

Modulating the Input Laser of Squeezer Using Optical Phase-Locked Loop

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Abstract

In this project, the optical phase-locked loop is utilized to phase-lock two lasers, ensuring that their frequency difference remains fixed at the same value. The point of this project lies in designing the loop filter within the phase-locked loop, implementing both fast and slow modulation to control the laser output frequencies. As for the result, we have successfully designed a loop filter to complete the entire optical phase-locked loop system. Furthermore, we have achieved phase locking of the two lasers for periods exceeding several tens of hours, and even longer.

Introduction

Gravitational waves are detected using precise laser interferometers to capture faint signals from space. However, quantum noise affects these measurements, even in a vacuum. To reduce the effects, researchers utilize squeezed light, which exhibits reduced noise in specific directions. This project focuses on employing an Optical Phase-Locked Loop (OPLL) to synchronize the beat frequency between two lasers with a reference signal before generating squeezed light in a micro-ring resonator.

Phase-Locked Loop

VCO will eventually have the same frequency and phase as that of the reference signal. i.e. $v_{pd} \rightarrow 0$ as $t \rightarrow \infty$.

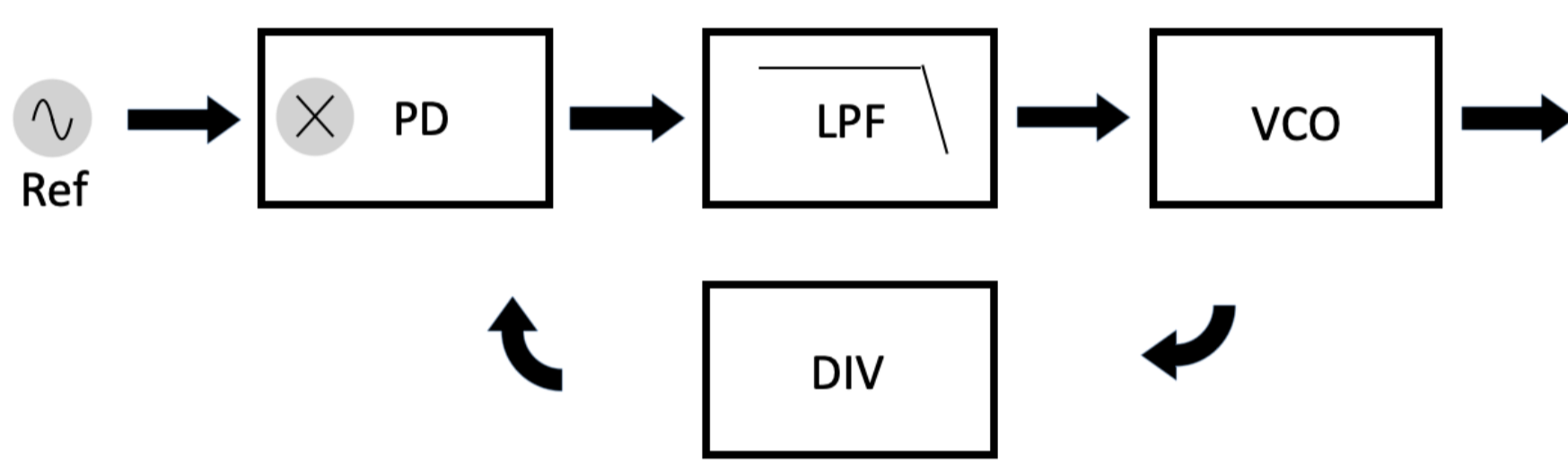


Figure 1. Schematic Block diagram of a Phase-Locked Loop

PD: Phase Detector; LPF: Low-Pass Filter; VCO: Voltage Control Oscillator; DIV: Feedback Divider.

