Lasers for Second and Third Generation GW Detectors

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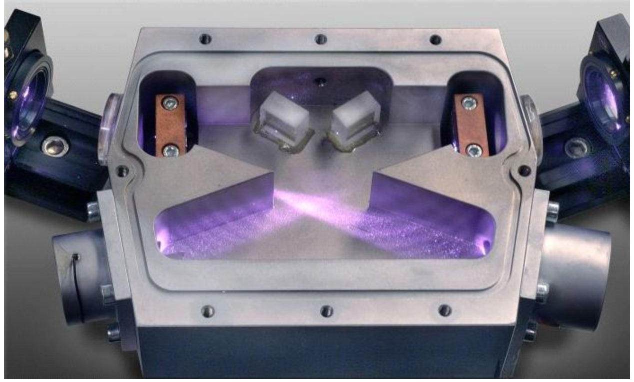
LASERS FOR GRAVITATIONAL WAVE DETECTION

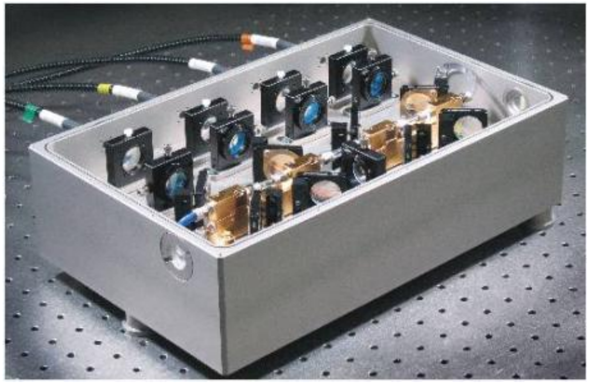
Laser Zentrum Hannover e.V. (LZH) is a non-profit research institute

Laser beam injected into Michelson interferometer for gravitational wave detection

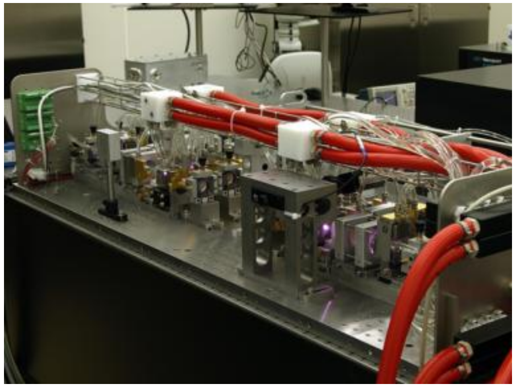
- Linearly polarized, fundamental mode, single frequency, low noise
- Laser developer for terrestrial gravitational wave detectors GEO600, VIRGO and LIGO in collaboration with Albert Einstein Institute (Hannover)
- Successful power scaling from 12 W to 35 W and 200 W to increase detector sensitivity
- 24/7 reliable operation for many months



