# Local and Remote Parametric Amplification of Magnetic Resonance Images

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**Abstract**

Simultaneous detection and amplification of magnetic resonance images is demonstrated using a lumped-element three-frequency parametric amplifier. A design is presented for intrinsically safe parametric amplification in internal imaging using a remote amplifier with signal transfer by magneto-inductive waves.

## 1. Introduction

High signal-to-noise ratio is crucial for high resolution in magnetic resonance imaging. Parametric amplification can provide high gain with a low noise figure, using a small number of components located inside the detecting element itself. Here we demonstrate local amplification of MR images using a lumped element circuit and propose the modifications needed for intrinsically safe internal imaging, based on remote amplification of signals transferred by magneto-inductive cables.

## 2. Local parametric amplification

Fig. 1a shows a three-frequency parametric amplifier, which consists of three resonators operating at signal, idler and pump frequencies $\omega_S$, $\omega_I$ and $\omega_P$ such that $\omega_P = \omega_S + \omega_I$. Currents at these frequencies circulate separately through the resonators, mixing only in a common path containing a varactor [1].

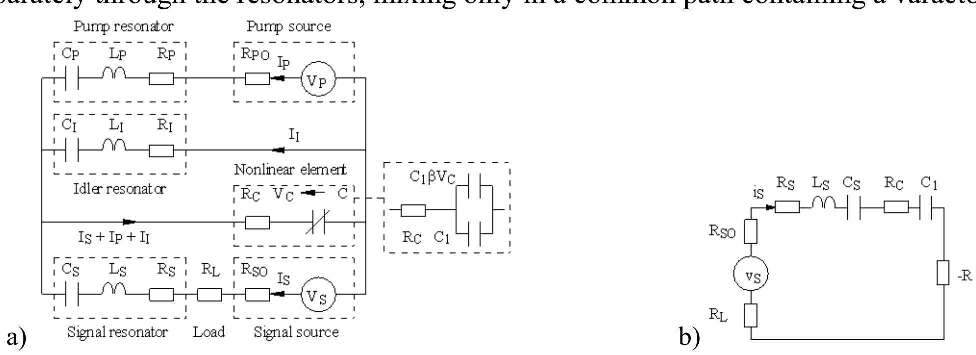



Fig. 1 a) Three-frequency parametric amplifier and b) equivalent circuit for high frequency idler.

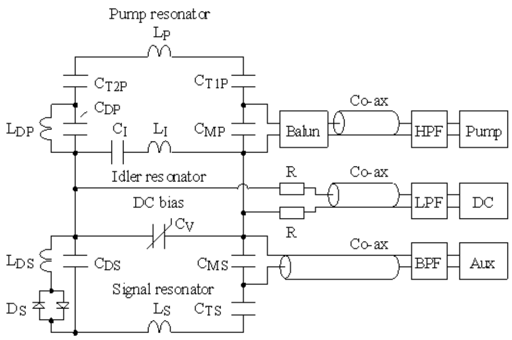
If the circuit is correctly tuned and the idler frequency is high enough, the effect is to insert into the signal loop a negative resistance whose value is proportional to the pump power (Fig. 1b). The gain is:

$$G = (R_S + R_{SO} + R_C + R_L) / (R_S + R_{SO} + R_C + R_L - R) = 1/(1 - P/P_{osc}) \tag{1}$$

Here P is the pump power and $P_{osc}$ is the power needed for oscillation.

## 3. Experimental image amplification

A parametric amplifier based on an L-C signal resonator tuned to the Larmor frequency can simultaneously detect and amplify magnetic resonance signals. However, several modifications are required for use in a MR scanner, including protection against direct coupling to the transmitter and elimination of ground loops. Fig. 2a shows the schematic and Fig. 2b the experimental realisation of a PCB based amplified detector, designed for operation at 63.8 MHz signal frequency (to allow $^1$H MRI in a 1.5 T magnetic field) and 100 MHz pump frequency. The circuit has a fixed, signal frequency tank in the pump loop, a similar, diode-switched tank in the signal loop and a balun-coupled pump.

a) 

