A Magnetic-Field-Tolerant Low-Noise SiGe Pre-amplifier and T/R Switch

D. I. Hoult[1], and G. Kolansky[1]

[1]Institute for Biodiagnostics, National Research Council Canada, Winnipeg, Manitoba, Canada

Introduction

GaAs field effect transistors (FET's) are common in pre-amplifiers for array coils; in common source mode, they combine a low noise figure with a large ratio of optimal source impedance to input impedance, making them apparently ideal for use in current blocking. However, a poster at this conference in 2008 [1] warned of possible loss of gain and noise figure in magnetic fields. The warning is in accord with scattered publications [2-4 are representative] and D.I.H.'s experience with the first GaAs FET's [5] in 1975. Hall effect is the culprit. In constructing a Cartesian feedback instrument for use in high magnetic fields, we check all components in fields up to 7 T, and in measuring the gain of FET's routinely used in our institute, confirmed in fields greater than 2 T a dependence upon orientation. The dependence is a function of electron mobility and conductor length; thus one would expect silicon bipolar devices to function well to fields > 7 T, albeit with poorer noise figure. Now there is a "rule of thumb" that the greater the ratio of the cut-off frequency of any transistor to its operating frequency, the better the noise figure is likely to be provided flicker noise is inconsequential. We therefore investigated SiGe bipolar transistors for they can operate at frequencies as high as 40 GHz. We report here on the successful employment of Infineon BFP740 (transition frequency $f_T \sim 40$ GHz) at 123 MHz, but anticipate that it will be useful over the entire MR frequency range.

Methods

Preamplifier: The transistor's scattering (S-) parameters were first characterised in common emitter mode up to 1.5 GHz, the limit of our network analyser, and then converted to transmission (ABCD) matrices for use with numerical optimisation tools in *Mathematica* [6]. At 123 MHz, the transconductance was $0.14–0.009i\ \Omega^{-1}$ and resonance analysis gave an input impedance of 1.54 k Ω in parallel with 1.5 pF. An initial estimate of optimal source resistance was made with a simple single-transistor amplifier: the collector load to + 5 V was 50 Ω coupled to a commercial low noise amplifier, and base capacitance was tuned out with an inductor at 123 MHz. A.C. coupling was used on base and collector and care was taken to keep all trace lengths as short as possible. Various surface-mount resistances were then connected between the base and ground and the noise output measured as a function of resistance. The data were fitted to a standard model of transistor noise [7] and an optimal source resistance of 100 Ω was returned. (During later noise figure measurements with hot/cold sources, this value was found to be accurate.) Thus current blocking of 1.54 kΩ /100 Ω ~ 24 dB was anticipated. In progressing to trial amplifier designs, it became apparent that the transistor easily oscillated at frequencies far beyond the limits of our measuring equipment. This was inferred by the antiquated method of monitoring the collector current as a finger was pressed on various circuit parts. A small surface-mount capacitor (a few pF) connected as tightly as possible between collector and emitter in conjunction with resistive collector loading < 150 Ω cured the problem but it is stressed that trace inductances must be the absolute minimum possible. A shield that bisects the transistor is also advisable. Cartesian feedback demands minimal group delay, which negates the use of simple collector tank circuitry. Instead, a π-section network was used to couple to a low-noise PNP output transistor as shown in Fig. 1. Note that the biasing of the first transistor is passed through the network in a feedback configuration. Noise matching from a 50 Ω source was accomplished conventionally with variable capacitors $C_1$and C_2 and inductor L_1. With the transistor removed and resistor R_1 = 100 Ω temporarily in place, the capacitors were adjusted for an input impedance of 50 Ω. Resistor R_1 was then removed, the transistor replaced and capacitor C_1 replaced with a fixed value. Finally, the design was optimised in *Mathematica* for gain, flatness, bandwidth and stability using the Rollett stability criterion.

