Einstein-Telescope: German Community Meeting

Stabilized High-Power Lasers for 2nd and 3rd Generation Gravitational Wave Detectors

Benno Willke

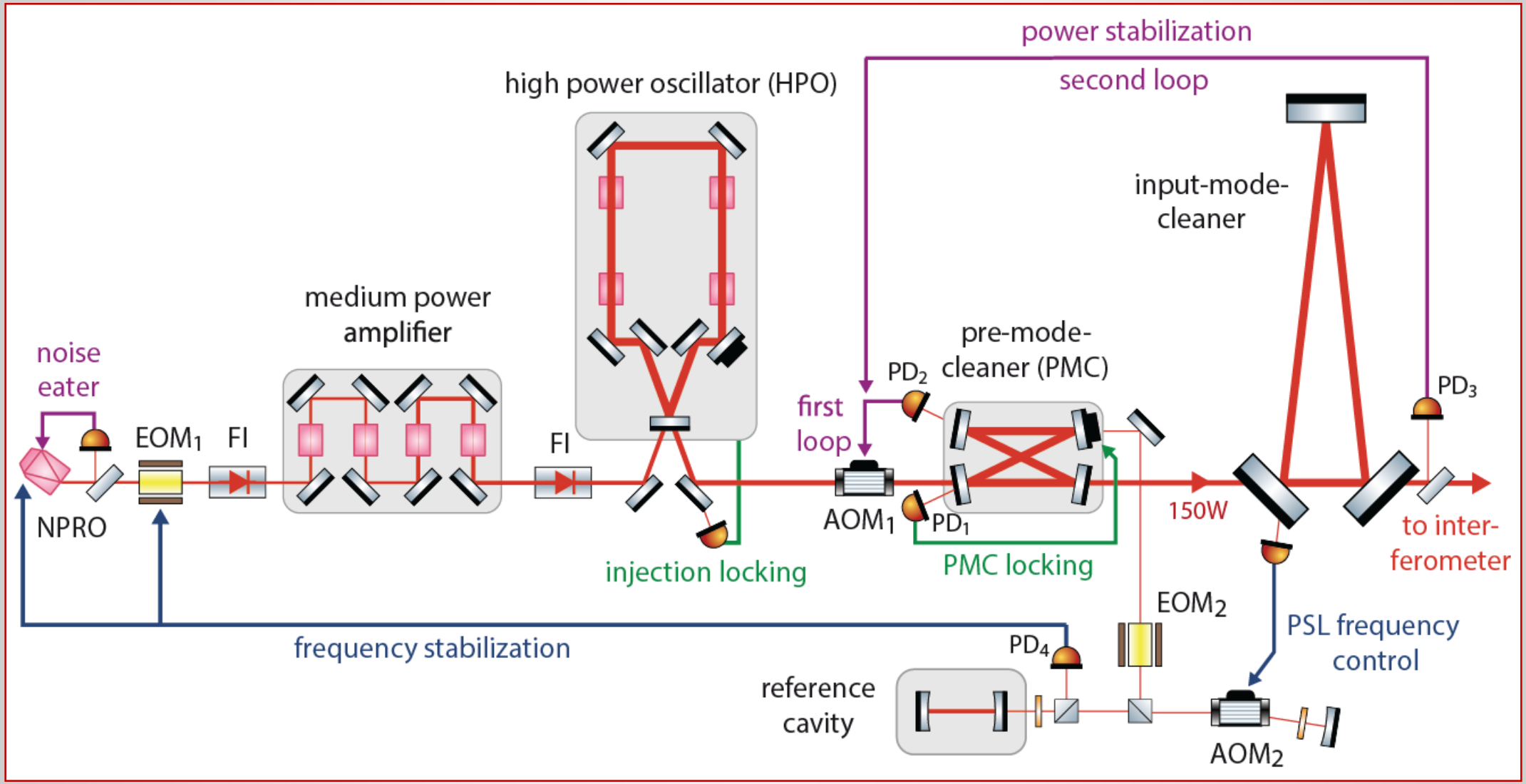
(for the laser team at AEI and Laser Zentrum Hannover)

17 Jan 2020 (Hannover)

General Requirements

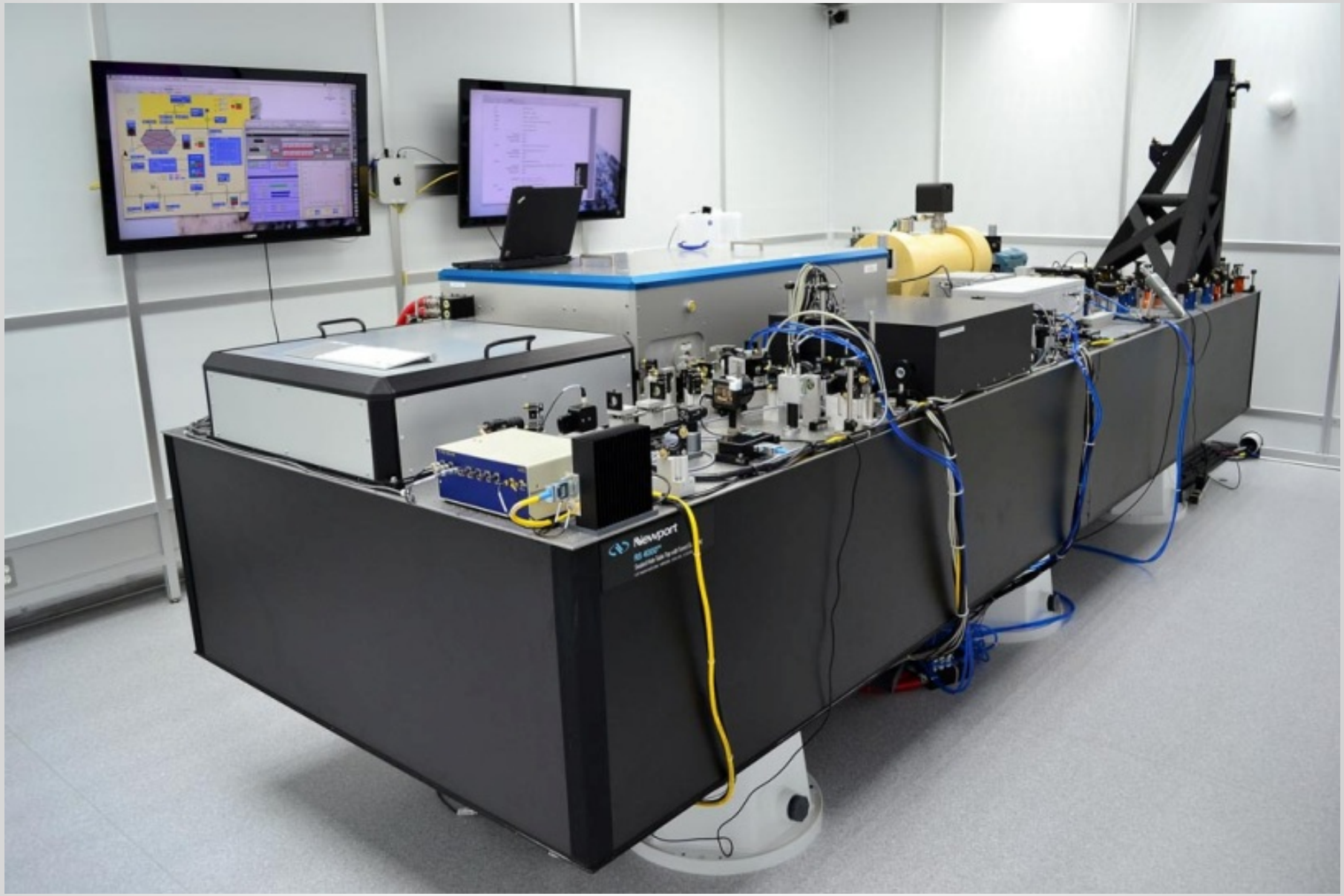
- Several hundred Watt power (cw, single-frequency, linearly-polarized)
  - To enable high circulating power in interferometer arms
- High spatial purity and low beam jitter
  - Good coupling to input-modecleaner
  - Low shot noise on sensors for laser and input-modecleaner stabilization
- Low free running noise (in laser power and frequency)
  - Acceptable stabilization effort (loop gain and cross-couplings)
- Low-noise sensors (for laser power and frequency)
  - To achieve required stability for light entering the input modecleaner
- Fast actuators (for laser power and frequency) with large range
  - To allow for required loop gain in stabilization control loops
- High robustness and reliability with low maintenance requirements

Advanced LIGO Pre-Stabilized High-Power Laser

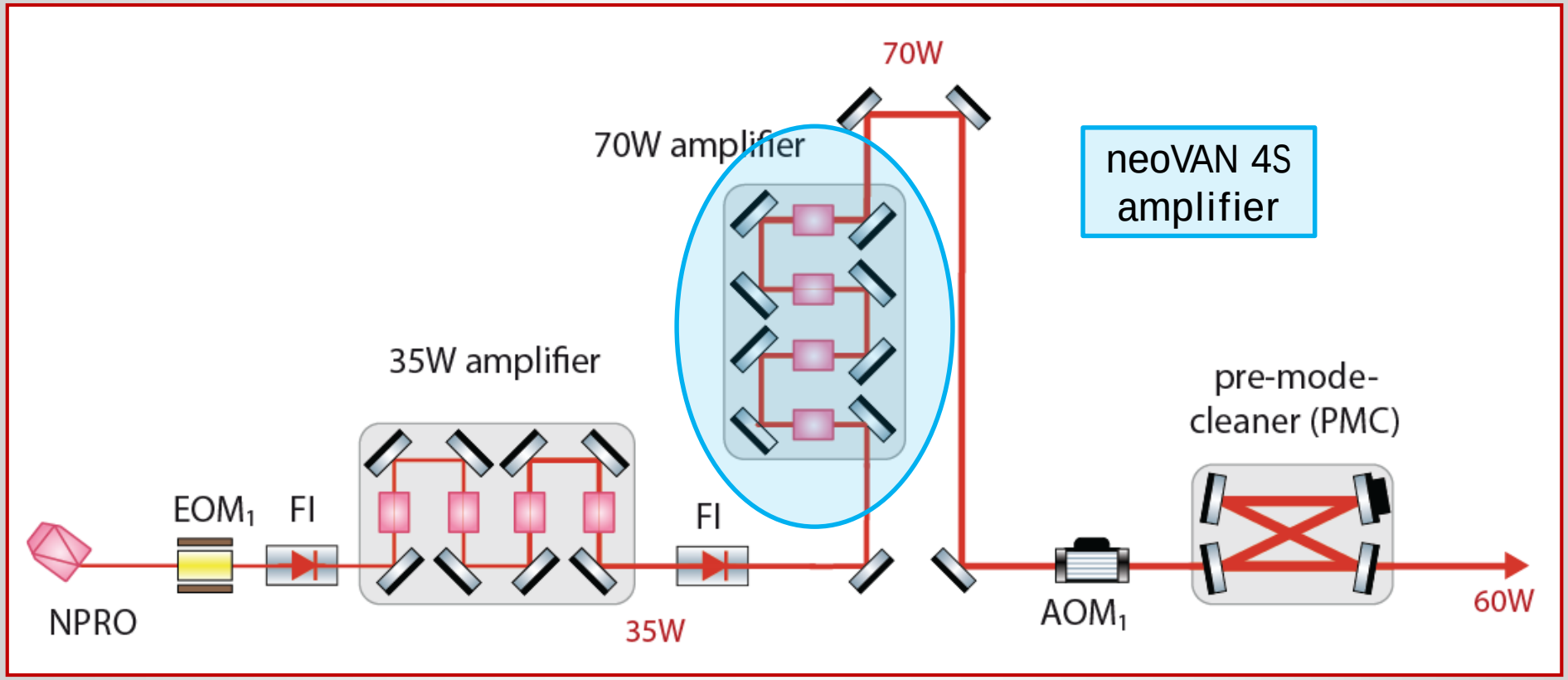


Kwee et al. Opt. Lett. (2009), Kwee et al. Opt. Express (2012)

