Preamplifier Design: Basic Concepts to Advanced Design

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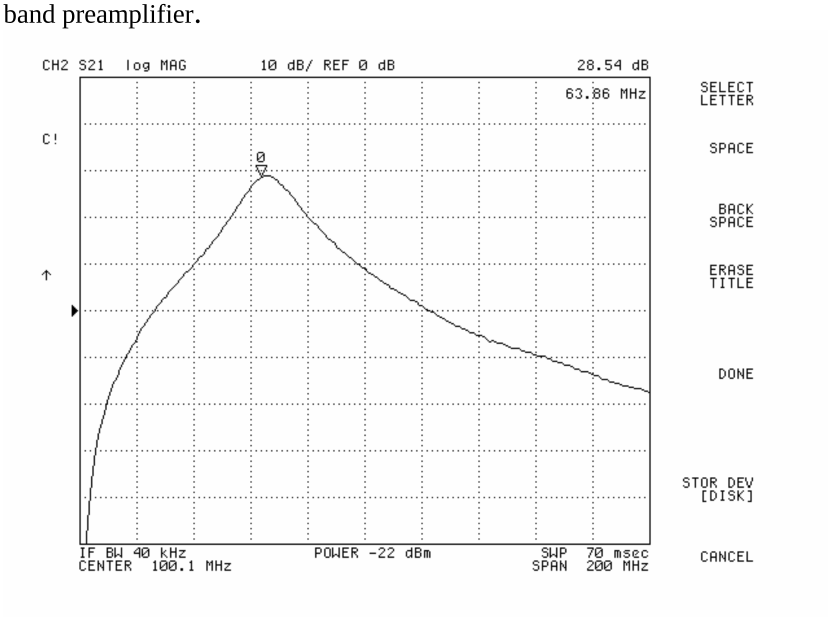
Background

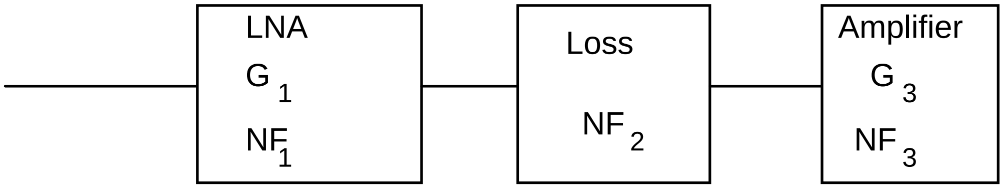
Before describing preamplifiers, it is important to understand some basics of electrical theory. A signal trace seen on an oscilloscope or computer screen is typically a time-varying voltage. (In our case the spin moment induces a voltage in a loop and is subsequently sampled.) Electrical power is proportional to the square of the voltage. Because of the extremely large dynamic range of many signals, including MRI signals, the decibel (dB) scale is often used. This is normally used with some reference value. For example the power out of a typical LNA could be 1000 times greater than the forward input power. The dB scale can be used to describe the power gain and is

$G(dB) = 10\log\left[\frac{P_{out}}{P_{in}}\right]dB$. Here $G(dB) = 10\log[1000]dB = 30dB$.

Noise figure is a measure of how ideal the noise performance of a component. For an amplifier with gain G, the noise figure is typically defined (in dB) as $NF(dB) = 10\log\left[\frac{N_{out}}{GN_{in}}\right]dB$. If the preamplifier generated no noise of its own, the noise figure would be 0 dB since the ratio inside the log function would be 1. Real LNA's have noise figures of approximately 0.5dB. This means that an ideal preamplifier (as taken from the aliens of Area 51 for example) could only improve SNR by about 6%. Super-cooling the preamplifier could, in principle, obtain most of this 6% gain as well. It is interesting to point out that LNA's always <u>lower</u> SNR. They lower SNR less than if they are not used, but still they can only lower it. This figure shows a typical gain curve for a low impedance narrow band preamplifier.