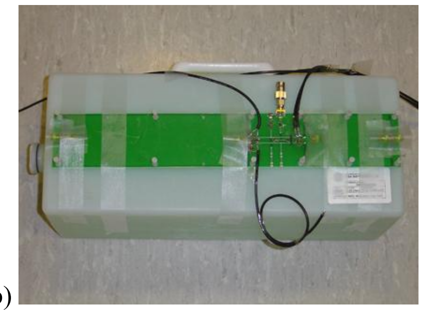
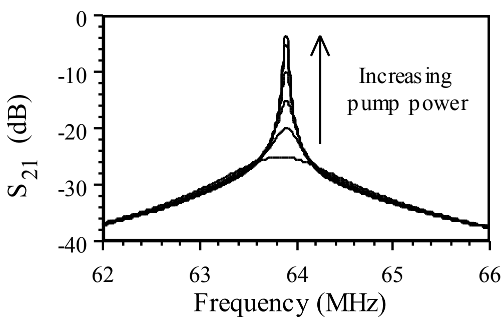

b) 

Fig. 2 Parametrically-amplified MRI detector: a) schematic and b) experimental device.

Fig. 3a shows the frequency variation of detection sensitivity at different pump powers. There is a steady increase in Q-factor and gain as the pumping rises. Fig. 3b shows the variation of experimental signal gain with pump power, which shows good agreement with the prediction of Eqn. 1 (assuming P= = 14.2 dBm) and demonstrates a maximum gain of around 25 dB.

a) 

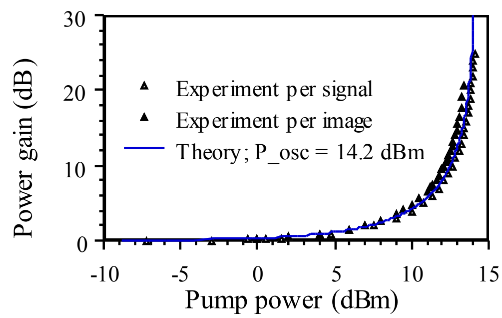

b) 


Fig. 3 Experimental amplifier performance: a) frequency response at different pump powers; b) gain characteristics.

Fig. 4a shows the arrangement for imaging a large cuboid phantom in a GE Signa Excite scanner at St Mary's Hospital, Paddington. The system body coil was used for transmission and the amplified coil for MR signal detection. A $T_2$-weighted fast spin-echo sequence was used, with TR = 800 ms, TE = 91 ms, a flip angle of $90^o$, a 200 mm FOV and an echo train length ETL =12. Low noise, artefact-free images were obtained. Fig. 4b shows a sagittal MR image obtained without pumping, and Fig. 4c shows the corresponding image obtained with the amplifier pumped to around 20 dB power gain. Numerical values for gains were extracted from the images obtained at different pump powers and are shown superimposed on Fig. 3b. There is excellent agreement with the previous electrical measurement and also with theory.

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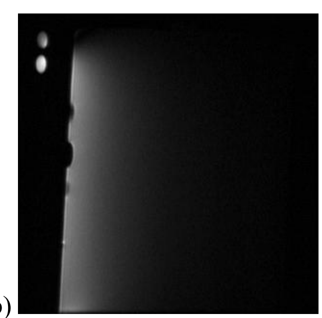
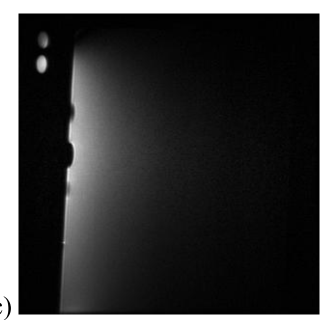
b) 
c) 

Fig. 4 a) Arrangement for magnetic resonance imaging; b) un-pumped and c) pumped images of phantom object.

## 4. Remote parametric amplification

Close-coupling of a small detector is key to high-resolution imaging of several internal organs. Unfortunately, safety issues are likely to prevent internal use of a parametric amplifier. Here we

ISBN 978-952-92-7734-6

propose the use of remote amplification, by coupling an internal detector to an external amplifier using intrinsically safe cable such as a magneto-inductive waveguide [2]. Fig. 5 shows a suitable arrangement, which consists of N L-C resonators, each of length a. Element 1 acts as the detector while element N contains the load, with the amplifier being represented by a negative resistance.