Advanced LIGO Pre-Stabilized High-Power Laser



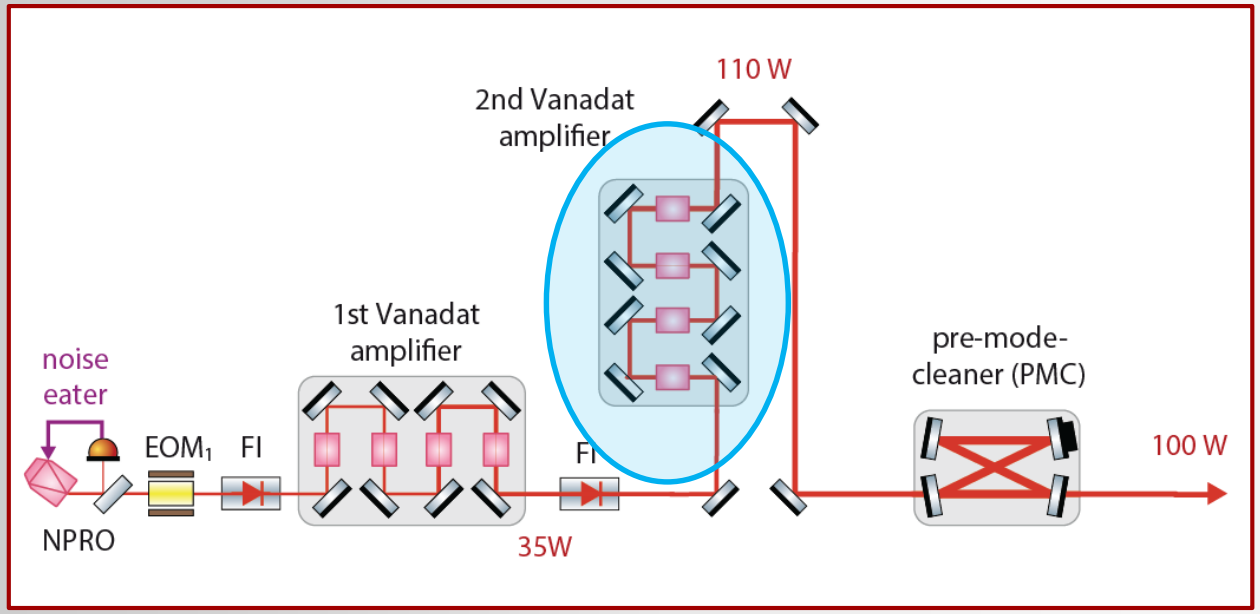
Modified aLIGO PSL for Observing Rum O3

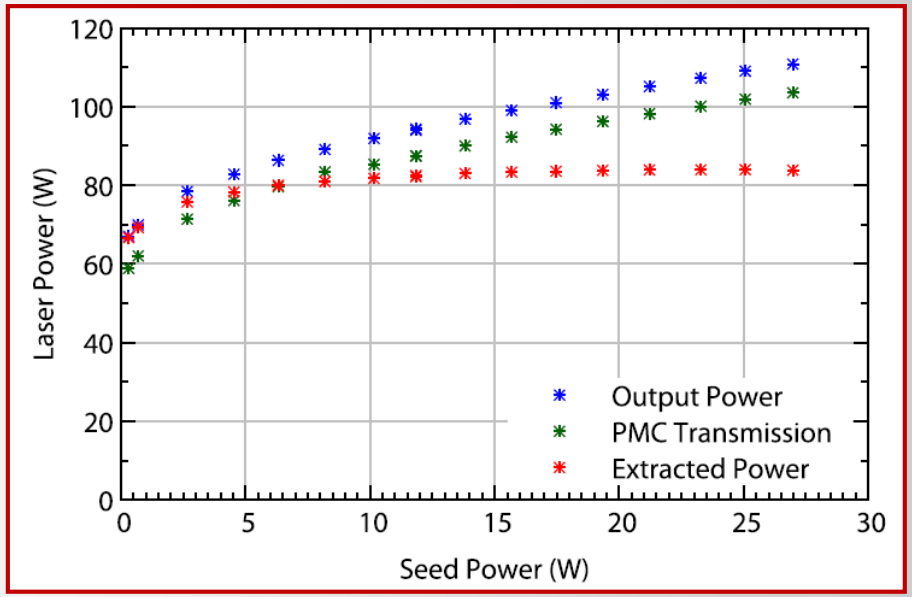


Thies et. al, Opt. Lett. **44**, No. 3. (2019)

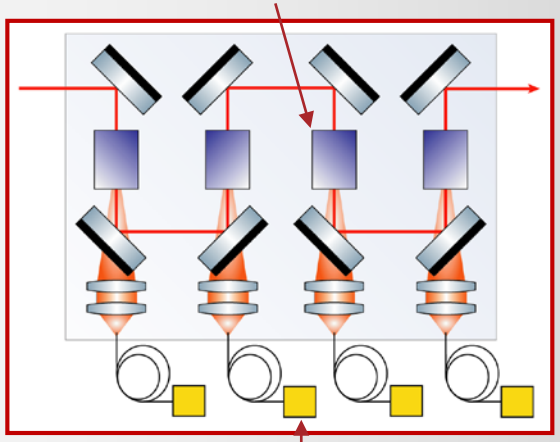
New Generation: neoVAN-4S-HP Amplifier

- First tested for Adv. Virgo at AEI
- Longer pump wavelength
  - 878nm vs. 808nm
  - VBG stabilized pump diodes
- 80W power extraction

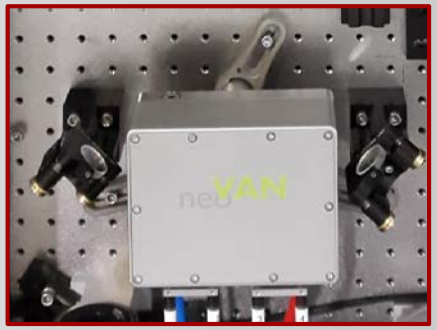




Four Nd:YVO_4 Crystals



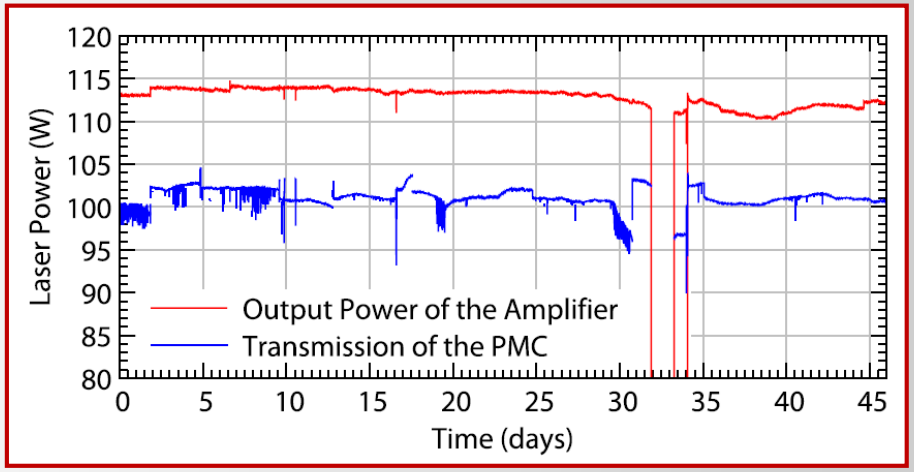
4 x 60 W Pump Diodes at 878 nm

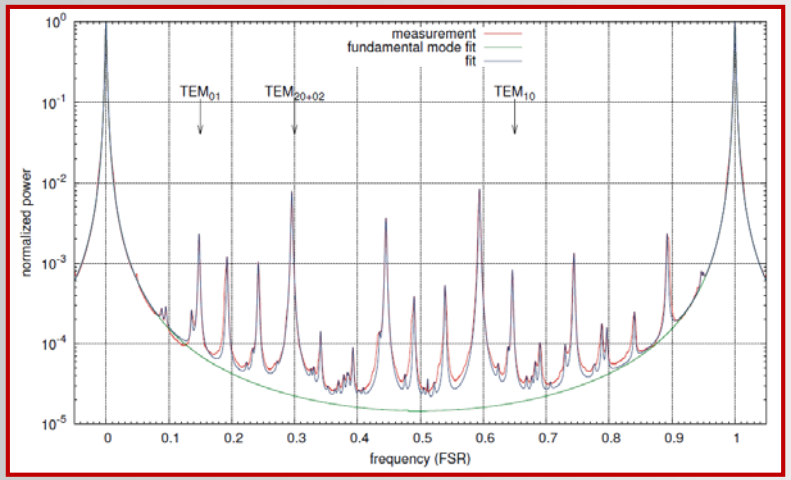


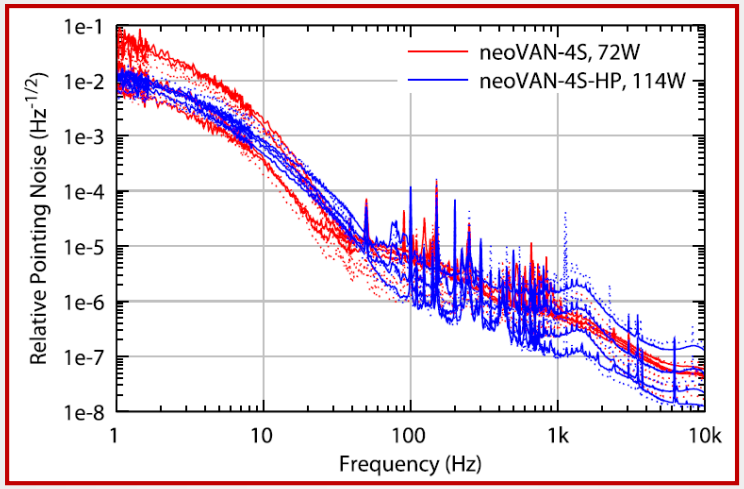
Thies et. al, Opt. Lett. **44**, No. 3. (2019)

