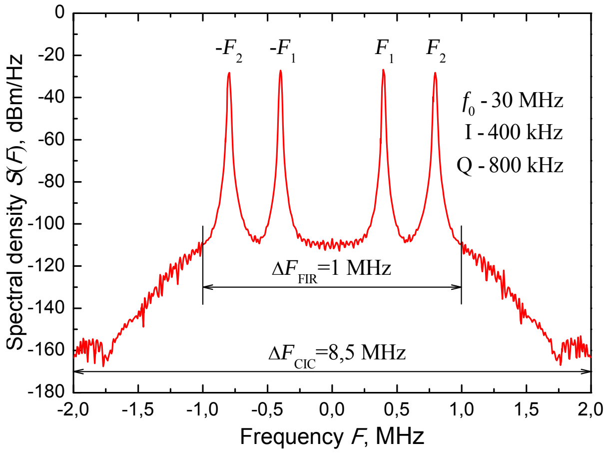

Fig. 6. Energy spectrum of demodulated signal. The peaks F_1 ($-F_1$) and F_2 ($-F_2$) reflect the information components of the QAM signal

Conclusions

The structure and MATLAB Simulink model of a digital quadrature receiver of nuclear quadruple resonance signals were developed. The synthesis of compensating filters and computer simulation of signal transformations in the receive path of radiospectrometer were performed.

It was established that the application of the principle of direct digitization of the free induction decay signal made it possible to significantly reduce the length of the analog portion of the receiver, and, consequently, reduce the noise of the useful signal and the level of out-of-band higher order spectral components. In particular, with a sampling frequency of 17 MHz and a cutoff frequency of the compensating LPF of 1 MHz, the level of side and out-of-band emissions in the effective bandwidth of the SDR is not more than -100 dB.

The operation algorithm and the structure of the proposed receiver based on the field-programmable gate array EP4CE15E22C8 eventually can be used over time in the implementation of portable systems for the registration of double NQR-NMR and NQR-NQR resonances, multidimensional NQR spectroscopy, NQR tomography of semiconductor solid state devices.

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***Authors**: prof. dr hab. inż. Oleksandra Hotra, Lublin University of Technology, Institute of Electronics and Information Technology, str. Nadbytrzycka 38a, 20-618 Lublin, E-mail: o.hotra@pollub.pl; dr inż. Andriy Samila, Yuriy Fedkovych Chernivtsi National University, Department of Radio Engineering and Information Security, str. Kocubynskogo 2, 58-012 Chernivtsi, E-mail: andriysamila@gmail.com; prof. dr hab. inż. Leonid Politansky, Yuriy Fedkovych Chernivtsi National University, Department of Radio Engineering and Information Security, str. Kocubynskogo 2, 58-012 Chernivtsi, E-mail: rt-dpt@chnu.cv.ua.*

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