12W laser for GEO 600



35W amplifier for eLIGO/VIRGO



200W aLIGO high power oscillator

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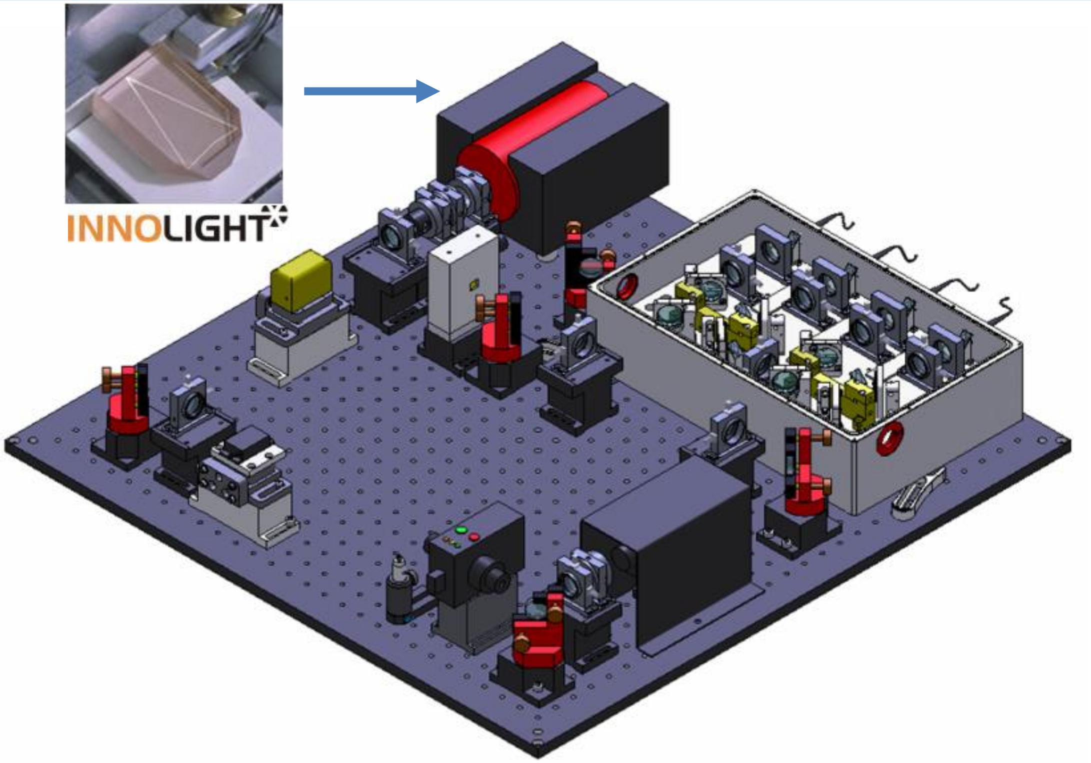
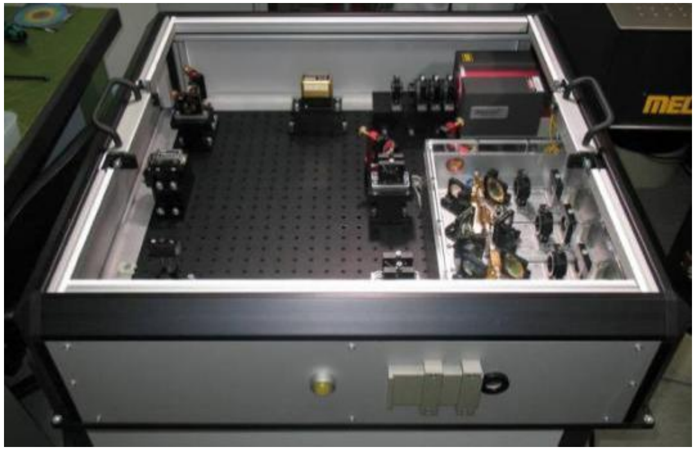
THE ENHANCED LIGO LASER SYSTEM