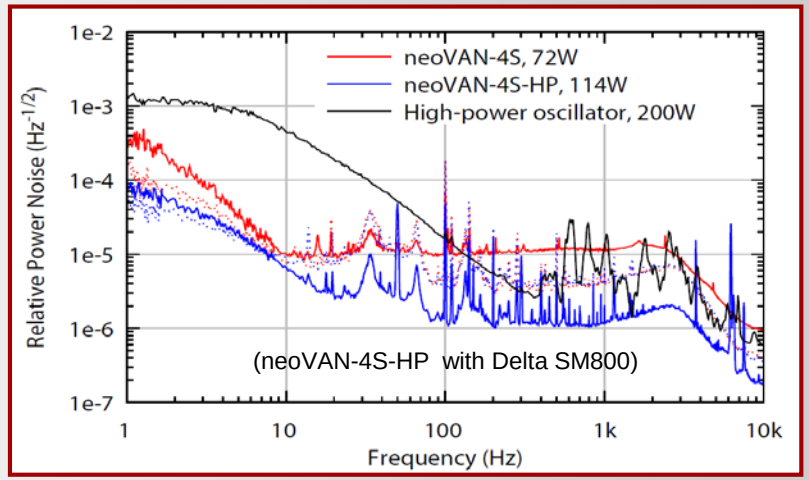
Performance of Nd:Vanadat Amplifier Systems

- 114 W output power for 27 W seed
- 3% higher order modes (similar to seed)
- 102W after filter cavity (PMC)
- Reduces beam pointing wrt. HPL
- significantly lower power noise than HPO
- 45 day stable operation with cold-start without realignment



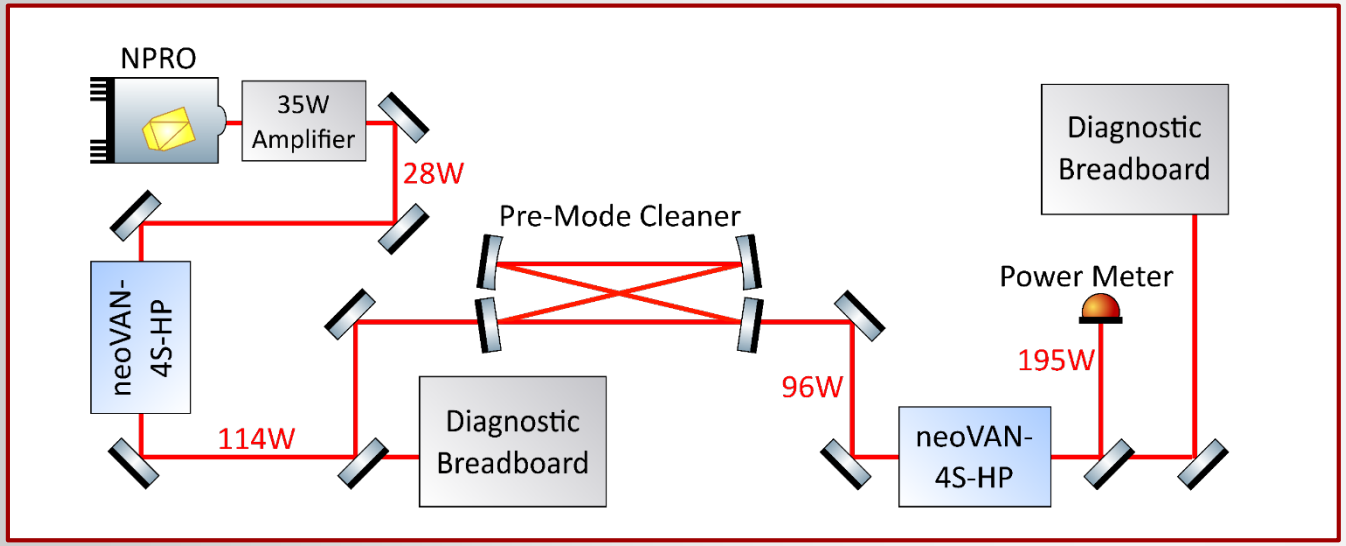




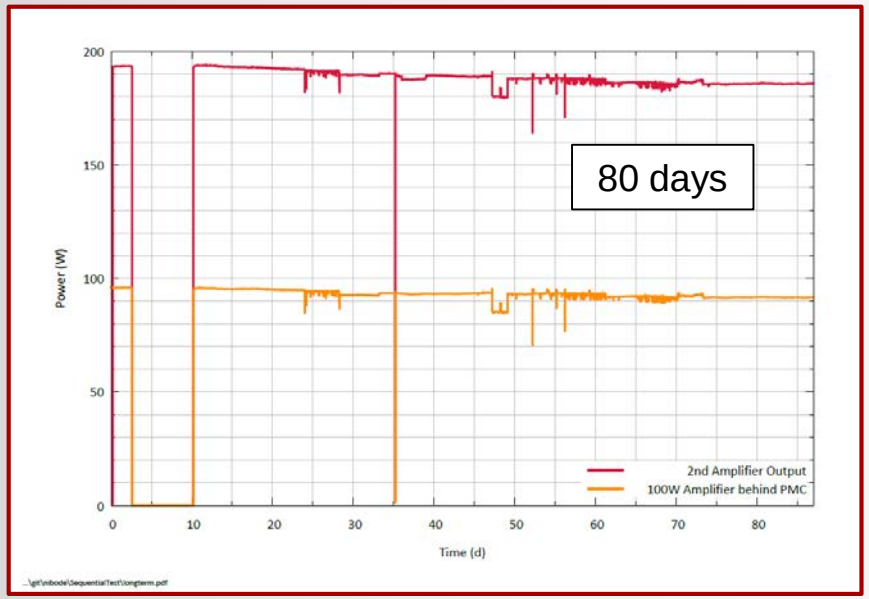


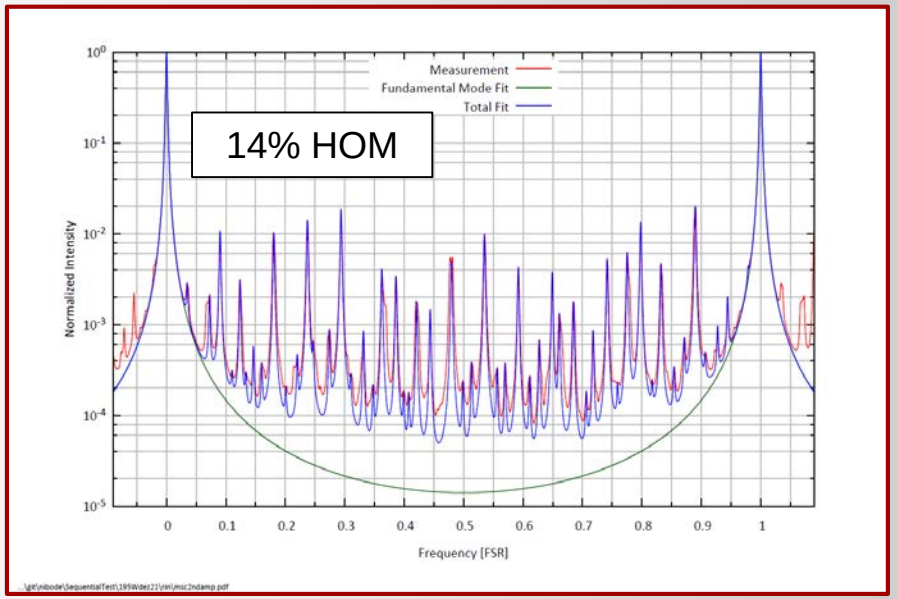
Thies et. al, Opt. Lett. **44**, No. 3. (2019)

Three Sequential Vanadat Amplifiers



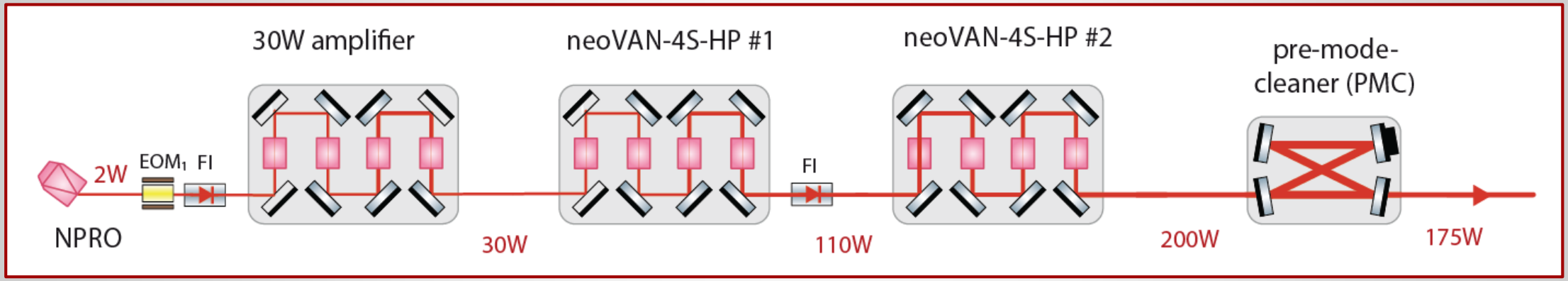
- Sequential neoVAN-4S-HP amplifiers deliver 195W
- similar noise performance as two-amplifier system
- Large higher-order mode content (14%) indicates limit of power scaling



