Stabilized Laser System at 1550 nm Wavelength for the Einstein Telescope Low-Frequency Interferometers

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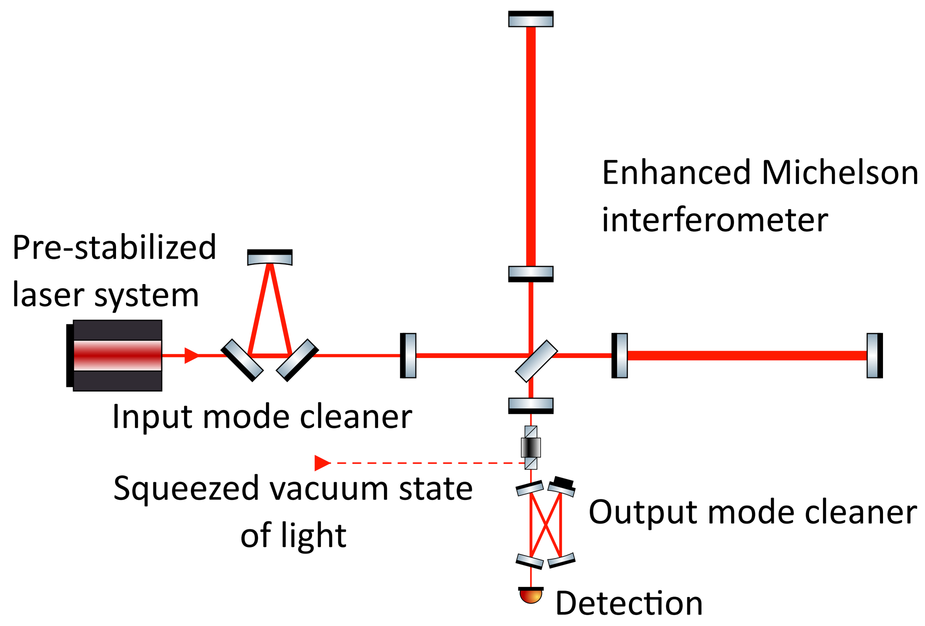
Laser Systems for Future Gravitational Wave Detectors

The main laser system of a gravitational wave detector (GWD) provides the laser beam for the interferometric differential arm length measurement.
Due to limited common mode rejection and other noise coupling paths in the interferometer the laser has to fulfill

- **single frequency** operation,
- a specific **laser power**,
- emission in the **fundamental Gaussian mode**,
- low laser **frequency noise**,
- stable laser power with low laser **power noise**,
- robustness for long-term and **reliable operation**.

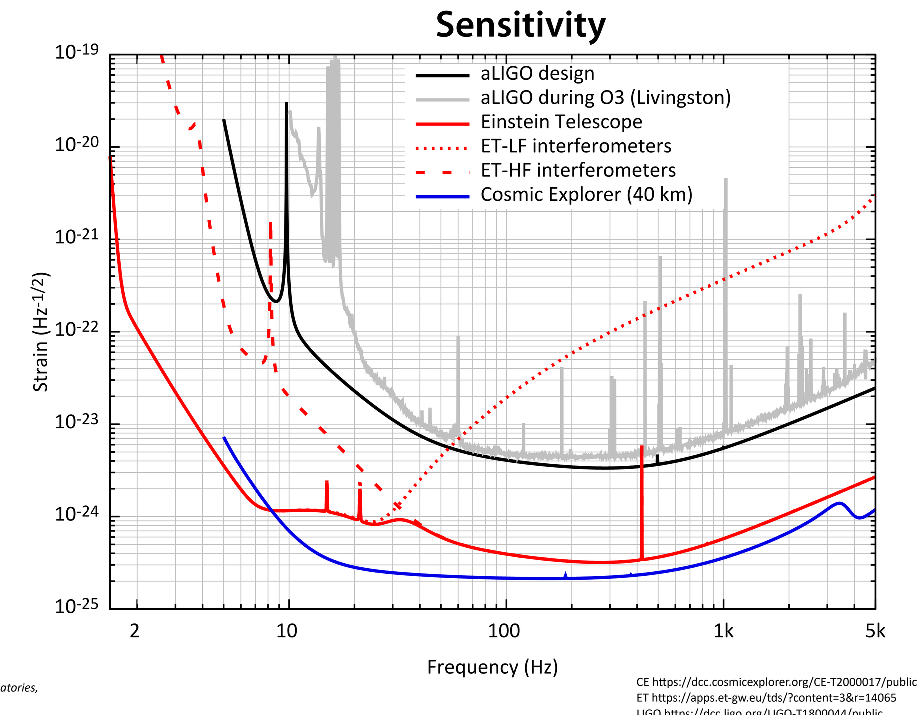


Laser wavelength considerations

- Mirror **thermal noise** starts to limit the GWDs sensitivity.
- Therefore, **cryogenically cooled silicon** or sapphire mirrors are proposed.
- Silicon requires the change of the laser **wavelength to 1.5 µm - 2 µm** due to absorption in the bulk material.