Pump diode and electronics unit

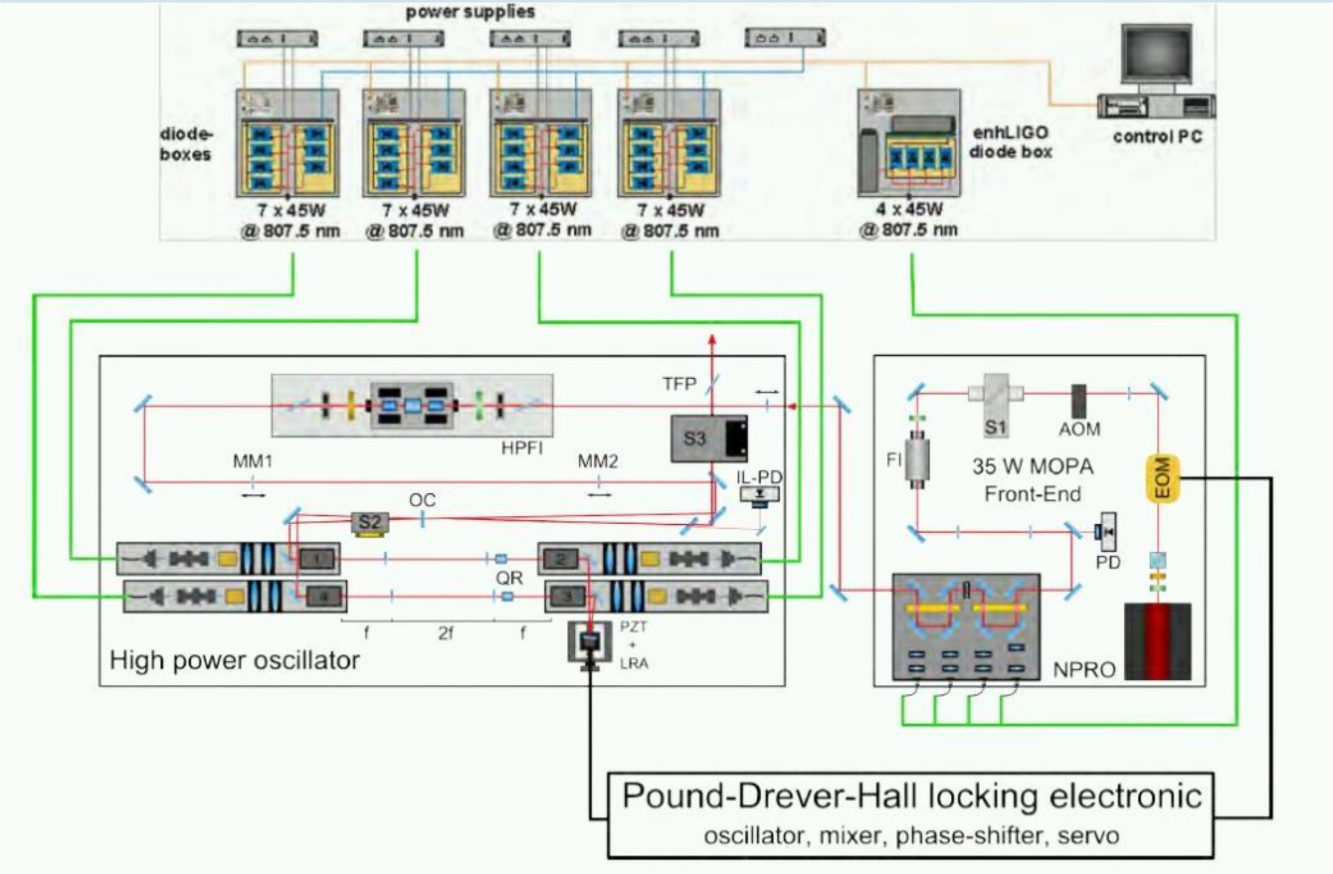


Seed and amplifier

- Input signal: 2 W Nd:YAG NPRO with kHz linewidth
- Amplified to 35 W with 4 stage Nd:YVO_4 amplifier
- Used 2008 – 2010 in Enhanced LIGO

M. Frede et al., OE 15, 459-465 (2007)

LASER FOR ADVANCED LIGO



- Injection locked high power Nd:YAG ring oscillator
- > 200 W of single-frequency kHz linewidth output at 1064 nm

L. Winkelmann et al., Appl. Phys. B 102(3), 529-553 (2011)

LASERS FOR ADVANCED LIGO

- First laser installation successfully completed in Livingston (Louisiana)
- Second laser system delivered to Hanford (Washington), being installed NOW
- Third laser system in production

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TWO LASERS FOR 3RD GENERATION GWD

Einstein Telescope (ET) Design Study Document (conceptual design):

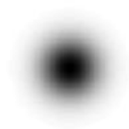
Laser 1 (HF):

- Wavelength: 1064 nm
- Output power: 500 W
- Beam shape: LG_{33}

All power values after input mode cleaner!