Transmit/Receive Switch: The switch in Fig. 1 is a nominal quarter-wave design using low-loss semi-rigid 50 Ω cable and is designed to handle 300 W of RF power at 123 MHz. The line lengths shown are the results of simulation but did not need adjustment. When transmitting, all PIN diodes are conducting. When receiving signal, line 2 and PIN diodes P_2 and P_3 form a T-section attenuator that greatly reduces leakage of noise into the pre-amplifier. *Set-up*: Line 1: with P_1 conducting or shorted and P_2 removed, line 1 is adjusted for maximum impedance at the probe terminal. Line 2: with P_1-P_4 conducting and P_5 reverse-biased, C_3 is adjusted for maximum insertion loss from transmitter to probe; Line 3: with all diodes conducting C_4 (high voltage) is adjusted for minimal insertion loss. Note that ordinary diodes are placed on the first transistor base for further power protection. For compactness, the lines were wrapped into coils – that coupled with switched field gradients! Each green ground connection in Fig. 1 was therefore actually four 1 nF capacitors in parallel with 22 Ω resistors. Finally, the switch and pre-amplifier were mounted in an internally copper-coated plastic case. The copper's thickness was adequate for RF screening but thin enough to give only minor eddy currents and torque.

Results

No observable field dependence at 7 T. Spot noise figure at 123 MHz: with T/R switch 0.7 dB, without 0.6 dB. Gain: 30 dB over 73 to 163 MHz (-3 dB). Group delay: 5.4 ns. Overload recovery: time constant = 2 µs, but with onset of first-transistor conduction, feedback hastens recovery. T/R switch: isolation ~65 dB, insertion loss: ~1 dB. Current blocking: probe dependent, 18 – 22 dB with T/R switch.

Conclusion

A suitable replacement for GaAs pre-amplifier FET's has been found.

References

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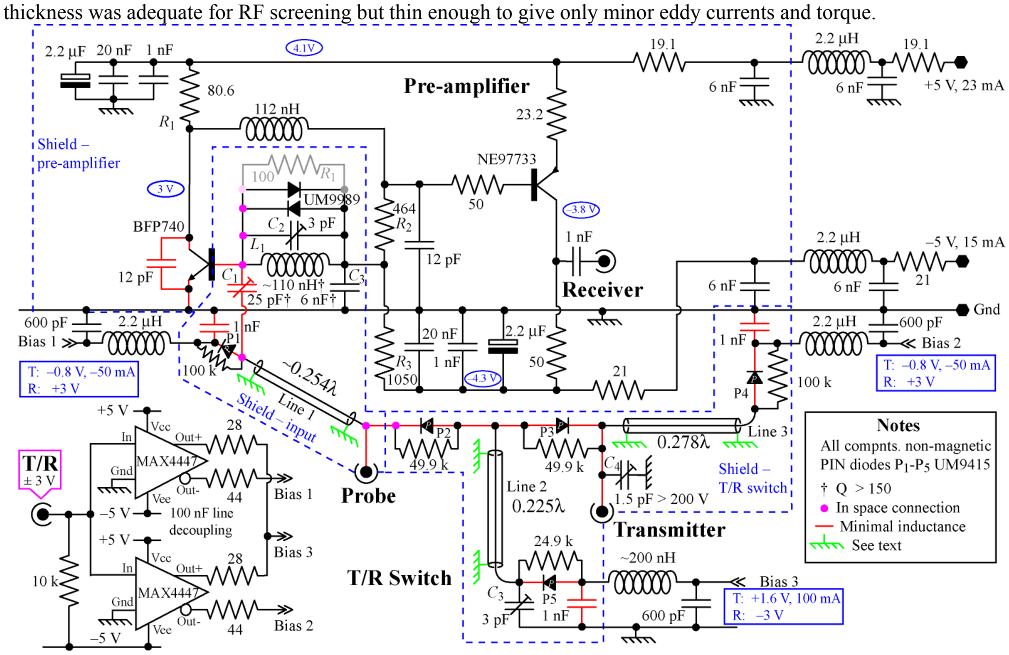

Figure 1. The circuit diagram of a magnetic-field-tolerant pre-amplifier and transmit/receive switch for 123 MHz.