Proposed input laser powers:

Einstein Telescope low frequency: 3 W at 1550 nm
Cosmic Explorer phase 2: >140 W at 2 µm



Stabilized Laser System at 1550 nm Wavelength for Future Gravitational-Wave Detectors

Selection of laser sources and amplifiers at 1550 nm wavelength

Characterization of Laser Systems at 1550 nm Wavelength for Future Gravitational Wave Detectors
https://doi.org/10.3390/instruments6010015

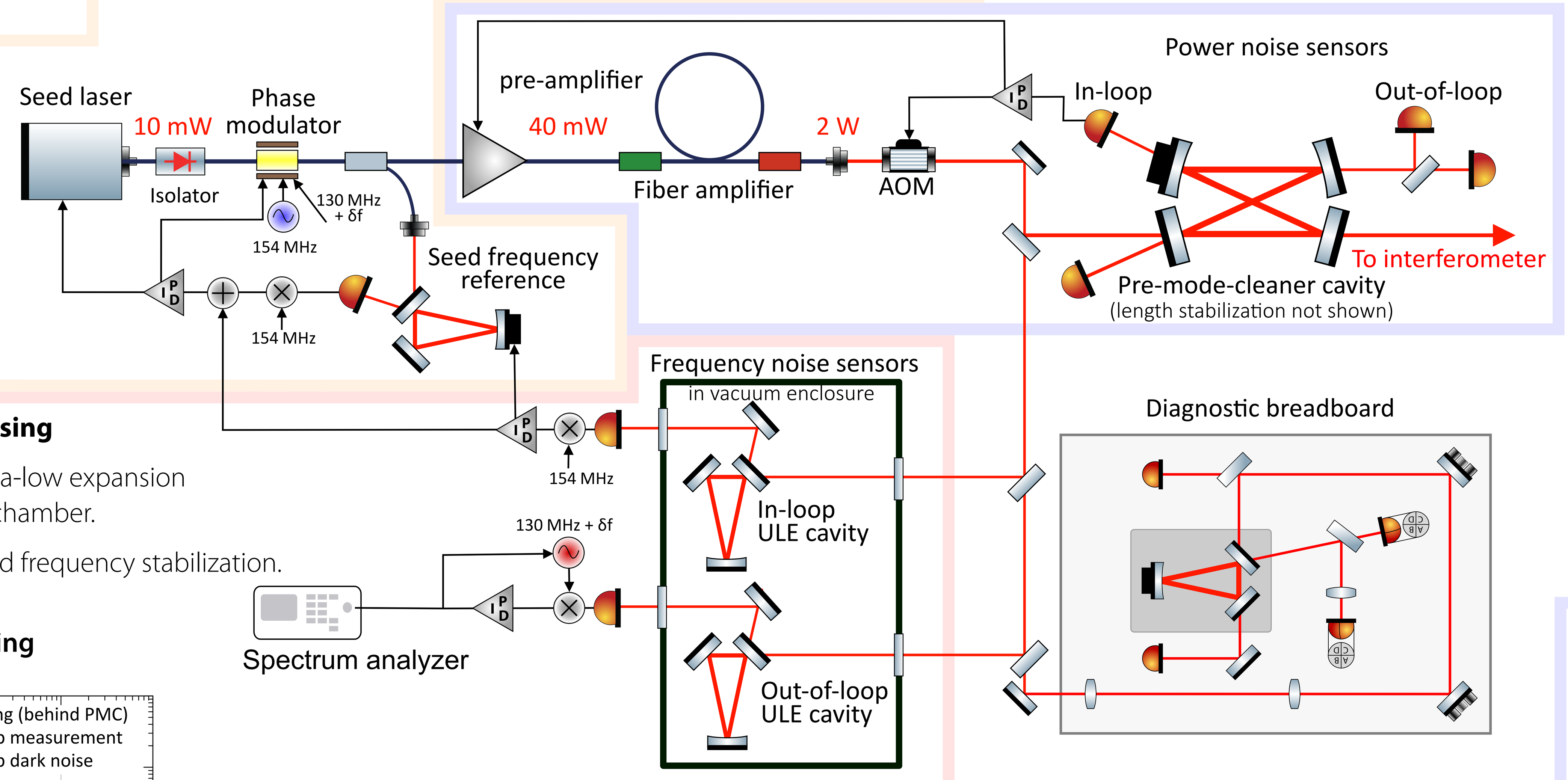
- Optimized combination of seed laser and amplifiers
- Laser stabilization with out-of-loop verification
- Designed for the needs of ground-based GWDs

