A Full Digital Servo for Ultra-Stable Laser Frequency Stabilization

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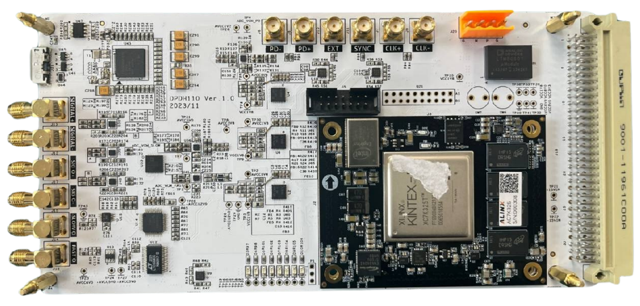
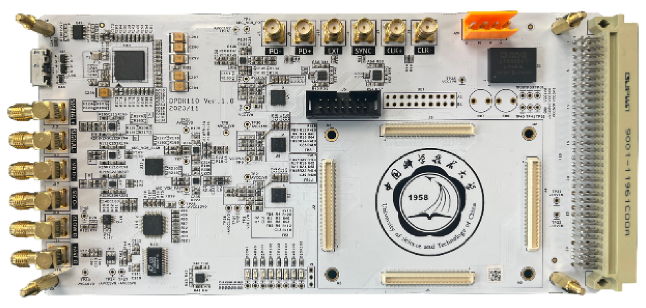
Introduction

Frequency stable lasers are important to physics experiments like optical clocks. To achieve high stability, **Pound-Drever-Hall(PDH)** method is used. A PDH laser frequency locking system consists of optical system including a ultra stable cavity, feedback servo and laser. We develop a full digital servo for PDH locking system. Compare to analog system, our digital servo is highly configurable and have large dynamic range. The biggest challenge of digital servo is latency, and we manage to achieve a digital servo with latency as low as 120ns, making a few MHz feedback bandwidth achievable.





- Full digital design
- Low latency
- General-purpose
- Low Noise

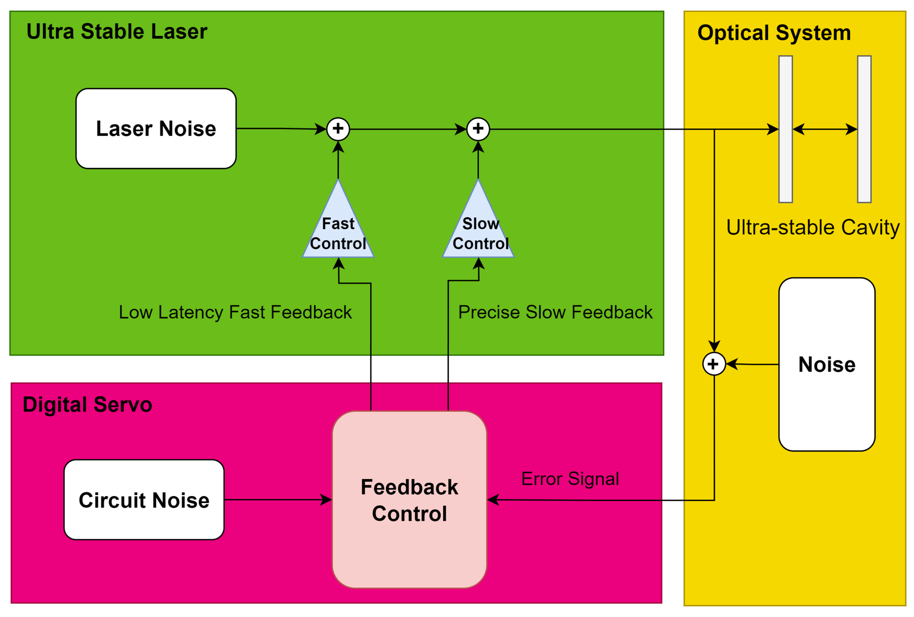


Fig.1 PDH Frequency stable system

System Design

Fast Channel

Fast channel provide high feedback bandwidth with less precision. ADC3583 sample error singal at 55MSPS. A configurable 3rd-order process the sampled signal then output with LTC1668 DAC. The 3rd-order parallel structure keeps calculation latency the same as 1st-order.

