Short Recovery Time NMR Probe

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Abstract: *A NMR probe for low frequency and short recovery time is presented in this work. The probe contains the tuning circuit, diode expanders and quarter wavelength networks to protect the receiver from both the amplifier noise and the coil ringing following the transmitter power pulse. It also possesses a coil damper which is activated by of non active components. The probe performance shows a recovery time of about of* $15\ \mu s$*, a sensitive* Q *factor reduction and an increase of the signal to noise ratio of about 68% during the reception at a work frequency of* $2\ MHz$*.*

Introduction

An important reason for the use of low frequency NMR pulsed spectrometers applied to petro-physics studies is that nuclear relaxation caused by fixed paramagnetic impurities, rising from the interaction between the nuclear spin and unpaired electron spins, is better detected al low fields.[1, 2] This feature is in conflict with several characteristic design of the spectrometer blocks, this is because the signal to noise ratio (ξ), the natural ringing time (τ) and the quality factor (Q) of the probe coil have a frequency dependence that comes into play. This work describes both the design criteria design and the advantages of a relatively simple probe with a non active damping circuit for the above mentioned NMR studies. The probe, in a conventional NMR spectrometer, is connected to the power amplifier and to the receiver, in a T shape configuration, in such a way to allow the rf power to go into the probe and the nuclear signal input only to the preamplifier. These three blocks of the spectrometer, the transmitter, the probe and the receiver, are usually interconnected in the well known Lowe $\lambda/4$ arrangement.[4] The probe must be tuned in such a way that during the rf pulse its impedance should be adjusted to the output impedance of the transmitter to ensure the maximum power transfer (a). Simultaneously, the receiver should be isolated from the probe to protect it from large rf voltages (b). During the reception, the probe should be isolated from the transmitter output to avoid noise and the weak nuclear signal should be driven to the receiver input. Also the probe should have a short ringing (c) time after the rf pulses, and the signal to noise ratio of the NMR signal (d) should be as high as possible. Additionally, the interconnections between the three blocks depend also of the frequency and its variations generate instruments artifacts that adversely affect both the signal to noise ration and the data collection (e). Features (c) and (d) are interrelated since τ depends of Q being

$$\tau = \frac{2Q}{\omega_0} \qquad (1)$$

with

$$Q = \frac{R}{\omega_0 L} \qquad (2)$$

where $\omega_0 = \gamma B_0$ is the Larmor frequency, γ and B_0 are the gyromagnetic ratio of the resonant nuclei and the fixed magnetic field respectively, and L and R are the inductance and the resistance of the coil probe. The signal to noise ratio is [1, 5]

$$\xi = \frac{S}{N} = \frac{1}{2} K\eta M_0 \sqrt{\frac{\mu_0 \omega_0 V_C}{F k_B T_C \Delta\nu} Q} \propto \sqrt{Q} \qquad (3)$$

where K is a numerical factor, $K\sim 1$ for solenoidal coils, η is the filling factor, M_0 is the nuclear magnetization, μ_0 is magnetic the permeability of the free space, V_C the volume of the coil, F the noise figure of the preamplifier, k_B the Boltzmann's constant, T_C the coil temperature, and $\Delta\nu$ the bandwidth (in units of Hertz) of the receiver; and the magnetization M_0 for protons is [1]

$$M_0 = \frac{1}{4} N\gamma^2\hbar^2 \frac{B_0}{k_B T_S} \qquad (4)$$

Typically a recovery time $T_R\sim 20\,\tau$ for the coil ring down to noise is expected to be the performance of a classical probe having a $Q\sim 50$ working at a resonance frequency of $2\,MHz$ an00d following a 500 V rf pulse. Many techniques for probe design are in the literature. At first glance two sets of probes may distinguished, namely those probes possessing active circuits either to drive the coil ring down spoiler or to polarize cross diodes and others [6, 7], although very efficient, without active circuits but very complicated to implement. [8, 9] Instead, in this work the proposed probe is conventional and relatively simple without any active driver which results of an easy implementation.

