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A NMR Parallel Q-Meter with Double-Balanced-Mixer Detection for Polarized Target Experiments

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A NMR PARALLEL Q-METER WITH DOUBLE-BALANCED-MIXER

DETECTION FOR POLARIZED TARGET EXPERIMENTS

by

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ABSTRACT

A constant-voltage, parallel-tuned nuclear magnetic resonance (NMR) circuit, patterned after a Liverpool design, has been developed for polarized target experiments. Measuring the admittance of the resonance circuit allows advantageous use of double-balanced-mixer detection. The resonant circuit is tolerant of stray capacitance between the NMR coil and the target cavity, thus easing target-cell-design constraints. The reference leg of the circuit includes a voltage-controlled attenuator and phase shifter for ease of tuning. The NMR output features a flat background and has good linearity and stability.

For experiments using polarized targets, the accuracy of the polarization measurements strongly affects the precision of the experiments, since the figure of merit is the polarization squared times the intensity (number of free protons). In the past we have used a conventional parallel-tuned Q-meter circuit and corrections calculated by J. Hill and D. Hill[1] to obtain the polarization. Using this method, the polarization can be measured to ~6%. An important circuit parameter was the size of the amplitude modulation compared to the carrier wave, often referred to as $\Delta V/V$. As $\Delta V/V$ is made smaller, the error decreases, as does the signal-to-noise ratio. A common way of reducing $\Delta V/V$ is to spoil the Q; but as the circuit Q approaches 1, the circuit performance degrades and can cause considerable problems in tuning. The stability of our Q-meter circuit in regard to temperature and resonance frequency was less than desirable and resulted in long-term drifts affecting values obtained for the target polarization.

As an improvement on the above circuit, we have developed a nuclear magnetic resonance (NMR) circuit based on the use of a double-balanced mixer (double-balanced demodulator) described by the Liverpool group.[2] The Liverpool approach avoids any dispersion corrections by splitting the radio-frequency (RF) voltage from a signal generator into RF reference and sampling voltages. The sampling voltage goes to a resonant circuit, is amplified, and then applied to a power splitter. One splitter output goes to the RF input of a double-balanced mixer. The other output goes to a microwave diode. The diode output is used to tune the resonance circuit and is also useful as an RF level monitor. The reference voltage is amplified, phase shifted, and applied to the local oscillator (LO) mixer input in phase with the mixer RF input voltage. The intermediate frequency (IF) mixer output contains only the absorptive (real) part of the NMR signal.

Figure 1 shows a circuit arrangement using a constant-voltage, parallel-tuned circuit. Our circuit minimizes the number of attenuators and amplifiers and includes features that simplify the tuning of the circuit. Isolation between the RF reference and sampling voltages is achieved by using a Mini-Circuits Laboratory (MCL) TDC 10-1 10-dB directional coupler, which has 35 dB of isolation between the two outputs. Termination of the directional coupler output to the resonant circuit is done in such a way that the source impedance (10 Ω) is small compared to the resonant circuit impedance, which implies a good constant voltage source. A handmade transformer samples the current in the resonant circuit and applies a voltage proportional to the current to an RF amplifier. The transformer is made using a 3-mm-diam form. One turn, the primary is wrapped on the form; then four turns, the secondary is wrapped symmetrically over the primary. The assembly is then removed from the form and potted using epoxy. The impedance of the primary is small (approximately 1 Ω), allowing the source impedance to the resonant circuit to remain small compared to the resonant circuit impedance.

A Watkins-Johnson (WJ)-G1 voltage-controlled attenuator on the reference side allows the adjustment of the RF levels to the reference and signal sides of the mixer. In the range of 0- to 25-dB attenuation, the phase change versus frequency is approximately 0.002°/MHz. The insertion phase shift is fairly constant from 0 to 10 dB of attenuation and increases 10° at 15 dB of attenuation. There is no change of attenuation versus frequency.

A Werlatone PSE3 voltage-controlled phase shifter in the reference arm eliminates the tedious task of constructing the correct length cable to give the in-phase condition at the mixer. The phase shifter has two outputs 180° out of phase from each other. When one output is used, the other is grounded. Each output provides ≈110° of phase shift for a control voltage range of 0 to +15 V. If the phase shift range is inadequate, a suitable high-frequency capacitor may be installed in series with the phase shifter to give a phase shift offset. The phase shift versus frequency is approximately 1°/MHz. The change in insertion loss versus frequency is negligible.

The mixer is a MCL SRA-1 double-balanced mixer. The power level of the reference RF applied to the LO port needs to be high enough to turn on the diodes. The recommended power level is +7 dBm. The pertinent specification is the conversion loss versus LO power. As the LO power decreases below +7 dBm, the conversion loss increases. A higher conversion loss means that the dc output of the IF that is proportional to the RF signal will be lower, implying a lower signal-to-noise ratio. A power level of over 11 dBm at the LO input will exceed the power rating of the mixer. The RF signal power level applied to the RF port of the mixer should be at -5 dBm or lower for linear operation. The higher the level (up to -5 dBm) the better the signal-to-noise ratio. Power levels above -5 dBm result in conversion loss compression, which implies nonlinearities. The mixer output at the IF port is a dc voltage plus harmonics of the signal generator frequency (≈106 MHz for a 2.5-T magnetic field). The harmonics are easily filtered out since the differential amplifier frequency response falls off rapidly above 500 kHz.