Laser 2 (LF):

- Wavelength: 1.5 µm
- Output power: 3 W
- Beam shape: TEM_{00}



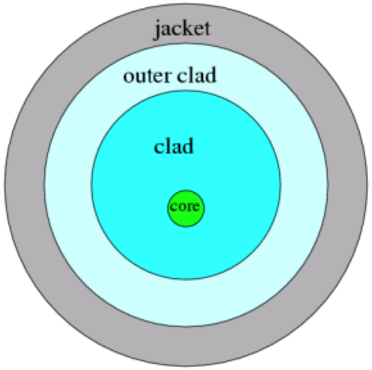
Requirements might change with interferometer design:

- Potential problems with LG_{33} in high finesse interferometer
- High power @ 1.5 µm might still be needed

BASIC COMPARISON OF 1 µm AND 1.5 µm WAVELENGTH

Design approach: Single-frequency master oscillator + fiber amplifier (MOFA)

Wavelength	1.0 µm	1.5 µm
Dopant	Yb	Er/Yb, Er
typ. Efficiency	up to 85%	up to 30%
Quantum defect	~10%	30-70%
rel. absorption cross section	~10	1
rel. dopant concentration	~10	1
Highest Output Power	~ 500 W (SBS limited)*	~ 150 W (high NA fiber, Yb-ASE limited)**



* Jeong et al. , IEEE JSTQE 13, 546 (2007)
** Jeong et al., OL 30, 2997(2005)
Beam quality!

Design consideration for active dopants: Erbium *or* Erbium/Ytterbium

- More pump light (976nm) needed/more heat generated for 1.5µm than for 1µm
- Er: high pump brightness due to smaller pump cladding for reasonable total absorption (low doping concentration/absorption cross section)
- Er:Yb: High absorption cross section for Yb (976 nm), energy transfer to Er, but only high fiber core NAs feasible (=small core diameter for TEM_{00})
- Er:Yb: Large gain values at 1µm for Yb-pump rate exceeding Er-Yb-transfer rate

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LASERS AT 1.5 µm WAVELENGTH

Long term design goal: >100 W @ 1.5 µm

Both Er as well as Er/Yb codoped fibers are being examined

Er/Yb codoping:

- How to handle parasitic gain and emission at 1 µm?

Tested fiber designs:

- “Standard” step-index large mode area (LMA) fibers*
- Novel multifilament-core (MFC) fibers**
- Specially designed photonic crystal fibers (PCF)

* V. Kuhn et al. IEEE PTL, 23(7), 432–434 (2011)
**V. Kuhn et al. J. Lightwave Tech., 28(22), 3212-3219 (2010)

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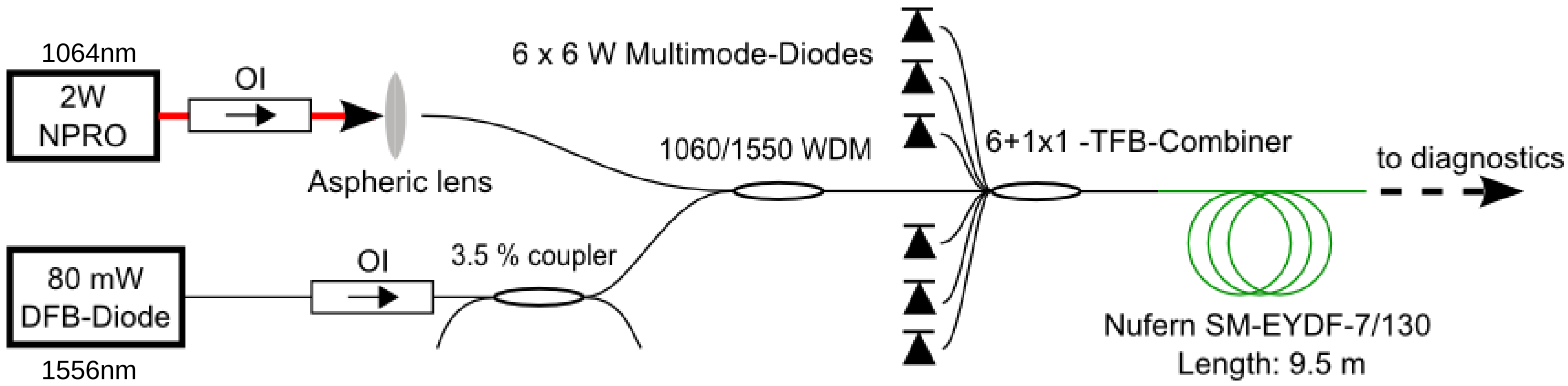
Er/Yb – MANAGE 1µm EMISSION – SETUP