The probe

Figure 1 shows a block diagram of standard T shape configuration, point *A*, of the NMR spectrometer where the receiver is protected from the transmitter rf pulse by a $\lambda/4$ line followed by a pair or crossed diodes to ground.[4] The probe, the power amplifier output and the receiver input are all matched to the same effective impedance, 50Ω, coincident with the characteristic impedance of all the interconnecting coaxial cables. Although this configuration has proven to be very efficient, at low frequencies, $2\,MHz$, it is necessary to replace the $\lambda/4$ line by a $\lambda/4$ network because the length of the coaxial cables.

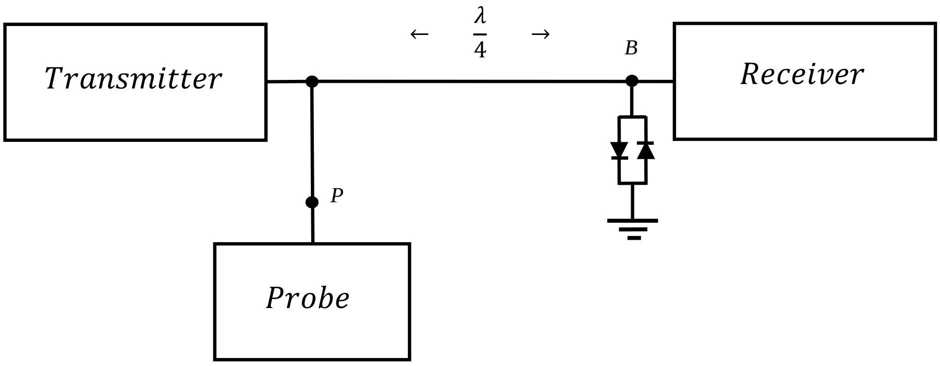

Figure 1. Block diagram of the NMR spectrometer.

Figure 2 shows a block diagram of the probe. It mainly consists of the tuning capacitors, C_1, C_2 and the sample coil L arranged in a parallel series connection, PSC (the convention is starting from the coil), it also possesses 2 diode expanders, DE1 and DE2, and three $\lambda/4$ networks, N1, N2, and N3. At the probe, point P is the output of the power amplifier which is connected to DE1, whose function is to allow the pass of the rf pulses but preventing the noise and low voltage level signals to be coupled to the receiver when the amplifier is not pulsing.

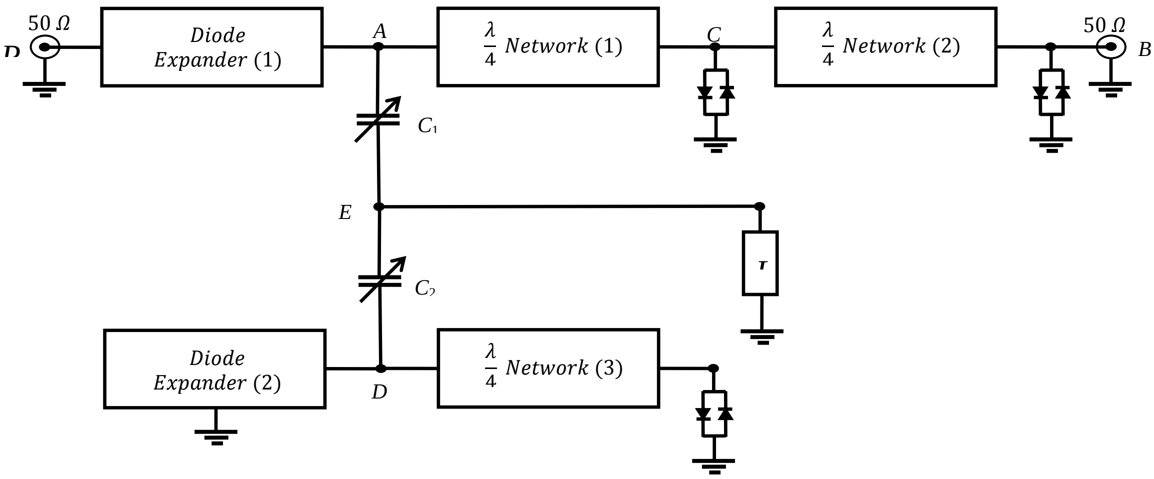

Figure 2. Probe block diagram.

