Third Sound Resonator Electronics

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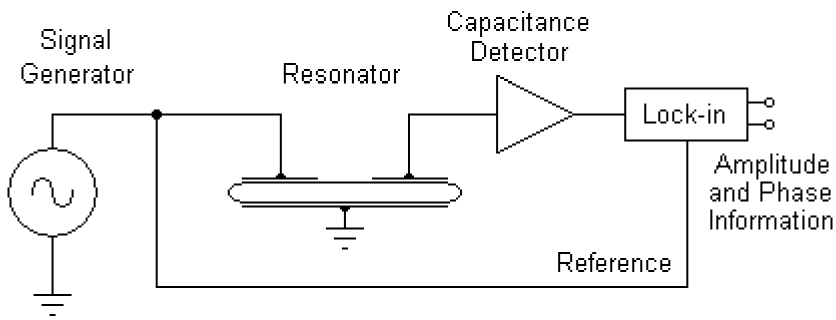
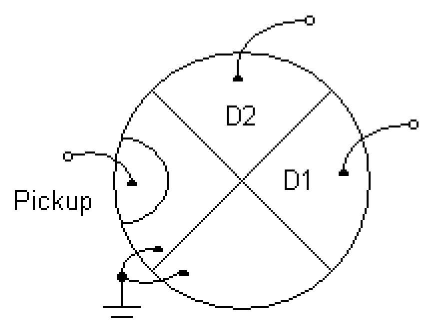
Overall Scheme



The goal is to detect film thickness sloshing inside of a resonating chamber. A signal generator applies an electric field of about $10^6 \cdot \frac{V}{m}$ to the film on two opposite surfaces inside one capacitor of the resonator. Changes in a second capacitance are converted to a voltage and detected with a lock-in referenced to the drive.

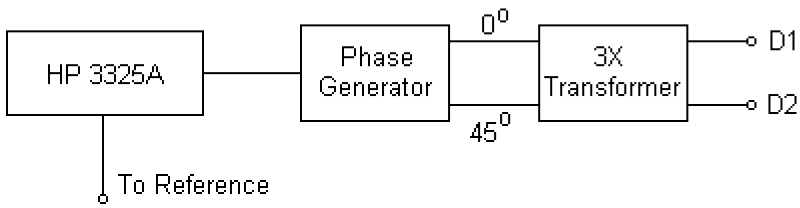
Drive

The third sound resonator consists of the superfluid film adsorbed onto the inner surfaces of a flat, circular cavity. There are actually two drive electrodes (D1 and D2 at right) to allow forcing of rotational modes. The opposite circular face is all grounded.



An HP 3325A signal generator feeds a phase shifter that generates a second drive voltage with a 45º phase delay. Both drives are then passed through audio transformers to allow for up to 30 Vpp drives in the 10 μm gap.

The drive forces are proportional to the square of the electric fields, so the frequency is doubled and the 45º phase shift becomes a 90º phase shift in the force. This combines with the 90º electrode orientation for the rotational force.

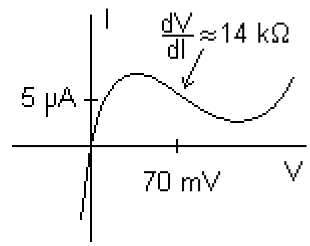


The 3X transformer has a phase shift at high frequencies given by

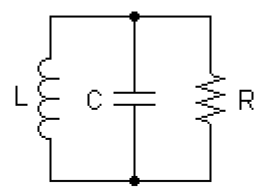
Tunnel Diode Oscillator (TDO)

The capacitance changes caused by the third sound are conveniently sensed by an LC oscillator incorporating the pickup. Static film thickness shifts are reflected in the average frequency, and the third sound oscillations show up as a frequency modulation. Tunnel diode oscillators are ideal - they are very stable, simple, and low power.

Tunnel diodes have a small negative dynamic conductance (large negative resistance) along with a very small DC biasing power. The curve at right is typical of the BD-7.



