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Noreddine Kachkachi, Axel Gansmuller, Hassan Rabah

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SoC-FPGA based compact NQR Spectrometer

Noredidine Kachkachi

CNRS

CRM2

F-54000 Nancy, France

noredidine.kachkachi@univ-lorraine.fr

Axel Gansmuller

Université de Lorraine

CRM2

F-54000 Nancy, France

axel.gansmuller@univ-lorraine.fr

Hassan Rabah

Université de Lorraine

IJL

F-54000 Nancy, France

hassan.rabah@univ-lorraine.fr

Abstract—Nuclear Quadrupolar Resonance (NQR) is a spectroscopy technique used for the characterisation of molecules containing quadrupolar atomic nuclei. The NQR is designed for a broad range of portable applications, nevertheless it suffers from a relatively weak sensitivity and susceptibility to external noise. In this context, we here present a solution with a high degree of integration and miniaturization based on a single System-on-Chip Field-Programmable Gate Array (SoC-FPGA) that integrates all the major digital hardware and software modules of the NQR spectrometer. The proposed spectrometer was successfully tested over the NQR frequency ranges by detecting the expected frequencies of several samples. Enhancement in sensitivity and new features were also achieved with regards to the previous spectrometers developed in our team.

Index Terms—NQR instrumentation, Sensitivity, SoC-FPGA.

I. INTRODUCTION

In NQR, the quadrupolar interaction is responsible for the nuclear spin polarization [1]. The frequencies of the received signal, called FID (Free Induction Decay), depend on the intrinsic molecular parameters constituting hence a kind of signature of the studied molecule. Unfortunately the NQR signal is very weak and susceptible to external noise, which makes instrumentation very challenging.

Several miniature and portable spectrometers using ASIC, FPGA, SOC-FPGA or SDR (Software Defined Radio) solutions are presented in literature [2]–[5]. However, those designed for NQR applications still have crucial RF components in the analog domain or limited performances for some digital modules.

The primary contribution of our work consists in the integration of all the major hardware and software functionalities on a single SoC-FPGA and a single board, thus achieving immunity to external RF noise enhancement and miniaturization. In addition to this, exceptional performances including an 8 ns pulse width resolution, ultra-broadband and embedded denoising algorithms readiness were achieved. This paper is based on our previously published article [6].

II. PROPOSED SPECTROMETER

At system level, the excitation channel of the spectrometer is composed of an external power amplifier and a conjunction of a pulse programmer and a digital transmitter module integrated in the SoC-FPGA that is located on the STEMLab 125-14 board [7]. The acquisition channel is made of an LNA, a 14-bit ADC and an acquisition digital module integrated in the

Zynq Z-7010 SoC-FPGA. In addition to the digital hardware components, this compact spectrometer embeds the pulser and the acquisition Linux applications on the SoC-FPGA.

The pulser is a home-made digital Intellectual Property (IP) designed in Register Transfer Level (RTL) Language. This module functions as the "bandmaster" of the spectrometer, that receives pre-generated instructions specific to experiments, already stored in the external DDR, and decodes these instructions to generate control signals that drive the RF excitation and acquisition modules.

The transmitter module generates an RF pulse that is controlled in phase by the pulser. The frequency of the pulse is controlled by pulser Linux application. The amplitude is adapted by an output interface.

The acquisition module performs acquisition and digital signal processing, including frequency translation, band-pass and decimating filtering, digital quadrature demodulation through a home-made DDC IP, and CIC decimation with a ratio programmable by the Linux application. Thanks to a genuine synchronization mechanism, it is possible for the spectrometer to execute on-the-fly (OTF) accumulation in the FPGA. The acquisition Linux application manages the copy and the read of the DDR memory zones as well as the FID transfer to the host PC. The acquisition module can be programmed to perform direct detection.

In addition to the previously described main modules, other auxiliary elements or Xilinx IPs were designed or re-used including (Fig. 1), a Pulser debug module, a Trigger module, a Top level registers interface, a Backbone, a clocks and resets generator and ILA (Integrated Logic Analyzer).

III. RESULTS

The design implementation was performed using Vivado. The FPGA resources utilization are shown in table I.

