Design and Experimental Implementation of a Low Frequency Pulsed Magnetic Field Generator

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Pulsed magnetic field generation is a critical aspect of all nuclear magnetic resonance (NMR) experiments. In this paper, a novel design for a low field, low frequency (less than 5 MHz), pulsed magnetic field generation circuit suited for unilateral NMR applications is presented. A pulsed sinusoidal current is generated at an inductive load connected to an FET-based switch. The inductive load resonates at a frequency of approximately 2 MHz, which is also the precession frequency of ^1H protons in an external magnetic flux density of 500 G. The designed circuit can be tuned to operate at resonant frequencies of other chemical species as well. In this paper, the design parameters and operation of the prototype pulsed field generator will be discussed.

Index Terms—**Electromagnetic delay, high speed switching, nuclear magnetic resonance (NMR), pulsed sinusoid.**

I. INTRODUCTION

PULSED magnetic fields find wide use in communication systems [1], optical switching [2], Q-switched pulsed lasers [3], [4], biological applications [5], [6], and medical applications, such as transcranial magnetic stimulation [7]. Nuclear magnetic resonance (NMR) is one such technique where the presence of particular nuclear species is detected by applying pulsed magnetic fields in the presence of static fields. The technique is popular in biological applications, and in particular, it is widely used for imaging human tissue [8].

In NMR, the detection process relies on the relaxation of nuclear magnetic moments in an externally applied magnetic field [9]. Generally, a uniform static magnetic field is applied to pre-align the magnetic moments in a particular orientation. Most of the magnetic moments tend to align in the lower energy orientation, while some will align in the higher energy orientation. At the same time, the moments are constantly precessing along the external magnetic field direction. This is known as Larmor precession and can also be induced by application of an external radio frequency (RF) pulse. The RF pulse causes temporary reorientation of the magnetic moments. Once the pulse is removed, the moments relax back to their original orientations. Different nuclei are thus identified based on the variable relaxation times measured using pickup coils.

In every NMR experiment, a transition or a spin flip between the energy states is initiated via application of a pulsed field. The energy required for such a transition is represented by

$$E = h\nu; \quad \nu = \frac{\gamma B_o}{2\pi}. \tag{1}$$

Here, h is Planck's constant. As expressed in (1), the extent to which one energy state is favored over the other is greatly influenced by the external dc magnetic flux density B_o and the strength of the small nuclear magnet (i.e., proportional to the gyromagnetic ratio, γ).

After the excitation (RF) pulse is removed, the nuclei will return to their thermodynamically stable states. The energy absorbed during the transition from the lower energy state to the higher energy state is released and the process is termed as relaxation. Variations in relaxation time allow users to distinguish between different nuclear species. Generally, ^1H nuclei are detected in medical imaging applications and images of the human tissue are created. Thus NMR measurements are a vital part of medical imaging and find wide applications in most health care centers.

In this paper, an approach to achieving a low frequency pulsed sinusoidal magnetic field is presented. The pulsed sinusoidal is applied to an inductive load repetitively. The pulsewidth is selected to obtain required reorientation of the magnetic moments [10]. The designed pulse generator would be used to study proton ^1H precession. Thus, a pulsewidth of 10 μs is selected (typical pulsewidths are between 1 and 50 μs). In this work, a description of the design steps, simulation method, and experimental operation of the pulsed magnetic field generator will be presented.

II. PROPOSED DESIGN

The design of the pulsed magnetic field generator incorporates three integral aspects. They are:

1) pulsed sinusoidal signal at Larmor precession frequency;
2) rapid switching of inductive load at Larmor precession frequency;
3) adequate pulsewidth to achieve precession.

To obtain a pulsed sinusoidal input signal, two square inputs are multiplied and passed through an electromagnetic delay line. The delay line generates a bandlimited pseudo-raised cosine pulse. This pulse is then used to drive the gate of a FET-based switch that is connected to an inductive load. Often a capacitor may be connected in series/shunt with the load to achieve sustained oscillations at the required Larmor frequency. In most cases, this may be avoided to reduce ringing or other secondary oscillations. To attain the desired pulsewidth, the input pulse parameters and delay line elements are tuned to the required frequency of operation.