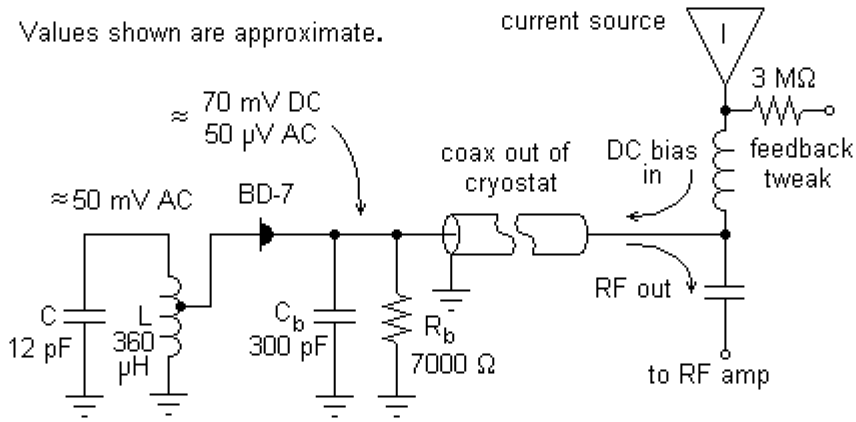
If the negative resistance (R_n) is arranged to be in parallel with an LC circuit, it can cancel any positive resistance (R_Q) associated with losses in the LC circuit and lead to exponential growth of oscillation instead of decay. The oscillations grow until the *average* negative resistance (averaged over the I-V curve) balances the regular dissipation, effectively regulating itself with $R = \infty$. This is typically 50 mVpp, depending on the details of the circuit



$$\frac{1}{R} = \frac{1}{R_Q} - \frac{1}{R_n}$$

The main LC tank (involving the resonator capacitance) is tapped about 3/4 down to best match the negative resistance of the diode to the tank, minimizing the oscillation voltage. "Marginal oscillation" makes the circuit less susceptible to external influences. The bias capacitor, C_b, grounds the diode for AC, and the bias resistor, R_b, turns part of the bias current into the bias voltage. The current source assures thermal EMF's don't contribute to the biasing conditions. For stability of the bias point, $R_b < R_n$. The total power dissipated in the diode and bias is <1 μW, and the same coax feeds the power and picks up the RF signal. The RF signal on the coax is primarily stray inductive pickup.

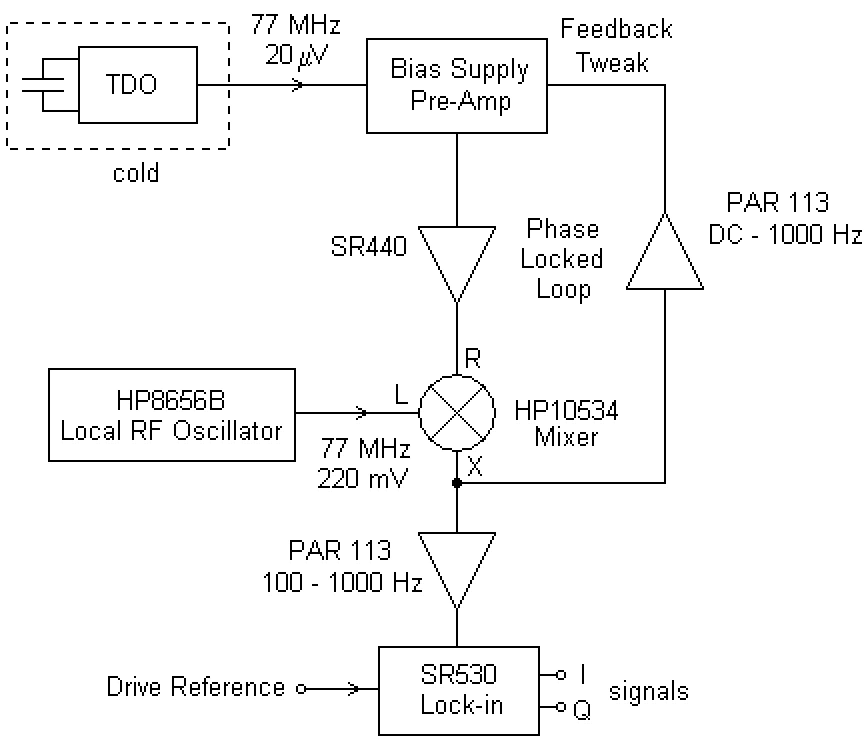
A voltage applied to the feedback resistor can be used to weakly control the bias point. This shifts the frequency due to the changing diode junction capacitance, and can be used to phase-lock the oscillator to a reference.