Seed frequency stabilization

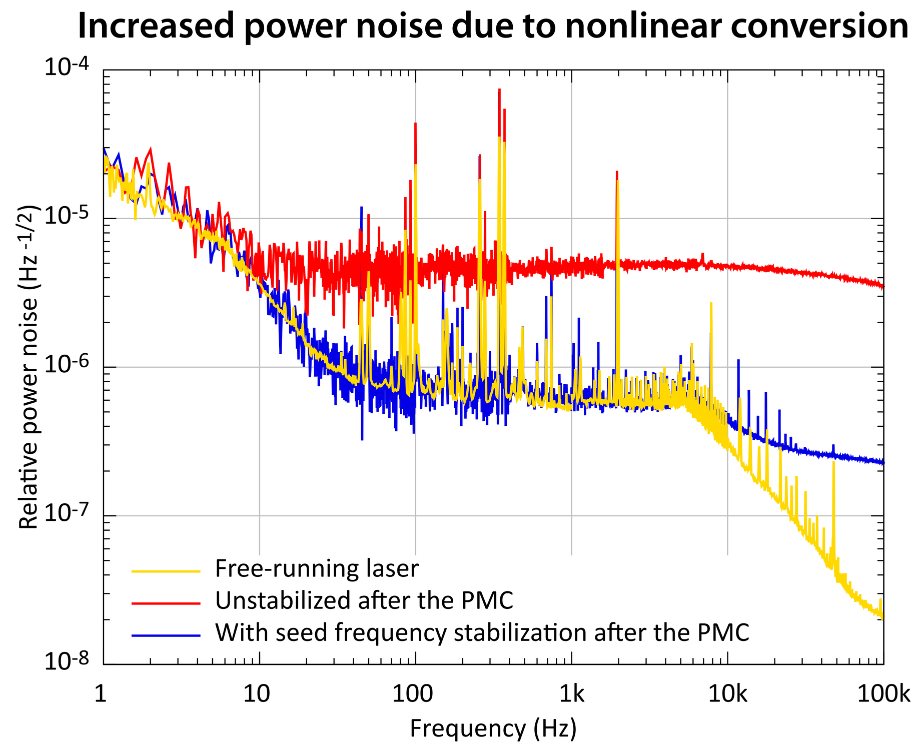
- Stabilization of the laser frequency with 2 MHz unity gain bandwidth
- Minimized loop delay by reducing signal propagating length
- Feedback to the laser and the fiber phase modulator

Nonlinear frequency noise to power noise coupling at the pre-mode-cleaner

- The mismatch between cavity resonance frequency and laser frequency results in a quadratic coupling to laser power in transmission.
- White laser frequency noise of the seed laser above 10 kHz dominates the power noise of light leaving the PMC.



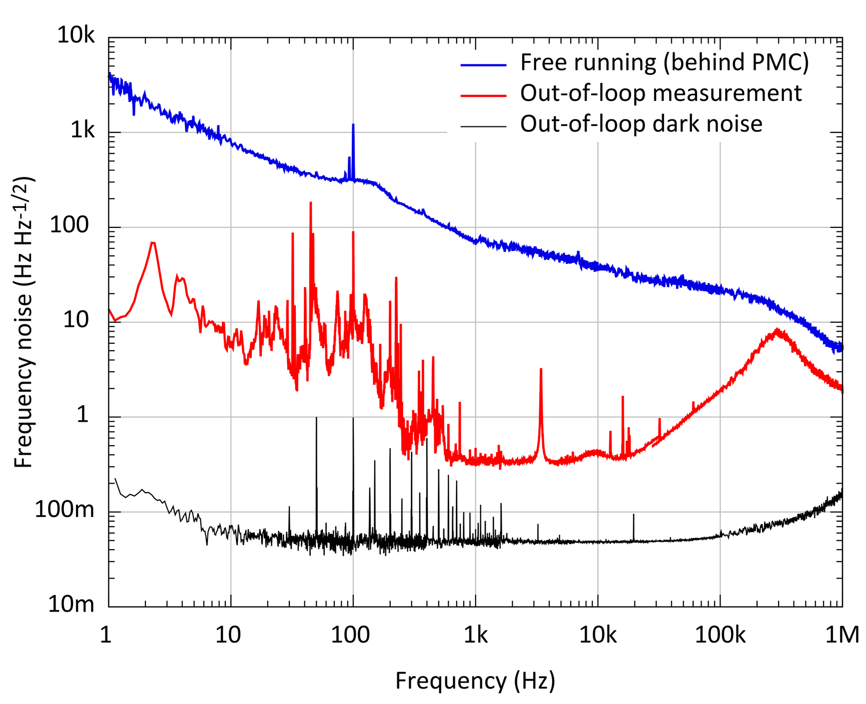
Increased power noise due to nonlinear conversion