- 440M overclocking calculation clock, fast channel servo latency about 120ns
- 16×32bit, 22×32bit fixed point multipliers and 20bit accumulator, total latency 20ns
- Saturation protection and overflow monitor

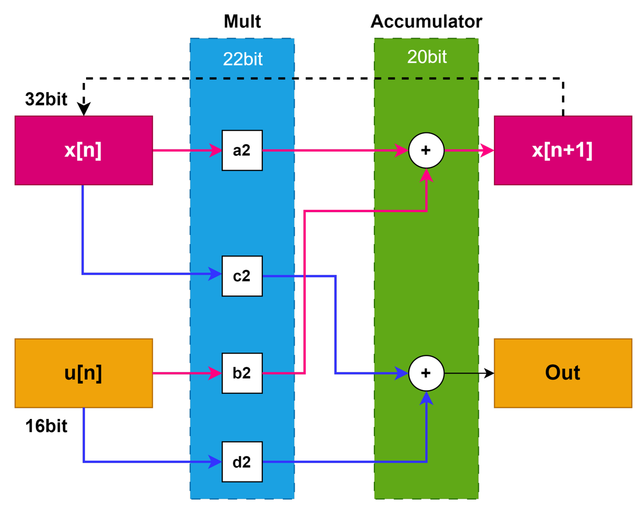


Fig.2 Single lead-lag Compensator Design

Slow Channel

Slow channel can provide precision high gain at low frequency. The signal is sampled at 5MHz by ADC3583, then get send to an optional 3rd-order lead-lag Compensator with larger bits and an incremental PID controller. DAC91001 running at 0.5MSPS is used to output precise analog signal. A ten-times decimation is used to match ADC and DAC speed. Slow channel can achieve gain of 80dB or more at 1Hz.

- full 32bit **3rd-order lead-lag Compensator** like fast channel
- full 32bit incremental **PID controller**
- saturation protection and overflow monitor

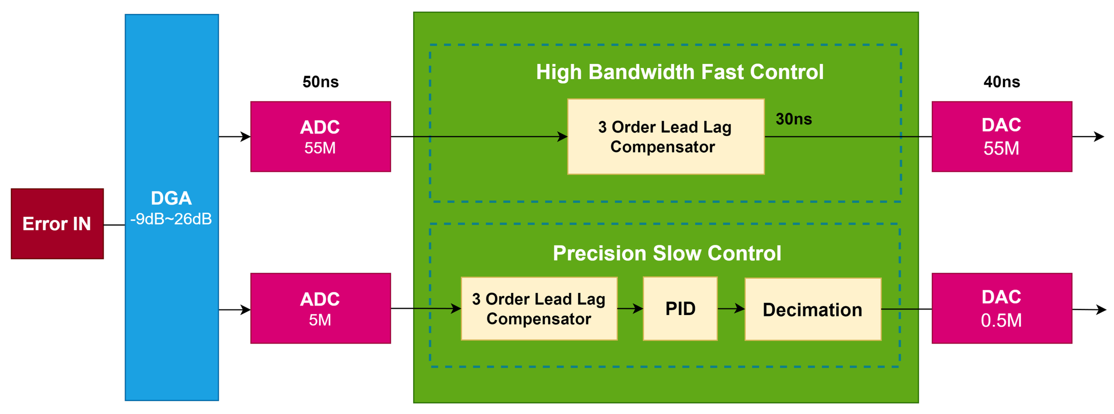


Fig.3 Servo System Design

Software Design

Software is developed to adjust params and monitor system status. A seperated frontend and backend design makes it suitable for different scenarios. Two available mode

- Rust-based **USB3 backend** for high speed data(up to Gbps) transfer
- **Webserver backend** for remote slow control and monitoring(including mobile devices)

