AWG Developments

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We note several developments that we made to our home-built pulse EPR spectrometer that are motivated out of necessity. Mainly these developments aim at improving the receiver sensitivity as well as the fidelity of the pulse-synthesizing unit. The issues hindering our spectrometer are as follows (1) a low frequency baseline signal that is prohibitive to DEER spectroscopy, (2) a high noise figure of the detection electronics (~5.5 dB), and (3) a low power microwave leakage from the pulse synthesizer.

# Microwave detector

We have made several changes to the microwave detector in our pulse EPR spectrometer. We show an updated schematic of the detection electronics, Fig 1, note the new incorporations are highlighted in red. Specifically we have incorporated; wide bandwidth video amplifiers and high pass filters to account for the low frequency baseline, a new high-power fast recovery limiter (Herotek – XX) and a high-isolation microwave switch (General Microwave – XX) to reduce the dead-time of the detector, and a new low noise amplifier to lower the overall noise figure of the detector.



Figure : Schematic of the microwave detector. The high power (1 kW) microwave pulses as well as the spin system signal come in as “signal” shown on the far left.

### Low frequency baseline issue

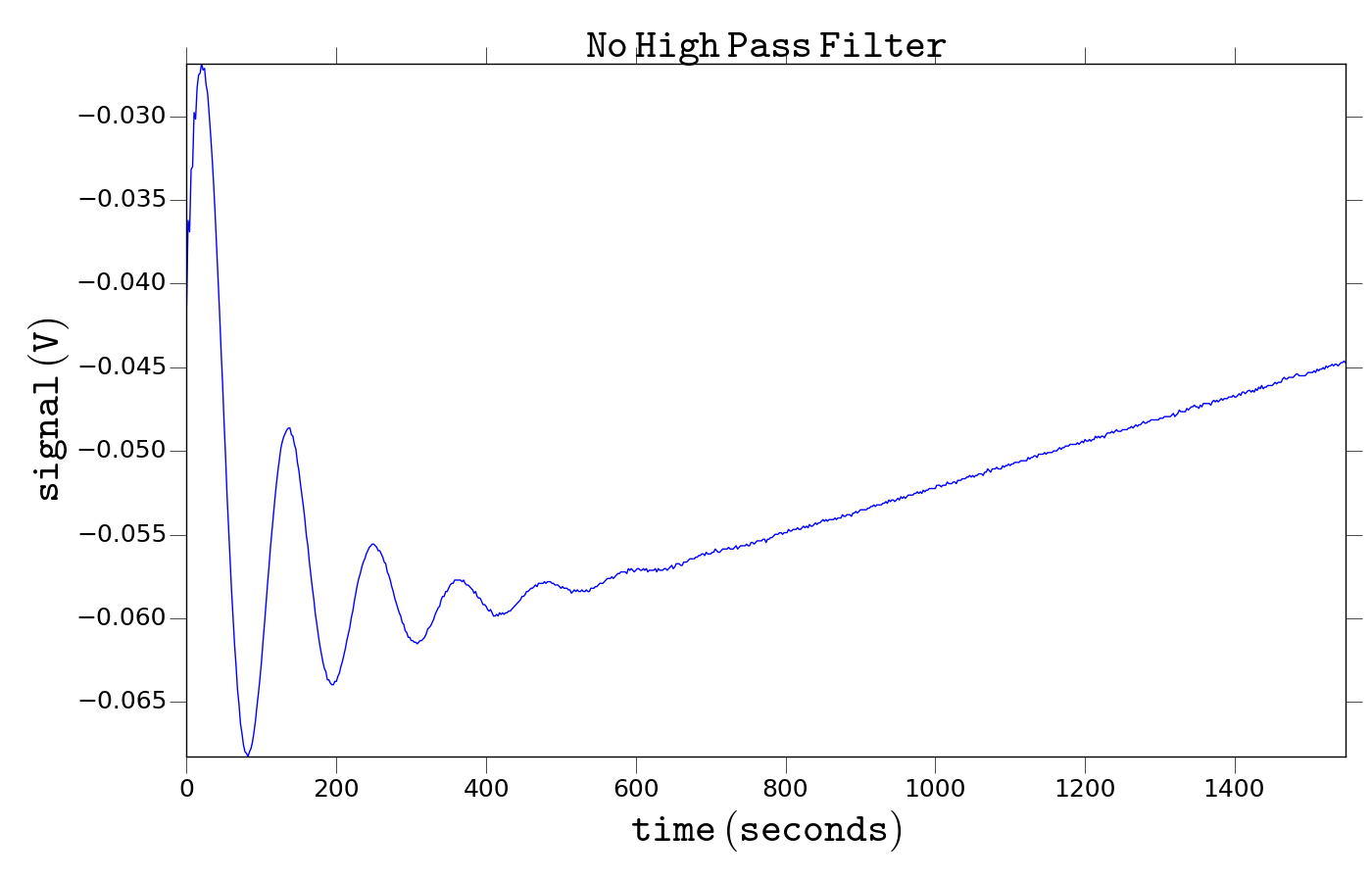
The receiver suffered from a low frequency baseline issue. We previously noted this being caused by the power saturation and long recovery time of the microwave limiter. However we found this was actually caused by the low frequency bound on the bandwidth of the video amplifiers inserted after the IQ mixer in the heterodyne detection system. This previously prevented the detection of EPR signal without off resonance background subtraction as the low frequency baseline did not cycle with the phase of the microwave excitation pulse preventing the full applicability of a phase cycling scheme. A representative dataset of signal taken on solid BDPA is shown to illustrate how the microwave baseline does not cancel out after a +x -x phase cycling scheme, Fig 1. 

