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Design and testing of a low impedance transceiver circuit for nitrogen-14 nuclear quadrupole resonance

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ABSTRACT

A low impedance transceiver circuit consisting of a transmit–receive switch circuit, a class-D amplifier and a transimpedance amplifier (TIA) was newly designed and tested for a nitrogen-14 NQR. An NQR signal at 1.37 MHz from imidazole was successfully observed with the dead time of ~85 μs under the high Q transmission (Q~120) and reception (Q~140). The noise performance of the low impedance TIA with an NQR probe was comparable with a commercial low noise 50 Ω amplifier (voltage input noise: $0.25\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$) which was also connected to the probe. The protection voltage for the pre-amplifier using the low impedance transceiver was ~10 times smaller than that for the pre-amplifier using a 50 Ω conventional transceiver, which is suitable for NQR remote sensing applications.

1. Introduction

Nuclear quadrupole resonance (NQR) is similar to nuclear magnetic resonance (NMR) in which energy gaps are generated by an external static magnetic field. Nuclei with a spin of one or more have electric quadrupole moments, and therefore their energies are split by the intrinsic electric field gradient, which is highly specific to the substance. Therefore, an additional external static field is not necessary to generate the energy gaps for NQR. One of the promising applications using nitorgen-14 nuclear quadrupole resonance (NQR) is non-invasive detection such as explosive substances [1–7], illicit drugs [8–11] and counterfeit medicines [12–15]. Especially in Japan, the non-invasive detection of methamphetamine hydrochloride to prevent from smuggling is expected by Japan Customs since it has occupied 80% of all detected illicit drugs in each year. The NQR frequencies from methamphetamine hydrochloride were recently confirmed at 1.217 MHz and 0.654 MHz [11], which is in the frequency range (0.5–5 MHz) for ^{14}N NQR. The phase memory time T_2^* (~0.7 ms for 1.217 MHz) is relatively short in this frequency range so that shortening dead time of the receiver is important [11].

However, the detection hardware consisting of a commercial NQR/NMR console, a power amplifier and a pre-amplifier becomes expensive for such applications. To lower the cost of the construction, a low impedance transceiver circuit was newly designed and tested using a mobile NQR/NMR console in this work. So far a low impedance series resonant circuit using a switching amplifier such as class-D/E amplifier has been used for generation of an RF magnetic field [16–19]. Some of works have been mentioned about the high impedance reception using a high impedance amplifier [18,19]. In this case, a protection circuit for the high impedance amplifier becomes an issue for NQR remote sensing applications where a high voltage over several kV is generating across an excitation/detection coil. To lower the protection voltage, low impedance NMR/NQR reception (0.5–5 MHz) combined with the low impedance NMR/NQR transmission (0.5–5 MHz) was proposed. In addition, to lower the dead time of the reception a class-D amplifier with small modifications to change the internal resistance of the amplifier at the falling edge of the transmission was developed.

For demonstration of the low impedance transmission and reception, we measured ^{14}N NQR from imidazole whose NQR frequency (1.368 MHz at 300 K) is similar to that from methamphetamine hydrochloride.

2. Methods

2.1. NQR spectrometer

All NQR experiments were performed on a homemade FPGA (field-programmable gate array) based NQR/NMR console with

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a proposed transceiver circuit. The console was constructed mainly from an FPGA developing board (DE0-NANO, Terasic Technologies Inc.), an FT2232H Mini-Module (Future Technology Devices International Ltd), a receiver amplifier made from an operational amplifier IC (LT6201, Linear Technology Corp.), an analog digital (A/D) converter (LTC2356-14) and a band pass filter (LT1568). The spectrometer was controlled using a laptop PC (MacBook Air, Apple Inc.) via USB connection. The FPGA hardware program was developed with Quartus II v10 (Altera Corp.). The NQR control software was written by LabVIEW 2012 (National Instruments Corp.) and Xcode 4.2.1 (Apple Inc.).

An output signal from a pre-amplifier was fed into the receiver amplifier and then filtered with the band pass filter before digitizing the signal with the A/D converter. The output of the serial signal from the A/D converter connected to the general purpose input/output (GPIO) in the FPGA board. The sampling frequency was selected as NQR frequency $\times 4$ divided by odd number for digital quadrature detection using band pass sampling [20–23]. Two PWM signals were out from the GPIO in the FPGA board to drive a class-D amplifier. The phase of the PWM1 signal was 180° different from that of the PWM2. A gate signal to switch the Q factor of the receiver circuit between the low and high Q state was also out from the GPIO in the FPGA board.

2.2. Transmit–receive switch circuit

One of the advantages for using a series resonant circuit as shown in Fig. 1(a) is that a large current from a low voltage source at the resonant frequency is possible since the resistance of the circuit can be less than a few Ω mainly owing to an inductor coil and leads between the electronic parts. Therefore, a large magnetic field from the coil is generated with a low voltage power amplifier for the transmission. If the resistance of the circuit becomes smaller, the quality (Q) factor of the circuit increases and then voltage amplification becomes larger. On the other hand, the reception of NQR/NMR signal using the series resonant circuit has a disadvantage that a general 50 Ω low noise amplifier (LNA) is not suitable since the loaded Q factor of the resonant circuit becomes too small. Generally, a parallel capacitor Cp to the coil is inserted for the impedance matching as shown in Fig. 1(b). In this case, the Q factor of the resonant circuit becomes half of the unloaded Q factor. To prevent the decrease of the Q factor, a transimpedance amplifier (TIA) with low input impedance was proposed in this work. To optimize the noise performance of the TIA inserted in the resonant circuit, a parallel capacitor Cp to the coil was inserted as shown in Fig. 1(b).

