Towards Optimal Noise Properties of NMR Antenna-Receiver Chain

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***Abstract*—A role of a small loop antenna, that acts as a probe in standard NMR systems, is reviewed. It is shown that the noise properties of a whole system are not always dictated just by proper resonant matching of the antenna and the use of high-quality pre-amplifier (as it is usually believed). Actually, the losses and mismatch of all other passive components may have a serious impact on the overall chain sensitivity. A simple theoretical and experimental investigation has shown that careful design of the NMR antenna-receiver chain can substantially decrease the overall noise figure, and therefore increase the system sensitivity.**

***Index Terms*— loop antenna, NMR, noise figure, sensitivity**

I. INTRODUCTION

The NMR (Nuclear Magnetic Resonance) spectroscopy is a subject rarely analyzed in antenna community although the loop antenna [1,2] is its key element. The NMR makes use of the interaction of atomic nuclei with its surroundings, which are of electrical and magnetic nature, using the nucleus as highly sensitive sensor at an atomic level [3-7]. The basic block diagram of a NMR system (used in experimental physics and material science) is depicted in Fig. 1.

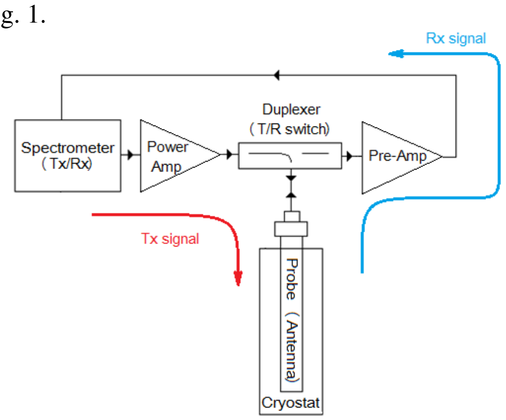

Fig. 1. Basic NMR system

Briefly, the system operates in two distinct modes: the transmitting mode and the receiving mode. During the transmitting mode, the RF source (an oscillator in so-called 'spectrometer') generates rectangular pulses, the duration of which can be adjusted in order to attain maximal measurement precision ([7]). The level of these pulses is boosted in the RF power amplifier and sent (via duplexer-T/R switch) to the cryogenically cooled small loop antenna (NMR probe). The antenna is placed in an environment with strong DC magnetic field and fitted with a network for resonant matching (at preselected measurement frequency), (Fig. 2). This matching (in the transmitting mode) assures maximal level of power delivered to the antenna. The (predominant) magnetic near-field of the loop antenna causes the reaction of a sample in the form of the Larmor's precession ([3]-[7]):

$$\omega_L = \gamma B_0 , \qquad (1)$$

Here, ω_L and γ stand for Larmor's frequency and a gyromagnetic ratio, respectively. Furthermore, the symbol B_0 represents the magnetic induction of DC (bias) magnetic field. After the diminishment of the transmitted RF pulse, the NMR system switches into the receiving mode. The receiving signal induced at the antenna can be calculated using the Faraday's law:

$$v_{A_{ind}}(t) = NS\mu M_{normal}\omega_L e^{-\frac{t}{T_2}} \cos(\omega_L t) \qquad (2)$$

In expression (2), v_{Aind} represents the induced voltage, N stands for the number of turns of the loop, S represents the loop area, μ is the magnetic permeability, and M_{normal} is the normal component of magnetization of a sample. The time constant T_2 is, the so-called, spin-spin relaxation time. The signal given by (2) is brought (via T/R switch and a low-noise amplifier) to the detector (IQ receiver in spectrometer), that does all necessary signal processing and detection. Of course, the purpose of tuning network (Fig. 2b), in the receiving mode, is to match the antenna to the system impedance (usually 50 Ω) and to assure maximal signal amplitude at the receiver input.

