Transformer-coupled NMR probe

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A R T I C L E   I N F O

Article history:
Received 26 October 2011
Revised 18 January 2012
Available online 1 February 2012

Keywords:
Probe
Matching
Inductive coupling
Transformer

A B S T R A C T

In this study, we propose an NMR probe circuit that uses a transformer with a ferromagnetic core for impedance matching. The ferromagnetic core provides a strong but confined coupling that result in efficient energy transfer between the sample coil and NMR spectrometer, while not disturbing the $B_1$ field generated by the sample coil. We built a transformer-coupled NMR probe and found that it offers comparable performance (loss <1 dB) to a conventional capacitor-coupled circuit. Our probe operates over a wide frequency range (500 kHz–5 MHz in this example) without the need for matching adjustments. Such probes could be useful for low-field mobile NMR applications of multi-frequency operation, such as imaging, relaxation, and diffusion measurements, as well as NQR.

1. Introduction

Magnetic fields with static gradients can be used for investigating relaxation, diffusion, flow, and spatial properties of materials by changing the NMR operating frequency. Such field configurations may be applied in mobile NMR devices for non-destructive inspections [1,2, and references therein]. To cover a wide frequency range with a tuned probe circuit, some mechanisms (e.g. mechanical or electronic) are required to change the component values that determine the circuit's resonant frequency. However, in a circuit that uses an impedance divider (e.g. capacitive coupling), one of the circuit elements affects both tuning and matching [3]. Therefore, tuning always requires the adjustment of two variable components. This complicates the tuning operation, especially when dedicated instruments (e.g. vector impedance meters) are not available.

Inductive coupling is an alternative method of impedance matching. When appropriately configured, it decouples the circuit's tuning and matching, hence simplifies the tuning operations [3–6]. This scheme has been known for many years [6, and references therein], but recent applications include microfluidic imaging [7], simultaneous imaging [8], and magic angle spinning [9,10]. One possible difficulty is the design of a coupling coil that does not distort the oscillating magnetic field $B_1$. As the sample coil itself comprises a coupling circuit, its $B_1$ field may be perturbed by the current carried by a coupled coil. This effect may be noticeable, for example, when the matching coil is (quasi) co-planar with a surface coil [6] or when the resistance of the sample coil exceeds a fraction of the matching impedance (i.e. in low-Q condition). Although the former effect can be minimized by pulling away the matching coil [6], such topologies might be difficult to implement when there are physical, electrical, and environmental constraints, such as in mobile NMR devices.

In this study, we propose a transformer-coupled circuit that uses a transformer with a ferromagnetic core for impedance transformation. The ferromagnetic core provides two benefits. Firstly, magnetic fluxes associated with the inductive coupling are largely confined within the core, and do not disturb the $B_1$ field generated by the sample coil. Secondly, the ferromagnetic core provides strong mutual coupling, thus resulting in maximally efficient energy transfer between the sample coil and an NMR spectrometer. This strong (ideally unity) coupling cancels out the reactance of the transformer's windings, yielding the independence of tuning and matching over a wide frequency range. Therefore, unlike the mutually inductive coupling circuit, where the matching coil may be tuned with an additional capacitor [Fig. 1b in Ref. 6], the transformer-coupled circuit has only one tuning capacitor to be adjusted in moving from one frequency to another.

In the previous usage of a transformer [see, for example, 11,12], it was located outside the tank circuit (i.e. in front of a preamp), and a $\pi$-cable of certain impedance was used as a part of the impedance transformation circuit. Such a circuit is frequency dependent, thus it requires additional mechanism to switch the operating frequency. Furthermore, if that is replaced by a $\pi$-circuit composed of lumped elements for low frequency operations, it would be much larger than a transformer itself. We instead used the transformer as a part of the resonant circuit to eliminate the need for a $\pi/4$ cable.

Use of the transformer may be difficult in high-field NMR due to the strong magnetic field and the losses associated with it. In mobile NMR devices, on the other hand, the magnetic field tends to be weak and intrinsically inhomogeneous, allowing the use of ferromagnetic cores. In addition, losses due to skin/proximity effects
in the windings and eddy currents in the core can be insignificant at low frequencies if the transformer is properly designed. Therefore, the use of transformer becomes a real possibility.

