Integrated Detection, Amplification and Wireless transmission of MRI Signals Using a Parametric Amplifier

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Motivation

It has long been a practice in the magnetic resonance community to use small implantable coils for localized spectroscopy [1] and imaging and there is growing interest in catheter coils for interventional MRI [2]. There has also been recent interest in using wireless or optical transmission of signals after amplification of the MRI signal [3]. In the case of implanted or catheter coils, it has been necessary to run wire from the coil to the preamplifier sometimes over long distances leading to sensitivity losses. Mutual inductive coupling has been utilized between the internal coil and an external pick up loop, however, this can introduce losses especially when the receive coil is implanted in tissue. It may be advantageous if there was a way to amplify the MRI signal and in a wireless manner so as to maximize signal to noise. Here it is demonstrated that amplification can be accomplished as part of the receive coil with a completely wireless strategy using a parametric amplifier [4]. The first generation device has significant gain (25 dB) and satisfactory noise figure (1.5 dB) and could transmit with excellent signal to noise ratio over large distances. There is potential to minimize the size of the device to be used in a transplantable device or as part of a catheter coil to detect MRI signals with higher sensitivity.

Method

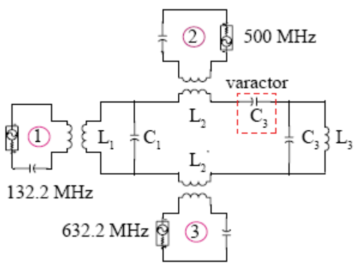

Figure 1. Circuit diagram of integrated coil and parametric amplifier

To build the integrated MRI detector/parametric amplifier, a triple frequency resonator was constructed as illustrated in Fig. 1. Three L-C meshes are assembled to resonate at 132.5 MHz for MRI signal detection of sodium at 11.7 T, 500.5 MHz for use by the receiver and 631.5 MHz which is the pumping frequency for the parametric amplifier. The Q of the unloaded resonator at each frequency was 119, 79 and 77 respectively. The three resonances are chosen such that the pumping frequency is approximately the sum of the signal frequency plus the detection frequency. The L_1 is the sample coil, while C_3 is a varactor (Skyworks Inc, Woburn, MA) which performs frequency mixing with parametric gain. There are also three single resonance loops which inductively couple with the triple frequency resonator at each frequency. Loop 1 resonates at 132.2 MHz to excite the sodium spins, loop 3 resonates at 632.2 MHz to provide pumping power to the varactor, and loop 2 resonates at 500 MHz loop to pick up the up-converted MRI signal.

Result

The basic performance with critical coupling of loop 1 and loop 2 to the triple frequency resonator was assessed with a two-port measurement. Loop 1 is only needed for Na excitation, and it can be replaced with a detunable transmit coil. Loop 3 is weakly coupled with the resonator at about -27 dB transmission, and the pumping power is empirically maximized to avoid oscillations. Under the optimal pumping power, the parametric amplifier had a noise figure of 1.5 dB and a gain of 25 dB. (The intrinsic noise figure is 3 dB down from 4.5 dB, which is the read out value from a noise figure meter, to remove the noise contribution from loop 1 which is critically coupled.)

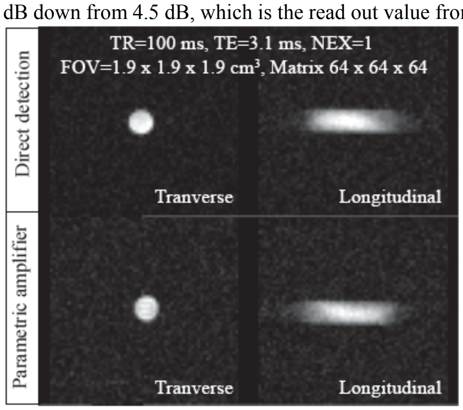

Figure 2. Na 3D FLASH image slices

The entire circuit was placed into an 11.7 T horizontal magnet (Magnex Inc, Oxford, UK) and ^{23}Na images were obtained. The output loop was kept at critically coupled position, and the pumping frequency was set to 632.7 MHz to set the observation frequency at 500.5 MHz, which is off-resonance from the residual water in the sample but within the bandwidth of the system receiver at 500 MHz (Avance 3, Bruker Inc, Billerica, MA). Figure 2 shows the 3D FLASH images obtained on a 1 M NaCl/D_2O solution contained in a 3 mm tube. The images are acquired by both direct detection with a single resonance sodium loop (top panels) and by the parametric amplifier (bottom panels). The parametric amplifier had about 93% sensitivity as compared to the direct detection of sodium.

Finally, the sensitivity profile was measured as the output loop was moved away from the triple frequency resonator. Fig. 3 shows the sensitivity comparison using different pumping frequencies. The horizontal axis is the ratio of distance separation over the size of the coupling loop, and the vertical axis represents the relative sensitivity, which is expressed against a reference of direct detection by a single tuned sodium coil of the same size as L_1. The S/N here is measured from a one pulse spectrum. In this figure, the bottom two curves plot the transmission coefficient between the resonator and the coupling loops at 132.2 MHz and 500 MHz respectively. These two curves correspond to the sensitivity profile at each frequency when no parametric gain is present. In comparison, the sensitivity becomes much better in the presence of parametric gain. At each pumping frequency, we maximize the spectrum intensity to optimize signal to noise. Higher pumping frequencies require a higher optimal power level. The sensitivity reaches a maximum at a pumping frequency of 634.7 MHz, when the intrinsic oscillation frequency of the parametric amplifier overlaps with output frequency. Under this condition gain is maximal and the signal can be detected very far from the sample (>0.4 m). It is likely that the 500 MHz signal has coupled to various possible transmission pathways from inside to outside the magnet. This interesting feature can potentially be utilized to couple the amplified signal to travelling wave detectors MRI [5] for better detection sensitivity.

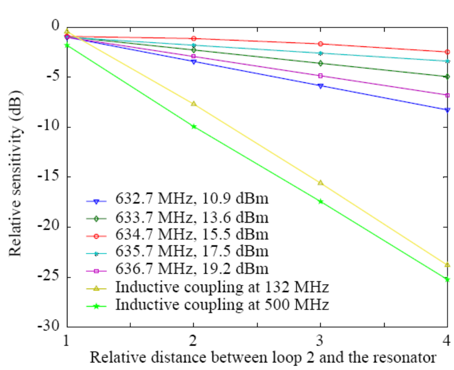

Figure 3. Distance dependent sensitivity

Conclusion

An MRI coil has been integrated with a parametric amplifier to achieve completely integrated wireless signal amplification and transmission. This detection scheme might benefit the design of implanted or catheter MRI coils. In addition the ability to modulate the detection frequency may have applications to receiver arrays. Future work includes the construction of parametric amplifiers with higher output frequency and smaller dimension.

Reference

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