Optical Path Setup

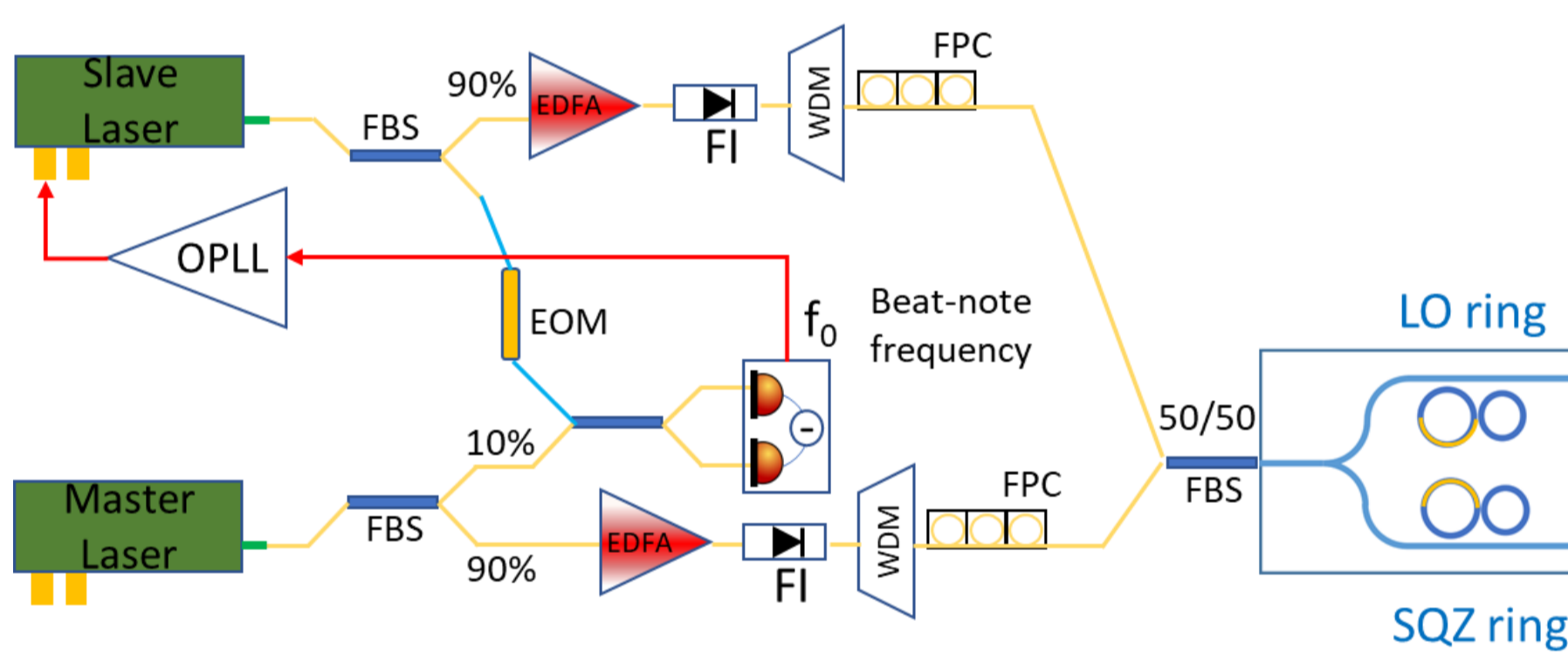


Figure 2. Experimental Setup

EDFA: Erbium Doped Fiber Amplifier; FI: Faraday Isolator; EOM: Electro-Optic Modulator; FBS: Fiber Beam Splitter; WDM: Wavelength Division Multiplexing; FPC: Fiber Polarization Controller; LO ring: Local Oscillator ring; SQZ ring: Squeezer ring.

Master & Slave Laser

The main goal is to lock the two lasers, which are the input of the micro-ring resonator as shown in Figure 1. The wavelengths of the two lasers are 1550.92 nm and 1554.13 nm respectively, which indicates the frequencies are up to THz and the signals cannot be directly used as the input of the phase detector. Therefore, a 50/50 coupler is utilized to create the beat note with much lower frequency to serve as the input of the phase detector. The output of the PD will then be sent to the slave laser (Pump1 in Figure 1.) to force the slave laser to follow the master laser.

However, since the beat note of the two lasers is still up to about 200 GHz, a N-bit feedback divider is implemented to further minimize the required frequency for the reference signal. An additional EOM may be needed to create sidebands if the reference signal is not high enough.