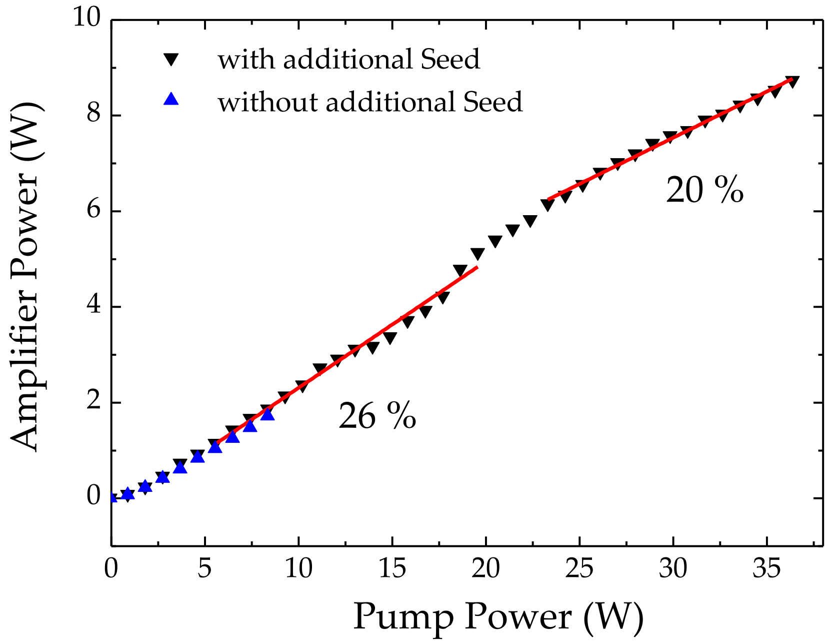
Inject 2nd seed signal at 1064 nm simultaneously to 1.5 µm signal

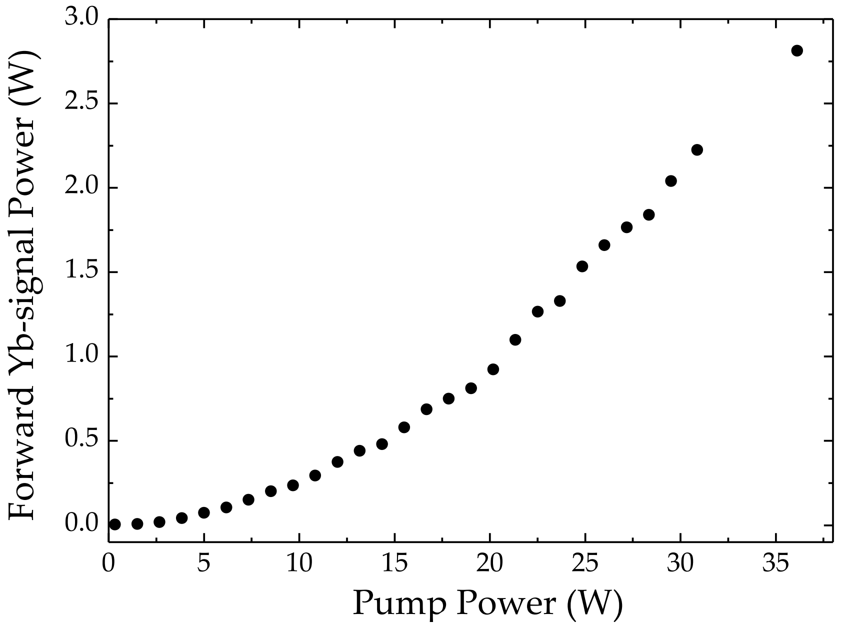
Auxiliary seed signal extracts excess energy from the Yb-ions

- Gain at 1.0 µm is clamped to large signal value
- Reliable suppression of parasitic lasing and/or giant pulse formation at 1.0 µm
- Potential efficiency depletion at 1.5 µm by competing signal?

