A SIMPLE METHOD OF MEASURING THE NOISE FIGURE OF THE NMR SPECTROMETER

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Abstract

Sensitivity is one of the fundamental parameters of the Nuclear Magnetic Resonance experiment. It depends particularly on the coil and impedance matching of the resonance circuit of the probe to the input amplifier. However, sensitivity is also influenced by the noise of the receiver of the spectrometer, and the insertion loss of the matching and switching circuits as well as of passive filters inserted in front of the input preamplifier manifests itself markedly. In this paper, a simple method of measuring the noise figure feasible in the NMR laboratory is described. Using non-standard probes and coils, the measurement of the noise figure enables one to estimate to what degree the detection system itself participates in the signal/noise ratio deterioration. The method can be used also for measurements of other radio-frequency signal processing systems.

Keywords:

noise measurement, preamplifiers, NMR spectrometers, radio receivers

1. Introduction

The noise figure is defined as the ratio of $(\text{signal/noise})^i$ powers at the input to the ratio of $(\text{signal/noise})^o$ powers at the output of the linear or quasi-linear two-port network [2], [4]. For an ideal noise two-port network, it amounts to one. For real two-port networks, the noise figure is higher than one. The detection part of the NMR spectrometer consists of a number of cascaded two-port networks, starting with the matching and switching circuits, rf filters, preamplifier, mixer, etc., and ending with audio filters and A/D converters. For the resulting noise figure n + 1 of the cascaded two-port networks it holds [2], [4]:

$$F = F_0 + \frac{F_1 - 1}{A_0} + \frac{F_2 - 1}{A_0 \cdot A_1} + \ldots + \frac{F_n - 1}{A_0 \cdot A_1 \cdot \ldots \cdot A_{n-1}} \qquad (1)$$

where $F_0, F_1 \ldots F_n$ are noise figures of partial two-port networks and $A_0, A_1 \ldots A_{n-1}$ are their available (power) gains. The noise figure is often expressed in decibels. Then, it holds $F_{[dB]} = 10 \cdot \log F$.

From the point of view of the noise figure, the receiver of the spectrometer is shown in Fig. 1. The whole system can be considered as quasi-linear, including the mixer, quadrature phase sensitive detector and A/D conversion. On this, the spectral analysis of the NMR signal is based. For a correct design, the resulting noise figure F is most frequently determined by the noise figure of the preamplifier F_1. In accordance with Eq. (1), this can be achieved because the amplification A_1 is sufficiently high, so that the influence of other stages is suppressed, and because the insertion attenuation of the circuits between

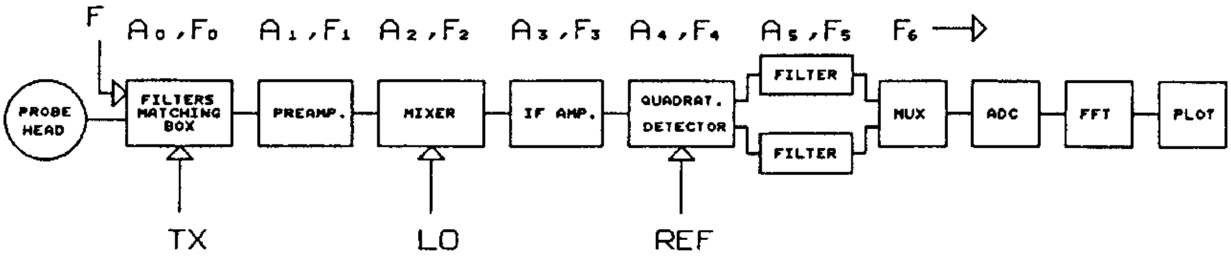


Fig. 1.
Spectrometer receiver block diagram.

the probe and preamplifier characterized by A_0 is minimum.

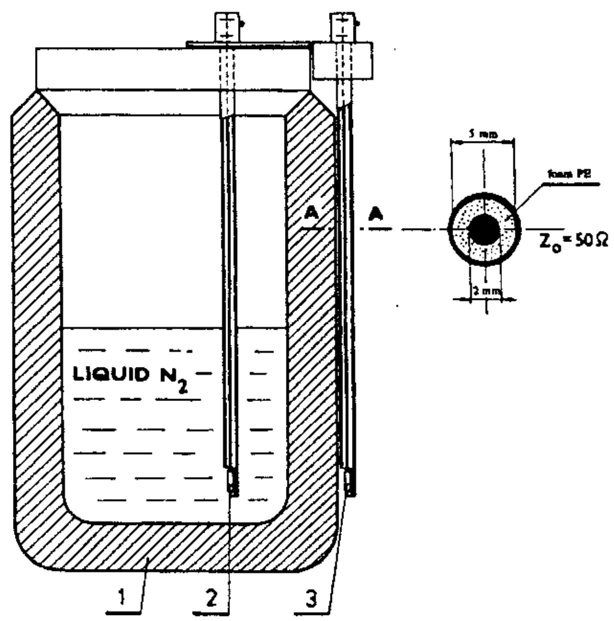
Attention should be paid particularly to the input circuits put in front of the input amplifier. If we consider them as a passive two-port network with power transmission A_0 that is impedance matched Z_0 at the input and output, then its noise figure F_0 equals $1/A_0$. If the noise figure of the receiver itself, starting with the preamplifier, is $F^*(\approx F_1)$, then for the resulting noise figure according to Eq. (1) we can write $F = F^*/A_0 = F^* \cdot F_0$ or $F_{[dB]} = F^*_{[dB]} + F_{0[dB]} = F^*_{[dB]} - A_{0[dB]}$. From the last expression it is obvious that the insertion attenuation of the passive circuits (cables, filters, matching and switching circuits) at the input is directly added to the noise figure of the receiver of the spectrometer expressed in decibels.