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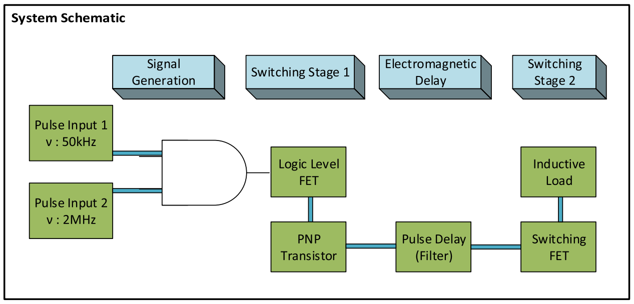

Fig. 1. System block diagram. The pulse generation sequence can be continuously repeated. The four system blocks are represented at the top.

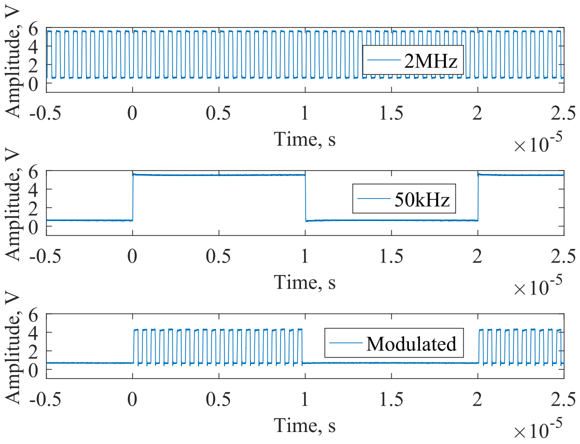

Fig. 2. Pulsed sinusoidal generated at the output of the AND gate. Input pulse frequencies were selected to be 50 kHz and 2 MHz.

A systems level schematic of this circuit as shown in Fig. 1 highlights the different stages in the design. A lower frequency of operation is selected since the designed field generator would be used for unilateral NMR systems that generally operate at low flux densities (about 1000 G). The magnitude of the magnetic flux density generated due to a solenoid shaped load can be estimated by

$$B = \mu N I. \tag{2}$$

Here, μ is the relative permeability, N is the number of turns in the coil and I is the current flowing through the coil. An alternative method is also described in [11]. It is important to note that ^1H has a gyromagnetic ratio of 42.1 MHz/T, and thus, for an external flux density of 500 G, the precession frequency would approximately be equal to 2.12 MHz.

III. DESIGN AND PULSE PARAMETERS

The designed circuit was simulated using Advanced Design Systems and PSpice. The simulated design will be described according to the different stages listed in Fig. 1.

For the signal generation stage, two different pulse generators were used to generate square pulses. The frequencies were selected to achieve a total repetition pulsewidth of 10 μs and a modulation frequency between 2 and 5 MHz. The two pulse generators were synchronized using an external clock signal. These square pulses were then applied as inputs to an AND gate and the outputs were applied to the current amplification stage of the system. Fig. 2 shows a representation of the pulse outputs measured at the input and output of the AND gate.

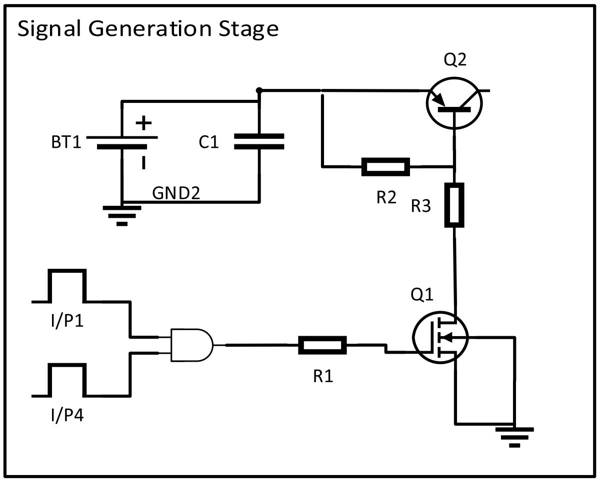

Fig. 3. Input buffer and first switching stage. A logic level FET is driven with the pulsed sinusoidal. The p-n-p transistor is driven by a 3 V source.

