LIGO-T0900451-v1

Characterization of a Voltage Controlled Oscillator

C. Isaac Angert* and Mentor: Dr. Daniel Sigg†
LIGO Hanford Observatory, California Institute of Technology, Richland, Washington 99354, USA

(Dated: October 2, 2009)

We assemble and test a prototype voltage controlled oscillator (VCO) for use in the pre-stabilized laser (PSL) control system in Advanced LIGO. The prototype will replace current hardware to ensure the VCO does not limit the noise performance of the PSL after Advanced LIGO upgrades. The VCO design requires a nominal frequency output at 80MHz and a range ±1MHz combined with low phase noise near -150dBc/Hz at 10kHz carrier offset. These requirements preclude the direct use of commercially available hardware such as VCO modules or crystal oscillators. The VCO design uses a frequency synthesizing approach to achieve required performance. Data gathered in testing include output phase noise, internal voltage noise and transfer functions. These data indicate that the VCO performs as expected and its noise performance is acceptable for Advanced LIGO.

I. INTRODUCTION

Virtually all present day knowledge of cosmic objects was obtained through observations of the electromagnetic spectrum. In the near future, improvements to the sensitivity of ground based gravity wave detectors such as the laser interferometer gravity wave observatory (LIGO) should give scientists the ability to regularly observe gravitational radiation and the unique processes that emit it. This new window to the cosmos may revolutionize our understanding of physics [1].

Currently, the LIGO interferometers have achieved sensitivity to gravitational strains less than $10^{-21}/\sqrt{\mathrm{Hz}}$ over a broad frequency range, which astrophysical calculations suggest to be the minimum necessary to obtain reasonable chances of observing gravity waves within scientifically useful periods of time. The Advanced LIGO project, of which this work is a small part, will upgrade LIGO hardware to increase sensitivity by a factor of 10. Advanced LIGO is thus projected to detect gravity waves with a frequency of roughly one event per day.

Conceptually, the LIGO interferometers can be thought of as devices that use laser light to compare the lengths of each of the interferometer's arms. The frequency of the laser used must be extremely stable if the precision needed for gravity wave astronomy is to be achieved. At LIGO, the pre-stabilized laser (PSL) subsystem responsible for generating a suitable laser beam for injection into the main interferometer. The voltage controlled oscillator (VCO) is part of a control loop in the PSL. It generates an RF signal with frequency proportional to a DC error signal originating from a Pound-Drever-Hall [2] lock operating at the mode cleaner. The RF signal generated by the VCO is used to drive an acousto-optic modulator (AOM) to correct frequency fluctuations in the laser, locking its frequency to the length of the mode cleaner cavity. In practice, the control loop just described does not operate on the main beam, but on a sampled beam that is to be locked to a Fabry-Perot cavity. However, an understanding of the complexities of the entire PSL is not necessary to understand the operation of the VCO.

Current VCO hardware makes use of a VCO hybrid module[11] running at 800MHz with a frequency range of ±50MHz. This signal is frequency divided by 10 to yield an 80±5MHz signal that can be used to drive the AOM. The process of frequency dividing also yields a reduction in noise levels appropriate for current Enhanced LIGO hardware. It was determined that the current hardware is limiting the frequency noise suppression of the PSL above roughly 100Hz as measured by the suspended mode cleaner [3]. Thus the VCO is included in Advanced LIGO upgrade plans.

II. REQUIREMENTS

Goals for the Advanced LIGO VCO are a factor of 10 reduction in phase noise, with a frequency output of 80±1MHz for a DC input signal ranging through ±20V. Given that the current frequency range of ±5MHz is larger than required [4], the overall strategy for the upgrade will be to further divide the VCO module output frequency, reducing its range while also reducing phase noise. The design of the VCO is primarily driven by the low noise performance and large (±1MHz) frequency range required. These two requirements preclude direct use of commercially available hardware such as a standalone VCO module or a crystal oscillator, the former having the required frequency range, but far too much phase noise and the latter having the required low noise performance, but far too little range.