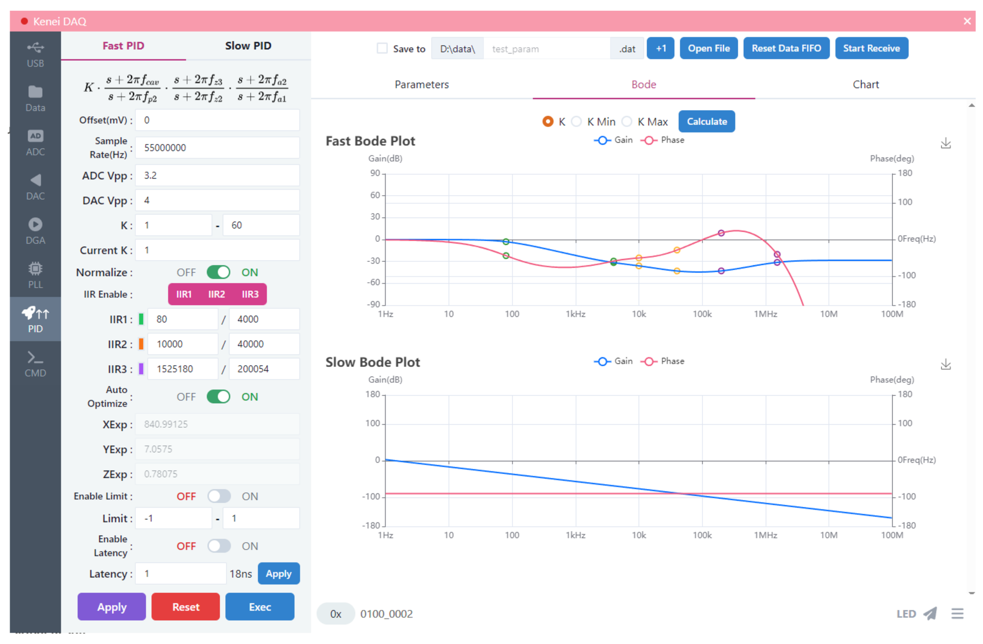


Fig.4 Software Interface

System Testing

Openloop Testing

Openloop performance is tested to verify the function of servo system.

Input-referred voltage noise spectrum is measured by shorting analog input. The input noise is approximately $1414.21nV\sqrt{Hz}@1Hz$.

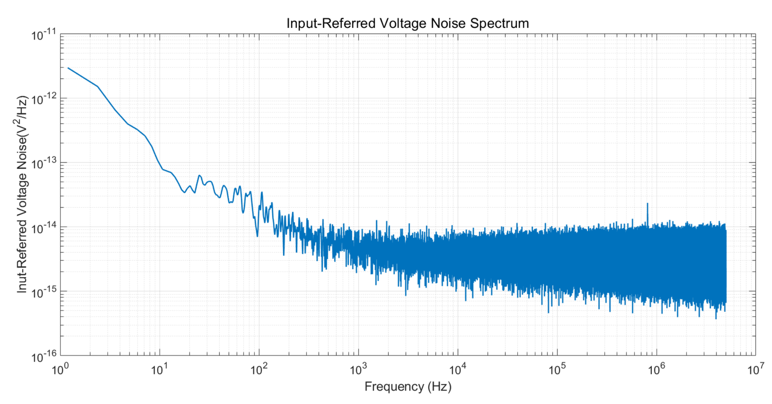


Fig.5 Input-referred Voltage Noise Spectrum

The openloop transfer function is tested using Vector Network Analyser(VNA).

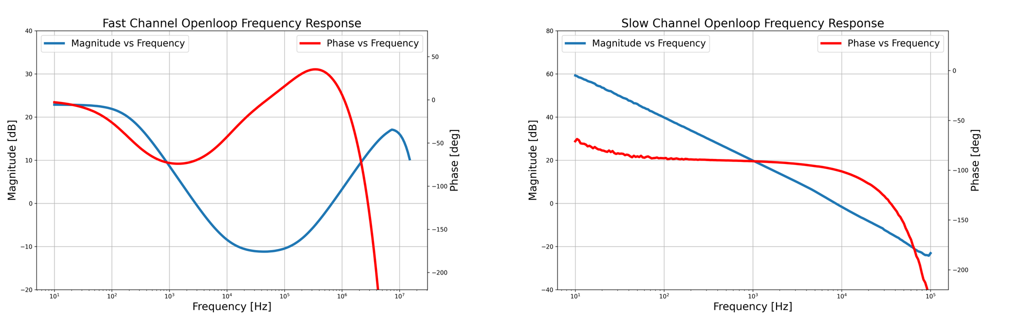


Fig.6 Fast(L) and Slow(R) Channel Transfer Function

Beat Frequency Testing

Two ultra-stable laser systems are tested:

- 30cm Ultra Low Expansion(ULE) glass cavity with 1397nm laser
- 10cm Si cavity with 698nm laser

A reference ULE ultra stable cavity is used for beat frequency test:

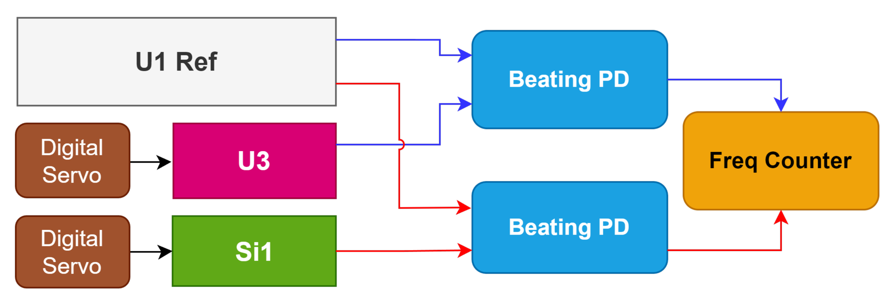


Fig.7 Beat Frequency Chart

We compare locking effect with a commercial **FALC110 analog servo**. ULE cavity system can achieve 3e-16@1Hz and Si cavity system can achieve about 5e-16@1Hz frequency stability with **both servo**:

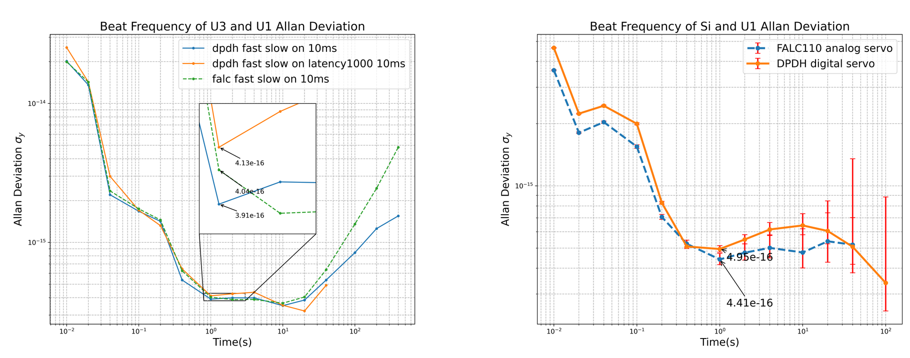


Fig.8 U3(L) and Si(R) Testing Result

Closeloop Testing

Beat Frequency result is limited by cavity noise itself. The performance of servo can be measured by error signal. When laser is well locked, system noise should be close to servo openloop noise.

The **digital servo noise** is $1933.35nV/\sqrt{Hz}@1Hz$, with $108.5nV/\sqrt{Hz}@1Hz$ **floor noise**. The **FALC110 noise** is $470.31nV/\sqrt{Hz}@1Hz$.

The inferred frequency **Allan Deviation** are:

- 2.08e-17 for FALC110 commercial analog servo
- 8.54e-17 for our digital servo

The closeloop transfer function $GKD(s)$ can also measured by VNA. The corner frequency is about 1.5MHz.

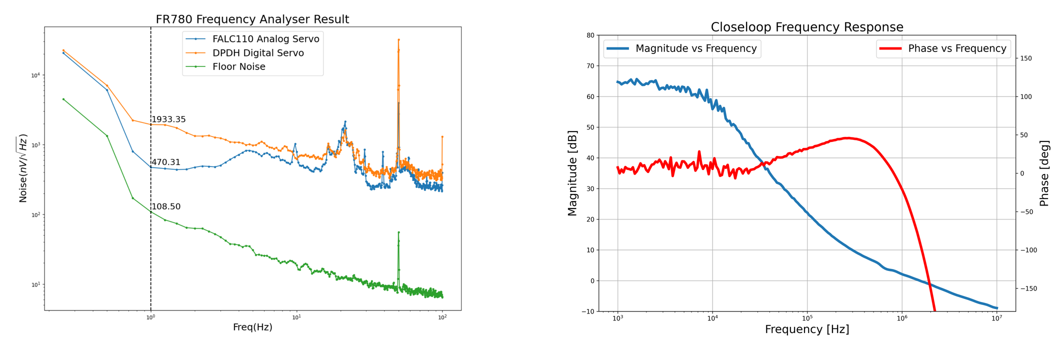


Fig.9 Closeloop Noise and Frequency Response

Software Demo

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Conclusion

- A high bandwidth digital servo is built for laser frequency stable system.
- The digital servo can perform as well as commercial analog servo, limited by laser itself.
- The current input noise is still too high and require improvement.

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