Designing a Transmitter and Receiver for Use in Strong Magnetic Fields

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Introduction

With increasingly high MRI magnetic fields, the use of phased arrays yields great cabling complexity while MR transmitters and receivers must be situated further from the magnet resulting in significant cable losses during transmission and greater potential for the reception of interference. A paper (1) in last year's Conference began to address such issues, with mixed success, using wireless transmission of the radio-frequency (RF) FID signals. A radical alternative is to place the entire RF section of the instrument close to the magnet, and then transmit and receive low-frequency signals using proven digital techniques – fibre optic transmission, Bluetooth-protocol wireless transmission, etc..

Now our work on Cartesian feedback (2) aims to render practical phased-array transmission. Increased bandwidth has been shown to be desirable, but long cable lengths thwart this goal. Thus again, but with greater urgency, a spectrometer close to the magnet is needed. Apart from power supplies, conventional RF electronics is kept in a low field because of the ubiquitous presence of ferrites. They play an essential role in mixers, tuned circuits, filters, splitters, combiners, etc. and proposing an instrument that does not use them is radical. Nevertheless, we have embarked on a programme to do just that and report here on progress.

Basic Building Blocks

RF Integrated Circuits: A new line of tiny RF integrated circuits for cell (mobile) phones from Analog Devices Inc. (3), with bandwidths over 2 GHz, paved the way for progress. The product line's attraction lies in increased dynamic range and lack of second order distortion, but overwhelmingly in its balanced amplification and signal handling. An example illustrates why this feature is so attractive.

A conventional receiver's intermediate frequency amplification– "the "IF strip" – comprises several gain stages resulting in high overall gain, e.g. 60 dB. Because the amplifiers are unbalanced, power rail IF current flows, and thus the first amplification stage must be heavily decoupled from the last if oscillation, caused by power rail feedback, is not to occur. Thus a typical rail layout has power flowing from the last stage to the first through a chain of ferrite decoupling filters. With balanced amplification, however, negligible IF rail current flows and so *stringent* decoupling is unnecessary. Ferrite chokes can then be replaced with air-cored inductors.

Inductors: We have found that inductors wound on small, commercially-available toroidal Teflon formers have surprisingly small distributed capacitance and hence a high self-resonant frequency, as well as good Q-factor (>200 typical). Use of a cone inductor, comprising several such toroidal windings of progressively shrinking diameter can form an effective replacement for ferrite chokes. Resistors can be added in parallel as necessary to spoil self-resonances.

Baluns and splitters: A broadband changeover from balanced to unbalanced operation and *vice versa* is now needed at some point – traditionally the domain of ferrite devices. Again, Teflon toroids are invaluable as formers on which miniature coaxial cable can easily be wound to produce effective broadband baluns/splitters.

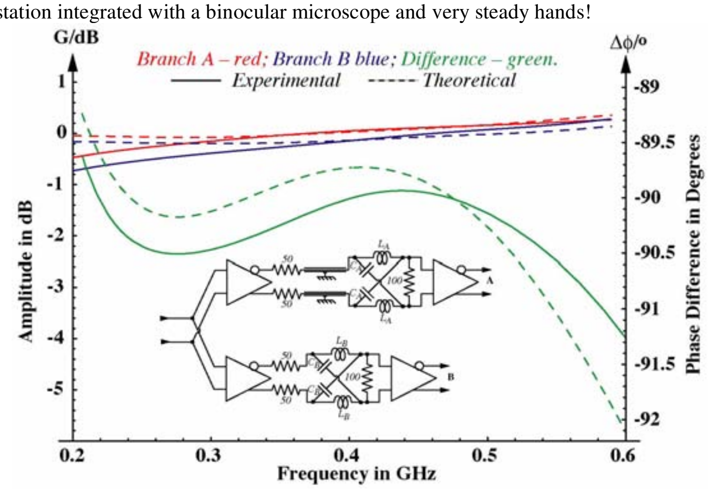
Broadband impedance transformers: Ferrite-based transformers are much-used in RF power amplifiers for impedance matching. However, we have found that coaxial line devices (Z_1:Z_2 = 4:1 and 9:1) can be successfully used. We continue research here, as we feel published bandwidth can be improved.

Results

Our first task was to develop a classic I-Q (quadrature) modulator (demodulator) that takes the balanced outputs of two digital-to-analogue converters (DAC's) and modulates a first IF of 20 MHz. (The Cartesian feedback method precludes digital IF generation at this juncture.) Two AD8343 Gilbert cell mixers were driven with balanced quadrature 20 MHz square waves derived from an 80 MHz source by division with ECL logic circuitry. The division circuitry was phase-stable. The constant-current balanced outputs of the two mixers were then connected in parallel and passed to a broadband, tuned toroidal transformer giving an isolated balanced output. Desired response and group delay were accomplished using numerical optimisation techniques in "Mathematica". When tested as a single sideband modulator by using equal sine and cosine signals from the two DAC's, the rejection of both carrier and unwanted sideband was found to be > 60 dB over a 2MHz bandwidth, a limit imposed by the speed at which the DAC's could be driven. This excellent result is an order of magnitude better than the typical performance of ferrite-based mixers.

Two such modulators create quadrature 20 MHz signals for single-sideband 2[nd] IF generation between 300 and 500 MHz. We reverted to analogue designs to generate quadrature RF references, but the availability of balanced signals opened up new design opportunities. Using again numerical optimisation techniques in "Mathematica", we found that a combination of two coaxial lines and two classic, balanced, all-pass circuits could achieve excellent results, as shown. The agreement between experiment and theory is good, given the normally-destructive effect of parasitics. However, readers are cautioned that fabrication of circuit boards to achieve such results requires a good computer-controlled micro-milling machine, a soldering station integrated with a binocular microscope and very steady hands!

A final example concerns the production of RF power. A balanced signal path lends itself naturally to the use of push-pull class AB power amplification, and using coaxial transformers we have been able to modify a well-known design using MRF151G MOSFET's to produce a 150 W amplifier with unbalanced output that covers a bandwidth from 125 to 175 MHz. This should be enough to power one element of a phased array, but we research coaxial combiners in case more amplifiers are needed. Such amplifiers require a power supply that can deliver high current for brief periods and rather than run very bulky cables from a power supply outside the magnetic field, we have opted to use batteries that are trickle-charged from without. The danger here, as opposed to the use of a rectification/capacitor power supply is that there is essentially no short-term limit on the current that can be drawn, so circuit breakers and fast blow fuses are essential.



Effective schematic of a wideband, balanced quadrature splitter and its gain and differential phase characteristics compared with theory.

Conclusion

It is clear that it is possible to construct a spectrometer that will function close to the magnet. In the process, considerable size reduction and enhanced performance is possible. It remains to confirm that a high-amplification, balanced IF chain can be satisfactorily constructed.

References

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2. D. I. Hoult, G. Kolansky, D. Kripiakevitch, S.B. King, J. Magn. Reson. **171**, 64, 2004 and previous article.
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