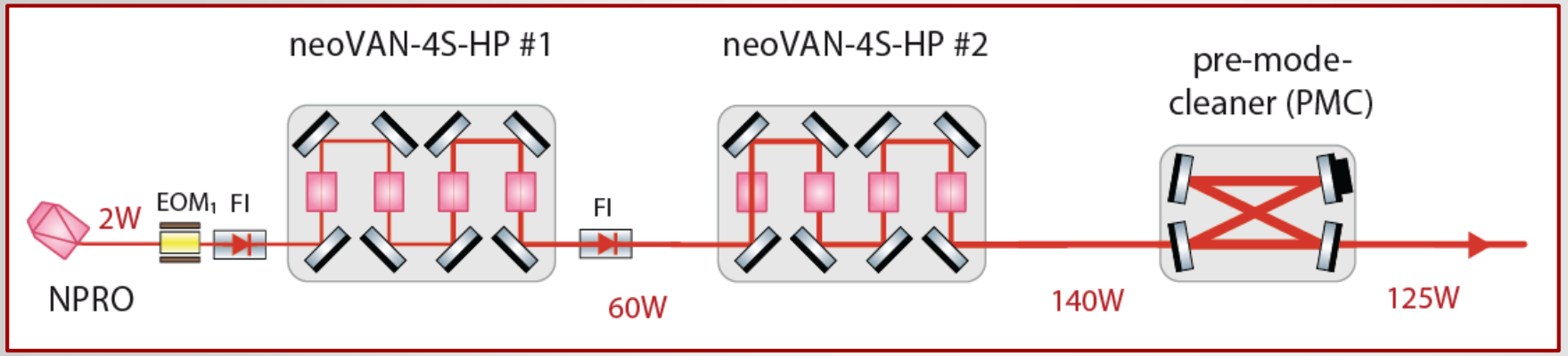


O4 Laser System: Option 1

Test of sequential neoVAN-4S-HP amplifiers at AEI



Advanced LIGO laser system for O4



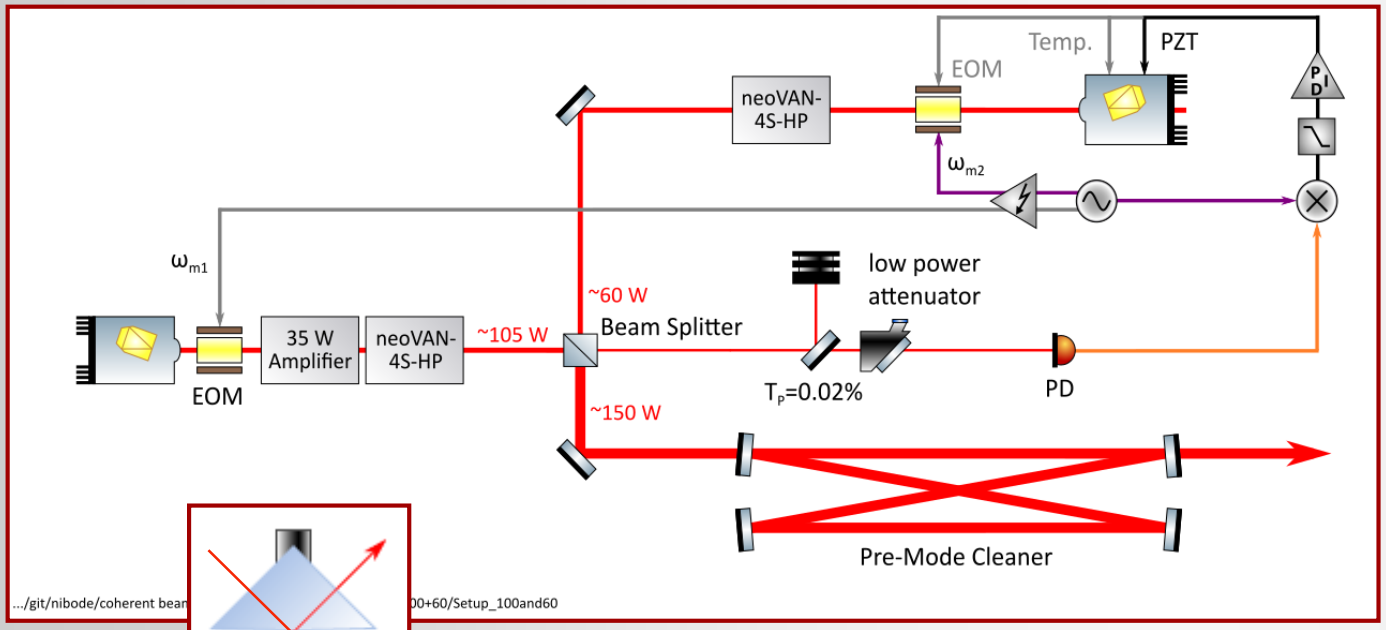
Requirements For Next Generation GWDs

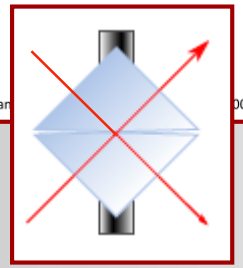
Project	Wavelength	Power	Spatial mode
Einstein Telescope low f	1550 nm	3 W	HG_{00}
Einstein Telescope high f	1064 nm	500 W	HG_{00}
Voyager	≥ 1550 nm	200W	HG_{00}
Cosmic Explorer (II)	≥ 1550 nm	1kW	HG_{00}
Asia- Australia GWD	1064 nm	200 W	HG_{00}

- Single-mode, single-frequency, linearly polarized, low free running noise
- Stabilization: factor 10 better than second generation GWDs
- Fast actuators with large range and low cross coupling
- High reliability
- Low maintenance downtime and costs

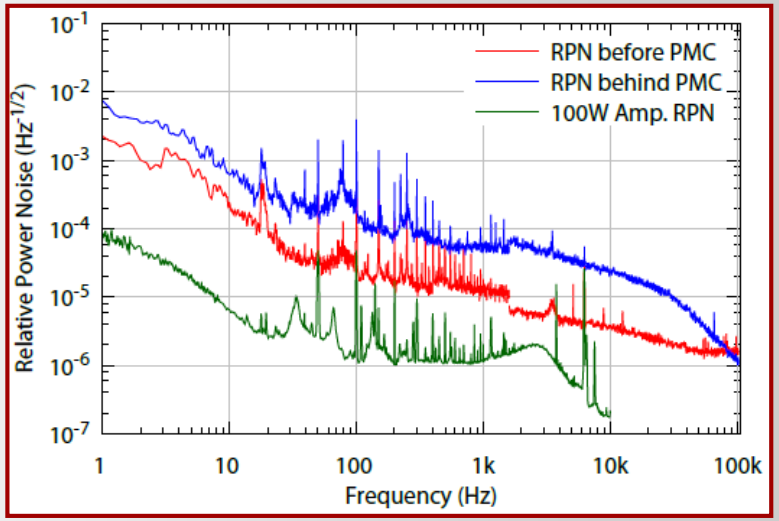
All numbers are still subject to change !

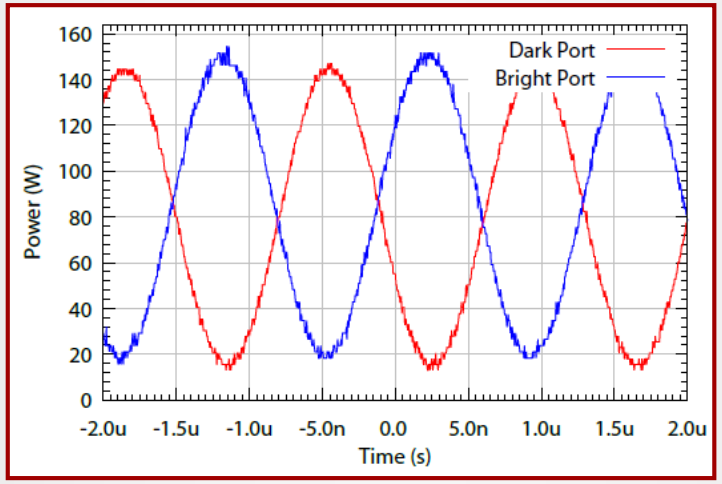
Coherent Beam Combination

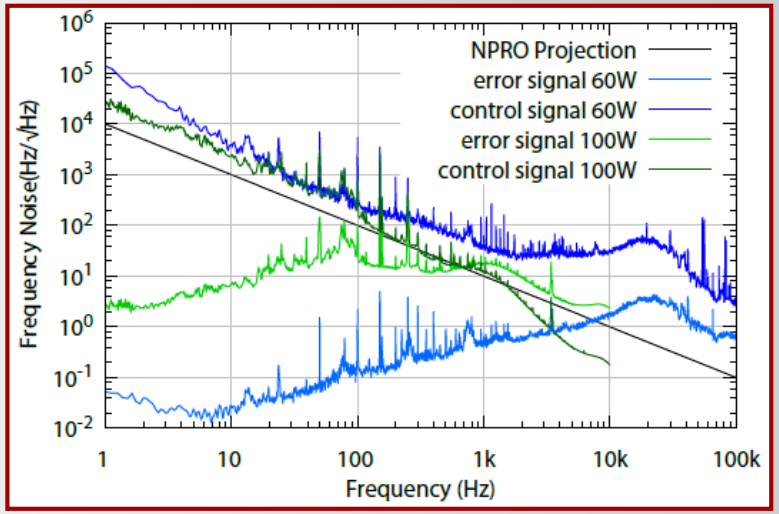




FTIR Actuator:
Variable beam splitter based on the effect of frustrated total internal reflection

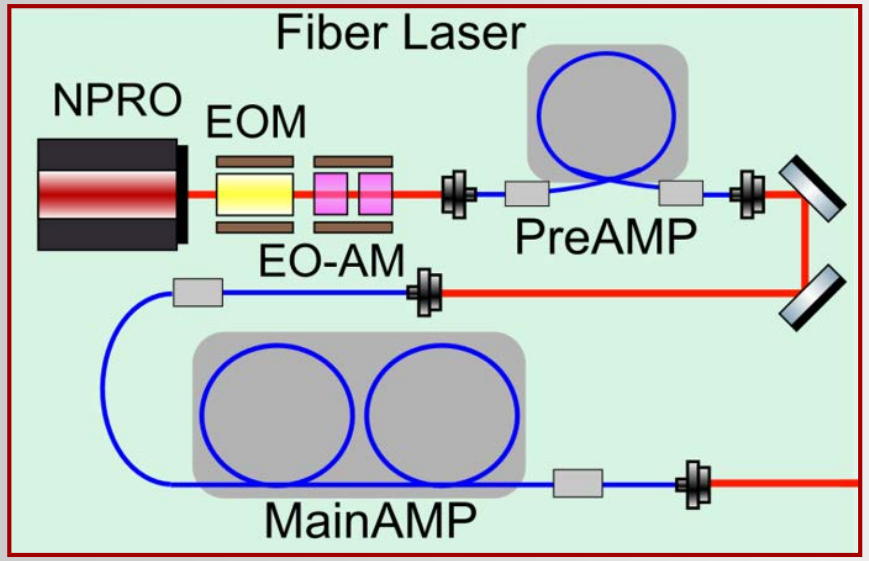




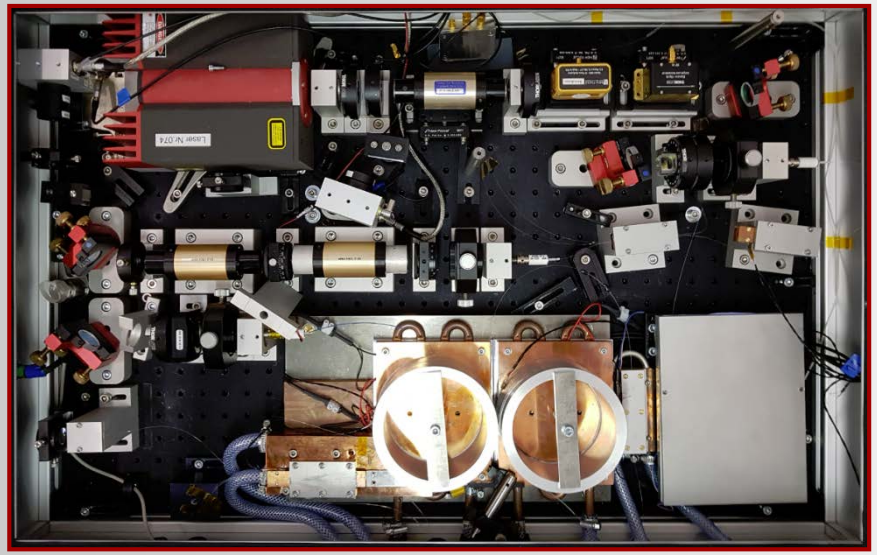


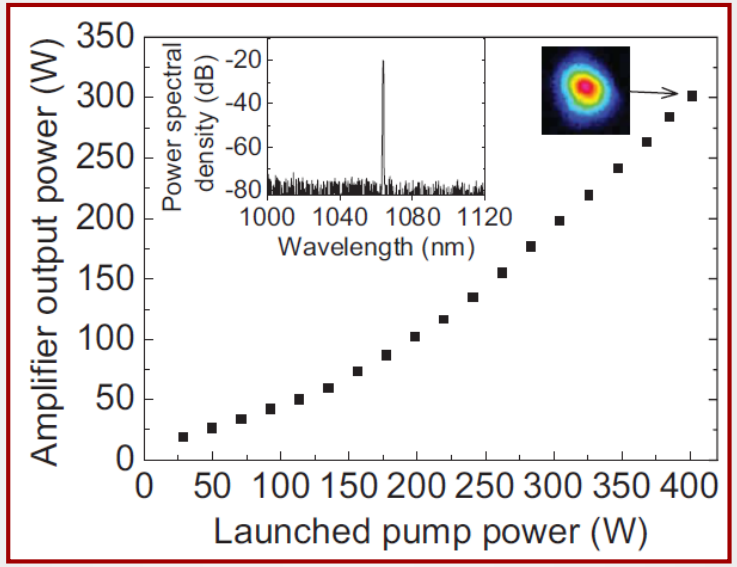
combination of 60W and 105W
⇒ 150W laser beam