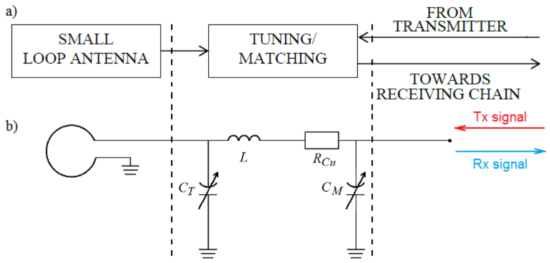

Fig. 2. a) NMR probe – block diagram;
b) NMR probe – schematic diagram

II. INVESTIGATION OF NOISE PROPERTIES

One of difficult engineering problems in NMR spectroscopy is achieving good system sensitivity. Although the measurement conditions are extreme (magnetic field inductions up to 12 T and temperatures down to 7 K), the signal induced at the antenna is very low (a few μV). Not surprisingly, this fact puts constraints on system signal-to-noise ratio (SNR) and, therefore, on the system sensitivity. The NMR receiver uses averaging, so the most important factor is actually the cumulative averaging time (the measurement time). But, the common believe that the increase of the averaging order can always increase the system sensitivity is naive and certainly incorrect, as shown in [8]. After some number of averaging cycles, the presence of systematic errors (unwanted signal caused by DC magnetic field fluctuations, drift in electronic circuitry etc.) prevails and further averaging becomes useless. Thus, in order to achieve the shortest possible measurement time one should minimize the system noise figure, defined by:

$$F = \frac{SNR_{antenna}}{SNR_{receiver}}. \tag{3}$$

It is interesting to compare matching of the NMR probe with classic matching of the receiving antenna in communications. In communications, the basic constraint is usually the matching bandwidth, while the antenna temperature is of the concern only in satellite systems (due to low background noise temperature). In the NMR technology, the situation is (usually) just opposite. The bandwidth is very narrow (due to resonant matching). However, the resonant matching, together with low antenna temperature (typical value of 7 K), maximizes the $SNR_{antenna}$ value. In the NMR community, it is usually believed that the resonant antenna matching accompanied with a high-quality low noise pre-amplifier assures optimal measurement time.

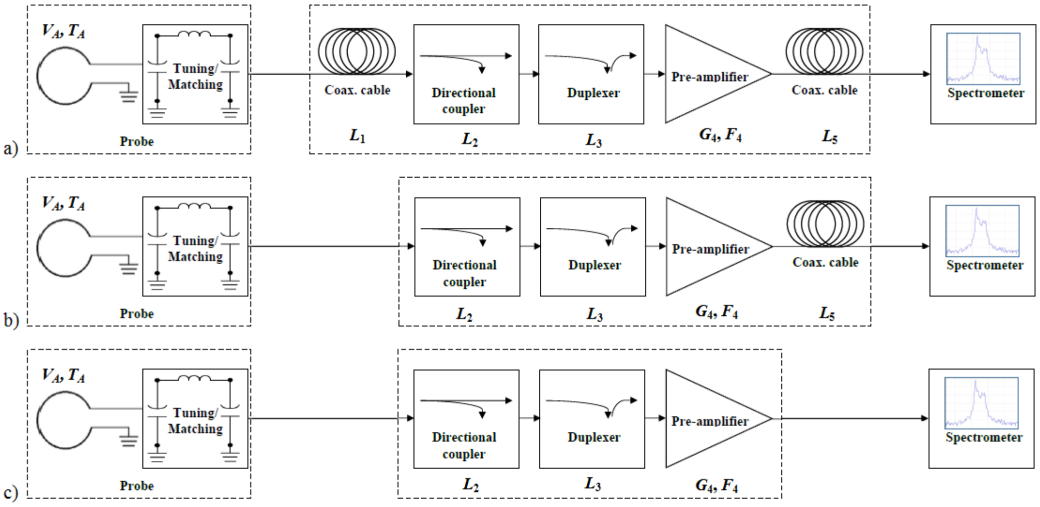

Fig. 3. NMR system's receiving chain models; a) Model 1; b) Model 2; c) Model 3

However, that is not entirely correct. A quick inspection of Fig.1 shows that the loss and inter-connection matching properties of the other components of the system (duplexer, cables, additional directional couplers usually used for monitoring etc.) may influence the SNR and sensitivity. This can be seen from the well-known equation that describes the noise factor of a chain of matched two-ports (F_0), [2]:

$$F_o = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots\ldots \frac{F_n - 1}{\prod_{i=1}^{n-1} G_i}. \tag{4}$$

Here F_i and G_i stand for the noise factor and gain of the i-th two-port. Thus, the optimization of the noise properties of complete antenna-receiver chain is needed.

Here, we investigate the noise properties of a representative NMR system used in physics research. The experimental system is shown in Fig. 3a. It is very similar to a basic structure from Fig.1, and it covers the frequency range up to 500 MHz (divided in a number of sub-bands, dictated by used directional couplers and duplexers). As a first step, we determined the scattering parameters and noise figure of all the components (antenna, couplers, duplexers and cables) using 'cold' measurements. These data were used for preparation of a linear model of the whole antenna-receiver chain (in MATLAB^{TM}) environment. For the sake of simplicity, the finite return loss at all component ports was neglected. This seems to be acceptable because all the components have characteristic impedance of 50 Ω and the probe was matched to 50 Ω, as well (by manual tuning). After this, the overall noise figure was calculated using (4). A sample of the results, in the 50 MHz – 80 MHz band, calculated for two different pre-amplifiers (MITEQ AU-1332-SMA and THAMWAY N141-206AA(D) is depicted by one family of curves in Fig.4 (Model 1-A and 1-B).