The Fluctuation-Dissipation Theorem is extensively used in the treatment and understanding of noise in electrical circuits. Essentially, it says that any passive material that dissipates power also generates noise in a precisely related way. For a receiving system, if cables connectors, switches, etc. drop 1dB of power as a signal passes through, it also has a 1 dB noise figure. The secret of the LNA is that the noise from the source preceding the preamplifier is amplified to such an extent that is can be considered as signal. This is because the amplified noise is much, much greater than the noise associated with loss in the system. This is exemplified by the cascade noise figure equation associated with the block diagram below.



The noise figures and gains are linear factors in this equation, and are thus not in dB. The loss in block 2 can be called G_2, a gain that is less than 1.

$$NF_{Total} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 * G_2}$$

To put some numbers with this, suppose NF_1 is 1.1, NF_2 is 1.6, NF_3 is 1.5, G_1 is 1000, and G_2 is 0.63. G_3 is unimportant to the total noise figure, which is

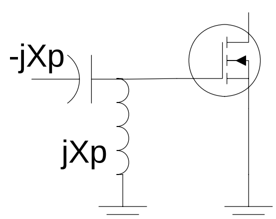
$$1.1 + .6/1000 + .5/630 = 1.101.$$

This demonstrates the importance of the first noise figure and gain. The large gain of the first stage creates high immunity from losses later in the system. From this perspective, the closer the preamplifiers are to the coils, the better the total noise figure.

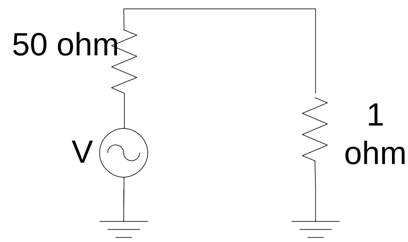
What does a low impedance preamplifier do and how does it work?

1. It reflects 95% or more of incoming power resulting in terrible power efficiency.
2. It kills the Q of coils (if matched a particular way).
3. It kicks butt for array coils.

Low impedance preamplifiers are now used almost exclusively in MRI (Roemer, et al, MRM **16**, 192-225 (1990)). The input impedance of these devices is typically from around 0.5 ohms to 3 ohms real. There will be later discussion of the schematic for these devices, but for now we only need to focus on the front end of a simple preamplifier.

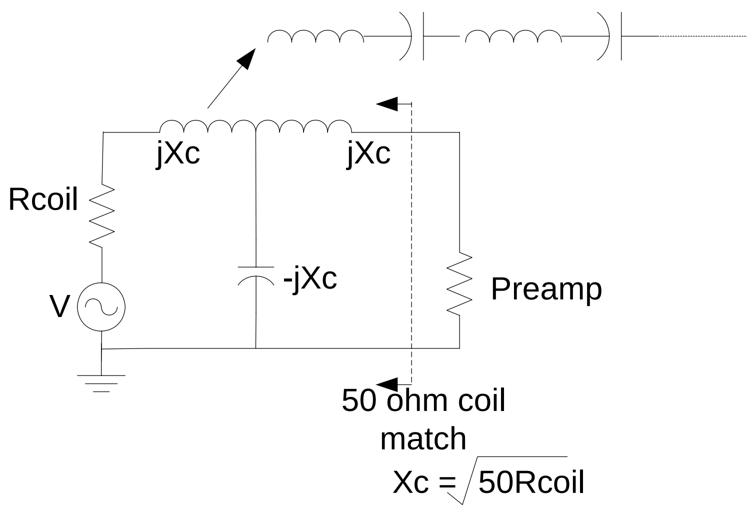


The FET input impedance is relatively high, so that the dominant impedance is just the series combination of the capacitor and inductor that have been chosen to be resonant at a given frequency. The residual impedance is predominantly the real part of the inductors impedance and some resistance from the FET itself. Generally the higher the Q of the inductor, and the lower the reactance of the inductor (and capacitor), the lower the input impedance of the preamplifier. For example, assume that the input impedance of the preamplifier is 1 ohm and consider some consequences.