Each one of the diode expanders, figure 3, consists of two branches, oppositely directed, each of them are built with a combination of both switching and Zener diodes, connected in such a way that they reversely conduct when the switching diodes conduct in the direct mode, in order to conform a low level voltage blocking device. The threshold voltage for both DE1 and DE2 is $\pm 15\,V$. Additionally, DE2 connects C_2 to ground at point D allowing the reduction of the tuned circuit recovery time. Between point A and B two $\lambda/4$ networks, N1 and N2, are connected in series and terminated to ground through crossed diodes at points C and B respectively. The attenuation to high rf voltage by a single $\lambda/4$ network terminated with crossed diodes does not exceed $40\,dB$; and since twice that amount is required, at least two attenuation stages are required. As a result of the attenuation of the rf pulse by $40\,dB$ after the first stage, there is still a residual peak to peak voltage, of the order of $10\,V$ that depletes the diodes of charge carriers. Consequently, two sets of pairs of crossed diodes are needed to terminate the first $\lambda/4$ network at point C. Also N3 terminates to ground point D, its function is to present large impedance to the nuclear signal while grounding oscillatory artifacts at frequencies other than ω_0.

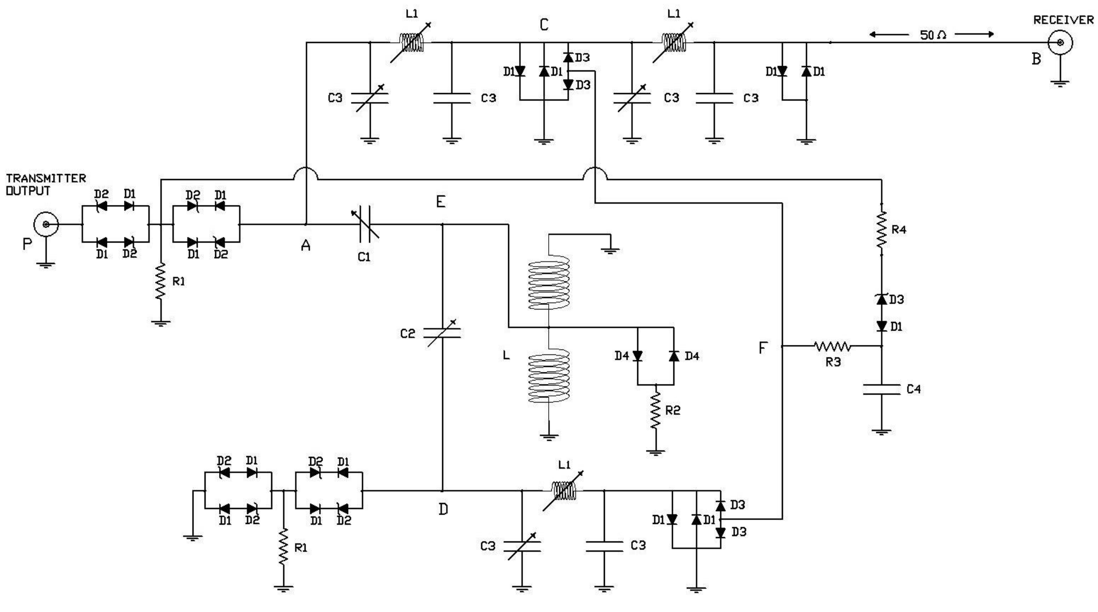

Figure 3. Probe circuit. $R_1 = 1\,k\Omega$, $R_2 = 900\,\Omega$, $R_3 = 1\,k\Omega$, $R_4 = 200\,\Omega$, $C_1 \approx 40\,pF$, $C_2 \approx 1490\,pF$, $C_3 = 1.6\,\mu F$, $D_1 = 1N41448$, $D_2 = 1N5342B\ 6.8V\ Zener$, $D_3 = 1N5347B\ 10V\ Zener$.