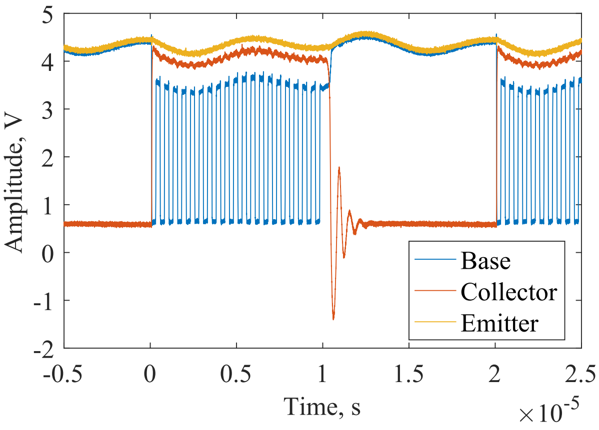

Fig. 4. Voltage waveforms at different terminals of the p-n-p transistor. Slight ringing is observed at the collector terminal.

The generated pulsed sinusoidal is then applied to the gate terminal of a logic level FET. The FET acts as a buffer between the signal generation and the first switching stage. The FET has a low ON resistance and gate threshold voltage and can thus respond quickly to fast switching signals. The drain terminal of the FET is connected to a p-n-p transistor as seen in Fig. 3. Under large signal conditions, the transistor will act as a switch. The transistor can also act like a current amplifier based on the $(R2/R3)$ ratio, emitter voltage, and the user's design requirements. The output from this stage (see Fig. 4) is then applied to the delay line stage.

The output from the first switching stage is fed to an electromagnetic delay line (see Fig. 5). The delay line was initially designed to operate at a frequency of 2 MHz [12] as that is the expected frequency for hydrogen precession in an externally applied flux density of 500 G. A pulse repetition rate of 20 μs was selected. The delay line acts as a raised cosine pulse generator. The rise time and the fall time of the pulses can be adjusted by tuning the inductive $(L1)$ and capacitive $(C2, C5)$ elements, respectively. The impedance of the delay line was scaled to take into consideration the input capacitance of the switching FET. The scaling factor, K, and the other pulse parameters are summarized in Table I.

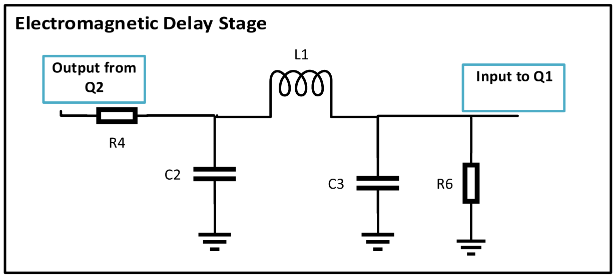

Fig. 5. Electromagnetic pulse delay line.

TABLE I
ELECTROMAGNETIC DELAY LINE PARAMETERS DESIGNED FOR A FREQUENCY OF 2 MHz

Parameter	50 Ohm Model	Scaled Model
K = $\frac{C_{fetinput}}{C_{50OhmModel}}$	1	3.26
R = $\frac{1}{2}\sqrt{\frac{L}{C}}$	50	15.4 Ω
L = $4R^2C$	7.95 μH	2.5 μH
C = $\frac{1}{2R\omega}$	795 pF	2592 pF