2. Noise figure measurement

The noise figure is measured using the noise generator that is connected to the input of the two-port network and generates white noise of some defined level. Using the RMS voltmeter connected to the output gate, the output power of noise is measured at the output (see Fig. 2). First of all, the output power of noise corresponding to the real impedance Z_0 at the input of the two-port network is measured. Then the level of noise at the input is increased so that its power is doubled at the output, i.e. increased by 3 dB. The noise generator usually gives directly the value of the noise factor F or $F_{[dB]}$. A good-quality noise generator, e.g. HP 8970B and the RMS voltmeter are not currently available. As a rule, simple noise generators do not allow precise measurement of small noise figures we are most interested in.

A unit (Fig. 3) was designed to be used as the source of noise for measuring small noise figures. It consists of two equally long coaxial lines with the characteristic impedance $Z_0 = 50\Omega$. To their ends, non-inductance 50 Ω resistors are connected. During the measurement, one resistor is at room temperature and the other is immersed in boiling liquid nitrogen of a temperature of 77 K. The output power of noise of the mass resistor is given by the relation $P_N = k \cdot \delta f \cdot T$, where k is the Boltzmann constant $1.38 \cdot 10^{-23} JK^{-1}$, δf is the noise bandwidth and T is its temperature. As δf is equal in both measurements, the ratio of output powers is given by the ratio of temperatures of both resistors. For the noise figure of the receiver we can write the relation

$$F = \frac{1 - \frac{T_L}{T_H}}{1 - \frac{P_{2L}}{P_{2H}}} \tag{2}$$



[1] Fig. 3.
Noise measurement unit.
1 - Foam Polystyrene Vessel,
2 - Resistor at a temperature of 77 K,
3 - Resistor at the ambient temperature.

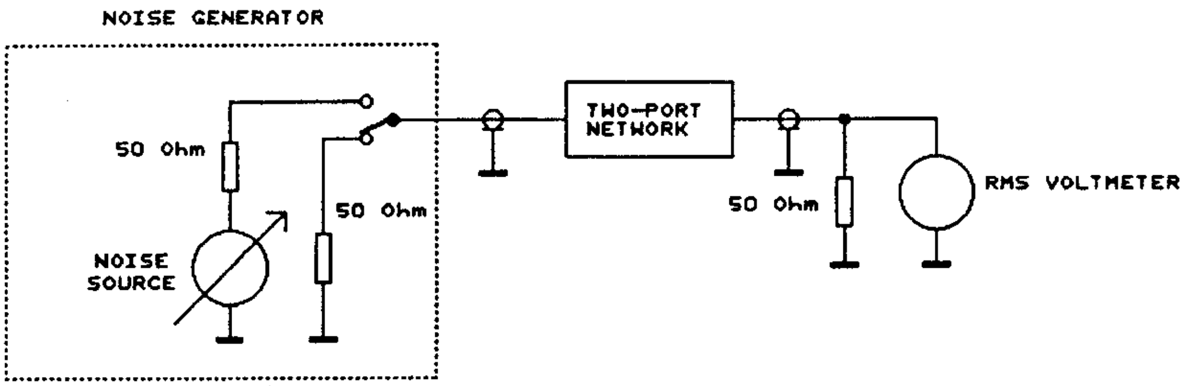


Fig. 2.
Noise figure measurement.

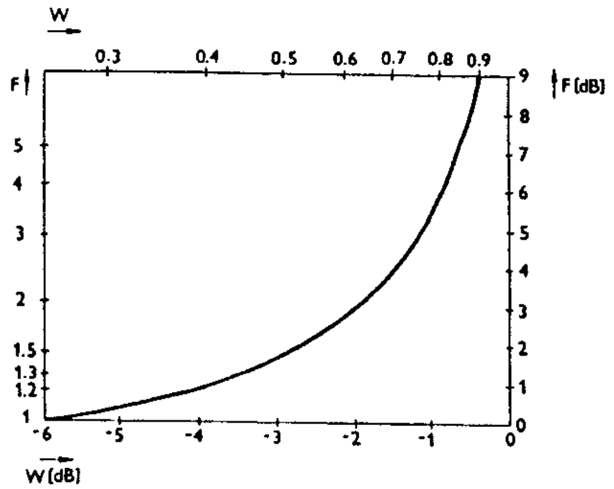


Fig. 4.
Relationship between the noise power ratio and the noise figure.

where T_L and T_H are absolute temperatures of resistors, and P_{2L} and P_{2H} are relative values of the noise power obtained at the output of the spectrometer. If we further introduce $W = P_{2L}/P_{2H}$ for the power ratio, then for $T_L = 77K$ and $T_H = 295K$ Eq. (2) can be written in the form:

$$F = \frac{0.74}{1-W}; \quad F_{[dB]} = -1.3 - 10 \cdot \log(1-W) \tag{3}$$

The relations between the values F, W, $F_{[dB]}$ and $W_{[dB]}$ according to Eq. (3) are graphically represented in Fig. 4.

