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COMMUNICATIONS

VARICAPS FOR NMR RECEIVING COIL MATCHING AND SENSITIVITY CHANGES

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RF receiving coils for NMR imager must be exactly matched to the receiver. It is not possible without variable capacitors. In some cases variable capacitors can be replaced by varicaps and the coil can be tuned remotely. The quality of varicaps is not as high as the quality of good variable capacitors. The study of the influence of the varicaps quality upon the sensitivity of the receiving coil yielded the presented equations. Examples with several graphs illustrate the achieved results.

K e y w o r d s: NMR tomography, receiving coil, varicap, sensitivity

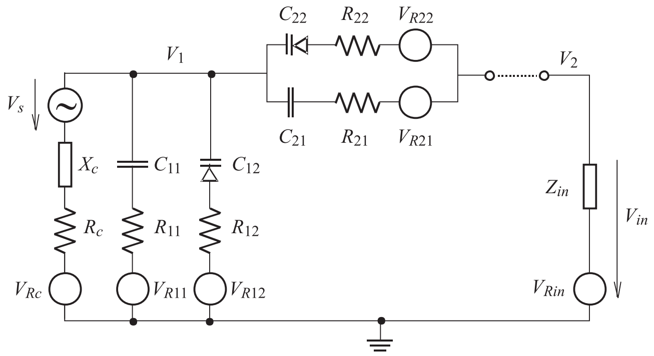

Fig. 1. Receiving coil tuned and matched by capacitors and varicaps with losses.

1 INTRODUCTION

If the NMR receiving coil should be exactly matched to the receiver and tuned to the working frequency of the NMR scanner, variable capacitors must be used. Classical variable capacitors have a high quality, are rather voltage-proof but suffer from mechanical wear and remote tuning and matching is difficult or impossible with such devices, mainly if small dimensions must be achieved. The remote control can be very useful in NMR practice. The proper matching and tuning of the coil depends many times on its position in the magnet, or the used impedance meter is not able to work near the magnetic field. There are more ways for remote capacitance changing. One of them is using varicaps. They can be utilized only for low voltage, that is why only receiving coils can be tuned with varicaps. The quality of varicaps is lower than the quality of good variable capacitors but they do not suffer from mechanical wear and are only part of the whole tuning capacitance so the lower quality need not influence the whole circuit significantly. In the presented study the sensitivity of a receiving coil tuned and matched with capacitances created together by capacitors and varicaps has been calculated. Calculated results are applied on examples with several figures.

2 SUBJECT AND METHODS

The receiving coil is tuned and matched in a typical circuit. The capacitances are created partly by capacitors and partly by varicaps. The quality of capacitors and varicaps can be determined *eg* by their dissipation factors. The resulting signal-to-noise ratio is calculated for the signal induced in the receiving coil. The calculated quantities are presented in the way to write a program for the calculation.

3 RESULTS

The considered coil (R_c, X_c) with its matching and tuning circuit is depicted in Fig. 1. Voltage signal v_s induced in the receiving coil causes voltage v_{in} in the load impedance $Z_{in} = R_{in} + jX_{in}$ (*eg* input impedance of an amplifier). Lossy resistors of the coil R_c, capacitors R_{11}, R_{21}, varicaps R_{12}, R_{22} and the load resistor R_{in} are sources of noise leaking into the load impedance Z_{in}. Noise sources v_{Rc}, v_{R11}, v_{R12}, v_{R21}, v_{R22}, v_{Rin}, produce a noise voltage, nevertheless for calculation of the spectral density they will be considered as harmonic signal sources. Potentials V_1, V_2 are auxiliary quantities helping to perform circuital analysis of the coil circuit.