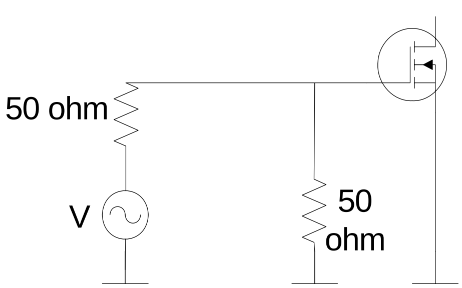


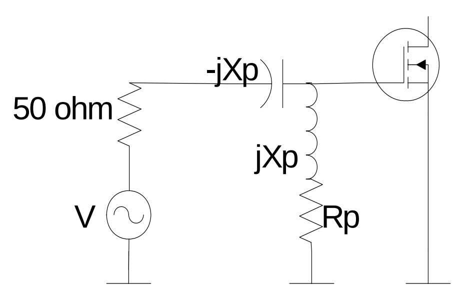
The power delivered to the 1 ohm load is $\left(\frac{1}{51}\right)^2 V^2$ whereas, if the preamplifier were a 50 ohm preamplifier the power delivered to the preamplifiers 50 ohms would be $\left(\frac{1}{2}\right)^2 V^2$. The power delivered to the low impedance case is 650 times less than for the matched case. Interesting.

Consider a coil that is matched using the following circuit:



The impedance "seen" by the spin voltage V, is Rcoil(1+50/Rpreamp). It can be seen that if the preamplifier is 50 ohms, then the matched condition occurs, and the impedance is just 2Rcoil. However if the preamplifier is 1 ohm, then the impedance "seen" is 51Rcoil. This represents an effective Q drop of a factor of 25.5 compared to the matched case. It also is associated with a current reduction by a factor of 25.5. This is the current that would create a secondary field that would induce voltage in other loops with mutual inductance. Therefore this effect lowers the inductive coupling by a factor of 25.5. These observations should go a long way towards explaining points #2 and 3 above. If the impedance of the preamplifier dips below 1 ohm, the effect is almost identical to using a diode decoupling trap, but without SNR loss.