Figure : Phase cycled free induction decay signal from solid BDPA. The non zero baseline component is not removed by the +x -x phase cycle of the excitation pulse. This indicates that the baseline is not microwave ring-down but in fact due to the detection electronics.

To solve this issue we inserted higher bandwidth (0.1 - 1000 MHz) video amplifiers (Mini Circuits ZFL-1000LN+) and 25 MHz high pass filters (Mini Circuits SHP-25+) to filter off any low frequency oscillation. We also used the DAC boards to modulate the excitation pulse by 150 MHz relative to the carrier microwave frequency to prevent the attenuation of EPR signal by the high pass filters, a phase cycled FID shown in Fig 3. This produced a high fidelity signal, Fig 4, we show the comparison of EPR signal with and with-out the high pass filters in place. We see both a large DC offset, indicated by the spike at zero frequency, as well as a negative spike at the minus frequency both issues are not seen in the signal taken with the 25 MHz high pass filters in place.

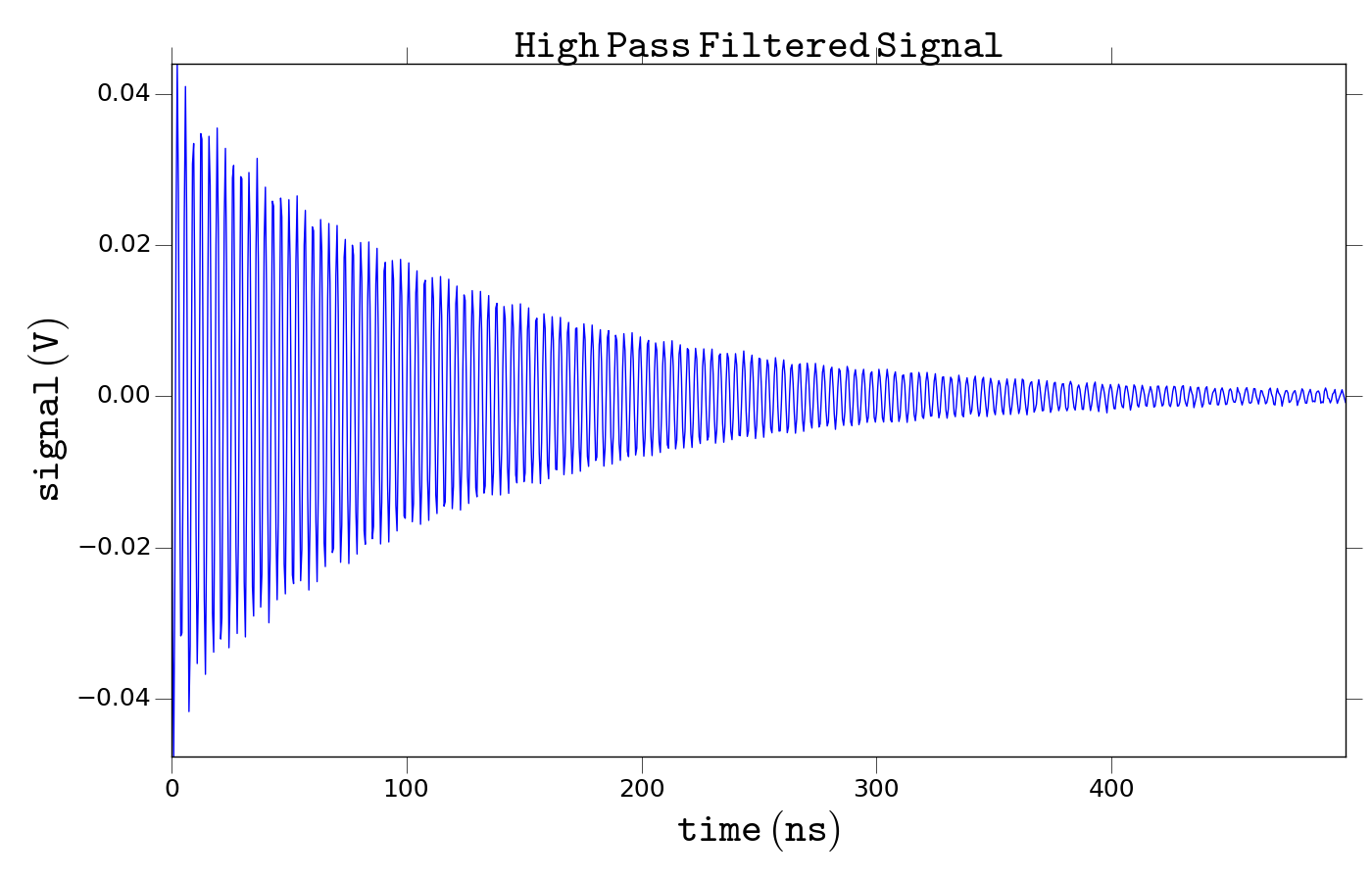


Figure : Phase cycled FID from BDPA taken with the 25 MHz high pass filters in place. Note that the excitation pulse is modulated by 150 MHz relative to the carrier frequency such that the high pass filters do not attenuate the EPR signal. The high pass filters do indeed remove the low frequency baseline.

