An Automated Cartesian Feedback Transceiver for Use in High Magnetic Fields

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Introduction

The potential advantages of the Cartesian feedback (CF) method of MR instrument design have been described previously [1-3]. In particular, the ability to decouple an array of transmitting and/or receiving coils has elicited considerable interest. Two years ago [4] we presented a partially completed, balanced, digitally controlled, multi-nuclear (10 – 1000 MHz) CF transceiver functioning in the strong field surrounding a magnet bore entrance. The emphasis was threefold: a 500 W MOSFET RF power amplifier; 40 dB blocking of induced, transmissive coil current over maximal bandwidth, and construction of a Universal Serial Bus (USB) digital control interface. Much work, however, remained: a pre-amplifier and transmit/receive (T/R) switch; system integration, software development, etc.. We here report the successful execution of the NMR experiment at 123.2 MHz with a full instrument immersed in a 2 T field and controlled by the well-known mathematics software *Mathematica* [5]. With a probe of loaded Q-factor 20, 40 dB of current blocking (decoupling) was attained over 20 kHz in transmission and over 160 kHz in reception.

Pre-amplification

A poster in 2008 [6] at this conference warned of possible loss of gain and noise figure with GaAs field effect transistors (FET's) in magnetic fields. This is due to Hall effect and the warning is in accord with scattered publications. Upon measuring the gain of FET's routinely used in our institute, we confirmed in magnetic fields > 2 T an orientation dependence, and therefore searched for an alternative device. This was found in a 40 GHz SiGe *bipolar* transistor, Infineon BFP740. It has a noise figure of 0.6 dB at 123 MHz and fixed gain in any orientation in fields as high as 7 T. With an added 300 W PIN diode T/R switch, the noise figure degraded to 0.7 dB; the pre-amplifier's current blocking ability was ~ 20 dB depending on probe matching minutiae, while the switch had an isolation ~65 dB and an insertion loss of 1 dB.

Design Philosophy

Any feedback system can oscillate if the feedback loop phase is incorrect and/or the product of loop gain and bandwidth is excessive. To protect both a patient and the RF power amplifier from the excessive energy inherent in transmissive oscillation or bad pulse programming, much effort was expended in designing a hardware shut-down system. Given the human propensity for error, it was also considered imperative to have computer control of the instrument so that all gains, phases and bandwidths could be both measured and appropriately and safely set *automatically* in both transmission and reception under any experimental circumstance. It was this imperative, with the need also to minimise group delay, that drove the use of baseband quadrature signal detection (QD) and modulation: all required measurements can be made on direct voltages, greatly simplifying and speeding the instrument set-up procedure. However, the papers on QD published in the 1960's and 70's are essential reading. They discuss placing spectra to one side of the frequency origin and the additional transmitter power and bandwidth needed; methods for reduction of origin peaks and "ghosts" – software and pulse sequence orthonormalisation techniques that with modern computers are easy to implement, etc..

Implementation

The *Mathematica* software [5], with its highly structured interpretive language rooted in plain English commands (e.g. our function 'CFFeedback["On"]'), was used for instrument control on a Linux-based host in conjunction with a programmable micro-controller communicating with *Mathematica* via the *MathLink* protocol [5]. With this combination, the mathematical calculations and programmes needed to measure and set feedback phase, gain and bandwidth were easily implemented.

Results

Transmission: 40 dB current blocking with a 500 W MOSFET RF amplifier over a 20 kHz bandwidth was attained with a probe having a loaded Q-factor of 20. Linearization of the transmitter by feedback results in formidable power performance at low price (the power amplifier cost only ~ $1000). Figs. 1 and 2 show that as power is increased, changes of B_1 field amplitude and, in particular, phase, associated with change of transistor capacitance with voltage and the heating of transistors and probes, are virtually removed. It follows that the instrument is ready for use shortly after having been turned on.