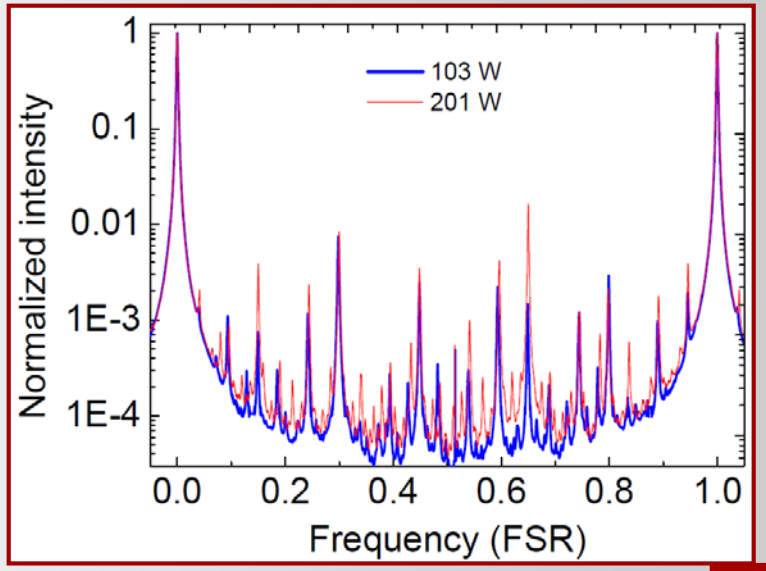
1064nm Fiber Amplifier – Proof of Principle



- two stage fiber amplifier with NPRO seed
- good spatial profile
- output power up to 300W
- no long-term reliable operation

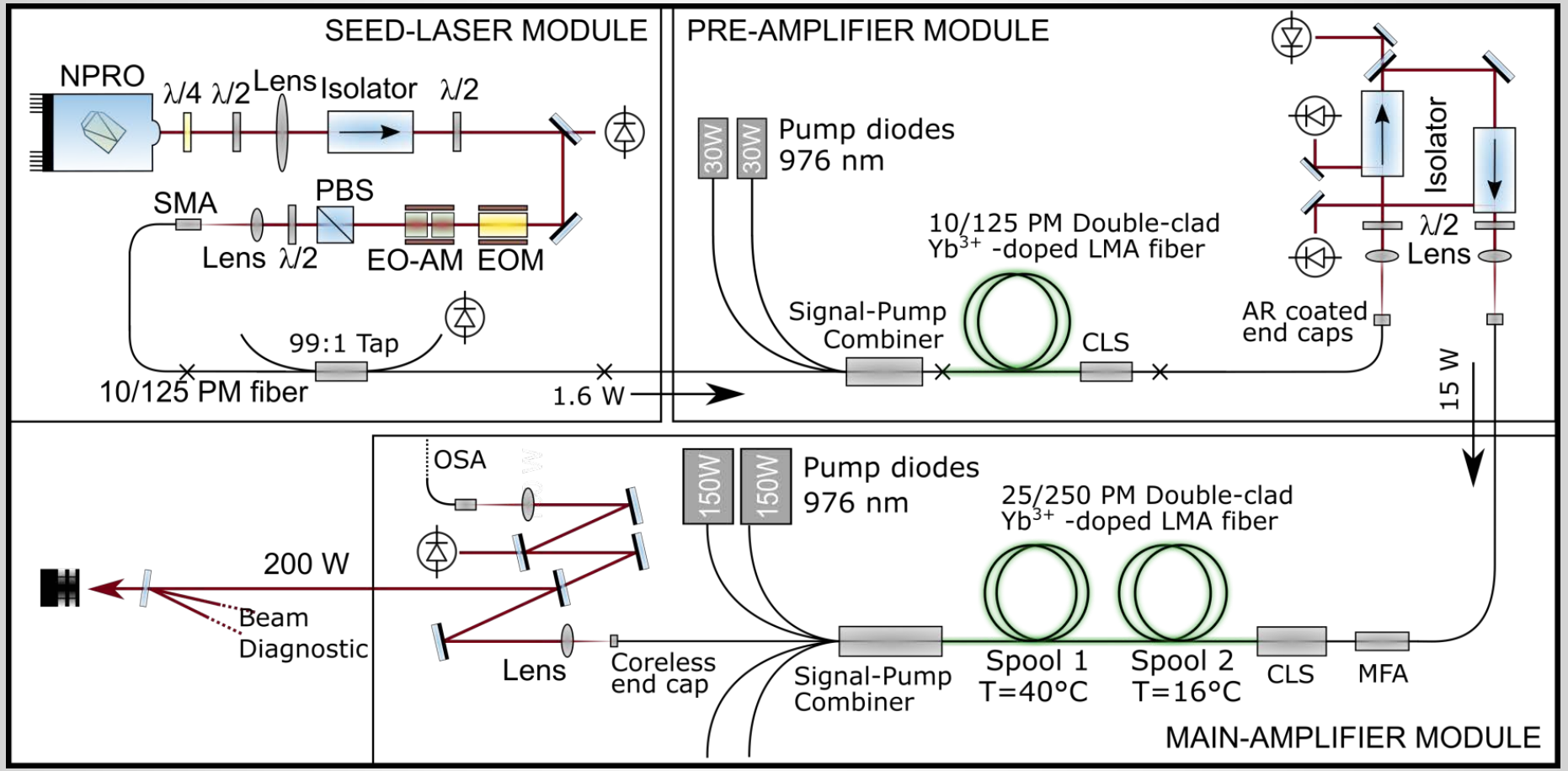






T. Theeg et al. IEEE Photon. Tech. Lett. (2012); T. Theeg et al. Opt. Express (2012)

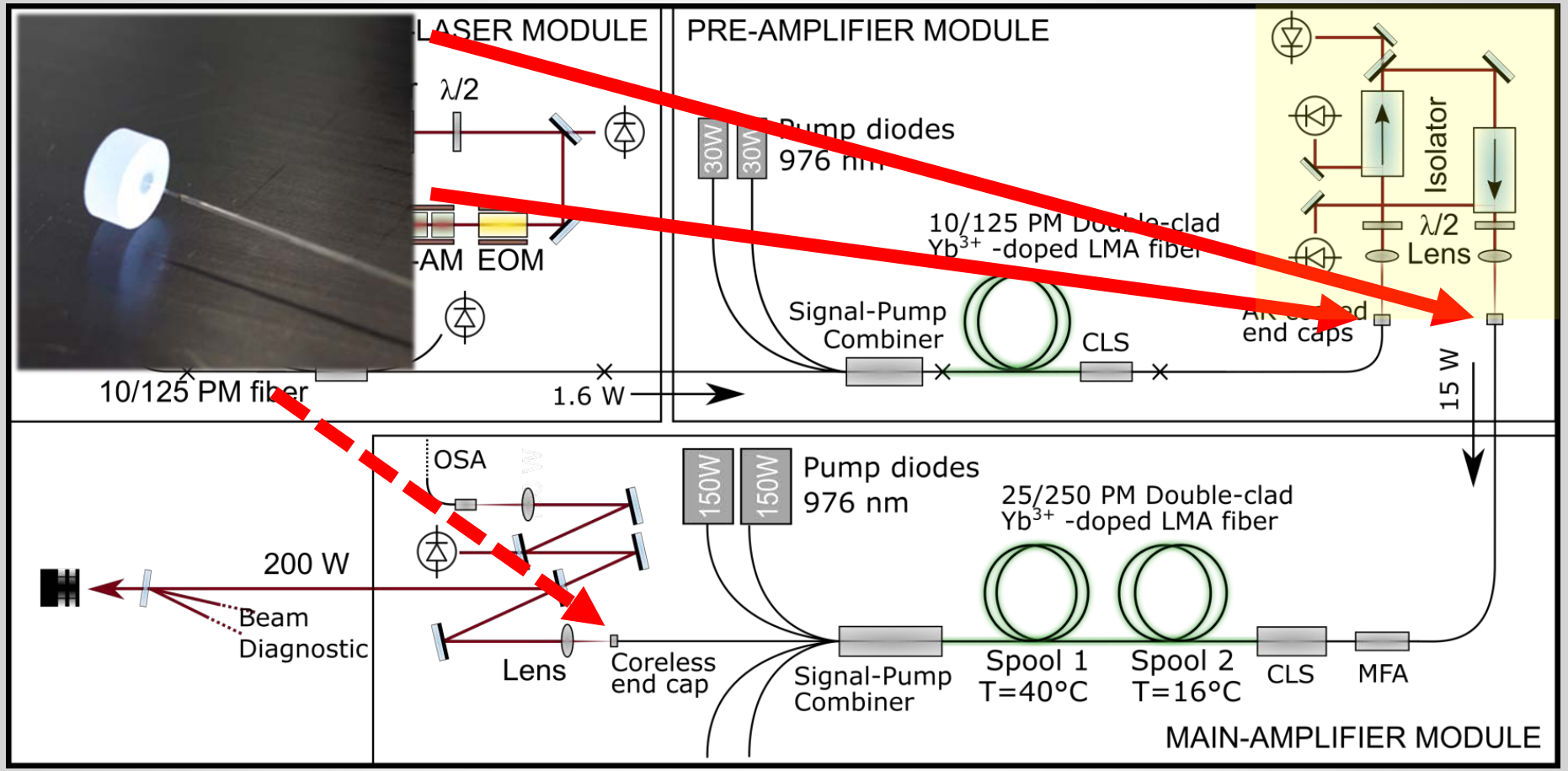
1064nm Fiber Amplifier - Engineering Prototype



new design with reduced number of splices, reduced reflectivity and higher optical isolation