PLL Demodulation

The tunnel diode oscillator based on the pickup capacitor is also (unavoidably) a voltage controlled oscillator (VCO). This voltage control can be used to phase lock the TDO to a local reference oscillator. The error signal required for the phase locking is then the demodulated capacitance signal. The TDO is actually a more stable VCO than the reference synthesizer. The result is essentially an FM radio receiver with much more sensitivity to the frequency modulation.

The RF signal is picked out of the bias supply with an internal tuned pre-amp and then sent to the mixer with an additional boost from the SR440. The signal is then mixed to "zero beat" with the local oscillator using the mixer as a phase comparator. The phase difference is DC amplified and sent back to the bias tweak input, correcting any phase error. If the loop is locked, the error signal is also the output, which gets filtered, amplified, and sent to the lock-in amplifier for recovery of the third sound signal.



The DC level of the feedback signal can be monitored as an indication of the receiver tuning, which can be adjusted by changing the frequency of the local oscillator. The sensitivity of the whole system can also be calibrated by modulating the local oscillator by a known amount. The overall sensitivity to TDO frequency is typically 300 μV/Hz with a noise level of 0.2 HZ in a 1 Hz bandwidth. For a 10 μm gap sensing capacitor, this corresponds to a film thickness noise level of about

$$\Delta h_{noise} = \frac{gap}{\varepsilon - 1} \cdot \frac{\Delta f}{f} = 500 \cdot \frac{fm}{\sqrt{Hz}}$$

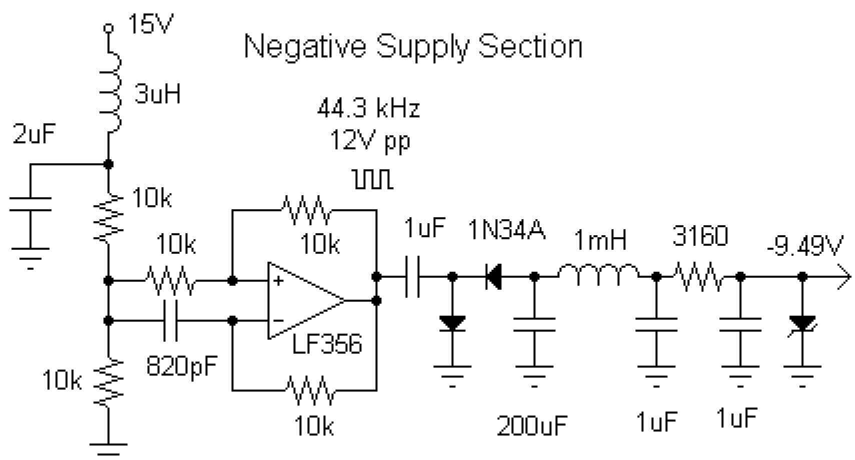
The actual performance depends on the mode and other small effects. One beauty of the system is that the absolute sensitivity calibration requires 1) the inductance of the LC tank element, 2) the capacitor area exposed to the film, and 3) the empty and filled (gap completely filled) oscillation frequencies. All of these are easy to obtain.

The sensitivity of the electronics chain to TDO frequency modulations is calibrated by measuring the response of the detector to an modulation introduced into the reference. This calibration needs to be done at the signal frequency, which is twice the drive frequency. Since the loop locks to the difference of the two oscillators, the PLLCAL signal is opposite in phase to the equivalent modulation of the TDO.