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* `cia384@truman.edu`; `http://www2.truman.edu/~cia384`; Truman State University
† `sigg_d@ligo.caltech.edu`

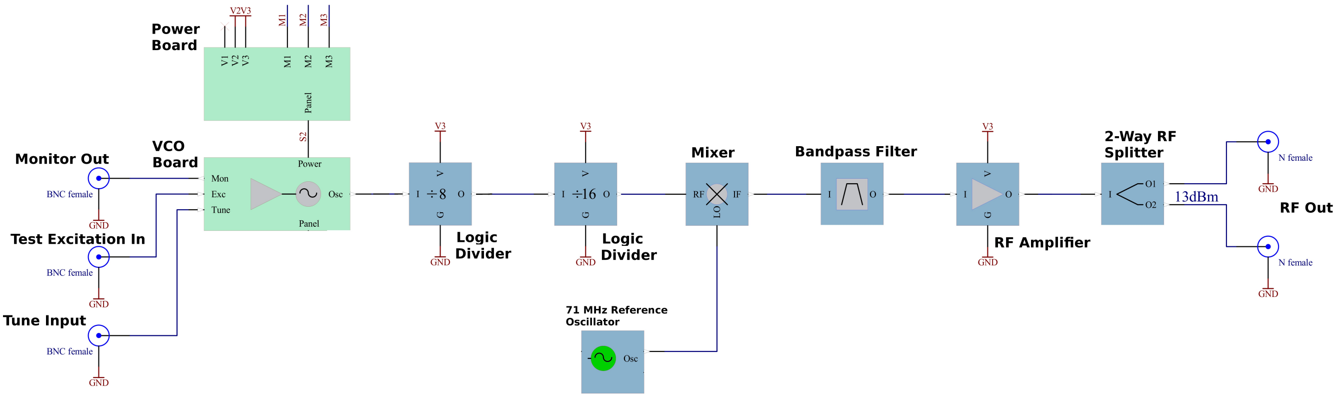

FIG. 1: Conceptual block diagram of the Advanced LIGO VCO design [5].

III. DESIGN

The VCO design (FIG. 1) utilizes a synthesizing approach, combining a VCO module with a crystal oscillator to obtain the desired combination of low noise and large frequency range. The VCO module [6] produces a 1GHz signal with a range of ±130MHz that is frequency divided to an 8±1MHz signal and mixed with a stable 71MHz reference signal to obtain an output signal near the nominal 80MHz input frequency needed for the AOM. The device fits inside a rackmount enclosure. It is internally laid out on 3 boards:

- A power board [7] externally supplied with ±17 and ±24VDC. The power board generates the correct voltages for other boards and modules, handles power state through front panel switches and monitors signals in the RF components.
- A low noise VCO board [8] takes an external ±20VDC input signal, modifies it and sends it to the VCO module which produces the 1GHz±130MHz signal. Modifications to the input DC signal include a flat 9dB attenuation and DC offset along with low-pass filtering starting at 1.4Hz and reaching a flat 27dB attenuation above 40Hz. See FIG. 2. This reduces higher frequency voltage noise, while preserving DC gain. The VCO board also includes a monitor and an external test input.
- RF components are mounted on an aluminum plate. They divide the 1GHz signal from the VCO board, mix it with the reference signal and filter the output.

A model of the circuit is described in Ref. [9].

IV. MEASURED SPECIFICATIONS

A. Transfer Function

The transfer function through the VCO board was measured. See FIG. 2. This measurement helps verify that the device functions as expected and helps to rule out circuit layout errors.

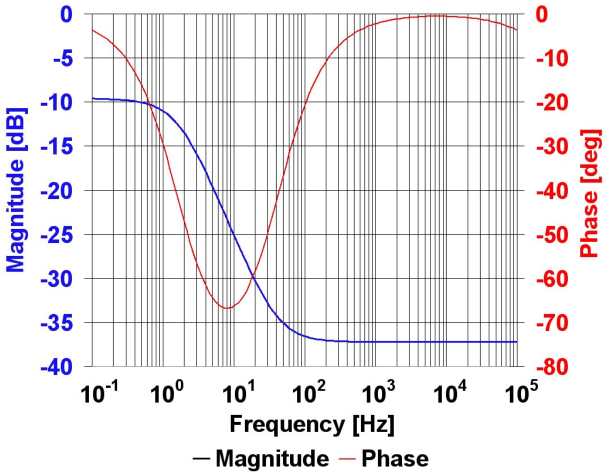

FIG. 2: Transfer function through the VCO board from tuning input to the input of the VCO module.