Experimental Result

Loop Filter Design

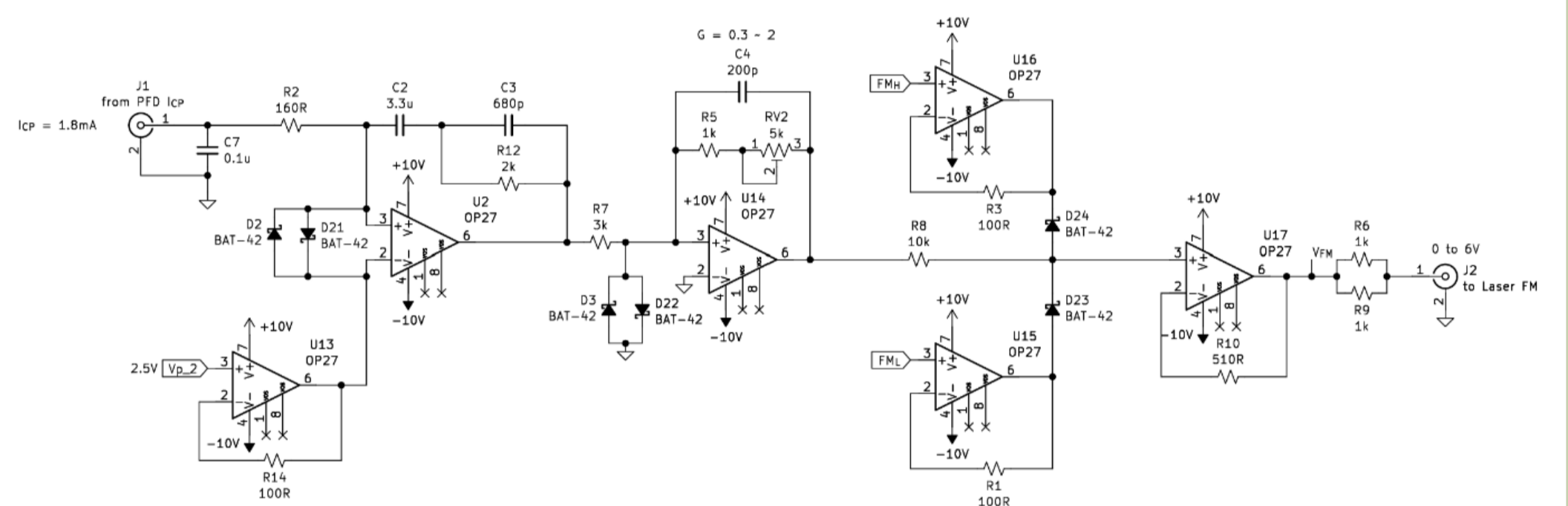


Figure 3. Loop Filter Design, Frequency Modulation Part

The circuit for fast modulation outputs voltage to the laser's FM input, with its frequency response shown in Figure 3-1. The first half consists of a low-pass filter aimed at filtering out high-frequency noise from the output of the FPD. Additionally, to avoid excessive high-frequency response of the laser to the input, causing ripple, we add a smaller capacitor (C3) to the low-pass filter to significantly attenuate frequencies above 117kHz.

