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An ultra-broadband low-frequency magnetic resonance system

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ABSTRACT

MR probes commonly employ resonant circuits for efficient RF transmission and low-noise reception. These circuits are narrow-band analog devices that are inflexible for broadband and multi-frequency operation at low Larmor frequencies. We have addressed this issue by developing an ultra-broadband MR probe that operates in the 0.1–3 MHz frequency range without using conventional resonant circuits for either transmission or reception. This "non-resonant" approach significantly simplifies the probe circuit and allows robust operation without probe tuning while retaining efficient power transmission and low-noise reception. We also demonstrate the utility of the technique through a variety of NMR and NQR experiments in this frequency range.

1. Introduction

Magnetic resonance (MR) probes typically use resonant circuits to achieve efficient RF power transmission and low-noise reception around the Larmor frequency $\omega_0 = \gamma B_0$ [1]. These circuits consist of the sample coil (inductance L) that both generates B_1 fields and detects MR signals, and a passive tuning and impedance-matching network. In a single-frequency probe, this network typically consists of a single tuning capacitor (capacitance C) in parallel with the coil, and a second "matching" capacitor in series with it. Such a network acts as an analog filter tuned to a resonance frequency of $\omega_c = 1/\sqrt{LC}$ that only allows efficient power transmission and low-noise reception over a bandwidth of approximately $2\omega_c/Q$. Here Q, the quality factor of the network, is often dominated by that of the coil, i.e. $Q \approx Q_L = \omega_c L/R$ where R is its effective series resistance. Quality factors of 100 or higher are common for non-conducting samples, which makes the operating bandwidth of the probe much smaller than ω_0. Multi-frequency MR probes can be built by combining several resonant circuits within the tuning network, but are complex, expensive, and require frequent tuning. Such multi-frequency probes are particularly challenging at low Larmor frequencies where the probe bandwidth ω_0/Q can become comparable or smaller than the nutation frequency $\omega_1 = \gamma B_1$.

This paper describes a broadband or non-resonant (NR) front-end system for MR experiments at frequencies below 3 MHz that addresses these issues by not using resonant circuits for excitation or reception [2,3]. A broad range of field applications are promising at such low frequencies, such as real-time process monitoring (e.g. food [4]), geological prospecting (e.g. well-logging for petroleum and mining [5,6]), and detection of explosives and other illicit materials using nuclear quadrupole resonance (NQR) [7,8]. Our system uses conventional RF pulses to manipulate the spins, unlike non-resonant methods based on reversing the direction of the static magnetic field [9]. However, unlike in a tuned probe, our transmitter directly controls the RF voltage across the coil, which makes the spin excitation insensitive to changes in coil and sample losses. In addition, our receiver also directly senses the MR voltage induced in the coil, which makes signal reception also insensitive to these losses (which change the coil Q). Similar benefits can be obtained through Cartesian feedback techniques [10], but these are difficult to implement in ultra-broadband systems.

Our approach is fundamentally different from previously reported broadband designs using delay lines or transmission lines [11–14]. Such probes are considerably less sensitive detectors than simple coil geometries, such as solenoids. By contrast, we use a standard, highly sensitive solenoid coil as our detector. The broadband nature of our electronics allows rapid switching of the operating frequency for multi-frequency and multi-nuclear MR experiments without tuning. The final detection bandwidth, which is usually small to maximize the signal-to-noise ratio (SNR), is easily adjustable since it can be set digitally during later signal processing. With this broadband front-end, we have therefore developed a digitally-defined MR system that is conceptually similar to modern RF systems found in mobile devices, which also combine broadband analog front-ends with digital hardware and

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software for narrow-band channel selection. We now describe the key features of our NR design and demonstrate its operation in several multi-frequency experiments. This paper focuses on applications in the 0.1–3 MHz frequency range with moderately-sized sample coils, but it is possible to extend the technique to higher frequencies if smaller coils are used.

2. Non-resonant system

A simplified block diagram of our NR system is shown in Fig. 1. The key features include a single un-tuned transmit and receive coil containing the sample, a switching transmitter using a H-bridge circuit, a transformer-based low-noise, broadband preamplifier, and a switch-based broadband duplexer with isolated driver. A commercial NMR console (Kea 2, Magritek, NZ) is used to program pulse sequences, synthesize low-power RF signals, digitize the receiver output, and perform further signal processing. The system is capable of generating two channels of RF pulses for double resonance experiments.

2.1. Transmitter

Our basic non-resonant transmitter design consists of a set of four MOSFET switches (denoted by A, B, C, and D) arranged in a circuit known as an H-bridge or full bridge, as shown in Fig. 1 [2]. The switches are controlled by two non-overlapping digital signals denoted as ϕ_1 and ϕ_2, as shown in Fig. 2. These signals are created by comparing the low-power sinusoidal waveforms (of amplitude V_{in}) that are generated by the Kea console with two reference voltages V_+ and $V_- = -V_+$. They alternately drive the two sets of switches, AD and BC respectively, such that the high-voltage source V_{BB} is connected with alternating polarity across the coil to create an oscillatory coil current. A load resistor R_1 can be used in series with V_{BB} in order to limit the current into the MOSFETs.