To combine the transmitter and receiver circuits as simple as possible, a transmit–receive switch circuit as shown in Fig. 1 (c) was newly designed. An NQR probe consisted of fixed capacitors (C Series: high voltage, TDK Corp.), a variable capacitor (NMTM120C, Voltronics Corp.) and a solenoid coil (ϕ 44 mm $\times$ 70 mm, L=29.1 μH, R=1.53 Ω at 1.37 MHz). The precise resonant frequency for the transmission and reception was tuned with changing the value of Cs2″, where Cs2″ consisted of fixed capacitors and a variable capacitor. During the transmission, this circuit is simplified to be a series resonant circuit with the high quality (Q) factor as shown in Fig. 1(a) since diodes of D1–D4 (SBYV27-200, Vishay General Semiconductor) become low impedance with the applied voltage more than the forward voltage drop of the diode, and T/R switch ICs of TR1, TR2 (MD0100, Supertex Inc.) and TR3 (MD0105) become high impedance with the applied voltage exceeding a value of ± 2.0 V. In contrast, during the reception, the circuit becomes equivalent to a resonant circuit consisting of series and parallel capacitors, and the inductor coil as shown in Fig. 1(b) since diodes of D1–D4 become high impedance and T/R switch ICs of TR1, TR2 and TR3 become low impedance. The on resistance of MD0100 is typically 15 Ω, while that of MD0105 can be ~3 Ω when the four channels in the IC package are connected together in parallel. In addition, the impedance matching to 50 Ω was also possible even if a general 50 Ω pre-amplifier was used in the receiver circuit.

The maximum protection voltage for the pre-amplifier was supposed to be ± 110 V due to the specification of the T/R switch IC (MD0100). A bipolar transistor Q1 (FZT853, Diodes Inc.) was used to change the Q factor of the receiver circuit by switching the resistance of the receiver circuit from ~25 Ω to ~1.6 Ω that was controlled by the gate signal generated from the NQR/NMR console. A capacitor C1 and a resistor R1 worked as a low pass filter to suppress the quick response of this switch action intending to minimize a ringing signal caused by switching of the transistor Q1.

2.3. Receiver pre-amplifier

A resistive feedback transimpedance amplifier (TIA) with low input impedance was adopted using a single low-noise and high-speed operational amplifier (op-amp) (CLC1001, CADEKA Microcircuits LLC. or LT6200-10, Linear Technology Corp.). The configuration

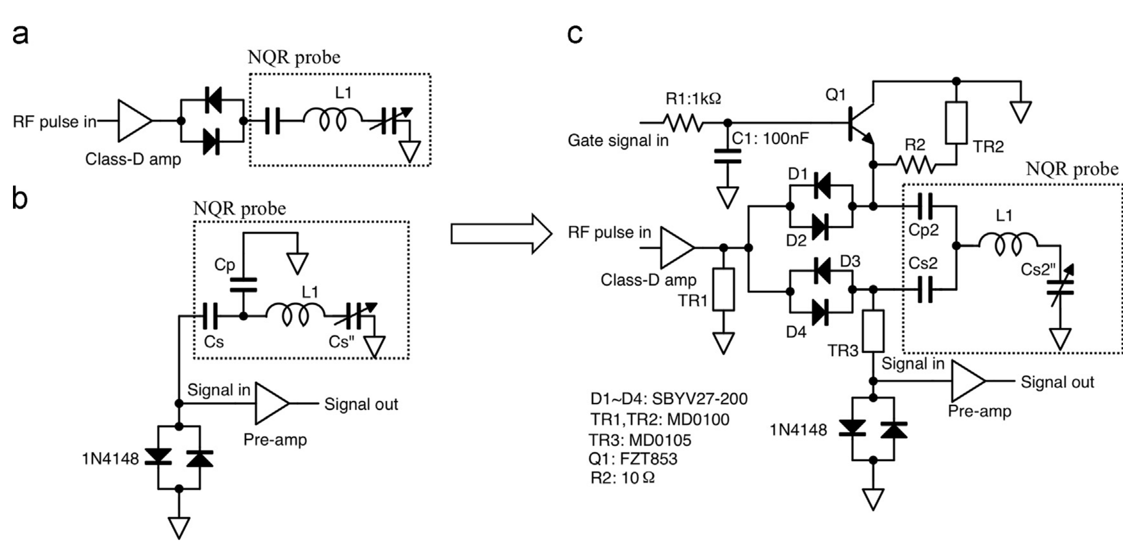

Fig. 1. A series resonant circuit for the transmission (a) and a resonant circuit with series and parallel capacitors to a inductor coil for the reception (b). A proposed transmit–receive switch circuit combined with a resonant circuit (c).

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