Wellmann et al. Opt. Express **27** (20) 2019

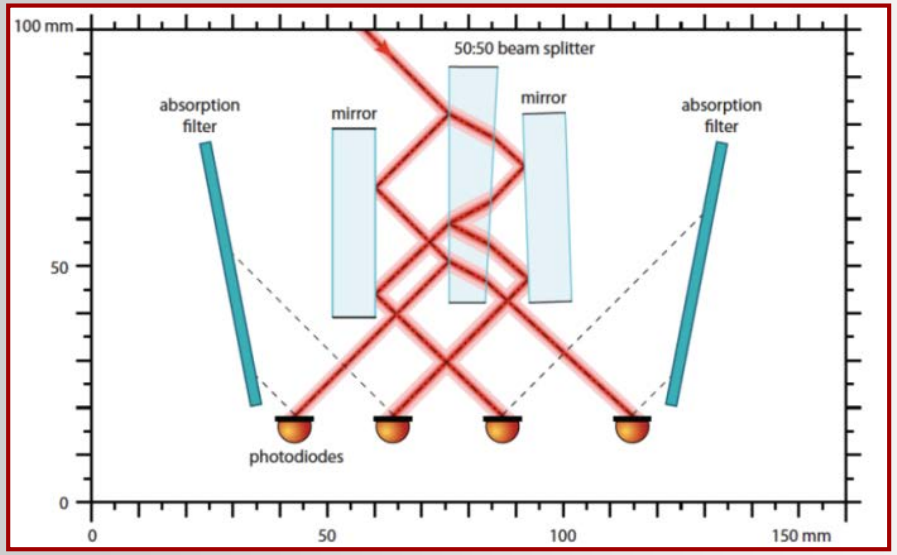
1064nm Fiber Amplifier Engineering Prototype

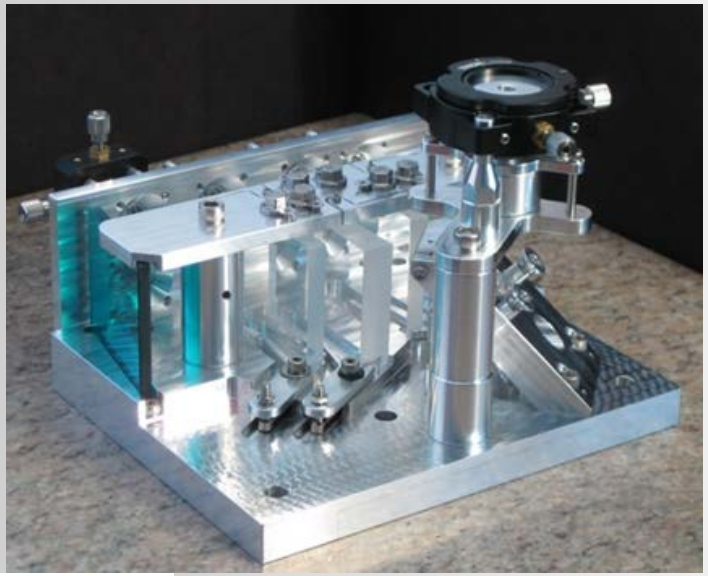


use AR coated fused-silica substrates at fiber-air interface in high-power FI unit and at high power output port

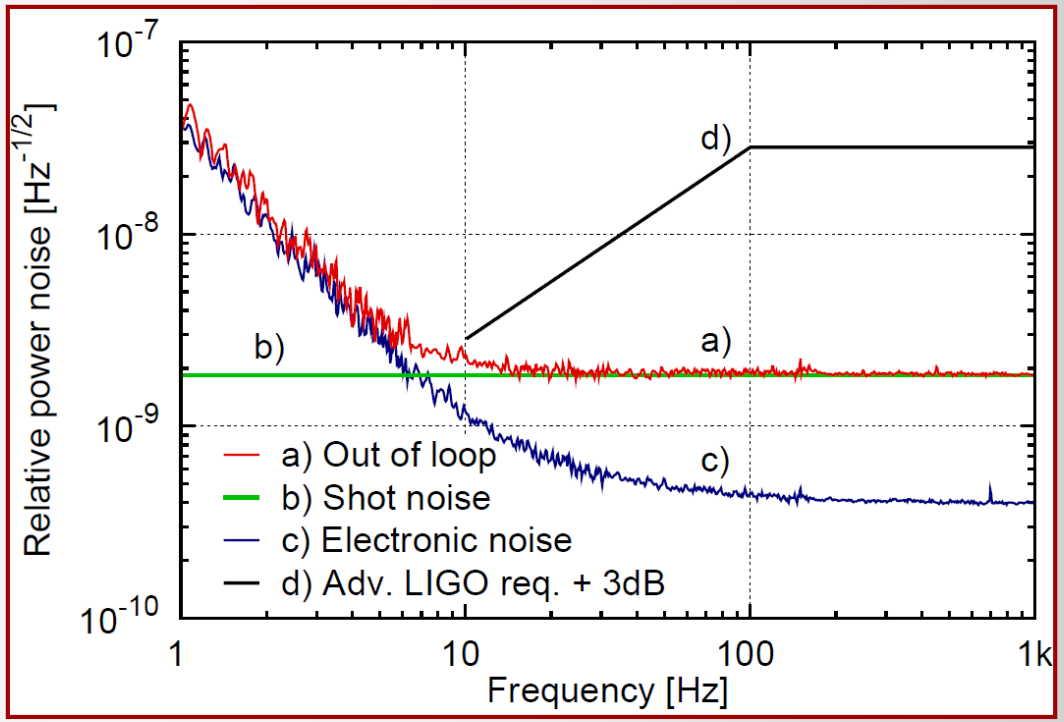
Wellmann et al. Opt. Express **27** (20) 2019

Power Stabilization





- beam is split onto two sets of four photodiodes (in-loop, out-of-loop)
- all stray beams are steered to absorption filters
- signal conditioning filters to reduce electronic noise coupling
- achieved $2 \times 10^{-9}\ 1/\sqrt{Hz}$ stability



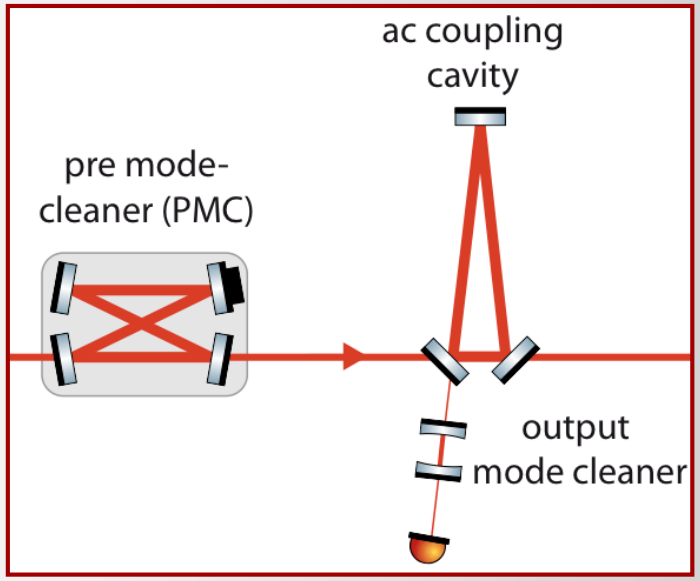
Kwee et al., Opt. Lett. 34 p 2912 (2009)

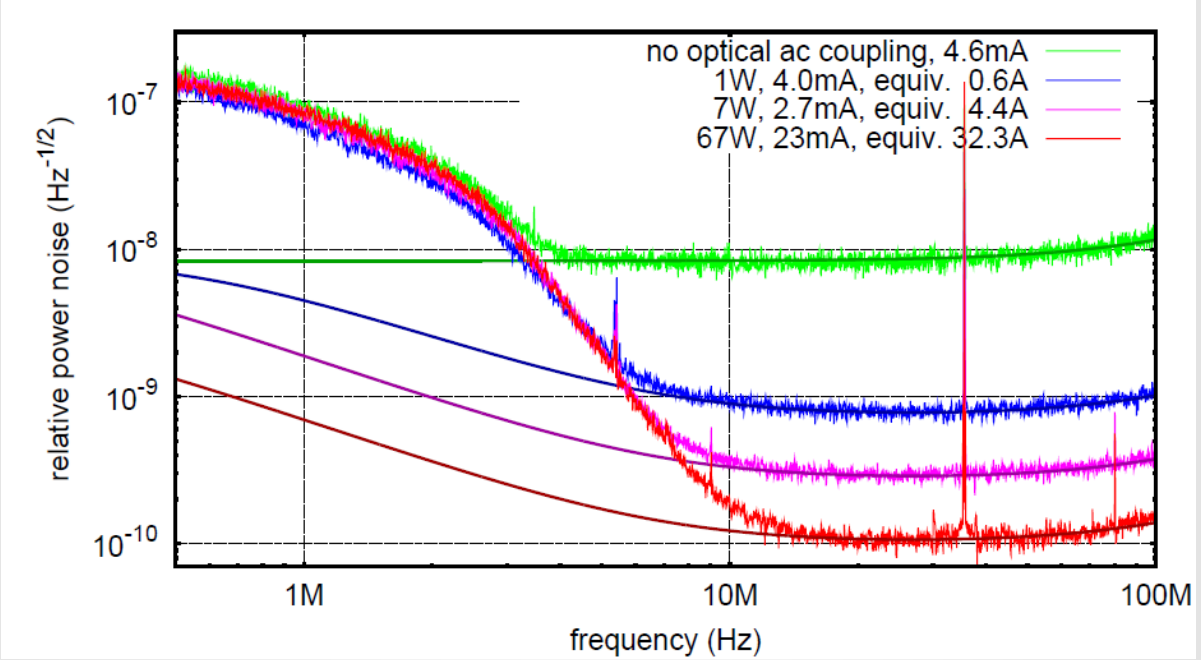
OAC with 32.2A Equivalent Photocurrent

- Power noise of 150W beam in an optical AC coupling scheme with output modecleaner
- Achieved sensing sensitivity

$$RPN = 1 \times 10^{-10}\ 1/\sqrt{Hz}$$

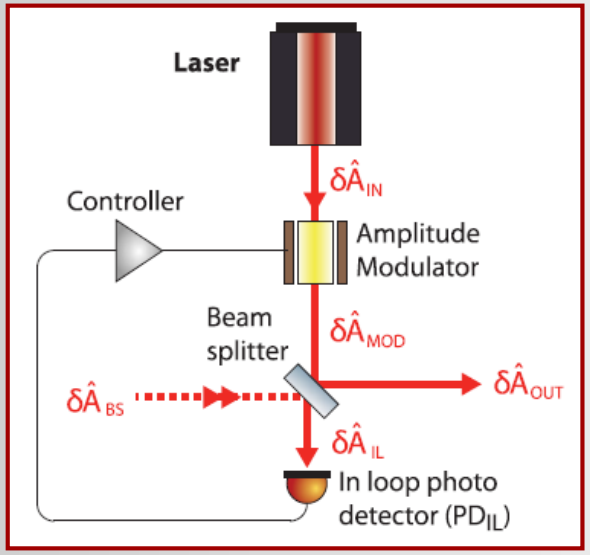
- This corresponds to shot noise of 32.2A photocurrent