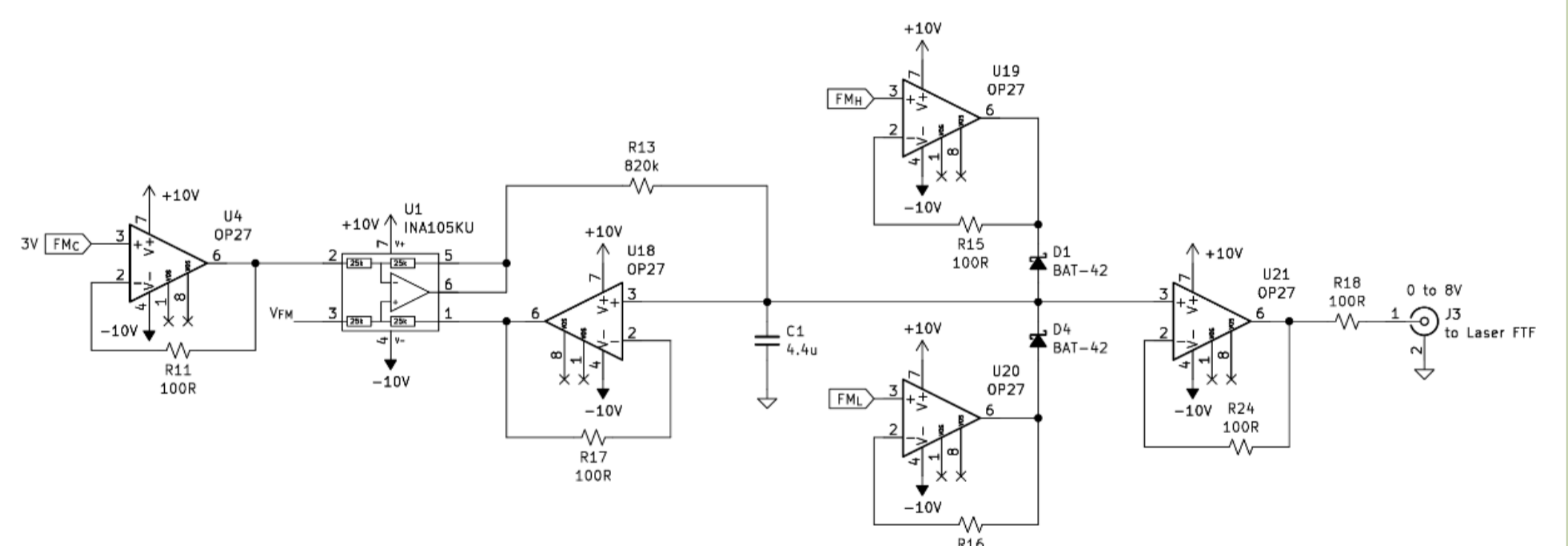


Figure 4. Loop Filter Design, FTF Part

Due to the integrator, slow modulation results in larger and slower changes in frequency amplitude. When the frequency difference between the beat note and the reference signal decreases, it switches back to fast modulation for continued locking.

Result

Figure 5. shows the successful phase-locked result, where the prominent frequency is the beat frequency.

Additionally, the signals below are noise. The primary objective for the future will be to reduce the amplitude of the noise signals below.

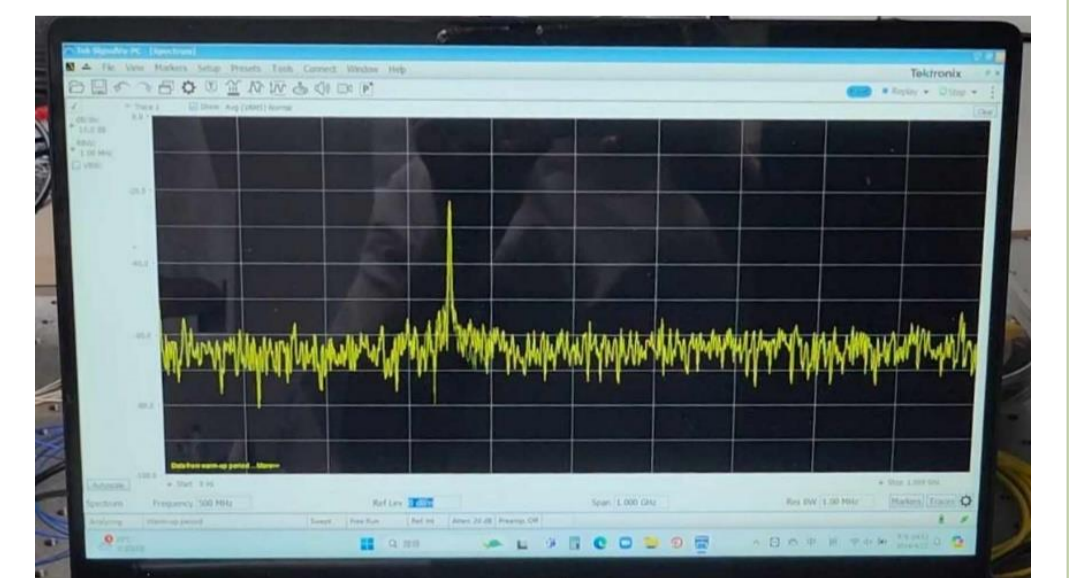


Figure 5. The Measure Beat Note Frequency of Two Lasers

Conclusion

In this project, we successfully stabilized the phase of two lasers for over ten hours by combining fast and slow modulation. Currently, the circuits are implemented on the board for easy modification, but it produces more noise. To improve output quality, we plan to replace them with printed circuit boards to minimize unnecessary interference.

Additionally, since the laser frequencies tested in this project are relatively low compared to those required for generating squeezed light, we may upgrade our measurement equipment to achieve the desired frequency response in the future.

[1] L. Barsotti, J. Harms, and R. Schnabel, "Squeezed vacuum states of light for gravitational wave detectors," *Rep. Prog. Phys.* 82, 016905 (2018).

[2] Y. Zhao, N. Aritomi, E. Capocasa, M. Leonardi, M. Eisenmann, Y. Guo, E. Polini, A. Tomura, K. Arai, Y. Aso, Y.-C. Huang, R.-K. Lee, H. Luck, O. Miyakawa, P. Prat, A. Shoda, M. Tacca, R. Takahashi, H. Vahlbruch, M. Vardaro, C.-M. Wu, M. Barsuglia, and R. Flaminio, "Frequency-dependent squeezed vacuum source for broadband quantum noise reduction in advanced gravitational-wave detectors," *Phys. Rev. Lett.* 124, 171101 (2020).