Reception: Fig. 3 essentially plots probe current versus frequency with the aid, for traces *a* and *b*, of small driving and sensing coils. To improve sensitivity, traces *c* and *d* use the pre-amplifier output; *c* was scaled to touch *b* at 123 MHz. The results demonstrate 40 dB current blocking over a bandwidth of 160 kHz – a performance unattainable with pre-amplifier blocking alone. These specifications for transmission and reception suffice for experiments on any commercial phased-array MRI instrument. We now turn our attention to applying the CF method to human phased-array imaging at 11.7 T in collaboration with NeuroSpin, Gif-sur-Yvette, France.

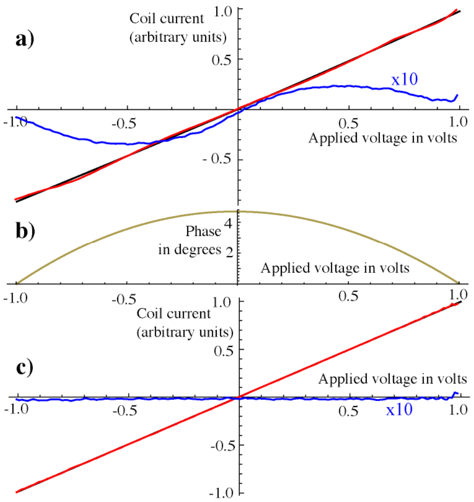

Figure 1. Transmission with a ramp pulse.
a) Normalised 0^o (red) and 90^o (blue) probe currents and b) fitted current phase, versus drive voltage; no feedback. c) 0^o and 90^o current *with* feedback. The phase variation is negligible (~ 0.05^o) and is not shown. The maximum RF power was 125 W.

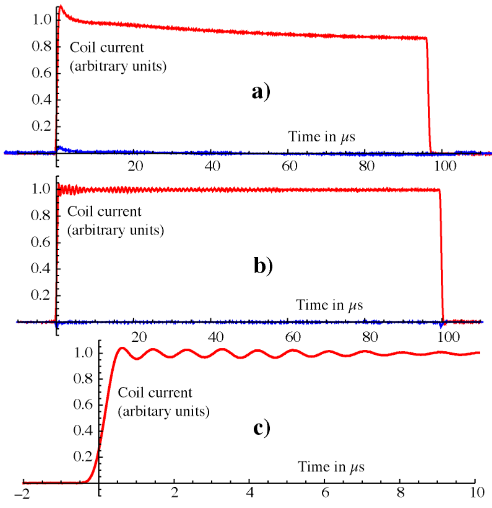

Figure 2. Transmission with a rectangular pulse.
a) Pulse droop due to component heating with a nominal 125 W pulse is corrected b) by 40 dB feedback with a 10 kHz filter. The ringing [b) and detail c)] implies the gain-bandwidth limit is being approached.

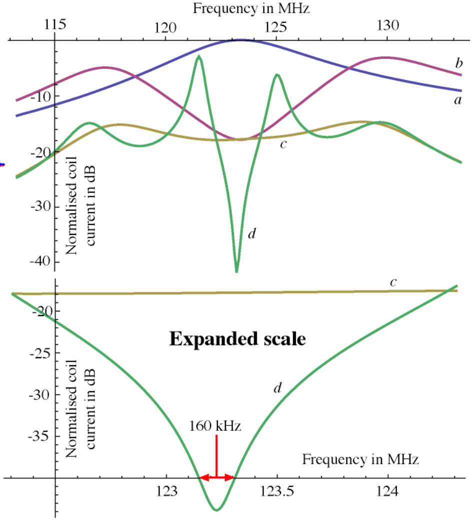

Figure 3. Receptive current blocking, probe Q = 20.
a) Isolated coil current vs. frequency; b) with the pre-amplifier attached giving 18 dB current blocking. Both plots used sense coils. c) The scaled pre-amplifier output and d) with 25 dB feedback added using a 100 kHz filter. Blocking is > 40 dB.

References

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