B. Phase Noise

Phase noise plots will be used to compare the performance of the VCO to the other components of the PSL, as well as to the current VCO. As shown in FIG. 3, the Advanced LIGO VCO improves phase noise by 20-30dB over current hardware. The phase noise between 1kHz and 100kHz is above the target specification due to the substitution of logic dividers where regenerative frequency dividers were originally specified. The extra noise added by the logic dividers is deemed acceptable. Peaks correspond to external electrical noise from the lab environment, as well as multiples of 60Hz. These are of little concern as the working environment for the VCO is known to be considerably quieter than the lab where the measurement was made [4].

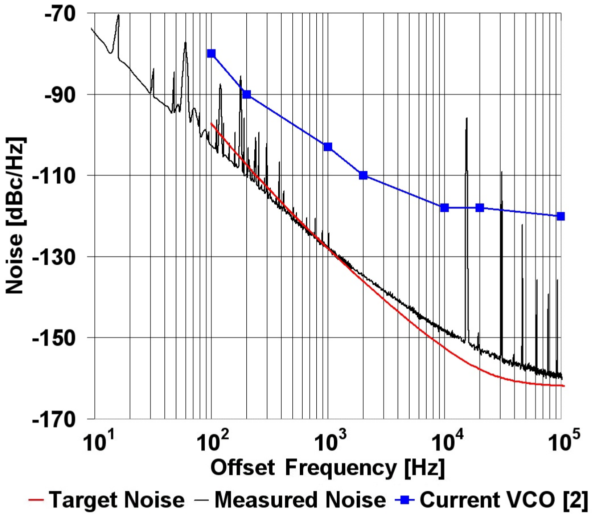

FIG. 3: Measured and predicted phase noise of the 80MHz Advanced LIGO VCO output signal compared to current VCO hardware.

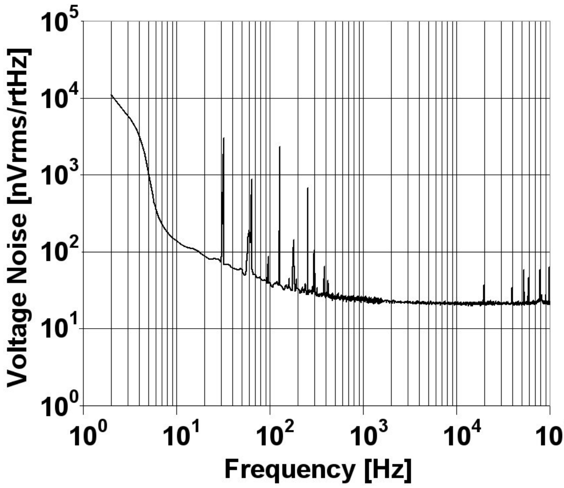

FIG. 4: Voltage noise on the VCO board. Note that this spectrum is passed through a -27dB roll off for frequencies >40Hz before input to the VCO module. See transfer function: FIG. 2.

C. Voltage Noise

Voltage noise added to the DC input signal as it passes through the VCO board is of secondary concern to output phase noise. Measurements (FIG. 4) serve as a check that all is working as expected and would serve as a troubleshooting step in the event that phase noise was found to be unacceptably large.

D. Output Parameters

The VCO provides two 13dBm outputs. The power roll off shown in FIG. 5 at high and low frequencies is caused by the poor performance of a divide by 16 logic divider. While this power roll off is not ideal, it is acceptable in the prototype. The logic divider in question will probably be replaced with a wider frequency version in later designs. FIG. 5 also includes measurements demonstrating the full ±1MHz output frequency range.

