Phase Measurements of a 140 GHz Confocal Gyro-Amplifier

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Abstract: *The phase stability of a 140 GHz, 1 kW pulsed gyro-amplifier system and its dependence on the cathode voltage were experimentally measured. The phase was determined to be stable both pulse-to-pulse and during each pulse. The phase shift with voltage was measured and found to be ~130°/kV, in agreement with simulated results.*

Keywords: gyro-amplifier; phase stability; DNP-NMR.

Introduction

A 140 GHz pulsed gyro-traveling-wave-tube (gyro-TWT) amplifier has been developed at MIT for pulsed Dynamic Nuclear Polarization Nuclear Magnetic Resonance (DNP-NMR) spectroscopy [1]. The gyro-amplifier uses a confocal geometry to achieve an overmoded interaction circuit with reduced mode competition and is designed to operate without severs. The confocal gyro-amplifier operates in the confocal HE_{06} mode and demonstrated a peak circuit gain of 35 dB, a bandwidth of 1.2 GHz, and a peak output power of 550 W at 140 GHz.

An approach for improving DNP efficiency is the exchange of continuous wave microwave irradiation for short, strong pulses as a means of increasing the bandwidth of a DNP experiment without increasing average power [2]. By sending a tailored train of pules into the gyro-amplifier, a high-power train can be generated for use in the spectrometer. Control over the phase of the microwaves could allow even broader bandwidths through manipulation of the electron spins [3]. While generating the pulses and controlling the phase is done by the input source, it is important to verify that the relative phase between pulses is not altered during amplification. For this approach to be successful, the phase must be stable to within 10°.

Other phase-sensitive applications include coherent radars, communication systems, accelerators and linear colliders. Thus far, the phase stability of gyro-amplifiers (or any amplifier) has only been measured up to W-band. Existing techniques are challenging above W-band because of limited components, such as the balanced mixer, and high ohmic loss in fundamental waveguide.

Methodology

A schematic of the diagnostic setup is given in Figure 1. The 2 μs, 140 GHz radio frequency (RF) pulsed input is generated by an extended interaction oscillator (EIO) and is split by a beam splitter prior to entering the amplifier. The diverted branch of the RF is fed into the local oscillator (LO) port of the balanced mixer, via a variable attenuator and a phase shifter. The amplifier output is fed into the RF port of the mixer via a variable attenuator. The use of both attenuator is to ensure that the signal reaching the mixer are equal and within its operating parameters.

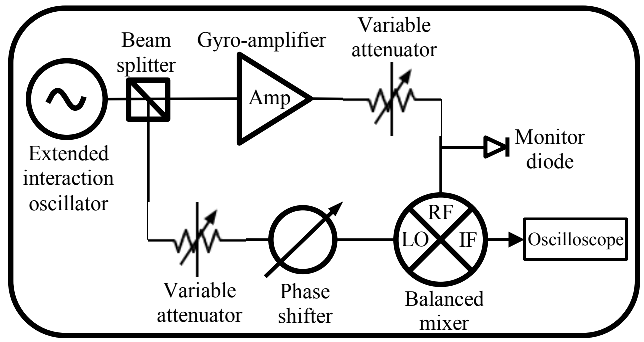

Figure 1. Schematic of the diagnostic setup for phase shift and phase stability measurements.

The mixer's intermediate frequency (IF) output is given by $f_{IF} = |f_{RF} - f_{LO}|$. Since the RF and LO frequencies are split from the same source, they are identical and $f_{IF} = 0$. Therefore, the IF output is a DC voltage, with its value a function of the phase difference between the RF and the LO. Calibration of the DC voltage with respect to phase change was achieved by recording many measurements with identical experimental parameters (cathode voltage, beam current, magnetic field, etc.) and varying the phase shifter (see Figure 2). A sine wave was then fit to measured results and provided the mixer's phase response.

By repeating this sequence of measurements and fitting sine waves at different cathode voltage, as seen in Figure 2, the phase shift as a function of voltage, $d\phi/dV$, was determined. Performing many (~10) measurements at a fixed voltage and phase shifter setting provided the phase stability of the gyro-amplifier (Figure 3).

Results

Figure 2 presents a single session of measurements, in which three voltage settings were measured. All other experimental parameter were fixed, namely the frequency, the magnetic field $B = 5.08$ T, the beam current $I = 1$ A, the input power level, the gun coil current and the ratio of the mod-anode voltage to the cathode voltage in the triode gun.