Other important components of the probe are the coil, L, and the tuning capacitors, C_1, C_2. The volume of the coil will be assumed to be identical to the sample volume. The samples studied in petrophysics are usually porous rocks with cylindrical shape having approximately a diameter of $38\,mm$ (~1.5") and a height of $64\,mm$ (~2.5"). The coil surrounding the sample volume is a solenoidal one, and in order to satisfy adequately conditions c, d and e, previously established, a coil having 15 turns and a resistance $r \cong 0.5\,\Omega$ will have at $\nu_0 = 2\,MHz$

$$\begin{gathered} n = 15\ turns \\ L \cong 4\,\mu H \\ x_L = \omega L \cong 60\,\Omega \\ Q \cong 120 \\ 3\tau \cong 160\,\mu s \end{gathered} \tag{5}$$

Although these figures seem reasonable, are not enough to obtain a good performance of the probe. First of all, it is desirable to double the number of coil turns and to reduce Q, at least by a factor of two. These changes will increase the transmitted power and consequently reduce the duration of the rf pulses. The implemented solution was instead of a single coil to use a coil with two segments connected in parallel.[10] At fixed work frequency with a reasonable bandwidth this kind of coil provides a larger sample volume, decreased Q factor, and a better ξ ratio (3). Furthermore, to provide a higher homogeneity of the rf magnetic field, H_1, across the sample volume, the connection point for both coils is such that an electrostatic plane of mirror symmetry bisects the sample generating two equally split parallel coils. Another geometrical consideration to be taken into account to optimize H_1 is the way the coils are wound, which depends not only of their volume but of the wire radius, ρ. Let a be the radius of the coils, and 2 g their length, as shown in figure 4. The amplitude of B_1 per unit current is given by

$$B_1 = \frac{\mu_0\, n}{2} \frac{1}{\sqrt{a^2 + g^2}} \quad , n \gg 1 \tag{6}$$

and to minimize the proximity effect between turns the distance between the centers of each turn should be 3 ρ.[3]

The resonant part of the probe consists of the inductance L and the capacitors C_1 and C_2. Introducing the notation

$$\begin{gathered} Z_L = j\omega L = jx_L \\ Z_1 = \frac{-j}{\omega C_1} = -jx_1 \\ Z_2 = \frac{-j}{\omega C_2} = -jx_2 \end{gathered} \tag{7}$$

the resonance condition for this circuit (CPS) is such that the reactive components must satisfy

$$\frac{x_1 x_2}{x_1 + x_2} = x_L \tag{8}$$

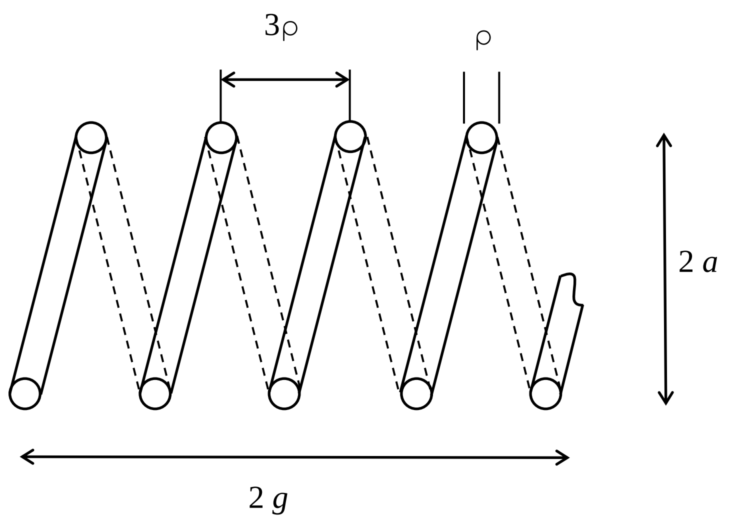

Figure 4. Coil winding geometry.