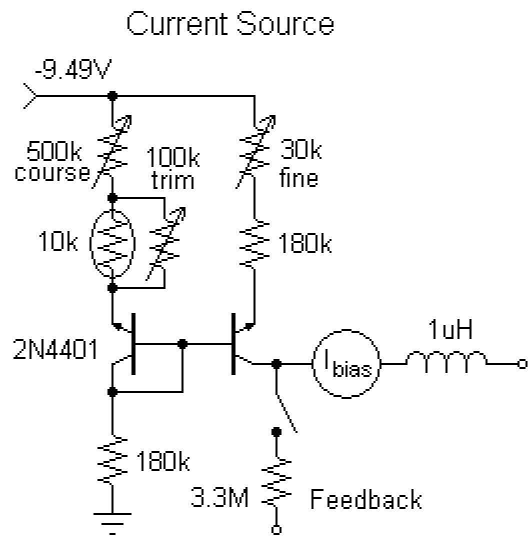
Bias Supply and Pre-Amp -- The "Bias Box"

The BD-7 tunnel diode is mounted for thermal anchoring in a configuration that requires a negative bias current of about 25 µA. The single coaxial cable from room temperature to the TDO serves three purposes: (1) power the TDO circuit with the bias current; (2) pick up the RF oscillation, and (3) send the feedback signal, through modulation of the bias current, required for the PLL function.

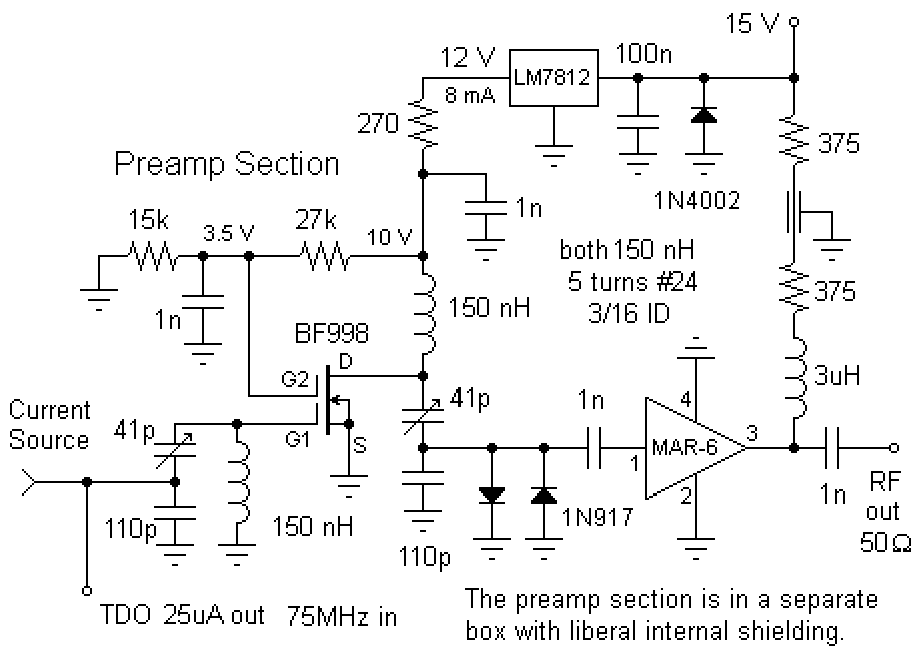
From a single +15 V supply on the cryostat stand, the circuit at right generates a negative voltage regulated by a zener diode. The 44 kHz of the voltage pump (and its harmonics) are outside of any range of interference for the detection chain.



The current source is a current mirror modified for adjustment and compensation for room temperature drifts. All resistors are wire-wound and the zener, transistors, and thermistor are close together and blobbed with silicone cement. The transistors are 2N4401 and the thermistor is a Phillips.10k NTC.



The pre-amp is based on a dual gate mosfet for the input stage, and a MAR-6 monolithic amplifier for a power boost. Both tank coils are 6 turns of #24 copper with a 3/16" ID. Each section (gates, drain, MAR-6, and power input) is separately shielded.



Summary of the preamp circuit characteristics from "...physics\electronics\TDO\preamp_check.xmcd"

voltage gain (50 Ω) $G = 34.4 \cdot dB = 52$

bandwidth Q	$Q = 32$
linearity limit	$24 \cdot mV$ in $800 \cdot mV$ out
input noise level	$V_{noise} = 1.2 \cdot 10^{-9} \cdot \frac{V}{\sqrt{Hz}}$