V. Kuhn et al., OE, 17(20), 18304 (2009) and OL, 35(24), 4105-4107 (2010)

Er/Yb – MANAGE 1µm EMISSION – RESULTS

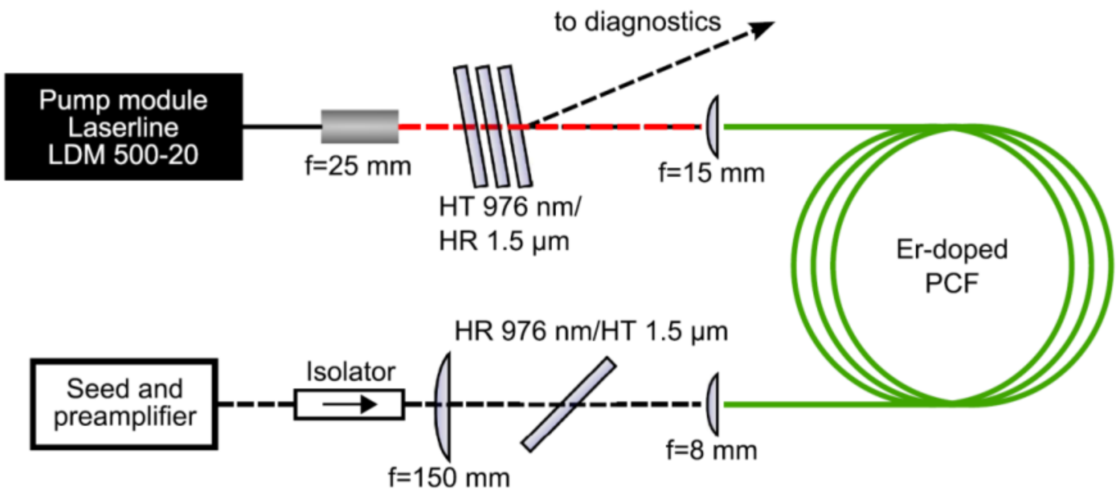


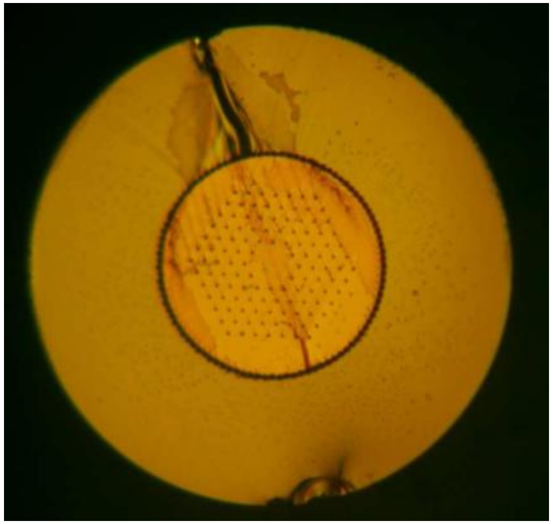


- Er slope efficiency not degraded by co-seeding with 1µm
- Slight rollover at > 6 W power at 1556 nm
- 3 W of Yb output at 1 µm can be used as additional pump source (reabsorption) for 1.5 µm signal by further active fiber length optimization