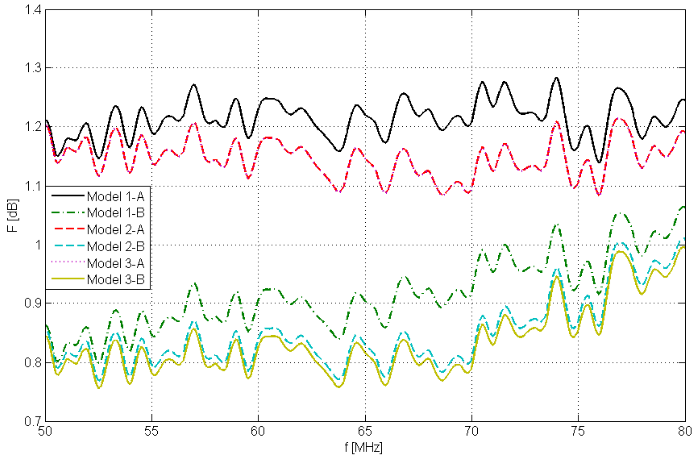

Fig. 4. Noise factor of models 1, 2; pre-amplifier A vs pre-amplifier B (A: MITEQ AU-1332-SMA; G_A=51 dB, F_A=1.03 dB, T_A=300 K; B: THAMWAY N141-206AA(D); G_B=28.5 dB; F_B=0.75 dB, T_B=7 K)

As expected, it can be seen that the use of a cryogenically cooled pre-amplifier with lower noise figure (Model 1-B) decreases overall noise figure comparing to initial set-up, (Model 1-A). However, this improvement is seriously affected by the losses of the components connected in front of the pre-amplifier (duplexer, coupler and a cable). In practice, the processing electronics is usually dislocated from the probe (in order to avoid unwanted influence of the high DC magnetic field). Therefore, the length of the input cable can be even a couple of meters. This introduces significant losses that (together with the losses of a coupler and duplexer) may increase the system noise figure for 0.5 dB (or even more). Thus, the insertion loss may almost completely override expected enhancement of the low-noise pre-amplifier. This can be seen from the results of calculation using Model 2 and Model 3 (Fig. 3b, Fig. 3c. and lower family of curves in Fig. 4). For instance, removing the input cable decreases the system noise figure by approximately 0.15 dB, in the case of cryogenically cooled pre-amplifier. As expected, removing the output cable does not enhance the system sensitivity significantly (due to high gain of a pre-amplifier).

One should note that presented analysis is, in a sense, over-simplified (or over-optimistic), because it neglects the mismatch between neighboring chain components. Thus, in the next step, the full ADS^{TM} model was developed. It takes into account all full scattering matrices of all the chain components. The results (not shown here due to lack of space) revealed additional noise factor increase of almost 0.2 dB (the case with cryogenically cooled pre-amplifier). Thus, the influence of the passive components non-ideality (loss and mismatch) on the system sensitivity may (in some cases) be significant. It is interesting that experiments performed so far indicated that correlation between the SNR improvement and shortening of the measurement time is not always consistent with theoretical predictions. Therefore, the development of detailed system model based on known methods of optimal noise-matching (used in RF engineering [2]) are planned in future research activities.

Finally, one should think of possible improvements in the NMR system design that could lead to optimal noise properties. Shortening of the connecting cables (particularly the input cable) appears as the simplest solution. However, due to practical constrains (vicinity of the area with high DC magnetic field), the cable length could hardly be shorter than 0.5 m. The next possibility might be to cool down all the passive components located in front of cryogenically cooled pre-amplifier. However, the literature is sparse of reports of similar systems, which puts doubts on a feasibility of this approach. One could also think of the improvement of the antenna itself by construction of several loops that could boost the output signal and improve the SNR. Yet another possibility might be use of the metamaterial technology, which has been gaining popularity in the last years [9].

III. CONCLUSIONS

It has been shown that the noise properties of a whole NMR system are not always dictated just by proper resonant matching of the antenna and the use of high-quality pre-amplifier (as it is usually believed). Significant improvement of the system noise figure is possible by optimization of the parameters of the passive components and connecting cables.

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