FPGA-Based Cavity Phase Stabilization for Coherent Pulse Stacking

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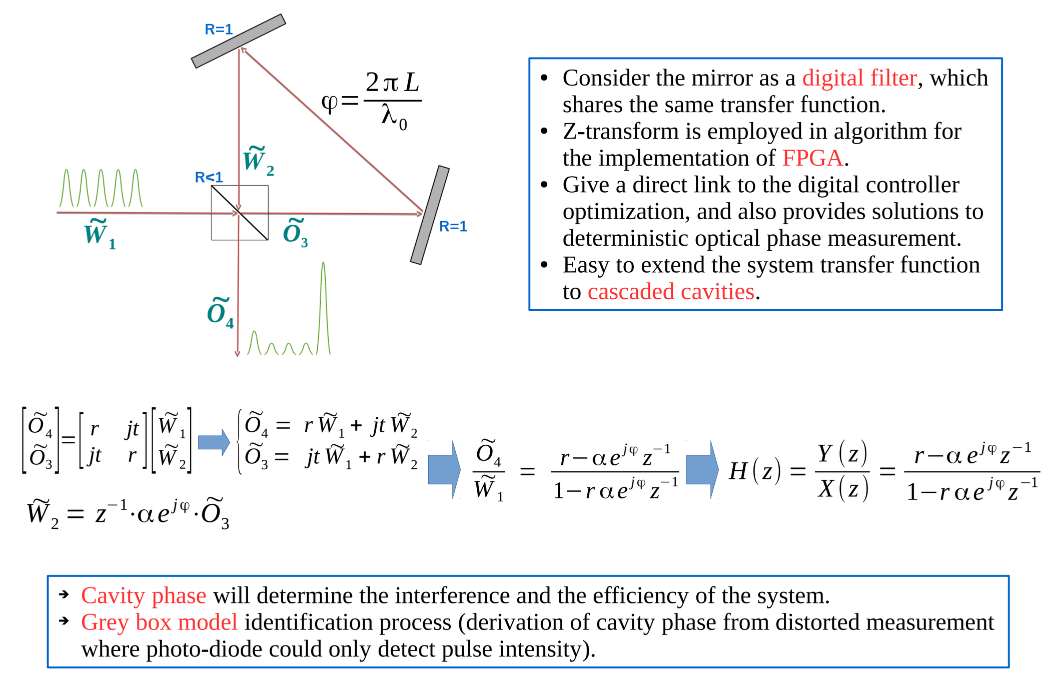
Abstract