During the rf pulse transmission the probe tuning circuit consists of C_1 in series with the parallel connections of C_2, R_2 and L, figure 5, the parasitic resistance of the coil being ignored for the analysis. The Q factor of the coil setting is related to the parallel resistance R_2 by

$$Q = \frac{R_2}{\omega L} \qquad (9)$$

Solving the impedance Z at point A in terms of the circuit components and imposing that the real part of Z being $50\,\Omega$, cero its imaginary part, and also imposing that $R_2 \gg 50\,\Omega$, it follows the well known result that

$$x_1 \cong \sqrt{50\,R_2}$$
$$C_1 \cong \frac{1}{\omega\sqrt{50 Q\omega L R_2}} \qquad (10)$$

Furthermore, the shortest coil ring down is achieved when the probe is tuned to have a real impedance $Z = 1/\omega C_1$, yielding a reduction of Q of the order of $\sqrt{Q}$.[9] The effective Q value of the circuit is then

$$Q_{eff} \cong 2\sqrt{\frac{QZ}{\omega L}} \qquad (11)$$

Substituting in equation (10) the values of $\omega = 1.26\ 10^7 s^{-1}$, $L = 4\,\mu H$, $Q = 115$, and $Z = 50\Omega$, it results that $C_1 \cong 39\,pF$.

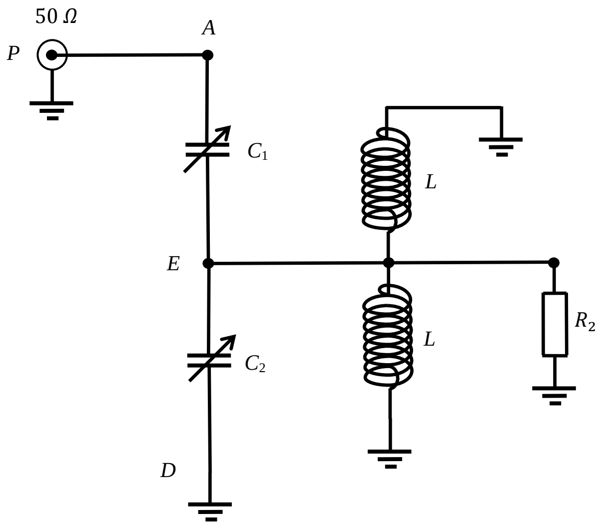

Figure 5. Equivalent circuit during the rf pulse.

RF high voltage damping

Although the arrangement of several $\lambda/4$ networks work well to protect the preamplifier from high voltage of the rf pulses, and simultaneously drive the whole power to the probe, it suffers of several drawbacks. First of all the crossed diodes at point C do not represent a perfect short during the pulse. Second, both the required matching of the probe impedance and the presence of the diode expander, DE1, introducing a little output impedance mismatch of the amplifier, yield to some standing waves due to reflections where none are expected. Third, the introduction of more $\lambda/4$ networks, more than three, is impractical mostly due to the noise introduced by the crossed diodes which affect the signal to noise ratio. The incident rf power is largest at point C and rapidly drops along the chain of $\lambda/4$ networks. This requires that the diodes placed at C should be capable of undergoing the largest overloads, reason why more than one pair of diodes is required, up to three pairs. On the contrary, the diodes at B are protected by the preceding ones at C and need to be fast rather than robust. Consequently, the use of germanium diodes is a better choice. When the pulse power is of the order of 250 W and the pulses duration are no longer than $40\ \mu s$, that being the case for Hahn or CPMG echo sequences for ^{1}H,[11] the standard 1N4148 switching diodes are adequate. It is clear that either for higher rf power, $T_{1\rho}$ and/or decoupling measurements the diodes choice becomes relevant. Additionally, it is important to point out that the $\lambda/4$ network between point C and B is better adjusted when it is not exactly equivalent to a $\lambda/4$ line. Thus, some of C_3 capacitors and coils L_1 are variable ones to allow the correct tuning.