2. Transformer-coupled probe

2.1. Basic operation

Fig. 1a shows an example of transformer-coupled probe circuit. For simplicity, we assume a lossless transformer. The transformer’s primary winding is connected to a series-tuned sample coil, and the secondary winding is connected to an NMR spectrometer. When the coupling between the primary and secondary windings is large enough, relationships of the voltage, current, and impedance between two windings may be described in terms of the turns-ratio. For example, in transmission, the current flowing in the sample coil is obtained as

\[ I_p = \frac{N_s}{N_p} I_s \]

where \( N_p \) and \( N_s \) are the number of turns in the primary and secondary windings, respectively. Therefore, it is \( N_s/N_p \) times larger than the input current. In reception, the voltage across the secondary is

\[ V_S = \frac{N_s}{N_p} V_P \]

Therefore, both the NMR signal and noise are amplified \( N_s/N_p \) times. From Eqs. (1) and (2), the impedance looking into the secondary is

\[ Z_S = \left( \frac{V_S}{I_S} \right) = \left( \frac{N_s}{N_p} \right)^2 Z_P \]

In this way, by choosing an appropriate turns-ratio, a desired step-up or step-down voltage/current/impedance ratio can be realized.

2.2. Tuning and matching

For an ideal transformer, inductances of the primary and secondary windings are neutralized by each other. Then, from Eq. (3), the equivalent circuit will be as shown in Fig. 1b. The impedance looking into the circuit from the secondary port is

\[ Z_m = \left( \frac{N_s}{N_p} \right)^2 \left( R_c + j\omega L + \frac{1}{j\omega C_t} \right) \]

The matching and tuning conditions are then described as

\[ \left( \frac{N_s}{N_p} \right)^2 R_c = Z_0 \]

\[ j\omega L + \frac{1}{j\omega C_t} = 0 \]

where \( Z_0 \) is the characteristic impedance of the system, usually 50 \( \Omega \). It can be seen that the matching and tuning are independent of each other. This makes the tuning operation quite simple. However, the impedance ratio is determined by the transformer’s fixed turns-ratio \( N_s/N_p \). As a result, it can be difficult to obtain a perfect impedance matching. The effects of impedance mismatch on the signal-to-noise ratio will be discussed later.

2.3. Signal-to-noise

Every NMR probe employs some sort of impedance transformation to interface a tuned coil with a spectrometer, which usually has 50 \( \Omega \) input/output impedances. When the NMR coil and all the other experimental conditions are kept the same, the observed signal and noise levels are solely determined by the transformed impedance of the probe and the losses associated with the impedance transformation, assuming that the probe bandwidth remains constant during the impedance transformation.

Transformers tend to have larger losses than high-quality capacitors. However, when the transformer’s coupling coefficient is sufficiently high, losses due to the inductive coupling will be negligible. Losses due to the skin/proximity effects in the windings and eddy currents in the core can be made insignificant at low frequencies by choosing an appropriate winding method and core material. As a result, transformer’s insertion loss can be made small, too.

As already mentioned, it is difficult to achieve a perfect impedance matching by using a transformer with a fixed impedance ratio. If there is an impedance mismatch between a source and a load, some fraction of power is reflected and not delivered to the load. Denoting the load impedance by \( Z_L \), the reflection coefficient is given by

\[ \Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \]

The power delivered to the load is then given by \( 1 - |\Gamma|^2 \). It follows that [see, for example, Ref. 13,14], for a source of 50 \( \Omega \) output impedance, more than 90% of available power will be delivered to the load if its impedance ranges between 26 \( \Omega \) and 96 \( \Omega \). Therefore, as long as the loading condition does not vary very much from sample to sample, losses due to the impedance mismatching will not be significant.

3. Materials and methods

In order to demonstrate the performance of the transformer-coupled circuit, NMR signal was measured and compared with that of a capacitor-coupled circuit using the same coil. In addition, transformer characteristics during transmit and receive operations were investigated.
3.1. Probe

Fig. 1a shows the probe circuit with the transformer. The sample coil consists of 33 turns of AWG16 magnet wire wound around a Teflon form with variable pitch (~4 mm at the center and ~2 mm at the edge). The overall dimension was 55 mm ID and 100 mm long, resulted in the self inductance $L = 20 \mu H$ and $R = 2 \Omega$ at 2 MHz when the coil was accommodated in a tight shield box composed of an aluminum frame and copper cladding. A tuning capacitor $C_t$ was connected to the sample coil to form a series resonant circuit, and a transformer with 1:36 impedance ratio (T36-1+, Mini-Circuits, Brooklyn, NY) was used to transform the impedance. The probe impedance as seen through a 2 m length of 50 $\Omega$ coaxial cable was adjusted to 90 + j 0 $\Omega$ at 2 MHz. In order to avoid the saturation of the ferromagnetic core, the transformer was oriented in such a way that the static magnetic field penetrated perpendicularly into the center hole of the toroidal core.