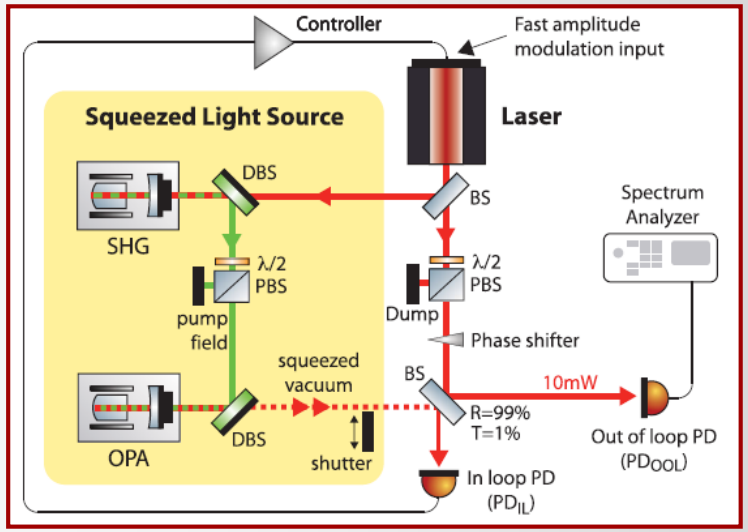




Kwee et al., Opt. Lett. (2011)

Squeezing Enhanced Power Stabilization

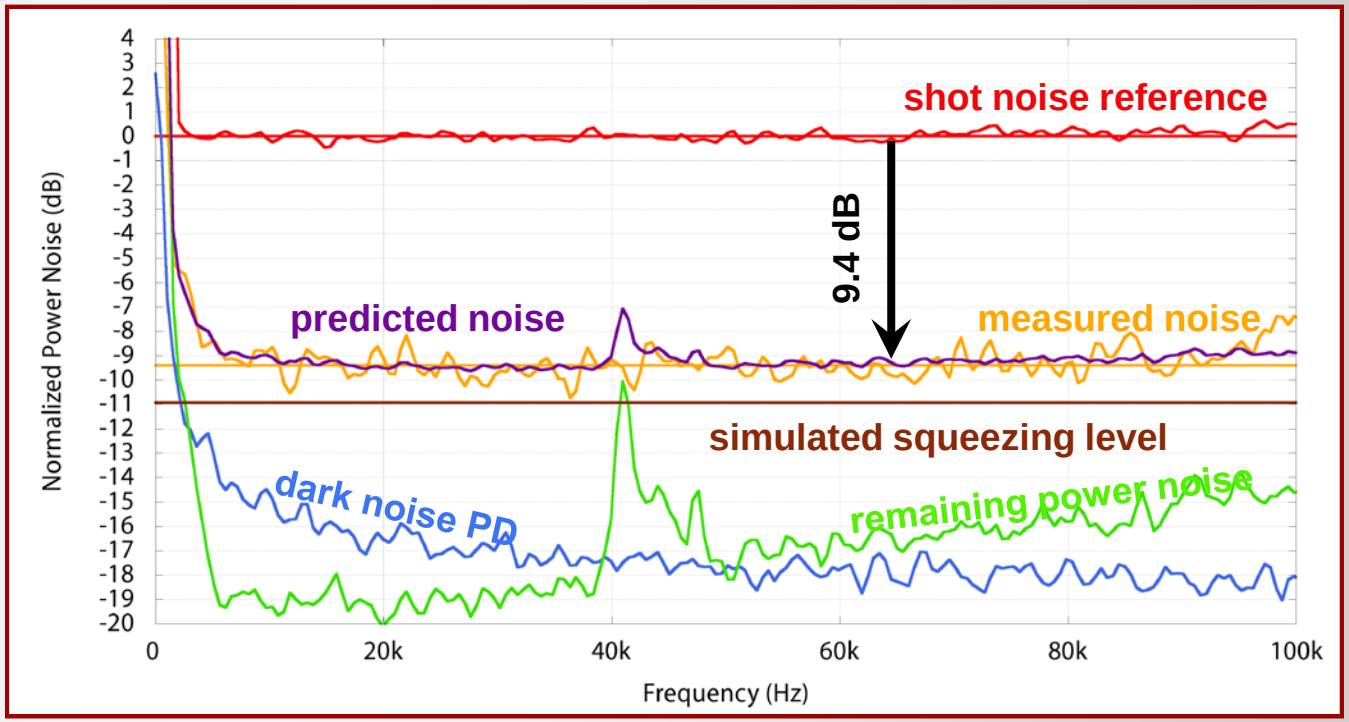




Simulation:
9.5 mW pump, 5.07 % losses, 10.9 dB

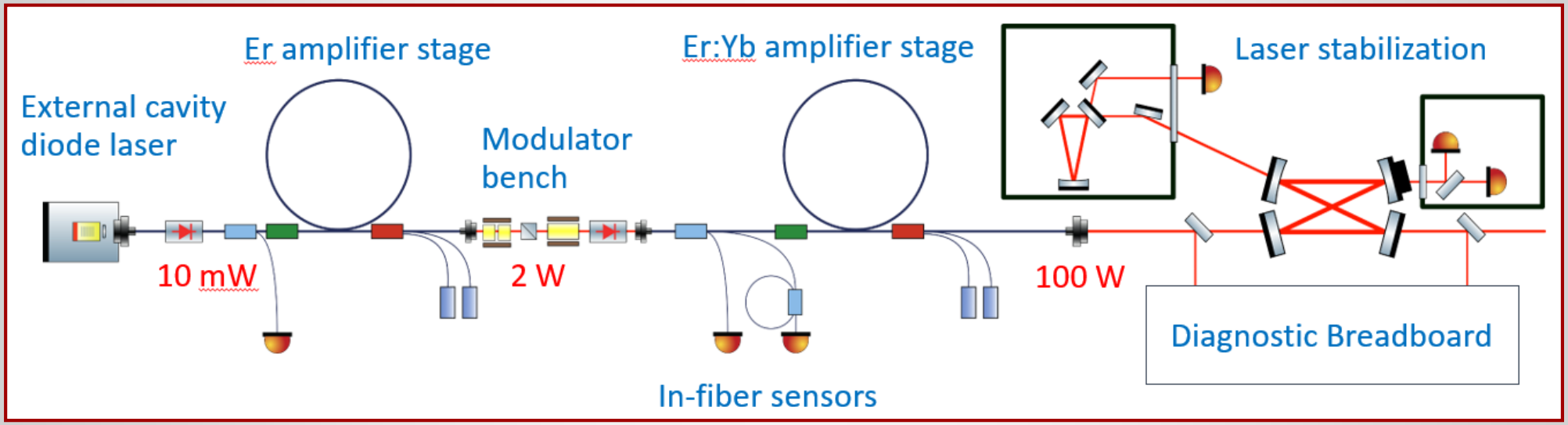
Prediction:
10.9 dB, +PDIL DN, +Stab IL noise

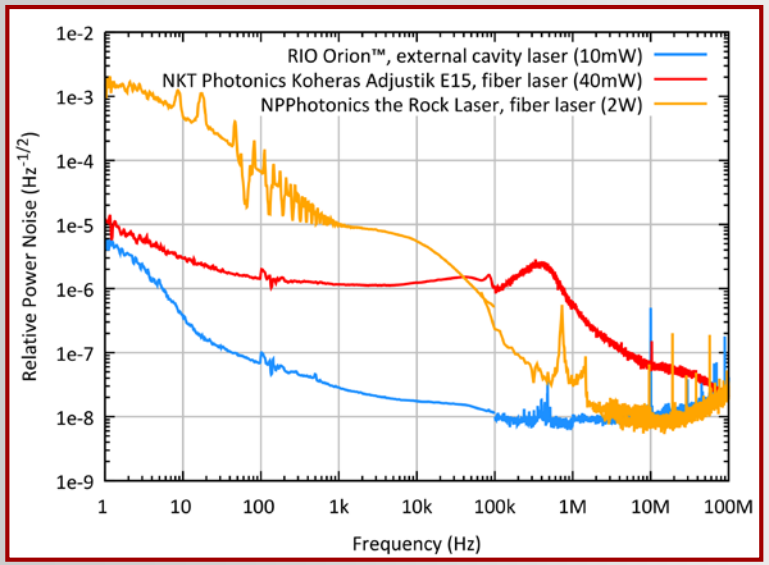
Limitations:
Losses, PD_{IL} DN, Loop Gain

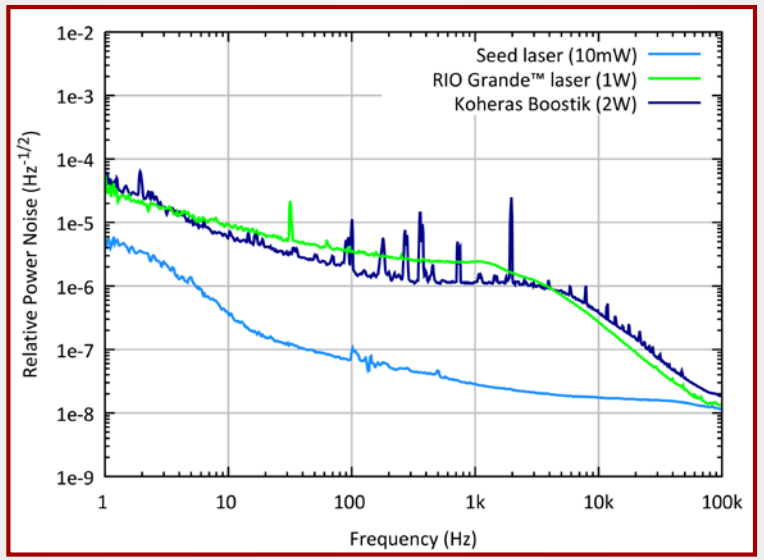


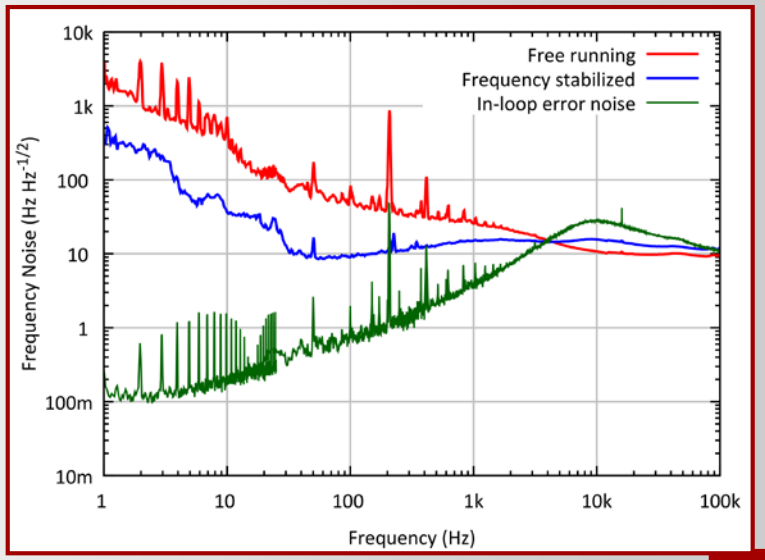
Vahlbruch et al PRL (2018)