V. Kuhn et al., OE, 17(20), 18304 (2009) and OL, 35(24), 4105-4107 (2010)

Er-DOPED PHOTONIC CRYSTAL FIBER AMPLIFIER



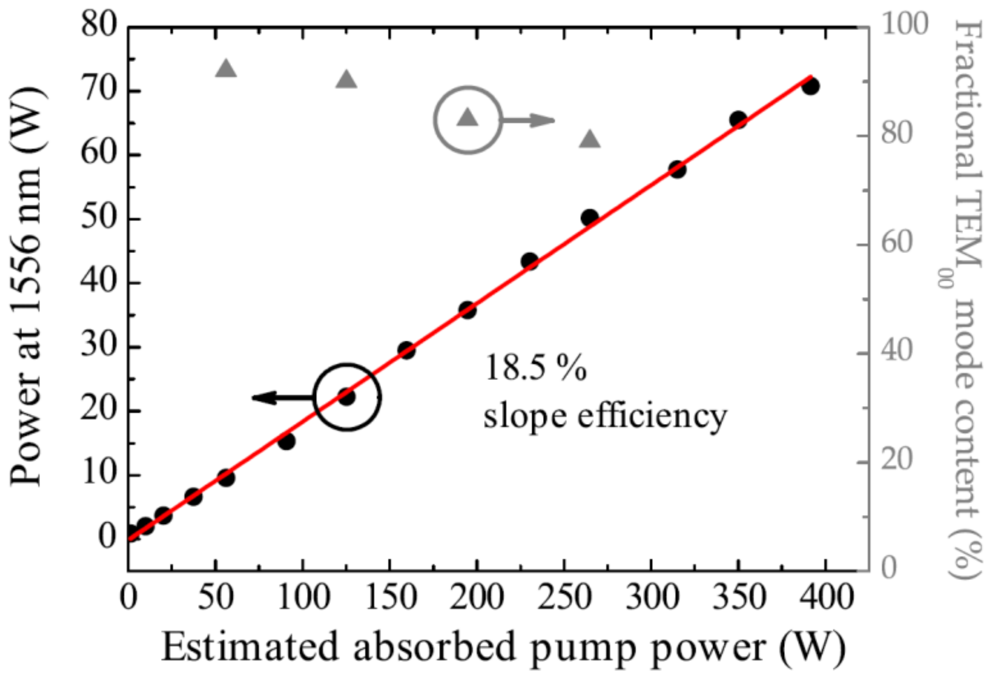


- Seed: 2 W single-frequency DFB fiber laser @ 1556 nm
- Counter-propagating pump
- Free space coupling for pump and seed light

- Active fiber: Custom made Er-doped PCF
  - Core size: 40 µm, NA: < 0.04
  - Mode field diameter: 31 µm
  - Pump cladding: 170 µm, NA: > 0.55
  - Absorption @ 976 nm: 0.6 dB/m
  - Fiber length: 19 m

V. Kuhn et al., OL 36(16), 3030–3032 (2011)

Er-DOPED PCF AMPLIFIER RESULTS

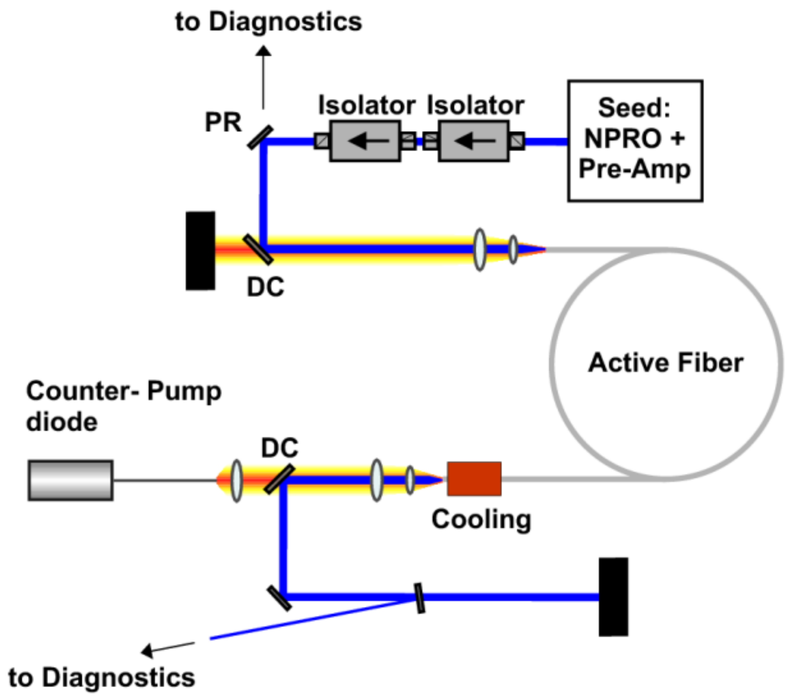


- Maximum output power: 70.8 W
- >80% TEM_{00} content
- Limited by available pump power / amplifier efficiency
- Amplified spontaneous emission (ASE) suppression: 44 dB