The error bars represent the standard deviation of the set of measured mixer outputs at each given setting, and are mainly the result of small fluctuations in the cathode voltage and beam current. The shaded areas show the uncertainties of the sine wave fits and were calculated to include all the measured data points. $d\phi/dV$ was calculated from these fits and found to be 130 ± 30°/kV. Additional measurement sessions gave similar values for $d\phi/dV$.

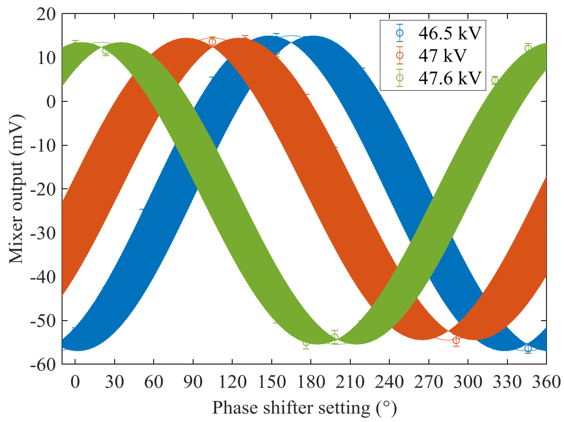

Figure 2. Mixer DC output as a function of phase shifter setting measured at three cathode voltages. The smooth curves show sine waves fitted to the data, with the uncertainties in the fit represented by the shades areas.

Figure 3 demonstrates a set of measurements taken with fixed experimental parameters. It is clear that the output is varying between shots. This variation corresponds to a spread of 7.35°. However, examination of the cathode voltage and beam current traces of these shots reveals jitters in their values. Indeed, the small jitters in the cathode voltage of ±48 V alone can cause phase variations of up to 12.5°. Furthermore, when examined closely, the flat top of the voltage trace in each individual is seen to fluctuate slightly, corresponding to the fluctuating mixer output traces. We therefore conclude that the Gyro-amplifier is extremely stable shot-to-shot, to the extent that its operating parameters are stable. Using the device with a more reliable voltage modulator and with a flatter voltage trace would provide a remarkably phase stable amplifier.

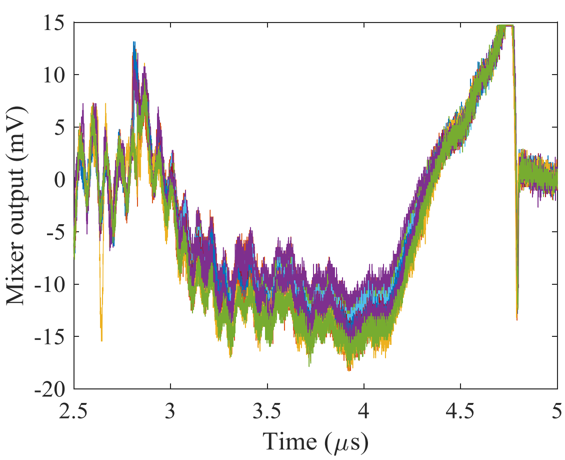

Figure 3. Mixer outputs of 11 shots with fixed parameters.

The output of the amplifier was measured with a calibrated diode at several voltage setting. The loss introduced by all passive elements was also calibrated. This gave us the ability to estimate the gain of the amplifier with the experimental parameters and compare with simulated predictions. MICHELLE simulations provided the beam radius in the cavity (2.1 mm), the velocity spread (6%) and the beam pitch angle, α (6.3 at 47 kV). These values were then used in Maryland Gyrotron (MAGY) simulations that predicted the gain and phase variation, which were compared with the measured values.

Obtaining a good fit to both the measured gain and the phase variation required that the variation of α with voltage be 0.03 per kV, while keeping $\alpha = 0.63$ at 47 kV. This value is larger than predicted by MICHELLE or adiabatic theory. The difference can be explained by a non-adiabatic behavior of the gun and by minute differences between the simulated and the actual magnetic field profile, which may arise from a shift in the gun coil position. Moreover, the gun performance could be affected by the deterioration of the cathode over time. Indeed, a witness plate study of the beam profile showed that the annular beam exhibits hot spots and discontinuities along its circumference. Further investigation of the gun is needed to fully establish the beam parameters.

The simulations predict a phase variation of ~120°/kV, well within the error of our experimental results.

Summary

We have measured the phase difference between the 140 GHz, 2 μs input pulse, generated by an EIO and the output of the gyro-amplifier. This phase difference was found to be stable as long as the operation conditions, mainly the electron beam voltage and current, are maintained. The variation of the phase with beam voltage was found to be 130 ± 30°/kV. This is in good agreement with MAGY simulations that predicted ~120°/kV.

Acknowledgements

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References

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