1550nm Laser Stabilization

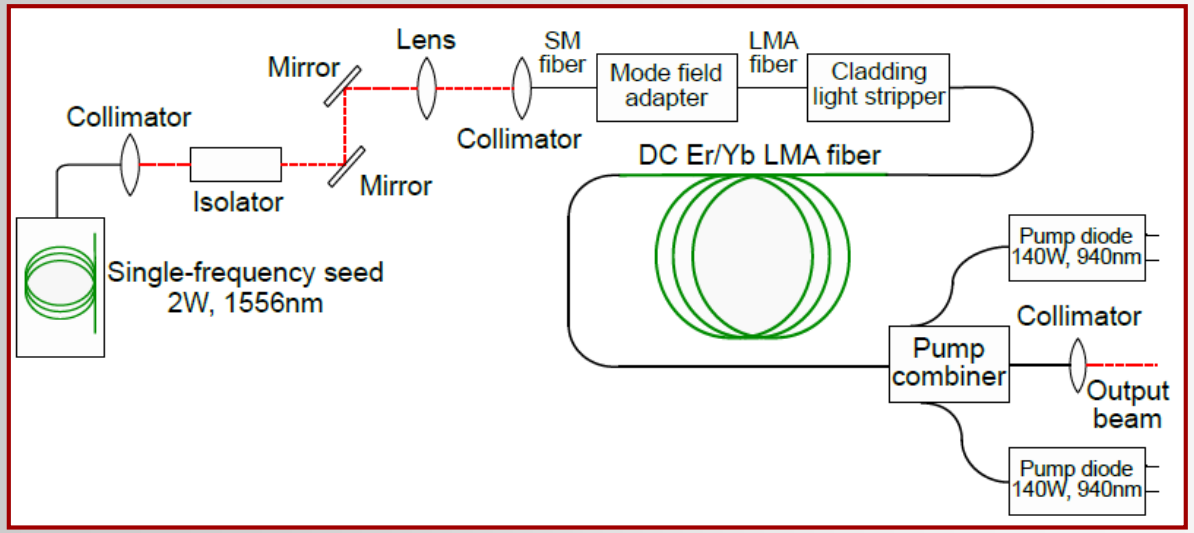




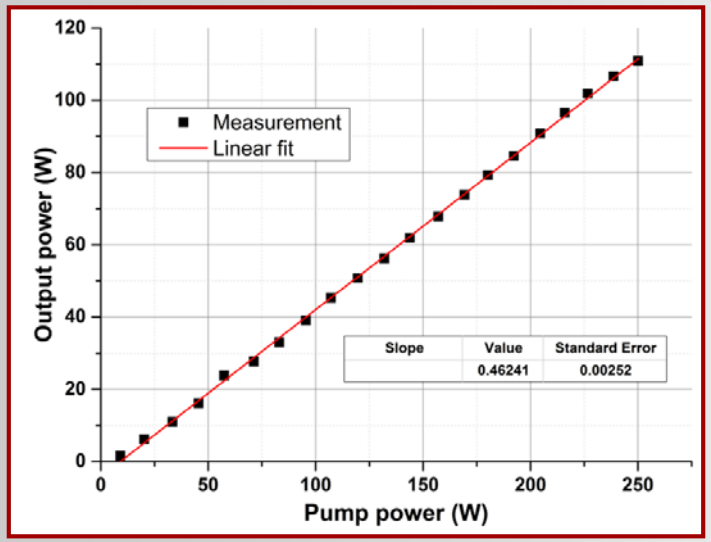


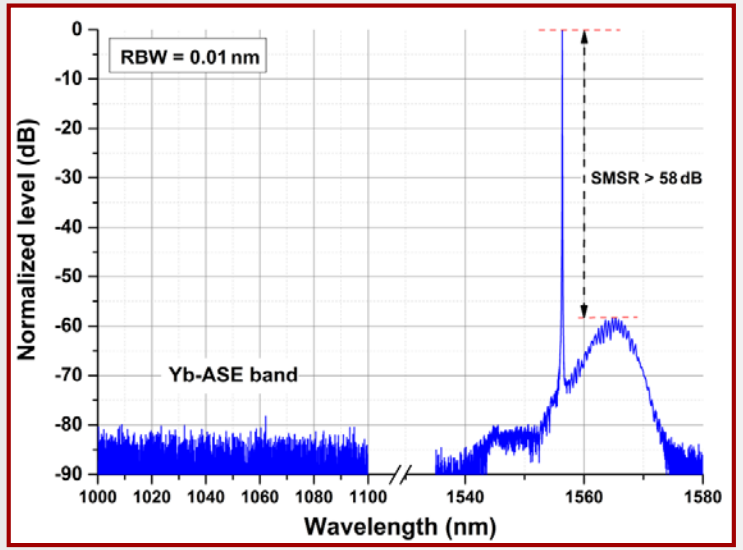


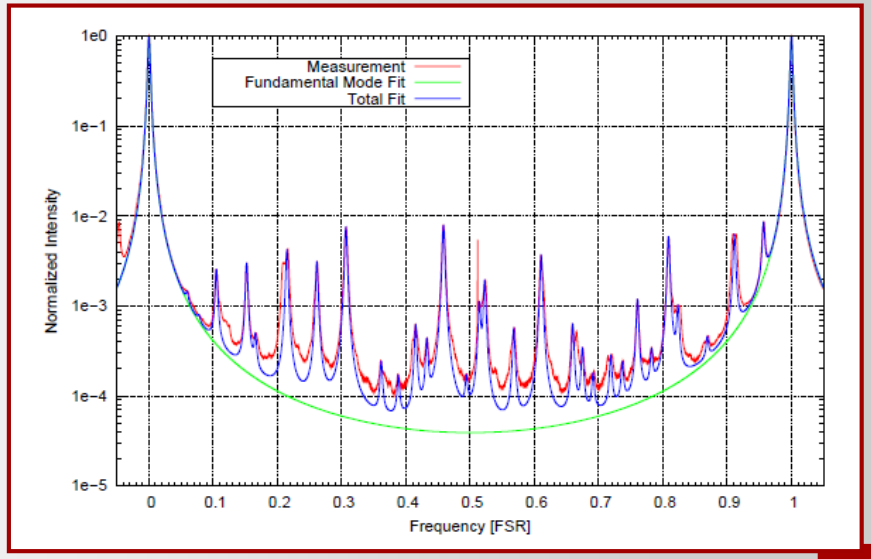
1550nm LZH Fiber Amplifier



- Off-peak pumping at 940nm
- Linear slope up to 110W
- At 110W no SBS (no excess power noise in MHz region)
- No Yb-band ASE and good suppression of Er-band ASE (~60dB)
- Output power limited by available pump power



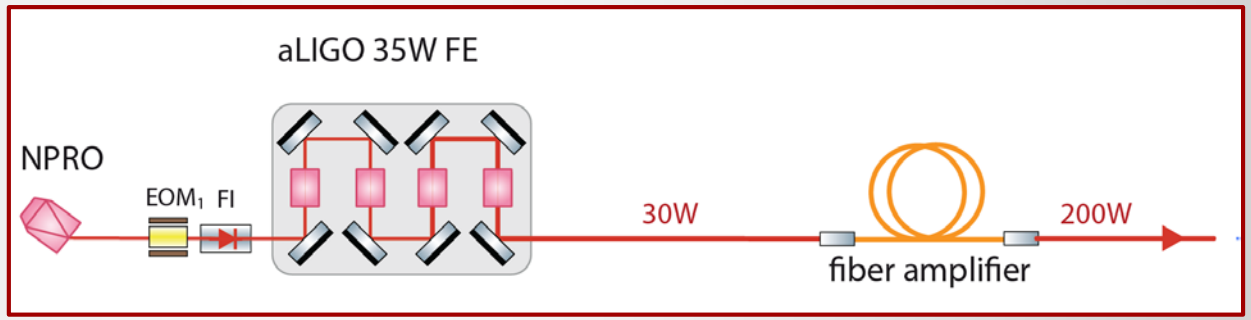




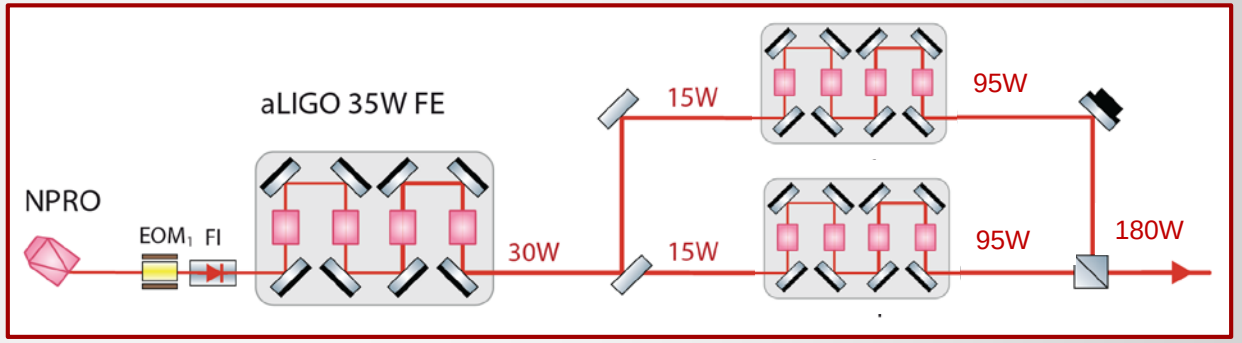
de Varona et al. Opt. Express (2017)

Future Plans

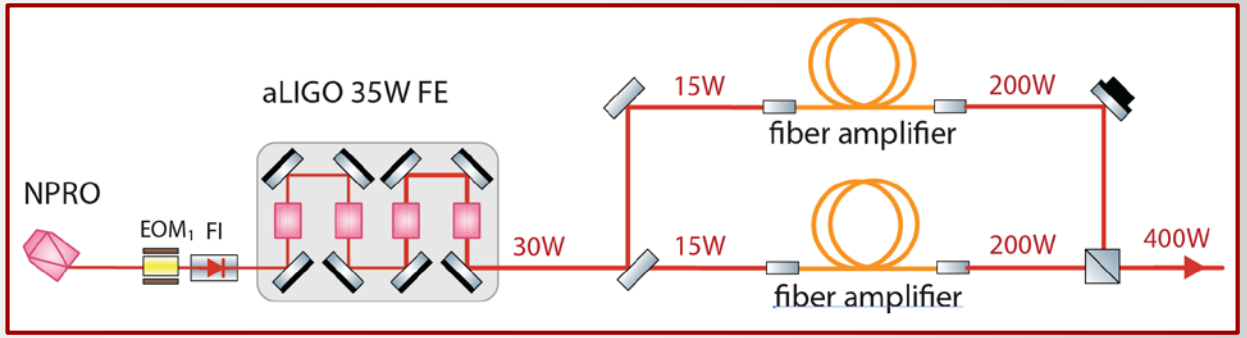
Combine aLIGO 35W laser with fiber amplifier



Coherent beam combination of two neoVAN-4S-HP



Coherent beam combination of two fiber amplifiers



Challenges

- Design and fabricate robust and reliable 250-300 W (fiber) amplifier for $1064\ \mathrm{nm}, 1.5\mu\mathrm{m}$ and $2\mu\mathrm{m}$
- Low-noise coherent combination of such laser with pure spatial beam profile, low beam jitter and low power noise
- Power stabilization at relative power noise level of $RPN = 10^{-10}\ 1/\sqrt{Hz}$
- Transfer laser stability to suspended reference frame of GWD