The circuit operation

During the duration of the high voltage rf pulse, figure 5 depicting the equivalent circuit, all the diodes of the probe conduct representing a low impedance. Neglecting the voltage drop across the diode expanders, points A is connected to the transmitter output, points B, C and D are grounded, the resistor R_2 is connected to point E and consequently the resonant circuit is damped yielding a low $Q \cong 18$. Since point C is connected to A by a $\lambda/4$ network its effective ground appears as very high impedance at A, therefore protecting the receiver from the rf pulse. Simultaneously with and generated by the rf pulse a driving pulse from C_4 is applied to point F causing that diodes D_3 to conduct and improving the grounding of diodes D_1. Therefore, R_4 and R_3 are chosen such that $C_4 = 0.1\,\mu F$ is charged during a time no longer than $\tau \approx 15\,\mu s$ and becomes discharged at a time 3τ after the end of the rf pulse. Thus the preamplifier is protected from the ringing of the probe while the diodes D_4 are conducting and $Q \approx 18$. This ensures that the work point of the first stage of the preamplifier remains stable during the rf pulse and the probe ring down.

After the rf level across the probe coil reaches $\approx 0.6\,V$, figure 6, the diode expanders, DE1 and DE2, are not conducting, also diodes D_4, and the $\lambda/4$ networks, N1 and N2 connect points A and B wile N3 connect point D to ground; the circuit behaves as depicted in figure 6. Under this condition the Q of the probe, for a probe matched impedance of $50\,\Omega$

$$Q \cong \frac{50\Omega}{\omega L} \cong 51 \qquad (12)$$

which is increased by a factor of ≈ 2.8 and improving the signal to noise ratio, ξ, by a factor of 68% during the NMR signal reception.

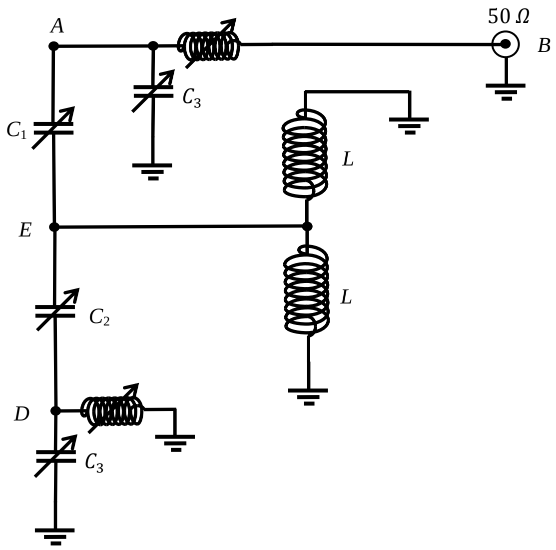

Figure 6. Equivalent circuit during the signal reception.

Conclusions

The NMR probe presented shows the advantages of being a relatively simple probe with a non active damping circuit. It keeps a low value for Q factor during the rf pulse transmission, while reducing sensitively the coil probe ring down, and thus reducing the recovery time of the preamplifier. All of these are achieved while improving the signal to noise ratio. Furthermore, during the signal reception the Q factor is increased yielding a better signal to noise ratio with good isolation of the transmitter. Furthermore, the probe performance at high frequencies is mostly limited by the quality of the capacitors and the inductors of the $\lambda/4$ networks.

Acknowledgements

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