Fig. 1c shows the probe circuit without the transformer. High-Q tuning and matching capacitors (100 E Series, American Technical Ceramics, Huntington Station, NY) were connected to the same sample coil as in the circuit in Fig. 1a, and the input impedance was adjusted to the same value (90 + j 0 $\Omega$). Therefore, the two circuits have the same impedance ratio, and should give the same signal and noise levels if there is no loss introduced by the transformer.

3.2. Transformer

When a transformer is used in an NMR probe circuit, there are several properties that should be considered for transmit and receive operations, such as the loss and power handling capabilities. Those properties were investigated by measurements and circuit simulations (see Appendix for more detail).

It was found that the loss depends on the termination impedance. When a resistor of a few ohms is connected to the primary winding, as in the series-tuned circuit shown in Fig. 1a, the loss is on the order of 1 dB. The loss is relatively constant up to +50 dBm peak pulse input; we did not observe any evidence of core saturation in this particular setup.

3.3. Experiment

NMR measurements were conducted in the fringe field of a 2 T superconducting magnet (Nalorac Cryogenics). The sensitivity of the two circuits (with and without the transformer) was compared with both circuits adjusted to the same impedance (90 + j 0 $\Omega$). In addition, the circuit without the transformer was used to investigate the effects of impedance mismatch; this circuit’s impedance was adjusted to 50 $\Omega$ (purely resistive), and its performance was compared with the transformer-coupled circuit, which had non-optimal impedance. The sample was a bottle of water doped with CuSO4 (OD = 49 mm, 50 mm long, $T_2 \sim 200$ ms). CPMG sequences with 20–100 $\mu s$ long refocusing pulses provided slices that were a few millimeters thick in the gradient field ($\sim 16$ G/cm). A compact NMR spectrometer (Kea, Magritek Limited, Wellington, New Zealand) with nominal 50 $\Omega$ input/output impedances was used for excitation and signal detection.

4. Results and discussion

4.1. Effect of the transformer

Because both circuits use the same coil and high-Q capacitors, this difference must be attributed to the transformer’s loss. This relationship remained approximately constant for refocusing pulses that were 40–100 $\mu s$ long. Therefore, we expect ~0.5 dB of SNR difference between two circuits, i.e. we have $\text{SNR} \propto B_s / \sqrt{P}$, where $B_s$ is fixed for a given pulse length and $P$ is the input power.

Fig. 2 shows the CPMG data obtained with 20 $\mu s$ long RF pulses. The transformer-coupled circuit gave 0.8 dB less SNR, in good agreement with the sensitivity estimate based on RF power. This
result is also consistent with the transformer’s characteristics as discussed in the previous section and in Appendix. When the pulse length was increased (while also decreasing the pulse amplitude), the signal intensity decreased for both circuits, since the signal bandwidth was limited by the excitation bandwidth in the gradient field. On the other hand, the noise level remained relatively constant since two circuits had the same impedance. The resulting SNR difference was 0.1–0.8 dB between the two circuits (Fig. 3). When compared with the capacitor-coupled probe matched to 50 Ω (purely resistive), the increase in required excitation power is ~1 dB, and the reduction of SNR is also ~1 dB for 20 μs long RF pulses.

We also anticipated ringing right after the RF pulses due to the ferromagnetic core. It was found that, for this particular transformer, the ringing lasts ~160 μs after each pulse. Therefore, echo time TE ~ 320 μs and greater provides NMR signal without a major distortion. Based on these experiments, we concluded that the transformer-coupled NMR probe offers comparable performance to a conventional capacitor-coupled circuit. However, the transformer’s ferromagnetic core causes noticeable ringing that may limit the shortest duration between the RF pulses and NMR signal acquisition (~160 μs for this particular transformer).