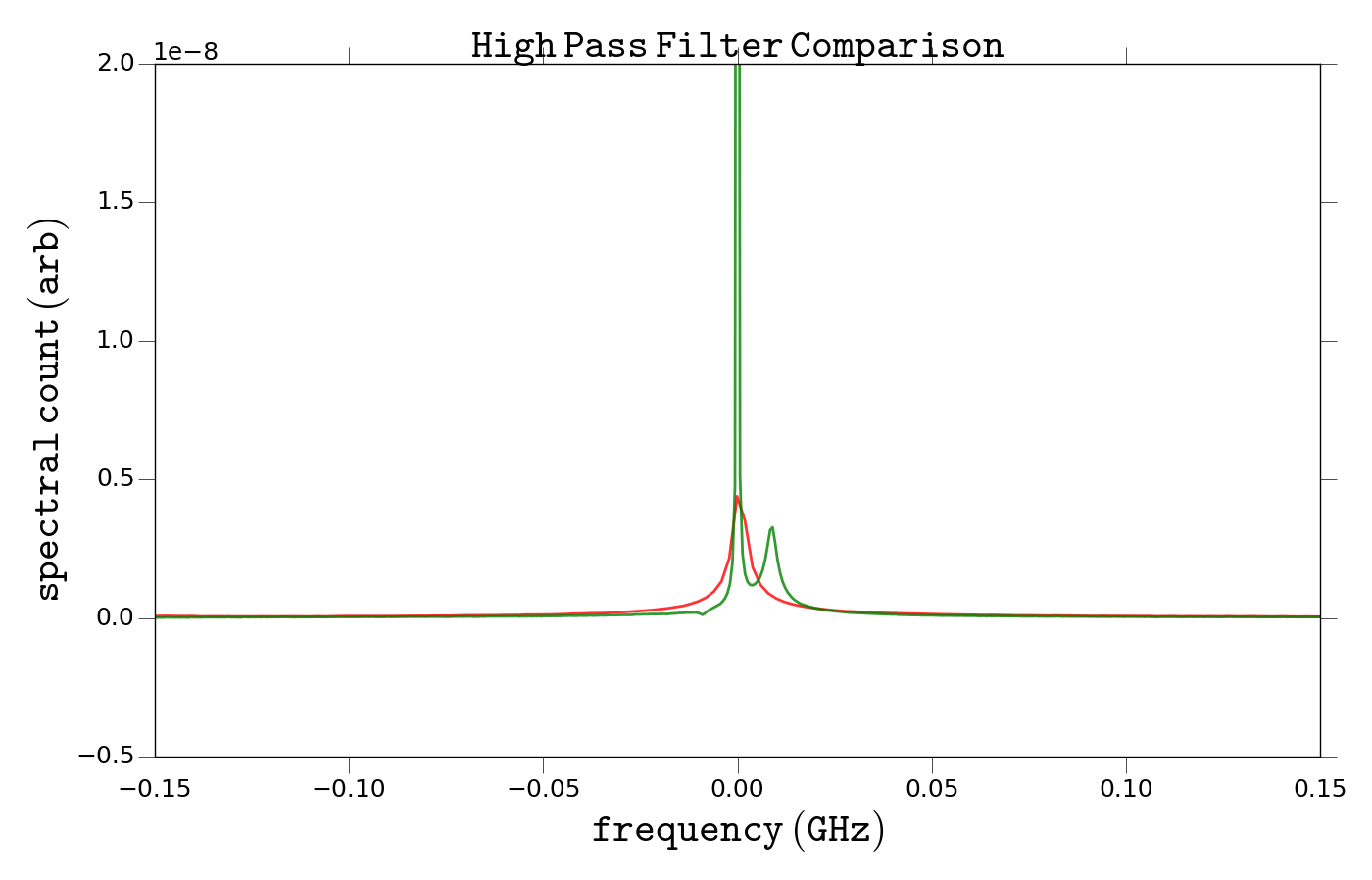


Figure : Comparison of EPR spectrum taken with (red) and without (green) the high pass filters in place. The signal taken with the high pass filters in place is left shifted by 150 MHz to overlay with the signal taken without the high pass filters. The large spike at 0 Hz in the signal taken without high pass filters is due to the non-zero baseline.

### Dead-time reduction

We previously mentioned purchasing a high power tolerance fast microwave switch that could handle a 1 kW pulse and recover within 10 – 100 ns. We pursued this idea further with Miteq but unfortunately the cost was prohibitively high at $20k for engineering costs as Miteq would have to develop the architecture for a one-off product. Once we determined this option was no longer possible we decided to go with a high power limiter and a fast microwave switch.

Before the incorporation of the Herotek limiter and General Microwave switch the dead-time of the detector was approximately 300 ns, mainly due to the recovery time of the old Aeroflex limiter. Now with the incorporation of the new electronics it is feasible to recover signal within 100 ns after a high power microwave pulse and a completely over-coupled resonator with minimal switch artifacts.

### High Noise Figure of Detection Electronics

Before modification we found the noise figure of the microwave detector was ~5.5 dB relative to thermal noise at zero frequency. In the ideal case the noise figure should be about 3 dB. We inserted a low noise figure LNA (Miteq AMF-3F-09001000-08-8P), with a noise figure of 0.8 dB and a gain of 34 dB, to try and combat this issue. The noise figure of the microwave receiver was negligibly improved to 5.5 dB by the addition of a new low noise amplifier, Fig 5.