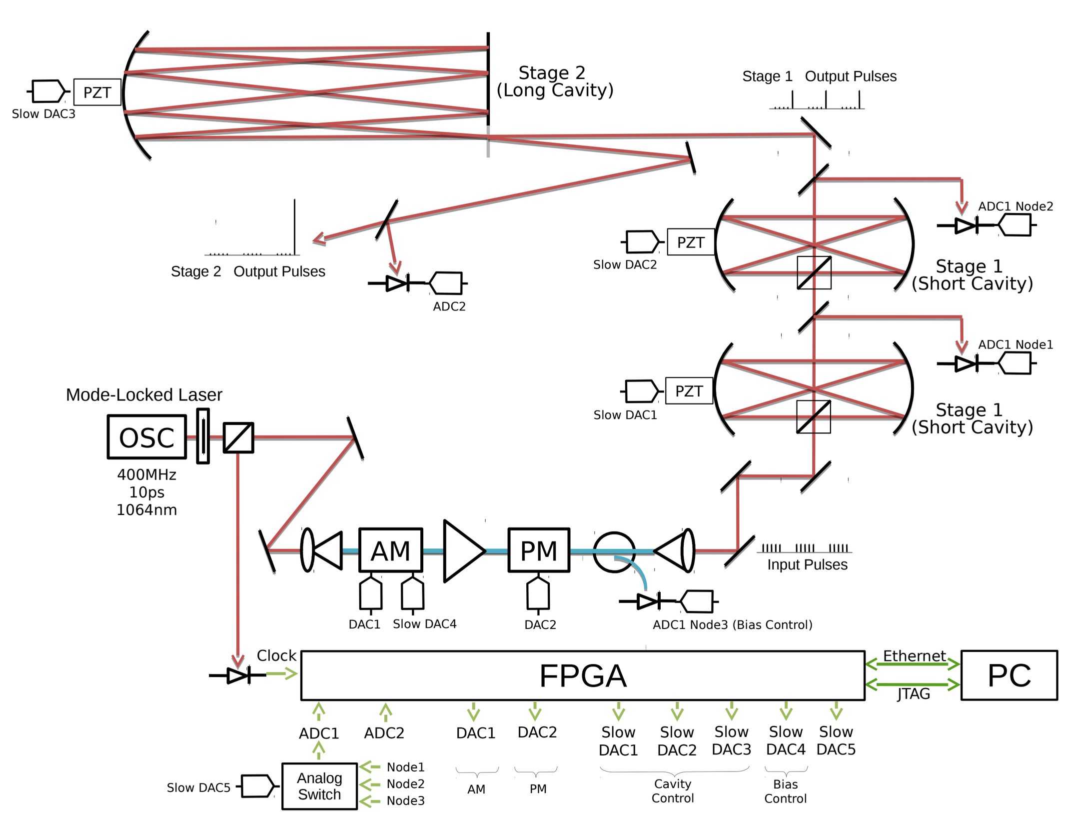
Coherent pulse stacking (CPS) is a new time-domain coherent addition technique that stacks several optical pulses into a single output pulse. This technique enables high average power, which will have a significant impact on laser-driven particle accelerators. We develop a robust and scalable digital control system with firmware and software integration for algorithms, to support the coherent pulse stacking application. We model coherent pulse stacking as a digital filter in the Z domain and implement a pulse-pattern-based cavity phase detection algorithm on an FPGA. A 2-stage (2+1 cavities) 15-pulse stacking system achieves a 11.0 peak-power enhancement factor. Each optical cavity is fed back at 1.5 kHz, and stabilized at an individually-prescribed round-trip phase with 0.7 deg and 2.1 deg RMS phase errors for Stage 1 and Stage 2 respectively. Optical cavity phase control with nm accuracy ensures 1.2% intensity stability of the stacked pulse over 12 hours.

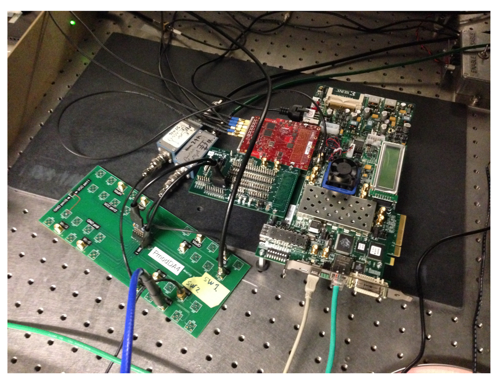
Z domain modeling

Model the coherent pulse stacking in Z domain.