4.2. Tuning and matching orthogonality

One major advantage of the transformer-coupled circuit is the independence of tuning and matching; i.e. the ability to adjust the tuning without changing the matching condition. The tuning/matching orthogonality was evaluated by changing the tuning capacitor while leaving the transformer (hence the impedance ratio) fixed. The result is shown in Fig. 4. Due to the inter-winding capacitances, perfect orthogonality was not accomplished. However, change of the impedance over a decade of frequency (500 kHz–5 MHz) was only 46–98 Ω, significantly smaller than that expected for a capacitor-coupled circuit. The reduction in SNR caused by this impedance variation would not be significant as discussed in the previous section. Thus, considering the transformer’s frequency range (see Appendix), the transformer-coupled probe would perform well over this frequency range.

5. Conclusion

In this study, we proposed a transformer-coupled NMR probe that operates over a wide frequency range (500 kHz–5 MHz in our example) without the need for matching adjustment. The transformer-coupled probe can simplify the tuning operation when moving from one frequency to another. Such a circuit will be useful for mobile NMR applications in which the gradient field is used for 1D profiling or diffusion measurement with changing operating frequencies. Also, the proposed approach would be useful for other applications that require covering a wide frequency range, such as NQR. In such a case, availability of transformers with high turns-ratio may limit the use of this approach at very high frequency (> a few hundred MHz).

Construction of a transformer-coupled probe is straightforward. If the specifications (e.g., frequency range and power handling capability) permit, a compact, off-the-shelf component may be easily incorporated and would not spoil the device mobility. The loss caused by the transformer was found to be small (<1 dB) when an appropriate transformer and frequency range were chosen. However, the loss depends on the load impedance (in our case, coil’s resistance after appropriate tuning). If the load impedance is quite different from the optimal impedance for which the transformer is designed, the loss increases rapidly as shown in Fig. A2a in Appendix. It is possible, to some extent, to design a transformer for particular load impedance.

We observed ringing (~160 μs for this particular transformer) after each pulse. The ringing behavior depends on many issues. Transformer’s core material, among others, has a significant influence on it. Since it also affects the other parameters, such as the loss (hence noise) and magnetic permeability, careful investigation is required to find an optimal core material. The surrounding magnetic field also acts on the ringing behavior. In our lab experiment using a fringe field (B₀ ~ 500 G) of a large SC magnet, we observed an increase of ringing duration from 160 μs to 400 μs when the transformer was rotated 90° with regard to the B₀ direction. It will require experiments to find the optimal direction, as well as the other properties that affect the ringing behavior. If there is enough space around the transformer, a static magnetic shield surrounding the transformer may be a help. Furthermore, ringing noise may be reduced by using an A/D converter with a large dynamic range. The ringing noise is usually suppressed by phase cycling, which requires that the A/D converter is not saturated with the input signal. If the A/D converter has a large dynamic range, we can detect weak NMR signal while avoiding the saturation of A/D input with large ringing. By combining these measures, the authors believe that the ringing, hence TE, can be reduced further.

There was no measurable effect that could be attributed to the disturbance in the B₀ and B₁ distribution by virtue of the transformer’s ferromagnetic core, which was shown to work well in a modest static magnetic field (~500 G). Therefore such disturbances are assumed to be negligible. However, the severity of the impacts of ferromagnetic core depends on many factors, such as the magnet/core geometry, core permeability, and required field homogeneity. Having a distance of several core diameters between the core and the region of interest (where the field homogeneity is required) will reduce the effect of the ferromagnetic core significantly. Another possibility is to use a magnetic shield made of materials with high permeability. Such a shield also causes local field inhomogeneities, but it would be easier to design shim magnet(s), if necessary, when the transformer is enclosed in a magnetic shield of a simpler shape (e.g., cylinder or cube) than as it is in a toroidal shape.

Although the impedance ratio (and thus the matching condition) is fixed for a given transformer, the impact on SNR will not be significant as long as tuning is adjusted appropriately. However, when the coil’s resistance is very small (<1 Ω), impedance
mismatch will be pronounced as a transformer with high impedance ratio may not be available.

The transformer under test is designed for small-signal applications, and the smallest practical core (OD ~ 4 mm) is used in the interest of compactness and wide bandwidth. Power handling capability may be further extended by using a larger core at the expense of bandwidth.

Acknowledgments

Authors would like to thank Douglas D. Griffin for his invaluable comments and suggestions about transformer measurements. Discussions with Martin D. Hürlimann and Robert L. Kleinberg were also very helpful. We also thank the two anonymous reviewers for their constructive comments and suggestions.

