

IMPROVEMENTS IN THE NOISE FLOOR OF THE GRAVITATIONAL WAVE ANTENNA NIOBÈ

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Abstract. The gravity wave detector at the University of Western Australia is based on a bending flap of 0.45 kg tuned near the fundamental resonant frequency of a 1.5-ton resonant-bar of 710 Hz. The displacement of the bending flap is monitored with a 9.5 GHz superconducting re-entrant cavity transducer. The performance of the transducer is related to the development of a low noise microwave pump oscillator to drive the transducer. In this study we describe how to improve the quality of the existing microwave pump oscillator using a second servo frequency control system.

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1. Introduction

In this work we discuss the possibility of improving the noise performance of a microwave oscillator used for monitoring the vibration state of the resonant-mass Gravitational Wave (GW) antenna ‘Niobè’ at the University of Western Australia (UWA).

The UWA GW antenna consists of two coupled mechanical resonators tuned at approximately the same frequency (700 Hz): a 1.5 ton niobium bar and niobium bending flap with an effective mass of 0.45 kg. The relative motion of two mechanical resonators is controlled with a 9.5 GHz re-entrant cavity parametric transducer. The latter is driven by a low-noise microwave pump oscillator based on a liquid nitrogen cooled Sapphire Loaded Cavity (SLC) resonator. The schematic diagram of the UWA GW detector is shown in Fig. 1.

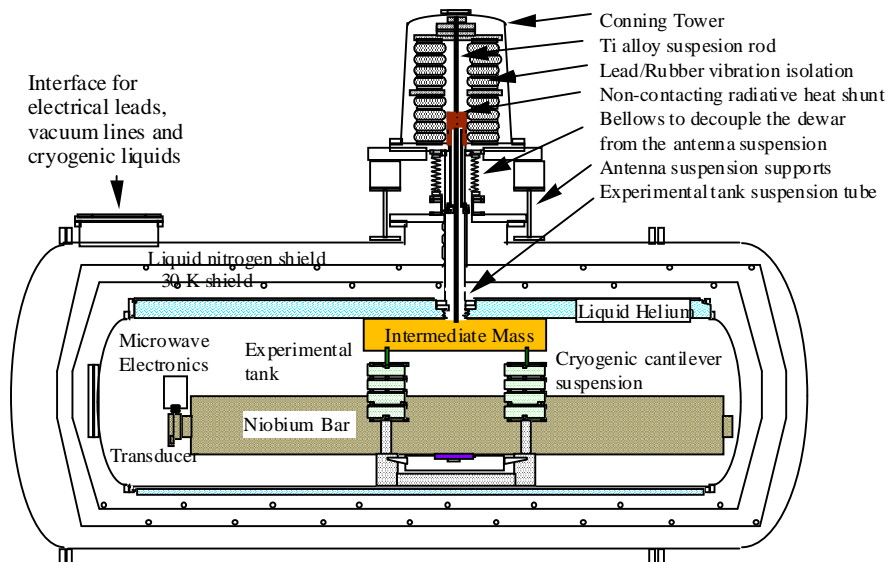


Figure 1: Niobè cross section (courtesy of Prof. David Blair and Dr. Ju Li)¹.

Relative motion of the coupled system bar-bending flap modulates the capacitance of the re-entrant cavity transducer^{1,2,3} resulting in sidebands components in the spectrum of a pump signal reflected from the cavity. Carrier of the reflected signal is suppressed at the output of a microwave interferometer as shown in Fig. 2. This allows a low-noise microwave amplifier to be introduced in front of the non-linear mixing stage in order to recover the original signal with an improved sensitivity.

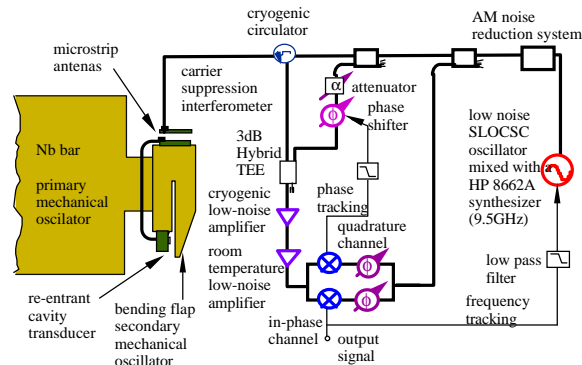


Figure 2: Niobè readout system (Courtesy of Prof. David Blair and Dr. Ju Li)¹.

One of the factors which affects the displacement noise floor of a measurement system in Fig. 2 is related to phase fluctuations of the microwave pump oscillator.

2. Description of existing LNO

The Liquid Nitrogen Oscillator (LNO) operates at frequency ~ 8.95 GHz. Its signal is mixed with that of low noise RF synthesizer to produce a pump signal for interrogation of the re-entrant cavity transducer. The LNO is based on a microwave loop oscillator, frequency of which is stabilized by means of a Pound frequency control system⁴. A simplified circuit diagram of the LNO is shown in Fig. 3.