Laser frequency stabilization and sensing

- The laser frequency is stabilized to a ultra-low expansion glass ceramic (ULE) cavity in a vacuum chamber.
- Feedback signals are injected to the seed frequency stabilization.

Out-of-loop frequency sensing



- The second ULE cavity is used as an independent sensor.
- Due to microscopic length differences, both cavities are not resonant at the same laser frequency.
- Therefore, a phase modulation side band in the 130 MHz range is controlled to resonate in this out-of-loop cavity.
- Error and control signals are used to calculate the laser frequency noise.

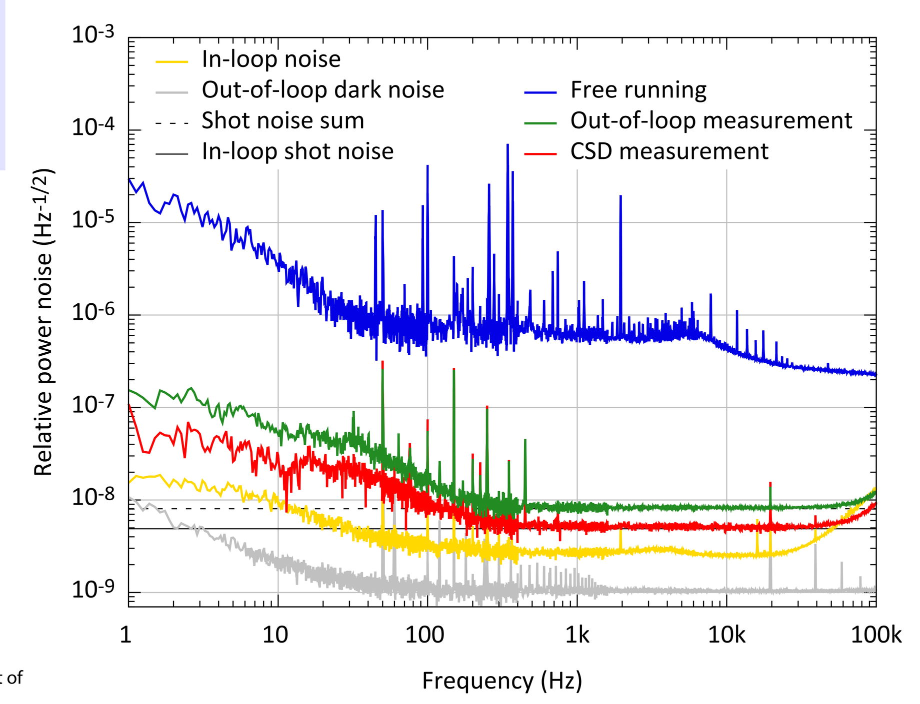
Stabilized laser system at 1550 nm wavelength for future gravitational-wave detectors
https://doi.org/10.1103/PhysRevD.105.122004

Laser power stabilization and sensing

- Feedback is sent to an acousto-optic modulator and the pre-amplifier current.
- Below 200 Hz the performance is limited by air fluctuations causing laser beam pointing on the slightly inhomogeneous photodiodes.
- Cross-spectral density measurement can reveal the in-loop shot noise limit.

Quantum correlation measurement of laser power noise below shot noise
https://doi.org/10.1364/OPTCON.450479

Laser power stabilized to the shot noise limit



Next Step: Laser Stabilization Experiment at Low Frequencies for the ET-LF Interferometers

- Improve the laser beam sensing in the detection band of the Einstein Telescope low-frequency (ET-LF) interferometers: **3 Hz to a few 100 Hz**.
- Test the transfer of laser light to a vacuum system
- Improve in-vacuum laser power sensing in the high current regime: >200 mA
- Characterize and tackle the electronic limitations of the Pound–Drever–Hall readout