Appendix A. Measurements of transformer properties

In this section, we describe the details of the measurements performed on the transformer used in this study (T36-1+, Mini-Circuits, Brooklyn, NY).

A.1. Coupling coefficient

The coupling coefficient $k$ affects the transformer’s energy transfer efficiency. In a transformer designed for RF applications, large mutual coupling is accomplished by using (1) a core of ferromagnetic material (e.g., powdered iron, ferrite) with higher permeability than air but low electrical conductivity (at low frequencies), and (2) the interwinding capacitances and wire inductances that form a transmission line (at high frequencies). The combination of magnetic coupling and transmission line propagation provides very small leakage inductances and a large operating bandwidth. If $Q$ of the windings is not too low (i.e., the losses within the transformer are not too high), $k$ can be obtained with [16]

$$k = \sqrt{1 - \frac{L_s}{L_m}} \quad (A1)$$

where $L_s$ is the leakage inductance measured with the other port shorted, and $L_m$ is the magnetizing inductance measured at each port with the other port opened. Our measurements yielded a consistent result of $k = 0.9998$ at both ports, indicating good coupling and effective power transfer between the two ports.

A.2. Frequency dependence of the transformer’s insertion loss

The transformer’s insertion loss was measured with a vector network analyzer (4395A, Agilent). Insertion loss may be defined as the ratio between the measured voltage across the output port and the voltage expected for an ideal transformer of the same impedance ratio, while considering the effects of termination impedance. To avoid reflection losses, two identical transformers were connected back to back (i.e., primary-to-primary or secondary-to-secondary), so that the stepped-up/down impedance is brought back to its original value if there are no losses in the impedance transformation. Measured $S_{21}$ data was then halved to obtain the insertion loss for a single transformer.

Our results are shown in Fig. A1. The transformer’s insertion loss largely depends on the frequency, as well as how it is connected. The best performance is obtained when the primary and secondary ports are connected to the terminating impedances for which the transformer is designed (50 Ω for the primary port in our case). This is because the transformer is wound using twisted wires that behave as transmission lines of certain characteristic impedance, and the required coupling occurs along the length of these lines as well as magnetically via the core.

The usable frequency range may be from several tens of kilohertz to 10 MHz for ideal conditions, but could be reduced when the load impedance deviates from the optimal value.

A.3. Load dependence of the transformer’s insertion loss

The transformer’s insertion loss was further investigated with changing the termination impedance. For this measurement, the secondary port (high-impedance side) was connected to a signal generator with 50 Ω output impedance, while the primary port was terminated with various resistors across which the voltage was measured. This setup is similar to the probe configuration shown in Fig. 1a. The result was verified by circuit simulations using EDA software (Genesys, Agilent), in which the measurement impedance/frequency can be chosen arbitrarily. The transformer’s $S$-parameter data was used as an input for the simulation.

Results are shown in Fig. A2a. For a load above 10 Ω, the loss is comparable with the value obtained with a VNA (Fig. A1). However, the loss increases when the load impedance is decreased further. When the load impedance is a few ohms, the loss is ~1 dB at 2 MHz, in good agreement with simulation. Fig. A2b shows the calculated insertion loss for a 2 Ω load. The loss increases quickly as frequency increases, resulting in a usable range (loss < 3 dB) that is limited to ~10 MHz.
A.4. Power dependence of the transformer’s insertion loss

The transformer’s power handling capability is crucial during transmission, because large input signals can saturate the ferromagnetic core, which will reduce the coupling coefficient, increase loss, and hence decrease the pulse amplitude and NMR signal. This property was measured in a similar setup as the measurement using a VNA (Fig. A1), except for the fact that the VNA was replaced with an NMR spectrometer to apply larger power. Two transformers were again connected back-to-back. One side was connected to the transmitter’s output port while the other side was connected to the receiver’s input port (with an appropriate amount of attenuation). Both ports have 50 Ω impedance. The receiver input was normalized with data measured without a transformer, so that any effects of transmitter/receiver non-linearity were removed. The pulse width, duration between adjacent pulses, and number of pulses were set to achieve similar conditions as the CPMG experiment described in Section 4.

Fig. A3 shows the insertion loss obtained from the transformer’s output-to-input ratio measured at several frequencies. The transformer showed good linearity under given conditions at all frequencies. The nominal loss is 0.8 dB at 2 MHz and increases at higher frequencies, as observed in the measurements using a VNA (Fig. A1).

References