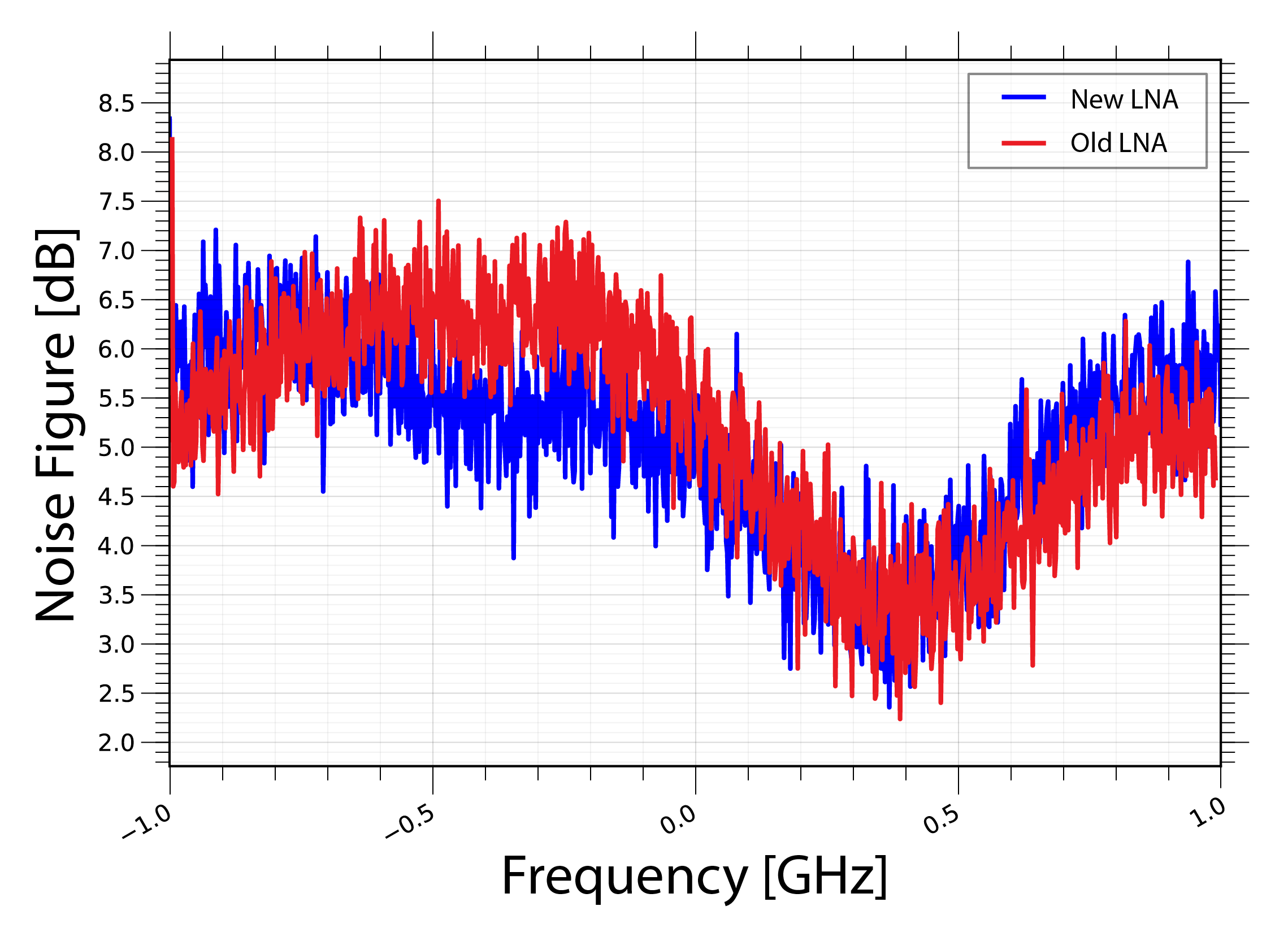


Figure : Comparison of the receiver noise in frequency domain with the two LNAs blue (0.8 dB noise figure) and red (1.3 dB noise figure).

# Microwave Synthesizer

The microwave synthesizer is controlled by the digital to analog converter (DAC) board which provides significant control on the output waveforms however the design is dependent on an IQ mixer which suffers from microwave leakage, when the DAC is set to put out zero power or no pulse there is a low power microwave leakage through the IQ mixer. Previously we accounted for this by an algorithm that determines optimum offsets for the I and Q channel to minimize this leakage however we still suffered from a – 40 dBm microwave leakage, which after amplification with the TWT was sufficient to perturb the spin system dynamics. We solved this issue by placement of a high isolation microwave switch after the IQ synthesizer, shown in red in Fig 6. We found the best isolation is achieved with the switch placed after the IQ synthesizer. xThe switch improves the fidelity of the microwave pulses reducing the microwave leakage to at or below – 80 dBm. A sample waveform is shown in Fig 7.