Lossy resistors of capacitors and varicaps can be calculated from their dissipation factors as

$$R_{11} = \frac{D_{11}}{\omega_0 C_{11}}\,, \qquad R_{12} = \frac{D_{12}}{\omega_0 C_{12}}\,,$$
$$R_{21} = \frac{D_{21}}{\omega_0 C_{21}}\,, \qquad R_{22} = \frac{D_{22}}{\omega_0 C_{22}}\,,$$

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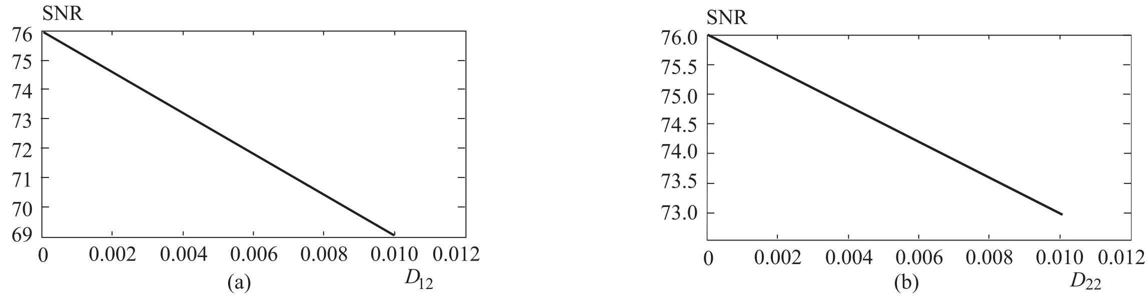

Fig. 2. Changes of SNR for varying dissipation factors of varicaps; a) D_{12} is varying from 10^{-4} to 10^{-2} and $D_{22} = 10^{-4}$; b) D_{22} is varying from 10^{-4} to 10^{-2} and $D_{12} = 10^{-4}$.

where ω_0 is the angular frequency to that the circuit is tuned and D_{11}, D_{12}, D_{21}, D_{22} are dissipation factors of varicaps and capacitors C_{11}, C_{12}, C_{21}, C_{22}.

The circuit can be described with the following equations

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}, \text{ where}$$

$$\begin{aligned}
a_{11} &= \frac{1}{R_c + jX_c} + \frac{1}{R_{11} + \frac{1}{j\omega C_{11}}} + \frac{1}{R_{12} + \frac{1}{j\omega C_{12}}} \\
&\quad + \frac{1}{R_{21} + \frac{1}{j\omega C_{21}}} + \frac{1}{R_{22} + \frac{1}{j\omega C_{22}}}, \\
a_{12} &= \frac{-1}{R_{21} + \frac{1}{j\omega C_{21}}} + \frac{-1}{R_{22} + \frac{1}{j\omega C_{22}}}, \\
a_{21} &= -a_{12}, \\
a_{22} &= \frac{-1}{R_{21} + \frac{1}{j\omega C_{21}}} + \frac{-1}{R_{22} + \frac{1}{j\omega C_{22}}} + \frac{-1}{Z_{im}}, \\
c_1 &= \frac{v_s + v_{Rc}}{R_c + jX_c} + \frac{v_{R11}}{R_{11} + \frac{1}{j\omega C_{11}}} + \frac{v_{R12}}{R_{12} + \frac{1}{j\omega C_{12}}} \\
&\quad + \frac{v_{R21}}{R_{21} + \frac{1}{j\omega C_{21}}} + \frac{v_{R22}}{R_{22} + \frac{1}{j\omega C_{22}}}, \\
c_2 &= \frac{v_{R21}}{R_{21} + \frac{1}{j\omega C_{21}}} + \frac{v_{R22}}{R_{22} + \frac{1}{j\omega C_{22}}} - \frac{v_{Rin}}{Z_{in}}.
\end{aligned}$$

The output voltage is

$$v_{in} = v_2 = \frac{D_2}{D} = \frac{\begin{vmatrix} a_{11} & c_1 \\ a_{21} & c_2 \end{vmatrix}}{\begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix}},$$

where D and D_2 are determinants.