The *duty cycle* of ϕ_1 and ϕ_2 is defined as the fraction of time these waveforms are active (at a logical value of 1) during an RF pulse. It is given by

$$D = \frac{1}{2} - \frac{\sin^{-1}(V_\pm/V_{in})}{\pi} \qquad (1)$$

Any power MOSFET is also associated with a parallel *body diode* that is intrinsic to the structure of the device. The combined device acts as an active switch (controlled by the gate voltage) for forward

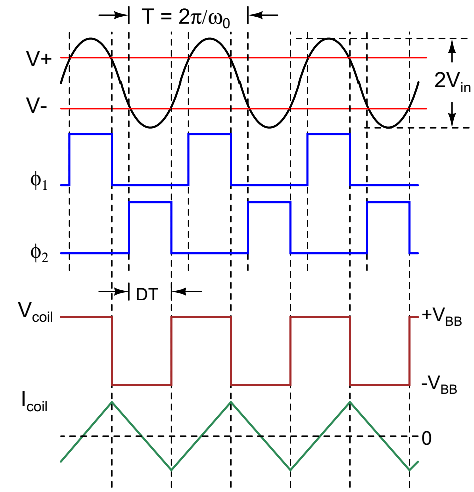

Fig. 2. Important waveforms for the non-resonant transmitter.

currents, which flow from the drain terminal to the source terminal through the MOSFET. It also acts as a passive switch (controlled by the drain-source voltage) for reverse currents, which flow from the source terminal to the drain terminal through the diode.

The transmitter circuit can operate in two distinct modes. The continuous conduction mode (CCM) is shown in Fig. 2. It occurs when $D \geqslant D_{crit}$, where D_{crit} is known as the critical duty cycle. The discontinuous conduction mode (DCM) occurs when $D < D_{crit}$, and is characterized by a period when the current in the coil is zero.

Fig. 3 shows the four possible states of conduction of the H-bridge circuit (labeled 1–4). The key to understanding these states is to remember that the coil current cannot change suddenly, i.e., must remain continuous. In state 1 current is being carried by two of the body diodes. This state continues till the current reverses direction and the diodes switch off. The two MOS switches controlled by ϕ_1 then start carrying the coil current, resulting in state 2. Once phase ϕ_1 turns off the coil current continues to flow through the two remaining body diodes (state 3) until it reverses direction. At this point it begins to flow through the two MOS switches controlled by phase ϕ_2 (state 4). Eventually the ϕ_2 signal turns off, the circuit returns to state 1 and the cycle continues.

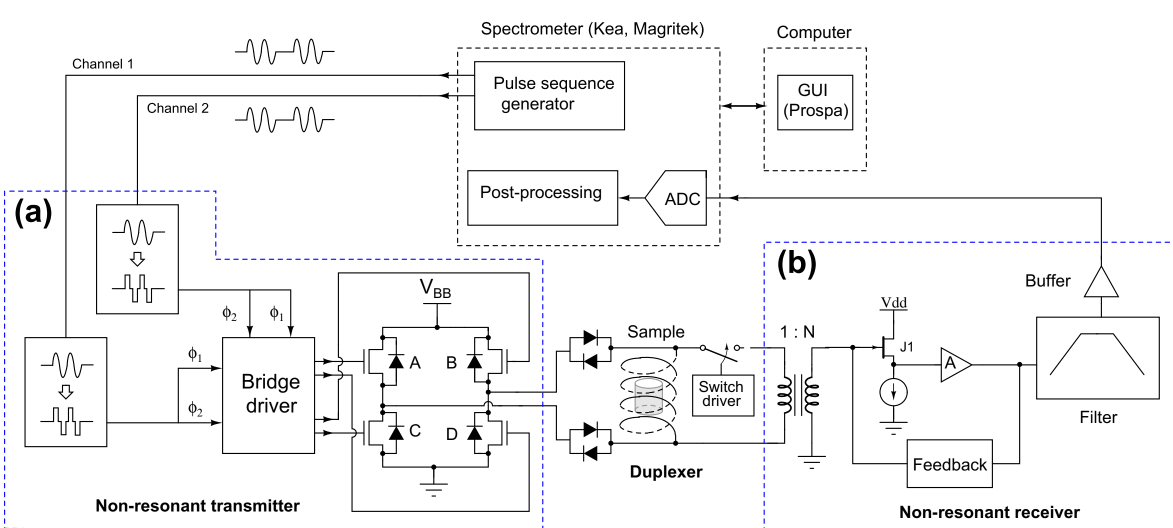

Fig. 1. Block diagram of the non-resonant MR system. (a) Transmitter block: the RF pulses are created by the two signals (ϕ_1 and ϕ_2) that control a H-bridge circuit. (b) Receiver block: the simplified front-end circuit uses a broadband $1:n$ step-up transformer.