System architecture

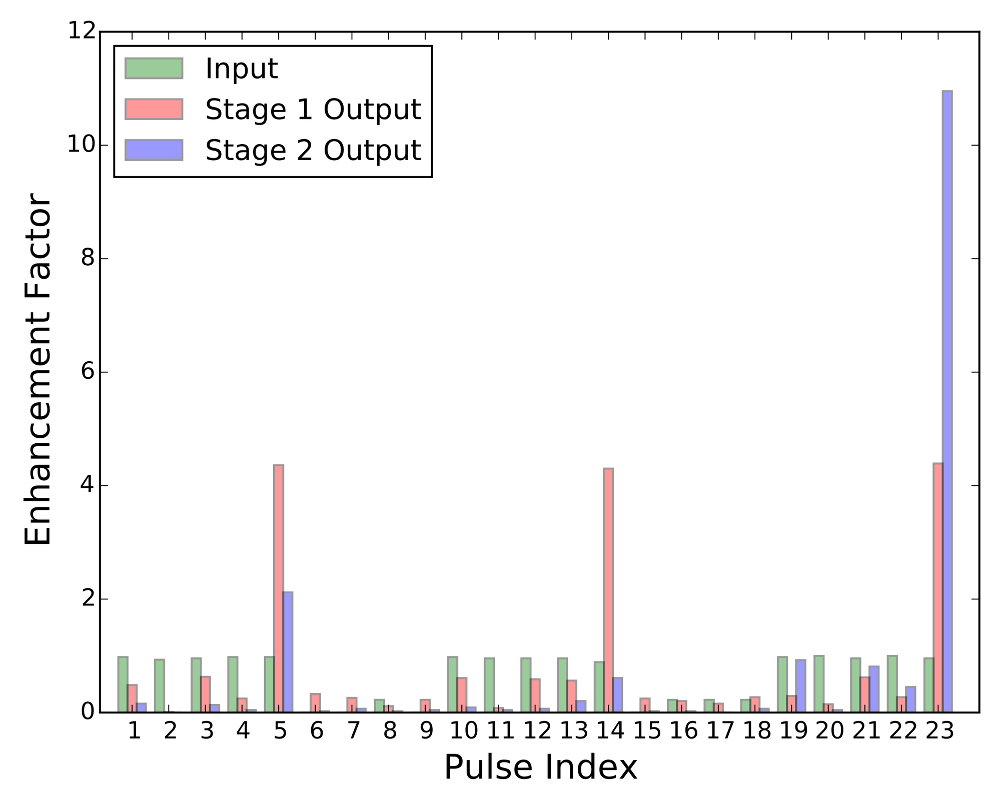




Hardware:
- ML605 + FMC110 + XM105
- 2-CH 12-bit A/D & 2-CH 16-bit D/A & 400Msps
- kHz Feedback Control Repetition Rate

Firmware:
- Bottom Layer: Hardware-Dependent Drivers
- Intermediate Layer: Data Communication (UDP)
- Top Layer: Project Specific DSP and control modules