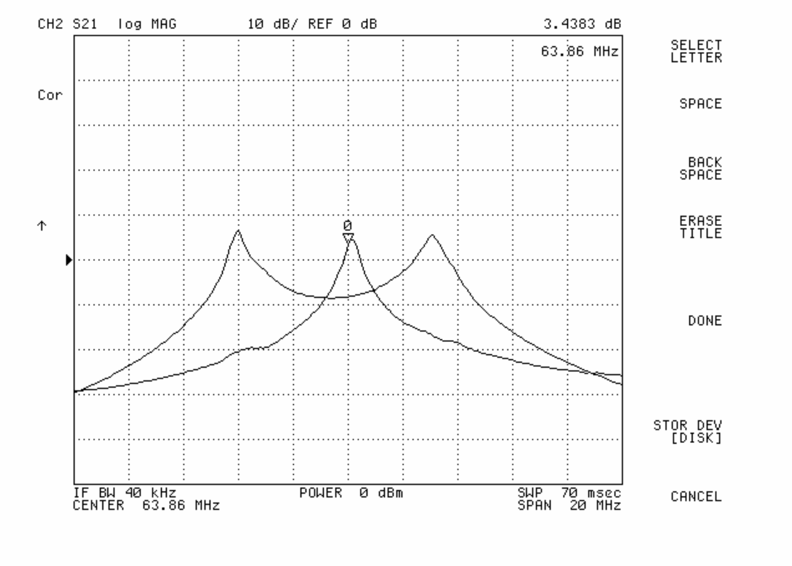




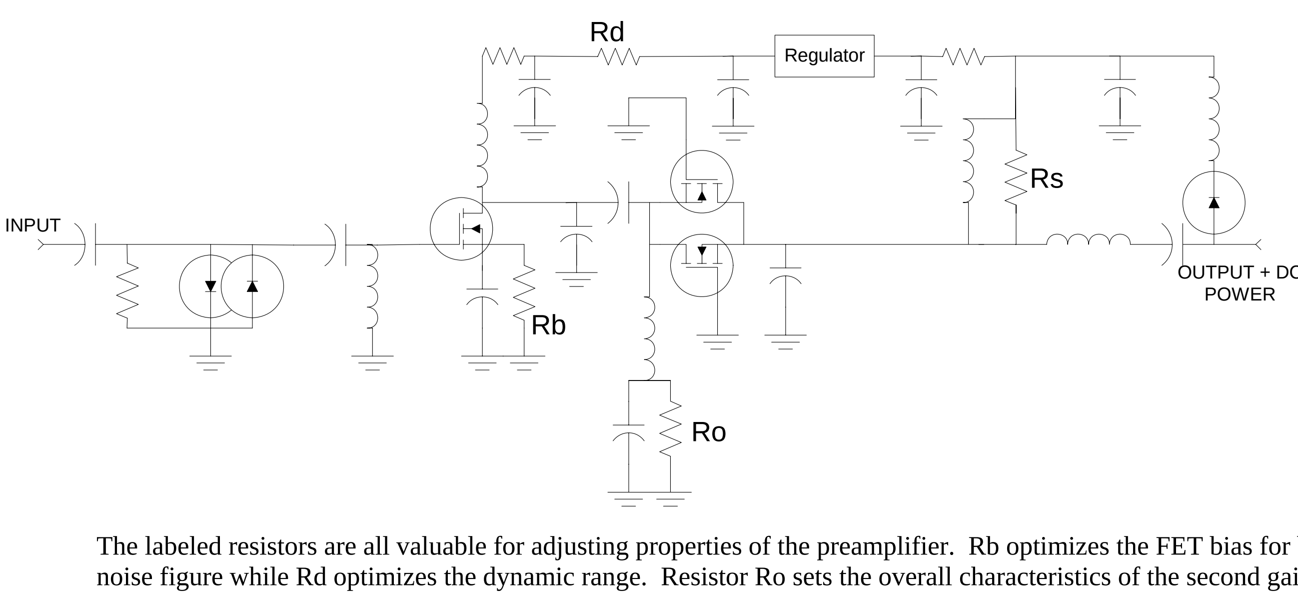
Consider the voltage delivered to the FET in the low impedance preamplifier case, compared to a 50 ohm case:

In the case of the low impedance preamplifier above, assume that Rp is 1 ohm and Xp is 250 ohms. These are feasible values, although the Q is quite high. To calculate the voltage across the FET, it will be assumed that the impedance of the FET can be ignored, and furthermore, approximations are used for Rp << Xp. The magnitude of the voltage at the resonant frequency across the FET input is then $\frac{250V}{51}$. In the case of the 50 ohm input the voltage is simply V/2. Thus the voltage is almost 10 times higher for the mismatched condition. Also interesting.

The figure below is a screen capture from a network analyzer showing plots of two different conditions. One condition is as discussed here, with a coil connected to a low impedance preamplifier. A shielded loop is used to excite the coil and the plot is the effective transfer function from the loop to the output of the preamplifier. The associated plot is the one with the low flat response around the frequency of interest. The second condition is the same except with a 90 degree phase shifter inserted between the coil and preamplifier. This results in a narrow band response as shown. The coil is totally un-decoupled as if it were freely resonating.



The overall configuration of the basic low impedance preamplifier can be observed from US patent #4,835,485. The following schematic is based on this design.



The labeled resistors are all valuable for adjusting properties of the preamplifier. Rb optimizes the FET bias for best noise figure while Rd optimizes the dynamic range. Resistor Ro sets the overall characteristics of the second gain stage and Rs controls gain vs stability of the output stage. Much of the schematic above is related to the biasing operations of the preamplifier. The simplicity greatly increases by making a schematic in which all RF chokes are replaced by opens and RF shorting caps (DC blocks) are replaced by shorts.