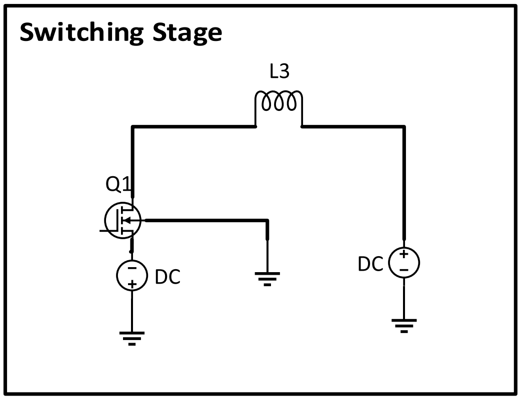

Fig. 6. Schematic for switching stage and inductive load. A resonant load is used at the drain of the FET.

The input pulse parameters were adjusted to obtain a pulse with a pulsewidth of 10 μs that is required for achieving sufficient reorientation (180 degrees) for the ^1H nuclei.

The modulated pulse is then applied to the gate of a fast switching FET (see Fig. 6). The FET can sustain high drain currents (up to 100 A) and high switching speeds (approximately 30 ns). Initial designs had a resonant RLC at the load of the FET. This load was assumed to sustain oscillating magnetic field that would be generated by the inductive coil. A feedback loop was also provided for quick dissipation of the pulse during the OFF-time of the signal. After initial measurements, the resonant load was replaced by a non-resonant inductive load to minimize the high oscillations introduced in the resonant configuration.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A prototype circuit (see Fig. 7) was designed to generate pulsed sinusoidal signals. The circuit can generate variable oscillating magnetic fields that is required for pulsed NMR applications. The signal generation stage can also be modified for continuous NMR applications.

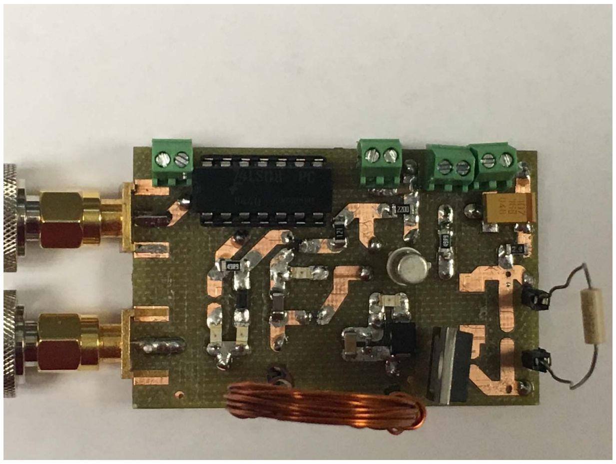

Fig. 7. Designed pulsed field generator circuit prototype.

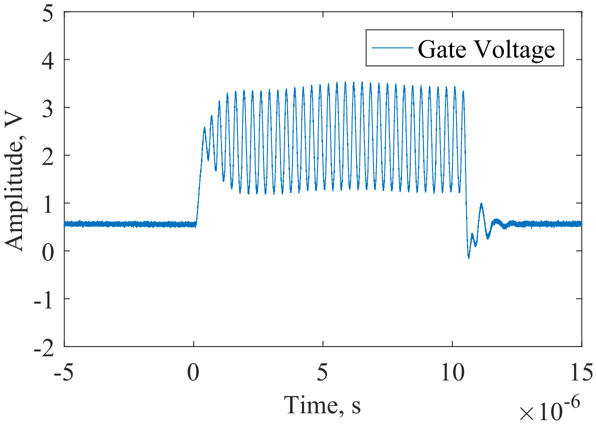

Fig. 8. Voltage measured at the end of the pulsed delay line. This is applied to the gate of the switching FET. The slight dc offset is necessary for activation of the switching FET.

The voltage at the gate terminal (see Fig. 8) should be sufficient to activate the switching FET. A negative offset was applied at the source terminal of the switching FET such that a conduction channel could form between the drain and source once appropriate gate voltage was applied.