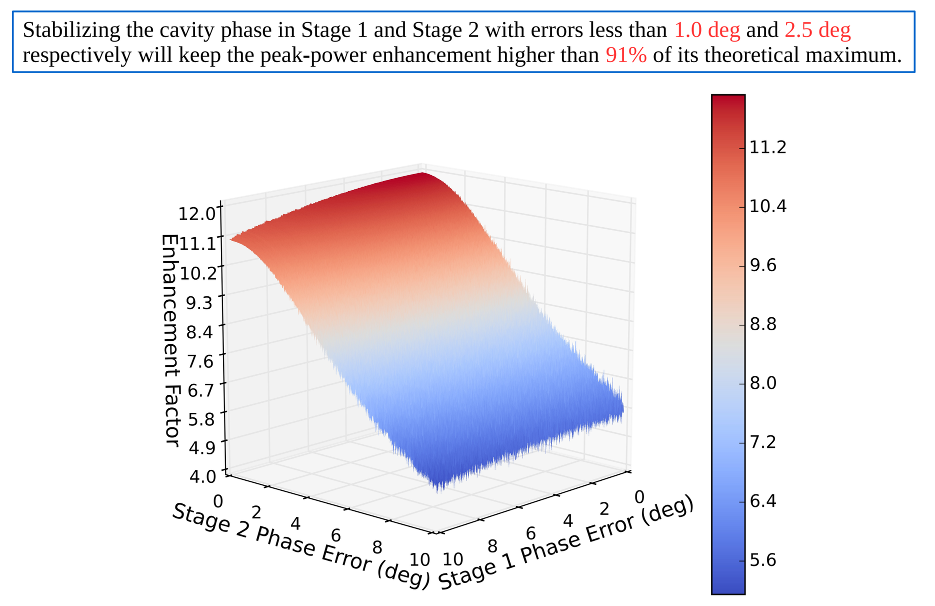
Stacking result



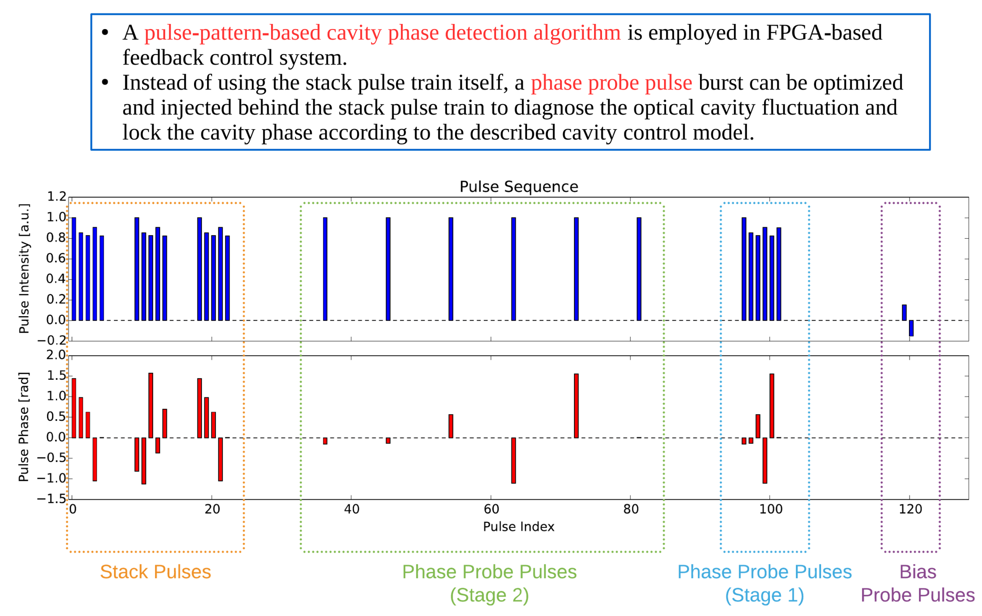
- A 2-stage (2+1 cavities) 15-pulse stacking system achieves a 11.0 peak-power enhancement factor, compared to the theoretical limit of 12.0.

Algorithm of cavity phase stabilization

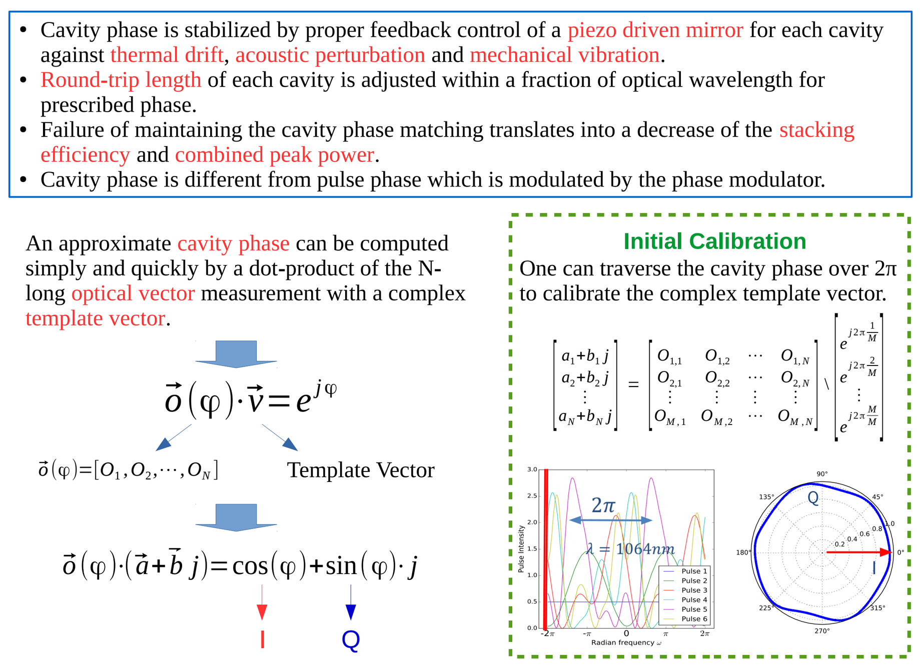
Failure to maintain the cavity phase matching translates into a decrease of the stacking efficiency and combined peak power.