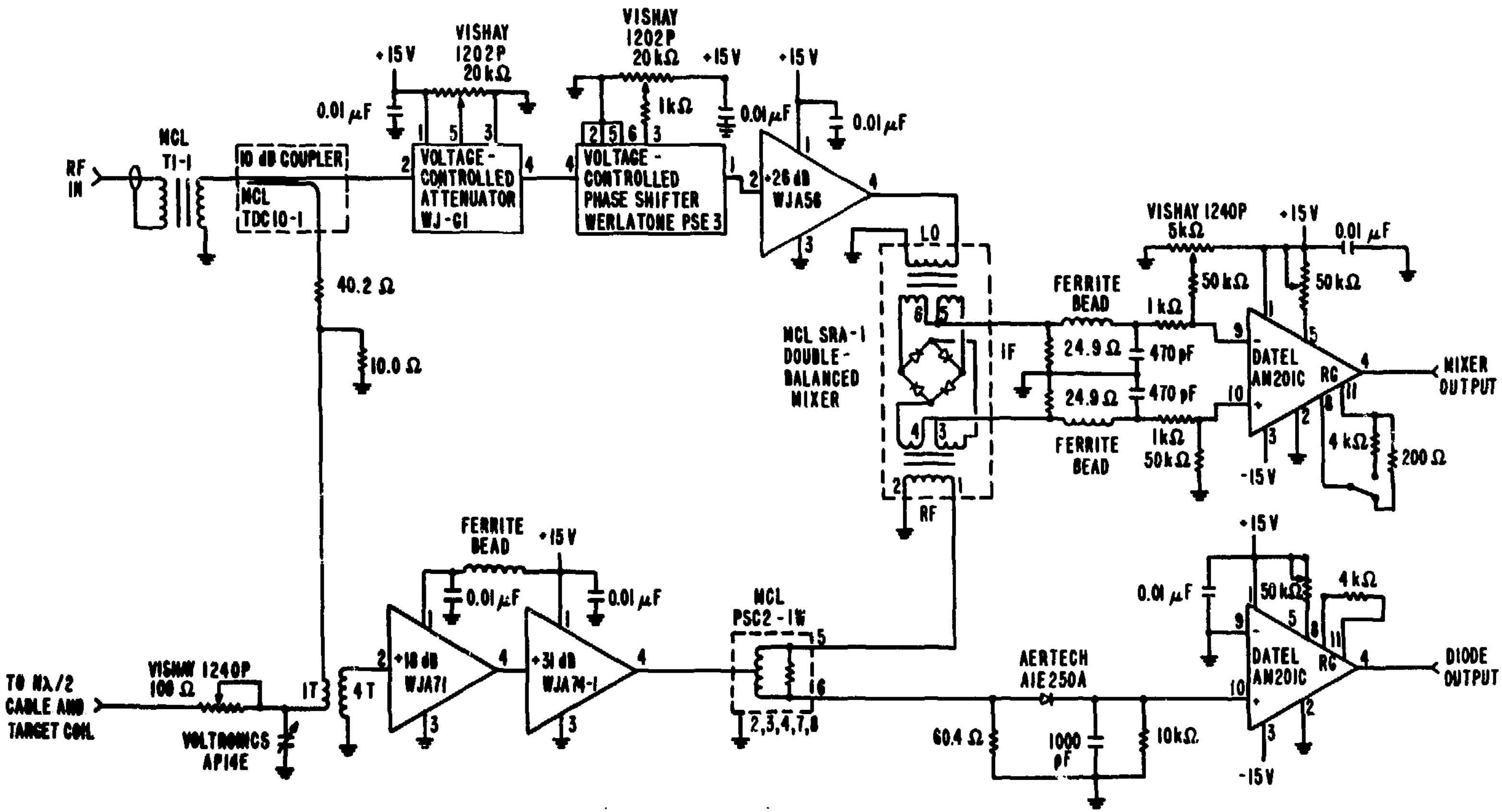

Fig. 1. A circuit arrangement using a constant-voltage, parallel-tuned circuit.

Some circuit features are incorporated to allow reasonable circuit performance in a noisy experiment environment. An isolation transformer at the RF input largely eliminates ground loop problems, which can cause silicon controlled rectifier spikes to be present on the NMR signal. The mixer output is terminated in 50 Ω (25 Ω each leg), filtered, and differentially amplified. A dc bias network allows the signal to remain dc coupled. The amplified mixer output goes to a unity gain isolation amplifier with differential outputs to greatly reduce 60-Hz noise problems encountered in transmitting the NMR signal 60 m to the experimental electronics trailer. A unity gain differential amplifier with good common mode rejection acts as a receiver for the mixer signal.