Besides several circuital elements (ce), the output voltage is also a function of signal and noise voltages

$$v_{in} = v_{in}\big(ce, v_s, v_{Rc}, v_{R11}, v_{R12}, v_{R21}, v_{R22}, v_{Rin}\big).$$

The spectral density corresponding to the noise voltage at the output of the circuit is given by

$$\begin{aligned}
S = 4kTR_c&|v_{in}(ce,0,1,0,0,0,0,0)|^2 \\
&+ 4kTR_{11}|v_{in}(ce,0,0,1,0,0,0,0)|^2 \\
&+ 4kTR_{12}|v_{in}(ce,0,0,0,1,0,0,0)|^2 \\
&+ 4kTR_{21}|v_{in}(ce,0,0,0,0,1,0,0)|^2 \\
&+ 4kTR_{22}|v_{in}(ce,0,0,0,0,0,1,0)|^2 \\
&\qquad + 4kTR_{in}|v_{in}(ce,0,0,0,0,0,0,1)|^2,
\end{aligned}$$

where T is absolute temperature of resistors and $k = 1.38 \times 10^{-23}\,\mathrm{Ws/K}$ is Boltzmann's constant.

RMS noise voltage at the output, measured with an instrument with noise bandwidth Δf can be calculated as

$$v_n = \sqrt{\int_{f_0 - \frac{\Delta f}{2}}^{f_0 + \frac{\Delta f}{2}} S\,\mathrm{d}f},$$

where f_0 is the working frequency of the imager at which the coil is tuned to resonance and matched to Z_{in}.

The signal-to-noise ratio then can be calculated as

$$SNR = \frac{v_{in}\big(ce, v_s, 0,0,0,0,0,0\big)}{v_n},$$

where v_s is the RMS voltage induced into the coil from a sample.

If Z_{in} is the input impedance of the preamplifier and SNR_{in} is the signal-to-noise ratio corresponding to voltages on it, then

$$F = \frac{SNR_{in}}{SNR_{out}}, \text{ where}$$

F is the noise figure of the preamplifier and SNR_{out} is the signal-to-noise ratio on its output. All voltages must be measured by an instrument with frequency bandwidth Δf.

Examples have been calculated for a low-field tomograph with $f_0 = 4.45\,\mathrm{MHz}$, $X_c = 75\,\Omega$, $R_c = 0.25\,\Omega$, $D_{11} = D_{21} = 10^{-4}$, $C_{12} = 23.18\,\mathrm{pF}$, $C_{22} = 8.76\,\mathrm{pF}$, $Z_{in} = 50\,\Omega$, $v_s = 1\,\mu\mathrm{V}$, $T = 291\,\mathrm{K}$, $\Delta f = 20\,\mathrm{kHz}$. The influence of D_{12} varying from 10^{-4} to 10^{-2} on the resulting SNR is depicted in Fig. 2a. $D_{22} = 10^{-4}$ in this example. Similarly, changes of SNR are depicted in Fig. 2b if D_{22} is varying from 10^{-4} to 10^{-2} and $D_{12} = 10^{-4}$. All necessary parameters of matching elements were calculated according to formulas in [1] (not considering losses of capacitors).

In the first example (Fig. 2a) the resulting SNR changes within 10 %. Better results are in the second example (Fig. 2b) where the resulting SNR changes within 4 %. It can be easily calculated that for D_{12} and D_{22} varying in the same span simultaneously the changes of SNR are within 17 %.

The above derived equations make possible to calculate many similar examples.

4 DISCUSSION AND CONCLUSIONS

The signal induced in the receiving coil from the excited sample depends on many factors: dimensions and shape of the sample, dimensions and shape of the coil, mutual ratio of the dimensions, exciting of the sample and so forth. Exact calculation of the signal from an experiment is difficult, maybe impossible, that is why the real signal was replaced by a voltage source for the SNR calculation. Thus the results from the calculation above are appropriate for comparison, not for real sensitivity calculation. In some cases comparing the noise voltage instead of the SNR can be more advantageous. Nevertheless, one must consider that changing dissipation factors of capacitors not only the noise but also the gain of the circuit are varied. In this manner not only the influence of varicaps on the resulting sensitivity can be estimated but also the influence of arbitrary lossy capacitors. The objective of the study was to provide a tool for simple judging the influence of losses in capacitors and in the used coil on the resulting sensitivity. The program was written using the program package Mathematica (Wolfram Research Inc., Champaign, IL) but it can be written in an arbitrary program language.

Acknowledgements

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