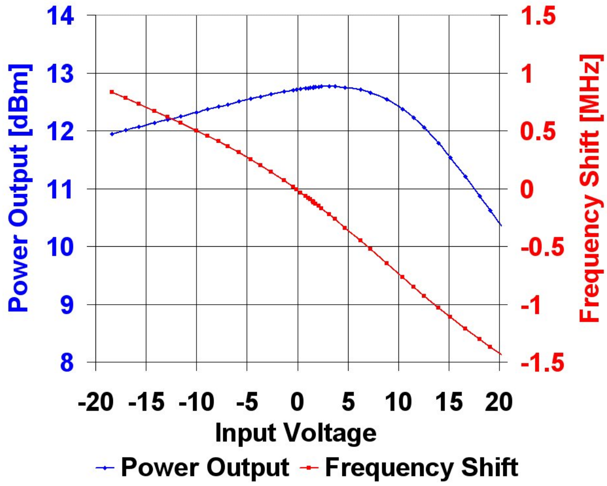

FIG. 5: VCO output power and frequency shift as a function of input tuning voltage.

V. METHODS

All spectra were measured using an SR785 network/spectrum analyzer. Note that the white-noise floor of the SR785 was near $6\mathrm{nV}_{\mathrm{rms}}/\sqrt{\mathrm{Hz}}$ in the voltage noise measurements. Noise to signal ratios on the SR785 were negligible otherwise. Phase noise measurements were made using the Blue Phase 1000 system from Wenzel Associates[10], which facilitates the locking of two oscillators to a single frequency, ω. The two locked signals are mixed (multiplied), producing sum and difference frequencies. Let $\phi(t)$ and $\psi(t)$ be phase deviations, then:

$$\sin(\omega t + \phi(t))\cos(\omega t + \psi(t))$$

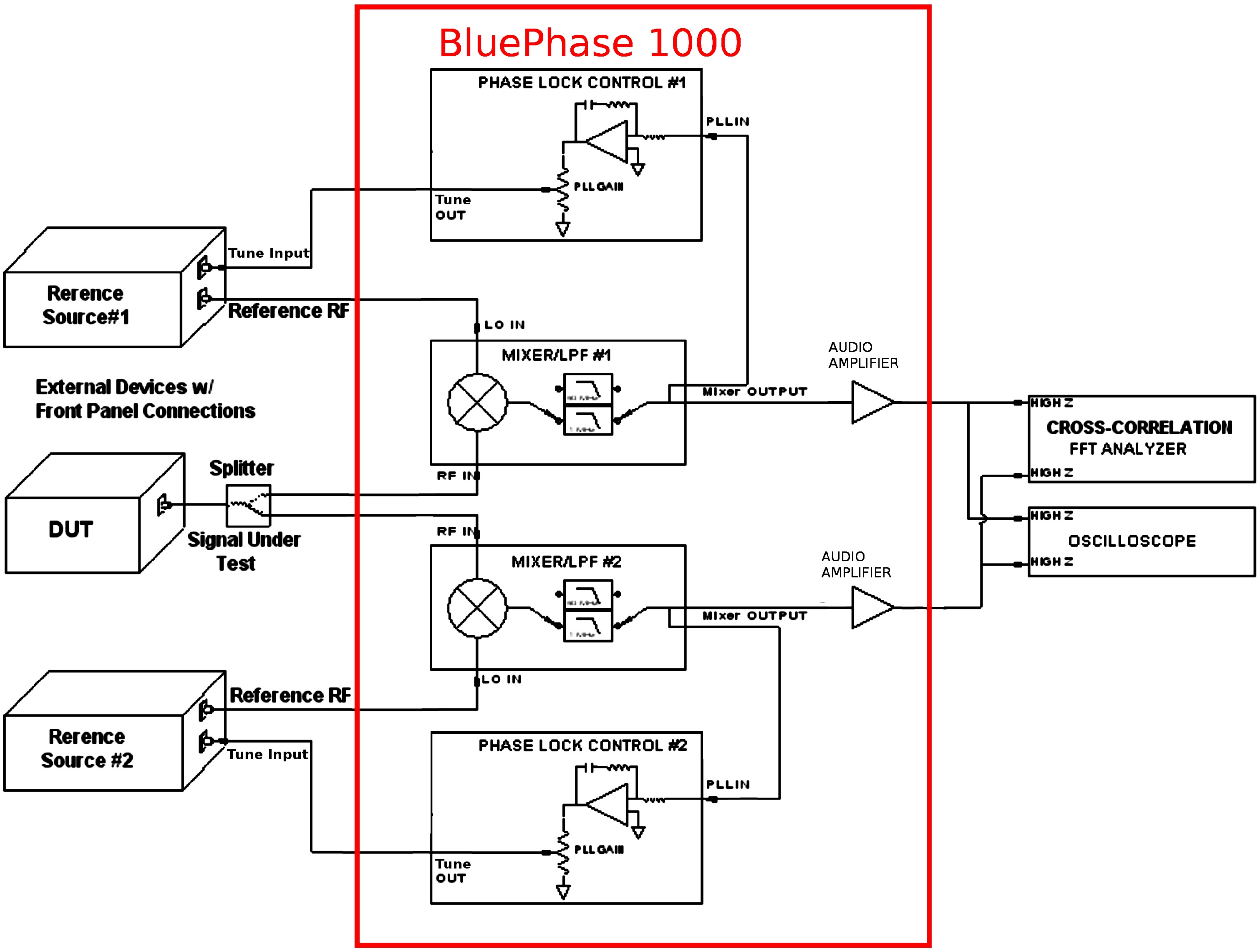

FIG. 6: Schematic diagram of a cross correlation phase noise measurement. Output from a test oscillator (DUT) is mixed with reference frequencies and low-pass filtered to remove RF components. Output is fed back to the tune input on the reference oscillators via phase lock controls (PLL), achieving frequency lock. Image adapted from [10].

$$= \frac{\sin(2\omega + \psi(t) + \phi(t)) - \sin(\psi(t) - \phi(t))}{2}$$

For an ideal oscillator ($\phi(t), \psi(t) = \text{constant}$), this produces an RF signal at twice the original frequency and another purely DC signal. For real oscillators ($\phi, \psi \neq$ constant), we obtain a low frequency signal (after low-pass filtering to remove the high 2ω frequency) that is proportional to the sum of the phase noise in both oscillators. If we wish to measure noise in a single oscillator, we have several choices:

- Two identical oscillators can be locked and the sum of their phase noise measured. Assuming the noise in each is identical, the measured power spectrum is divided in half to obtain the single oscillator noise.

- A noisy oscillator can be locked to one that has significantly smaller noise. The noise contribution of the quiet oscillator is then assumed to be negligible in the measurement.

- In what is known as a "cross correlation" measurement, two reference oscillators are locked to and their signals mixed with that of an oscillator under test (FIG. 6). This produces two noise spectra, each the sum of noise from the oscillator under test and one of the reference oscillators. When comparing the two spectra in time, noise contributions from the test oscillator should be correlated between both spectra and noise contributions from the reference oscillators should be uncorrelated. We can then subtract the uncorrelated parts of the noise spectra to obtain the noise of the oscillator under test. Although this method doubles the number of reference oscillators needed as well as setup complexity, it is preferred if hardware is available.

Note that in order to maintain a frequency lock, there must be sufficient low frequency gain in the phase lock control loop to remove low frequency phase drifts. A functional frequency lock thus suppresses low offset phase noise in the measured spectrum. For higher frequencies if the control loop has little gain, fast phase changes will not be suppressed and can be measured. Measurements of output phase noise in the VCO showed large noise suppression at frequencies <100Hz, where loop gain is high enough to have a non-negligible suppression effect. To obtain noise spectra at these low frequencies (such as in FIG. 3), the control loop transfer function was measured and used to correct for this suppression effect.

Acknowledgments

Thanks to my mentor Dr. Daniel Sigg. Also thanks to Paul Schwinberg for help assembling and understanding the circuitry. Thanks to the NSF REU program and Caltech SURF program for financial support, and LIGO Hanford Observatory for hospitality while completing this work.

This report has been assigned document number LIGO-T0900451-v1.

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[11] The VCO module is composed of a diode with strongly voltage dependent capacitance (varactor diode) in an LC circuit, allowing tuning of the resonant frequency through the diode bias voltage.