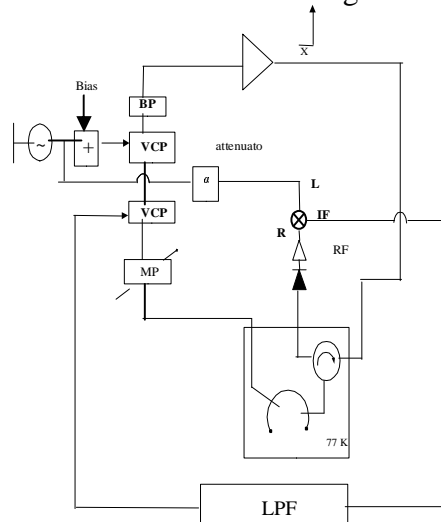


Figure 3: main components of the LNO.

The phase noise of the LNO was measured to be -126 dBc/Hz at 1 kHz offset from the carrier.

3. The second Frequency Servo Control System

To reduce the phase noise of the LNO⁵ at offset frequencies close to the mechanical resonant frequency of the Nb bar, an additional frequency control system with improved phase noise floor has been implemented. The frequency sensor of such control system is based on a double-balanced mixer monitoring the phase difference between the signals reflected and transmitted through the SLC resonator. At offset frequencies above a few hundred Hz the noise floor of a mixer-based frequency discriminator was proved to be almost 20 dB better than that of the Pound discriminator.

At low offset frequencies the mixer based frequency discriminator loses its advantage over the Pound discriminator due to its higher sensitivity to ambient temperature fluctuations and rise in the flicker noise. This requires a high-pass filter to be introduced into the path of the correction signal in order to preserve the LNO short-term frequency stability. Also, matching of the lengths of the transmission lines connecting the mixer with the SLC resonator is needed in order to maintain the quadrature phase relationship between the signals entering the mixer ports. Fig.4 shows the LNO with two frequency control loops.

An additional frequency servo consists of 2 amplifiers in series with maximum total gain of 80 dB followed by a low pass filter and a high pass filter. This frequency servo minimises the phase noise in the frequency range from 1 to 3000 Hz.

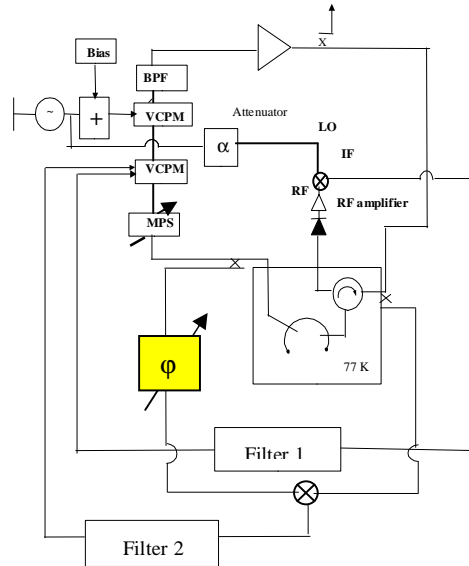


Figure 4: The new layout for the LNO.

4. The noise suppression calculation

Ignoring the noise floors of both frequency discriminators, one can estimate the effect of two frequency control loops on the phase noise of a free-running LNO from the following expression:

$$NS = \frac{\partial \omega_{oscillator}^{locked}}{\partial \omega_{oscillator}^{free-running}} = 20 \log \left(\frac{1}{1 + S_y \dot{\Sigma}} \right) \quad (1)$$

S_y is the oscillator frequency tuning coefficient and the dot sum denote a complex variable, where:

$$\dot{\Sigma} = K_{F1} \cdot S_{FD1} + K_{F2} \cdot S_{FD2} \quad (2)$$

where K_{F1} is the integrator transfer function, Pound frequency servo, SF_{D1} is the Pound frequency discriminator sensitivity, SF_{D2} is the frequency discriminator sensitivity of mixer based control system and K_{F2} is the all-pass filter transfer function used in the second frequency servo. Figure 5 shows the predicted suppression of the phase noise of a free-running oscillator as a function of the offset frequency. As follows from these data, a noise suppression of 30 dB can be achieved, when the loop gain approaches 75 dB.

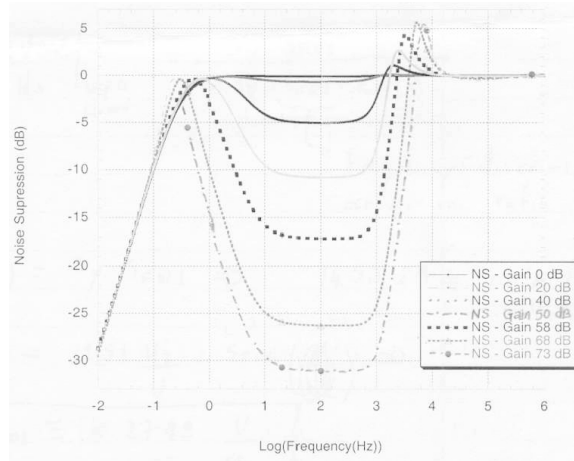


Figure 5: Noise suppression results.

5. Conclusion

Results of simulations show that the phase noise of a free-running LNO can be improved by almost 30 dB by implementing an additional frequency control system. This should allow a construction of a microwave pump oscillator with the phase noise spectral density of the order of $-150 \text{ dBc}/\text{Hz}$ at 1 kHz offset frequency for the future experiments with the UWA GW antenna.

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