A lower load inductance would allow for faster switching. The inductance value is dependent on the magnetic field needed. For unilateral NMR application, a magnetic flux density of 500–1000 G should be sufficient to acquire the required Larmor precession since the static magnetic flux density used for the pulsed NMR application is in this range.

In the present configuration, a peak pulsed voltage of about 9 V (see Fig. 9) can be obtained at the drain of the switching FET. It is necessary to note that a wider pulsewidth would lead to generation of a higher magnetic field since there would be more current flowing through the inductive load.

A representation of the experimentally measured signal levels at the inductive load in the designed circuit is in Fig. 9. Experimentally, the peak voltage is 9 V and correspondingly the peak current is recorded as 4.5 A. The corresponding magnetic field may be estimated using (2). In this prototype, a fixed inductor is used and a pulsating magnetic field is generated.

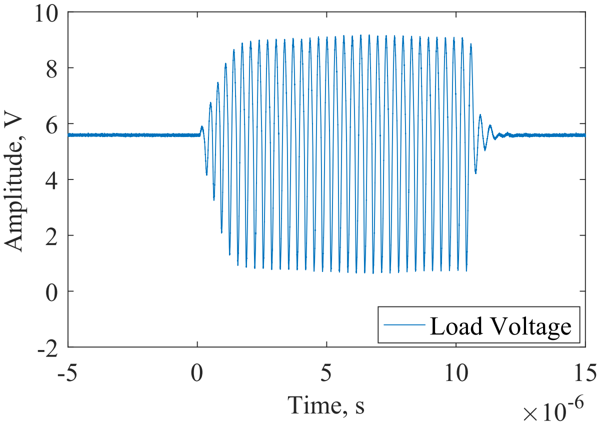

Fig. 9. Signal measured at the load of the switching FET. A small series resistance of 2 Ω was connected to estimate the peak current, and the applied drain voltage was 5 V.

Experimental measurements reveal several different factors for consideration. First, the two input pulses need to be synchronized. This was achieved by triggering both the sources with the same external clock pulse. Second, the source terminal of the switching FET needs to be sufficiently reverse biased to achieve activation of the gate terminal. Finally, the resonant configuration of the inductive load and the inductor used within the delay line are both sources of multiple oscillations or ringing. These need to be designed carefully based on the required application. In particular, the operational bandwidth, the resonant frequency of the load, and the fast discharge of the energy stored in the inductive load are design parameters that need to be carefully analyzed.

The pulsed field circuit was originally designed to operate at a resonant frequency of 2 MHz such that it could be used in an external flux density of 500 G. However, the actual impedance parameters used in the circuit vary slightly and were tuned. These impedance variations in the pulsed delay line have led to a resonant frequency of 1.8 MHz, which is close to the required ^1H precession frequency in an external magnetic flux density of 500 G. The energy stored in the inductive load was also found to produce ringing when connected in a resonant configuration. Thus, the resonant configuration was modified to a non-resonant load configuration.

V. CONCLUSION

In summary, a pulsed magnetic field generator was designed, simulated, and experimentally verified. Simulation results show that a pulsed sinusoidal with a resonant frequency of up to 5 MHz can be easily achieved by tuning the characteristics of the pulsed delay line. The prototype design and measurement results are presented in this paper. The parameters of the delay line can be tuned for achieving the required rise and fall time for each pulse. Tuning and optimization are needed to obtain pure sinusoidal pulses. The utility and portability of this designed system will find wide applications in small-scale magnetic resonance imaging systems, unilateral NMR systems, and different switching systems.

VI. FUTURE WORK

The design of the prototype pulsed field generator reveals several avenues of improvement. In particular, design of the inductive load needs to be improved to accommodate higher currents such that higher pulsed magnetic fields may be generated. At the same time, the generated magnetic field should have a discharge path when the pulse is switched OFF and possible ringing at the load needs to be controlled. Another interesting aspect would be the design of the input pulsed sinusoidal signal. A combination of these parameters would eventually lead to design of a user friendly and stable multi-frequency pulsed magnetic field generator.

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