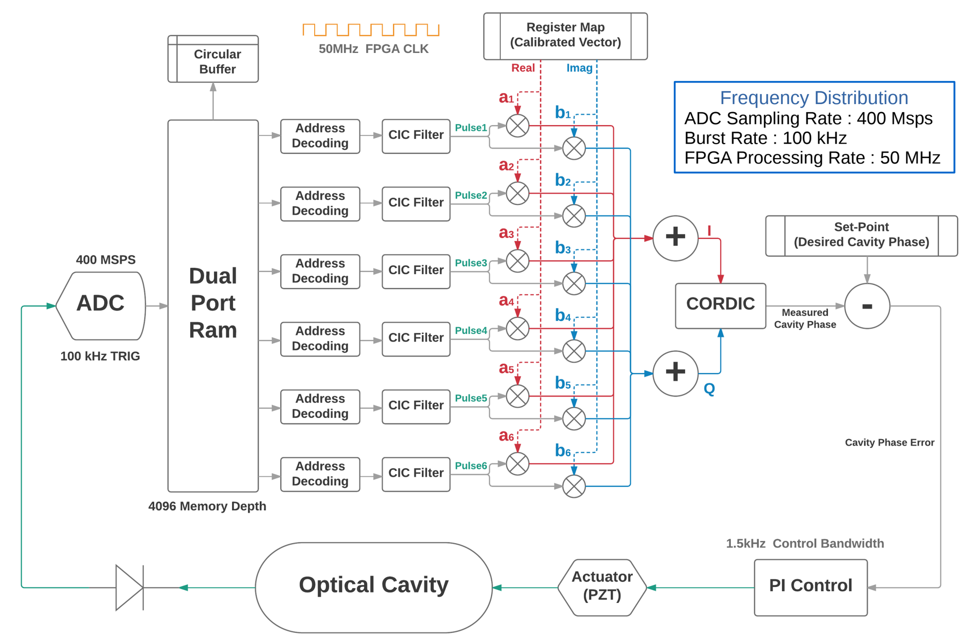
Phase probe pulses are introduced to detect cavity phase.



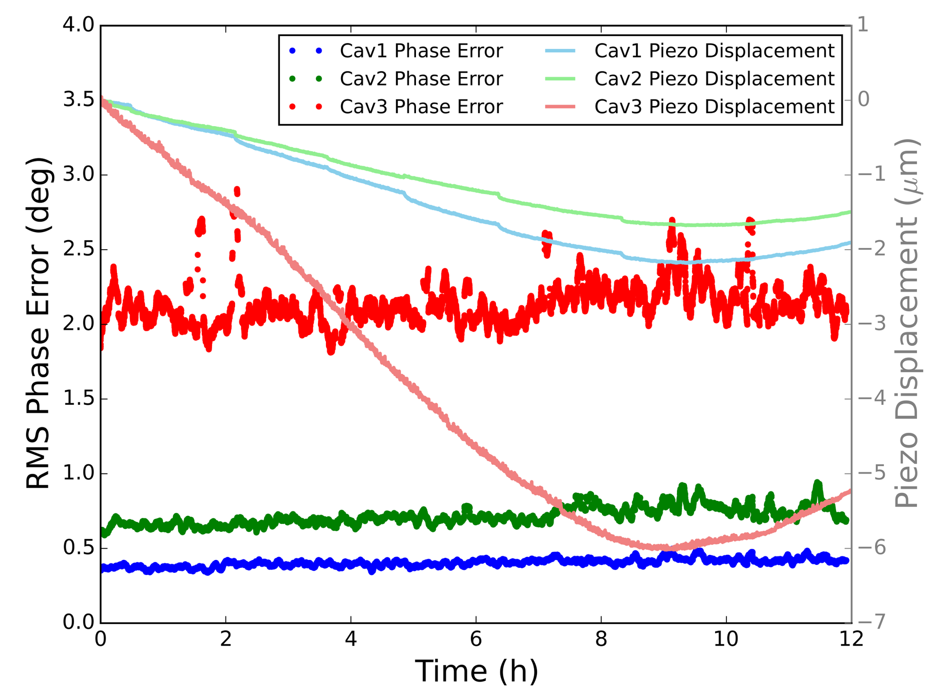
Pulse-pattern-based cavity phase detection algorithm.