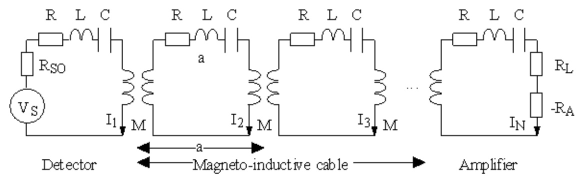



Fig. 5 Remotely pumped detector with a magneto-inductive interconnect.

Defining the parameters $\omega_0^2 = 1/LC$, $u_S = v_S/j\omega L$, $\kappa = 2M/L$, $Q_{SO} = \omega L/R_{SO}$, $Q_L = \omega L/R_L$, $Q_A = \omega L/R_A$ and $1/Q_T = 1/Q_{SO} + 1/Q_L - 1/Q_A$, the load current can be written in dimensionless form as:

$$i_N = \frac{(\kappa/2)\sin(ka)\,u_S}{\{(1/Q_{SO})(1/Q_L - 1/Q)\sin([N-1]ka) - (\kappa^2/4)\sin([N+1]ka) - j(\kappa/2Q_T)\sin(Nka)\}} \qquad (2)$$

The propagation constant $k = k' - jk''$ satisfies the dispersion equation $\{1 - \omega_0^2/\omega^2 - j/Q\} + \kappa\cos(ka) = 0$. For a loss-less system, resonance occurs when $k'a = \nu\pi/(N+1)$ where $\nu = 1, 2 \ldots N$ is the mode number. Each mode may be amplified. For low initial loss, the gain is approximately:

$$G_\nu = (R_{SO} + R_L + \alpha R) / (R_{SO} + R_L + \alpha R - R_A) = 1/(1 - P/P_{osc,\nu}) \qquad (3)$$

Here $\alpha = (N + 1)/\{2 \sin^2(\nu\pi/[N+1])\}$ is a weighting factor that describes the effective resistance seen by each mode. The gain $G_\nu$ and oscillation power $P_{osc,\nu}$ are mode-dependent. Since $\alpha$ has a minimum value $(N + 1)/2$ when $\nu = (N + 1)/2$, i.e. at mid-band, this mode will oscillate first. Figure 6 compares un-pumped and pumped responses of an 11-element system, with $Q_{SO} = Q_L = 25$ and $\kappa = 0.5$ a) without and b) with loss defined by Q = 100 in the MI cable. In Fig. 6a, the modal gains are all equal, and in Fig. 6b the mid-band mode is preferentially amplified, so the system should operate on this mode for high gain.

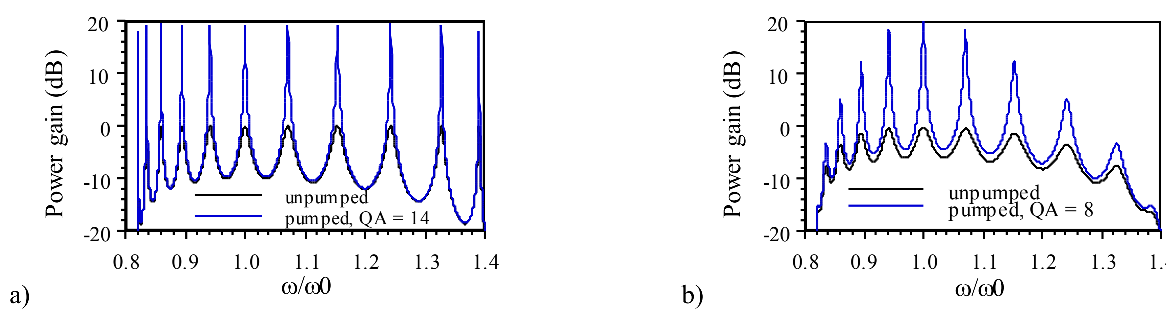



Fig. 6 Remote parametric amplifier: responses with and without pumping for a) loss-less and b) lossy MI waveguide.

## 5. Conclusions

Parametric amplification has been shown to allow high-gain local amplification of MR signals, while metamaterial interconnects and remote amplification can allow intrinsic safety in internal imaging.

## Acknowledgements

The financial support of the Leverhulme Trust is gratefully acknowledged.

## References

[1] Howson D.P., Smith R.B., "Parametric amplifiers" McGraw Hill, New York, 1970
[2] Shamonina E., Kalinin V., Ringhofer K., Solymar L. "Magneto-inductive waveguide" *Elect. Lett.* Vol 38, pp 371-373, 2002