In the case of the NMR spectrometer, we are interested in the total noise figure, including the spectrum record. The signal is simultaneously digitized. Assuming that the spectral density of the measured noise obtained by the Fourier transform and by the evaluation of the power spectrum is proportional to the output power of white noise [3], then the relative level of the output power of noise at the output of the spectrometer can be determined from the record. The parasitic dc component, which must be excluded by accumulation with a suitable alternation of the phase of the reference signal of the receiver, may be a problem. In our case, we introduced a new function for the determination of the relative noise level which processes the block of data immediately after the acquisition, i.e. in the time domain:

$$\chi = \frac{\Sigma[(Re_i - a)^2 + (Im_i - b)^2]}{N} \tag{4}$$

where Re and Im are the corresponding blocks of data, N is the size of the block of data and $a = (\Sigma Re_i)/N$ and $b = (\Sigma Im_i)/N$ are the mean values of both blocks of data, respectively.

When this function is used, the number χ is displayed on the screen. The advantage is that the dc component is perfectly eliminated even for a single acquisition. The relative level of noise power at the output of the spectrometer evaluated in this way was compared with that measured using the FLUKE RMS voltmeter at the output. Values obtained in both ways are summarized in Table 1 and they show a very good agreement.

3. Discussion

It follows from Eq. (2) that the above described method is suitable for measurement of small values of noise figures and is the more accurate the smaller the noise factor is. Values of the noise figure higher than 5 dB cannot be measured with a sufficient accuracy. However, in that case no good sensitivity of the NMR experiment can be achieved either [1]. On the contrary, the advantage is the precise measurement of small noise figures because these measurements are always hard to carry out, especially when simpler noise generators are used.

W_{RMS} - FLUKE 8290A $W\chi = \chi_L/\chi_H$ Eq. (4) F Eq. (3)	200 MHz				50 MHz			
	W_{RMS}	F	$W\chi$	F	W_{RMS}	F	$W\chi$	F
Filter 4 kHz, NS=1 SI=4k, AQT=2.048 s	0,5	1,48	0,51	1,51	0,58	1,76	0,56	1,68
Filter 50 kHz, NS=1 SI=4k, AQT=0.164s	0.51	1.51	0,51	1,51	0.56	1.68	0,55	1,64
Filter 50 kHz, NS=4 SI=4k, AQT=0.164s			0,51	1,51			0,56	1,68

Table 1
Noise measurement methods comparison

Let us note that the measured value of the noise figure corresponds to reality only if no backfolding of noise occurs in the mixer and quadrature detector and during the NMR signal digitization. In the opposite case, the measured value is proportionally lower and thus the results obtained are better than the real ones.

At present, GaAs based MESFETs, such as CF 300 or S 3030, allow the achievement of the noise figure of the preamplifier as low as about 1 dB and even less in the range of usual NMR frequencies (up to 600 MHz). For a good design, the deterioration of the noise figure of the receiver due to subsequent circuits is very low according to Eq. (1). It does not exceed 0.5 dB. From the point of view of the achievement of the maximum sensitivity, the insertion attenuation of circuits between the probe and preamplifier should be minimum and should not exceed 2 dB. The total value of the noise figure of the receiver obtained in the plane of connection with the probe will be therefore lower than 3.5 dB in the described case.

The results measured by the described method on our home-built spectrometer at the 200 MHz proton frequency and the 50 MHz carbon frequency are summarized in Table 1. In both cases, the probe connector was the plane of measurement. The transmitter and diode switch were disconnected.

Let us note that in all cases the real reference plane is the line end of the unit where resistors are connected to it (see Fig. 3). To obtain a high measurement accuracy, it is required that the attenuation of the coaxial cable, connectors (N type is better than the BNC type) and unit line be minimum. The real value of the noise figure is lower by the attenuation than the measured one.

Acknowledgement

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4. References

[1] Hoult,D.,I. and R.E. Richards,R.,E.: The Signal-to-Noise Ratio of the Nuclear Magnetic Resonance Experiment, J. Magn. Reson., 1976, Vol. 24, pp. 71-85

[2] Fundamentals of RF and Microwave Noise Figure Measurements, Hewlett Packard, Application Note 57-1, 1983

[3] Lindon,J.,C. and Ferrige,A.,G.: Digitisation and Data Processing in Fourier Transform NMR, Prog. NMR Spectrosc., 1980, Vol. 14, pp. 27-66

[4] Žalud,V. and Kulešov,V.,N.: Polovodičové obvody s malým šumem. SNTL, Praha, 1980, pp. 38-52.

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