Beam transfer into a vacuum chamber

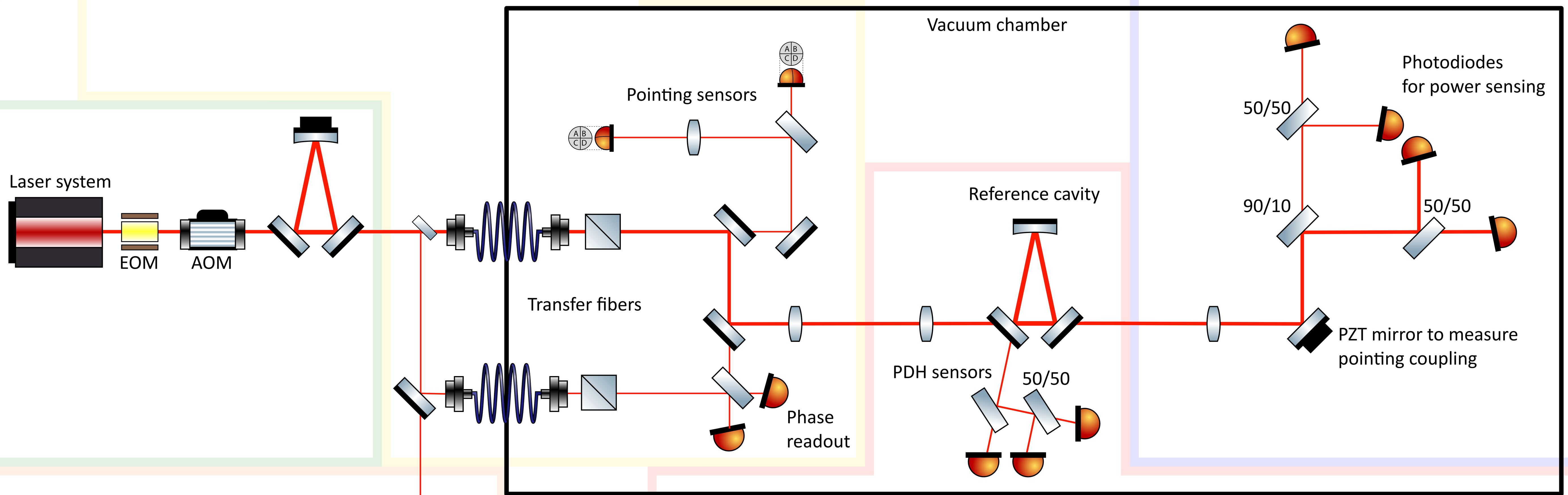
- Characterization of laser power noise and pointing noise added by the optical transfer fiber
- Test of power limitations with standard optical fibers
- Test the added phase noise by comparing two transfer fibers
- Comparison to free beam transfer (not shown)

Laser power measurement limitations

- Test the limits of in-vacuum power sensing for maximal laser power respectively maximal photo current.
- What are the limiting sensor and readout noise sources in the high current regime?
- Test pointing optimization, (noise) parameter spread of InGaAs sensors using cross-correlation and homodyne readout techniques between the photodiodes.
- Show sufficient techniques to stabilize to the demanded noise levels for ET-LF interferometers.

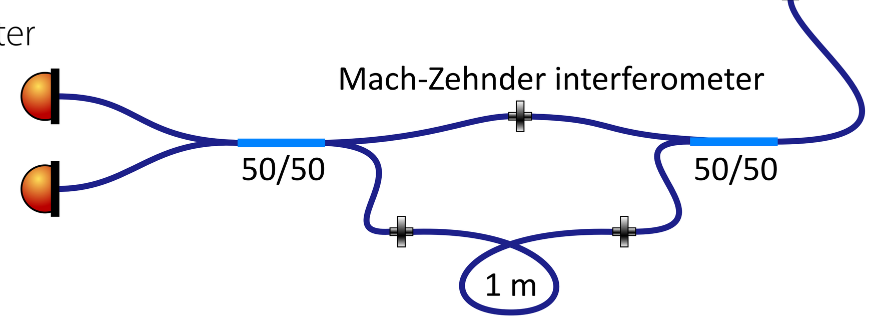
Seed laser and amplifiers

- Test improved power supplies for the seed laser (external cavity diode laser)
- A semiconductor amplifier is used as a pre-amplifier with fast power actuation.
- Test a new 16 W erbium based, commercial fiber amplifier
- Try to implement a fast current control in the last amplification stage for power stabilization.



Laser frequency at MHz frequencies

- Unequal arm fiber Mach-Zehnder interferometer
- Measure frequency noise up to 100 MHz
- Thermal stabilization on the mid fringe
- Homodyne readout to suppress power noise coupling



Laser frequency readout noise

- Pound–Drever–Hall readout of the error signal of an in-vacuum Invar spacer cavity
- Test the electronic noise and shot noise limitation with two other demodulated photodiode signals using:
- Coherence and cross-correlation measurements