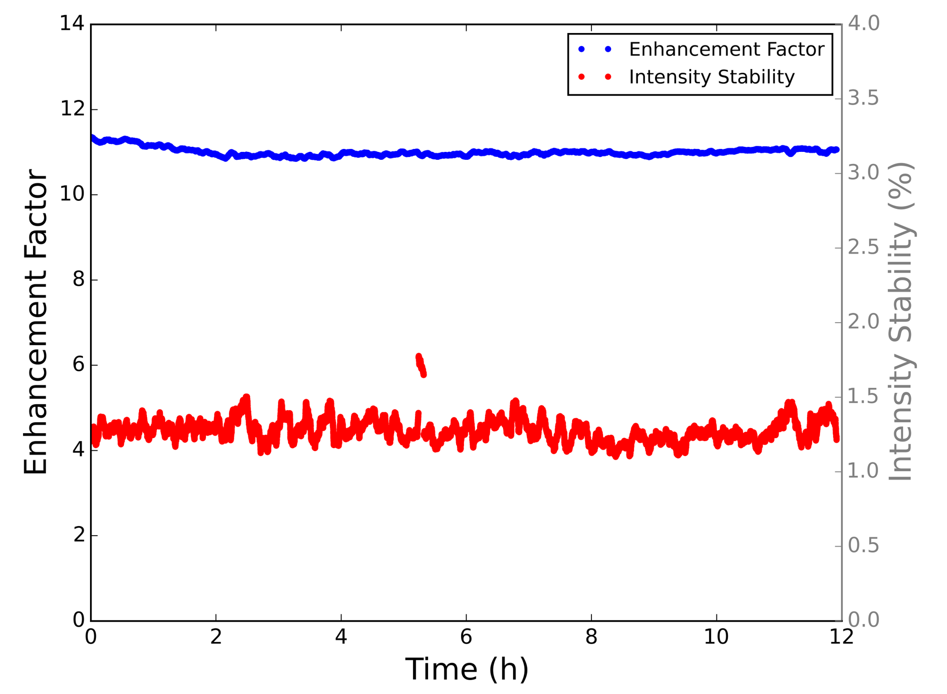
Digital processing chain of cavity control module.