The box that holds the circuitry is machined from a single block of aluminum approximately 4 cm by 12 cm by 17 cm. Three compartments provide the means of mounting the three circuit boards: the RF reference board, the RF signal board, and the differential amplifier board. The box is mounted on a constant-temperature, water-cooled copper plate to eliminate temperature-related drifts in the output signal.

The mixer dc output voltage is proportional to V_{REF} by V_{SIG} by cos θ,[3] where θ is the phase angle between the RF reference and signal voltages. When the circuit is properly adjusted for the in-phase condition at the mixer, the cos θ term allows only the real part of the signal (the part in phase with the RF reference) to appear at the mixer output, thus eliminating corrections caused by the dispersive component. When the signal voltage is at a minimum at resonance, the cos θ term also flattens the resonance curve and thereby reduces or eliminates the need for a dummy circuit to provide an equal resonance curve, which then may be subtracted from the signal resonance curve. The combination of real-part detection and reduced curvature of the signal background leads to the choice of either a constant-current series circuit or a constant-voltage parallel circuit. Although harder to describe mathematically, a parallel circuit is much less susceptible to stray capacitance of the NMR coils in a target cell.

Two different RF signal boards were designed to allow comparison of a constant-current series circuit and a constant-voltage parallel circuit. The tuning of either unit is essentially the same. Observing the diode output while sweeping the signal generator frequency, we adjusted a Voltronics AP14E variable capacitor for circuit resonance at the center frequency of the sweep. Power levels to the mixer are adjusted to approximate values and the resonance is readjusted, if required. We observe the mixer output while the phase shifter is adjusted for the in-phase condition that occurs when the resonance minimum is at the center frequency of the sweep.

The amount of curvature in the background of an observed signal strongly influences the amount of amplification of a signal, especially when the curvature is large compared to the signal noise. To compare the "flatness" of the outputs of the NMR boxes, we measured the maximum and minimum voltages of the observed resonance curves for a centered curve (center frequency equal to the resonant frequency) with constant frequency sweep. For the constant-current series circuit, the mixer output voltage difference was approximately one-third of the voltage difference observed at the diode output. For the constant-voltage parallel circuit, the mixer output voltage difference was approximately one-tenth of the observed diode output voltage difference—considerably "flatter."

Compared with the old Q-meter circuit, the new circuit has a number of advantages. Elimination of dispersive corrections to first order allows larger values of $\Delta V/V$ (higher Q values) resulting in improved signal-to-noise ratios. Observing a water sample in a 2.5-T magnetic field, the signal to noise was improved by a factor of 2 under similar resonance conditions. Although simple in concept, a flat background shape using a dummy circuit is difficult to achieve and causes data reduction problems. The relatively flat background of the constant-voltage, parallel-tuned circuit eliminates the need for a dummy circuit and consequently reduces the problems in data reduction. One significant problem with the old Q-meter circuit was the transmission of the signal using an RF carrier on long coaxial cables. Unless the cables were very well terminated, reflections would diffract the resonant curve into multiple peaks. The change of cable length with temperature also contributed to this problem, which is eliminated by the new circuit.

The new NMR circuit has been successfully used in experiments at the Los Alamos Meson Physics Facility. Figure 2 shows a typical thermal equilibrium signal (at 1 K), which was made as follows. The signal was measured 256 times by a Fabritek signal averager. The magnetic field was then changed so the signal was not observable in the sweep range. In the subtraction mode of operation, 256 additional sweeps were taken. For 16 measurements, the standard deviation is typically less than 4% and the standard deviation of the mean is typically within 1%. Thermal equilibrium measurements made at different times a week apart are in agreement with statistical errors. No long-term drifts have been observed. Positive- and negative-enhanced polarization measurements agree at the ≈2% level for $\Delta V/V$ of 20%, indicating that circuit linearity is fairly reasonable.

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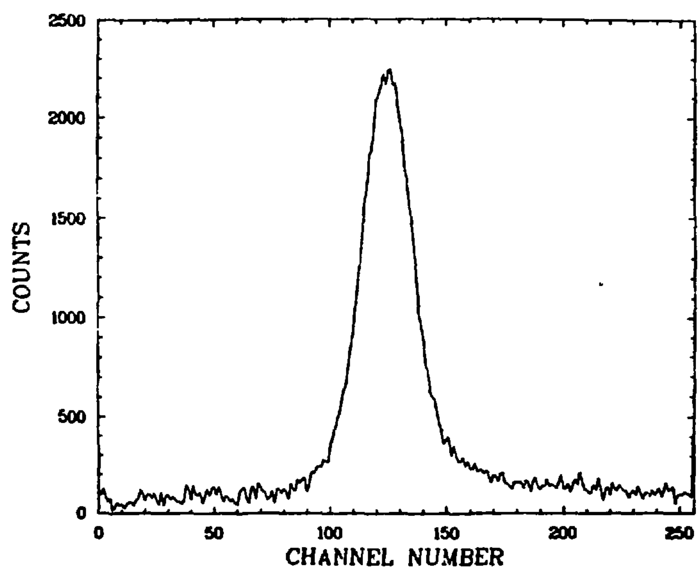

Fig. 2. Typical thermal equilibrium signal.

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