Figure : Schematic of the microwave synthesizer. The high isolation switch is shown in red.

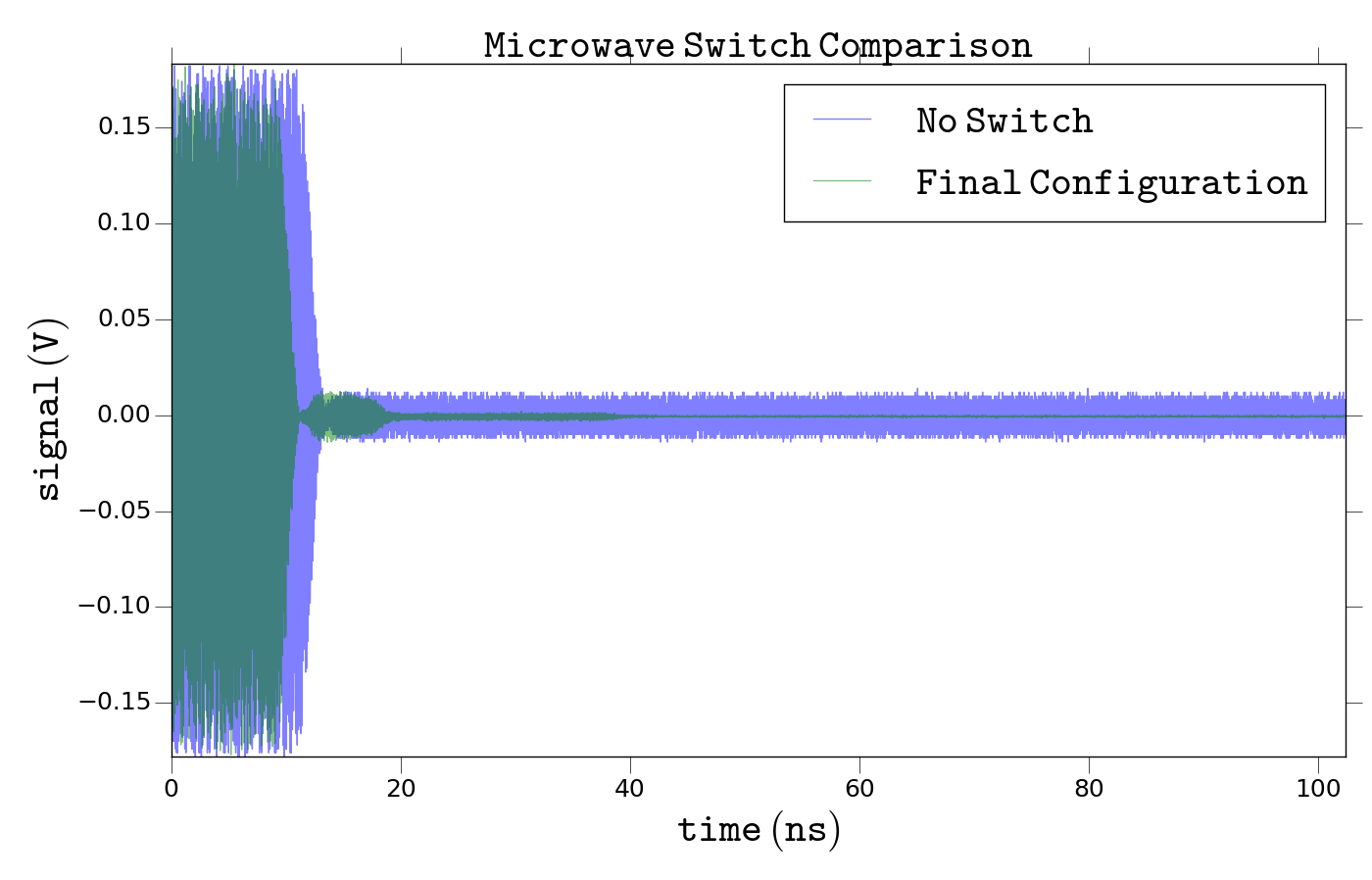


Figure : Comparison of the microwave pulse taken with (green) and without (blue) the high isolation microwave switch. The small blip that shows up in the green trace is a switching transient, a consequence of using the microwave switch.