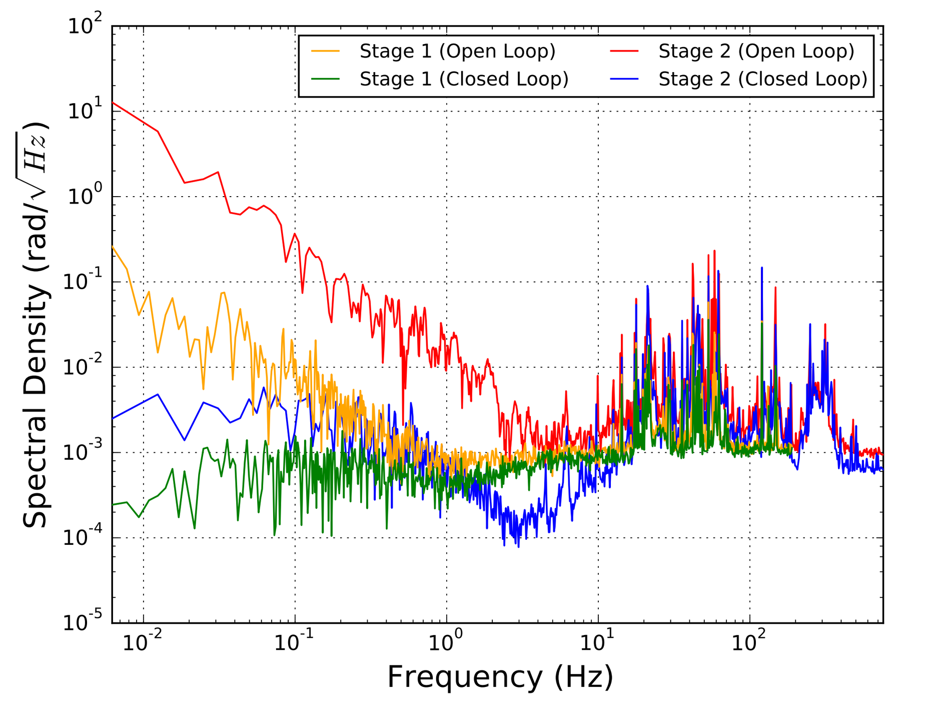
Stabilization results of coherent pulse stacking



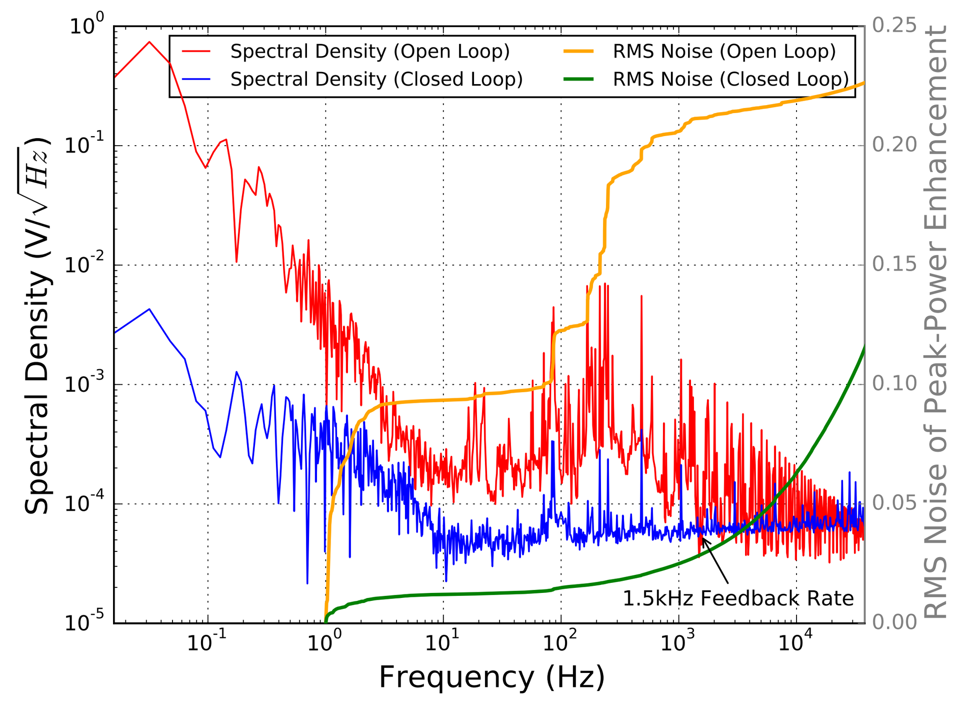
- Each cavity is stabilized with 0.7° and 2.1° (RMS) phase errors for Stage 1 and Stage 2.



- Intensity stability of the stacked pulse is kept within 1.2% (RMS) over 12 hours.



- Noise spectrum of the cavity phase.



- Noise spectrum of the stacked pulse.