Resource	Utilization	Utilization in %
LUT	14125	80.26
FF	18692	53.10
BRAM	27.5	45.83
IO	79	79

TABLE I: FPGA resources utilization

All ^{14}N spectra were acquired with single pulse excitation experiments using an NQR probehead. ^{35}Cl 1, 3, 5 – TCB spectra were acquired using a Bruker BBO 10 mm NMR

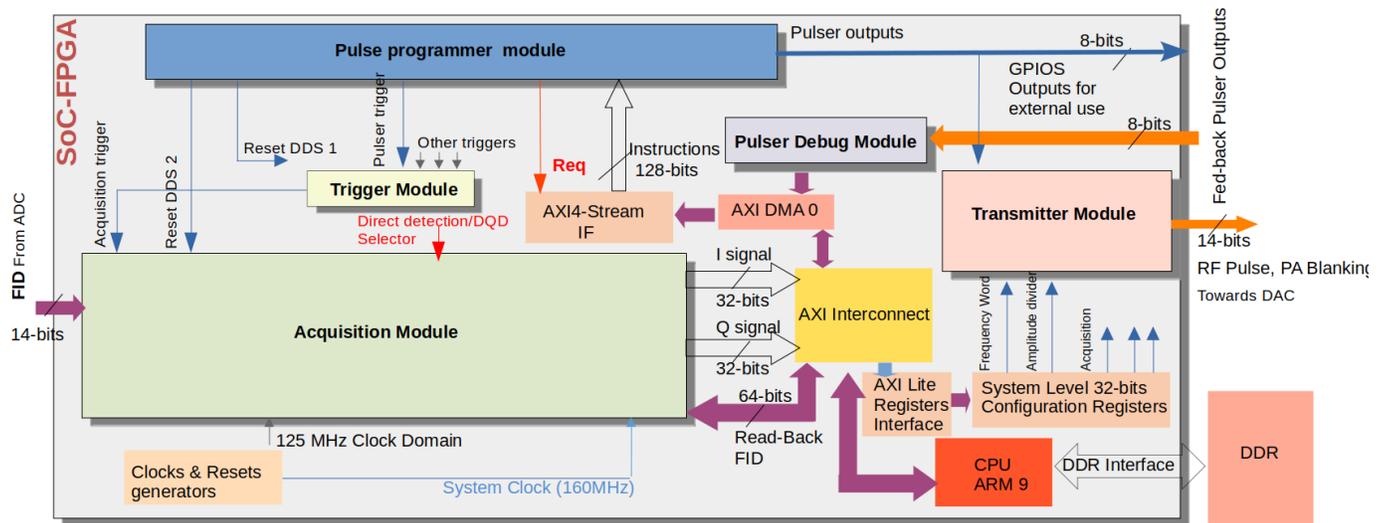


Fig. 1: building blocks of the proposed spectrometer micro-architecture on SoC-FPGA

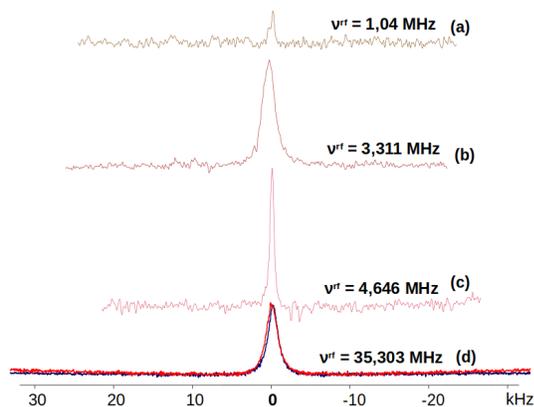


Fig. 2: Spectra (a) and (c) are for $NaNO_2$. Spectrum (b) is acquired on HMT. The bold ν_{RF} frequencies correspond to the respective excitation frequencies. Spectra (d) shows the superposition of two 1,3,5-TCB spectra, one acquired with Bruker Avance III 600 MHz NMR spectrometer, the other with our SoC-FPGA spectrometer. ^{14}N spectra were acquired at $T = 295K$, ^{35}Cl ones at $T = 298K$.

probe. Signal post-processing for spectral analysis was performed independently from acquisition on an external PC laptop.

As shown in Fig. 2, the spectrometer successfully detected all expected resonances for ($NaNO_2$), hexamethylenetetramine (HMT) as well as for 1,3,5-Trichlorobenzene (1, 3, 5-TCB). Thanks to the remarkable enhancement of sensitivity, the frequencies were detected using relatively small sample quantities and through straightforward "one-pulse" experiments, with very short experimental times. This compact NQR spectrometer enabled, to enhance sensitivity (about +28 dB), portability, and overall performance with respect to the initial NQR spectrometer developed by our team in 2007 [8]. As evident in the spectra in Fig. 2, the sensitivity of our compact

spectrometer matches that of the standard commercial Bruker spectrometer. Thanks to its high level of integration in the digital domain, the optimized architecture of this spectrometer increases the immunity of the system to external noise, enables to embed all the relevant signal processing and software on a single SoC-FPGA and permits outstanding performances. Moreover, this low-power and portable spectrometer (successfully tested with a 2 W amplifier) is fully flexible, easily configurable and up-gradable.

IV. CONCLUSION

In this paper we present a compact SoC-FPGA based spectrometer and illustrate its performances by presenting NQR spectra acquired for representative samples.

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