V. Kuhn et al., OL 36(16), 3030–3032 (2011)

LASERS AT 1 µm WAVELENGTH

Long term design goal: 1kW @ 1 µm, TEM_{00}
Design approach: Single-frequency master laser + fiber amplifier



Seed
500 mW NPRO
With ~1 kHz linewidth

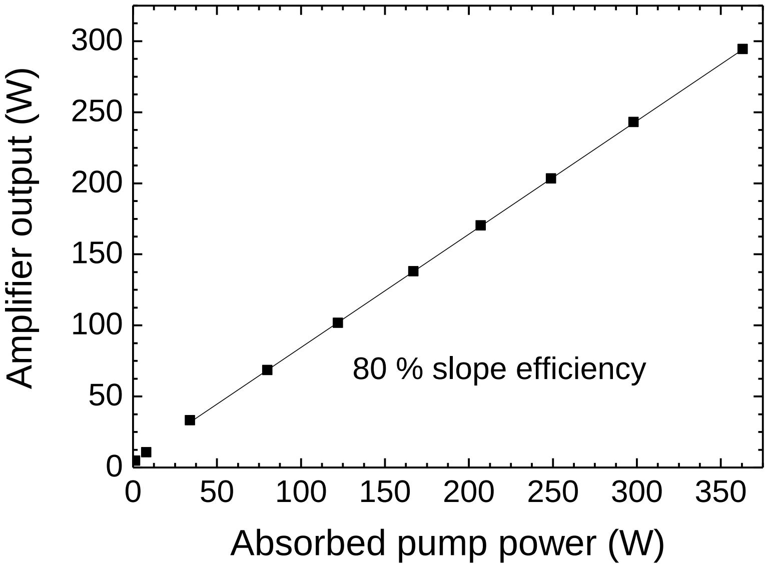
Pre-amplifier
Nufern PM-YDF-10/125
P = 10 W
(seed for main amplifier)

Pump modules
Fiber coupled,
Emitting at 976 nm

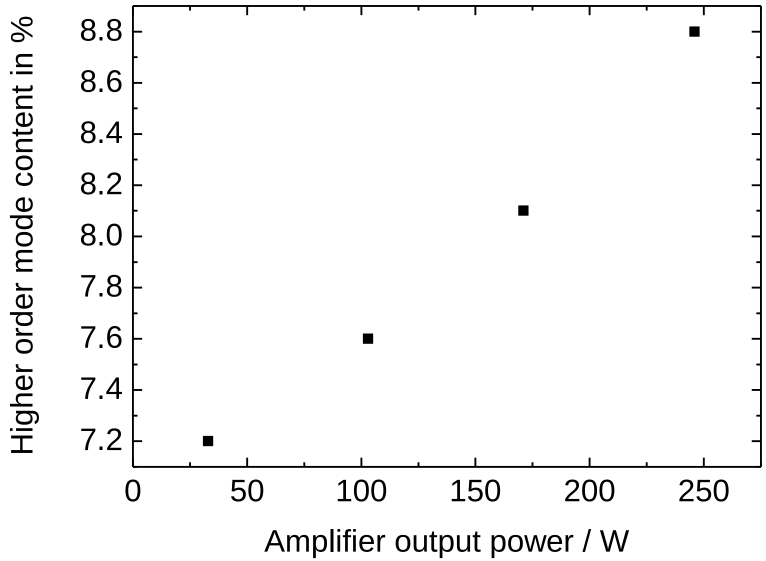
Working also on high power solid-state amplifier systems (not covered here)

MAIN AMPLIFIER WITH 6.8 m PCF (NKTP DC-400-40-PZ-YB)

Output power



Higher order mode content



- Maximum absorbed pump power: 363 W
- Maximum signal output power: 294 W
- Polarization extinction ratio: ~ 27 dB
- No evidence of stimulated Brillouin scattering (SBS)

- Higher order mode content increases slightly with amplifier output power

M. Karow et al., CLEO/Europe 2011, CJ7.4

MOTIVATION FOR COHERENT BEAM COMBINING (CBC)

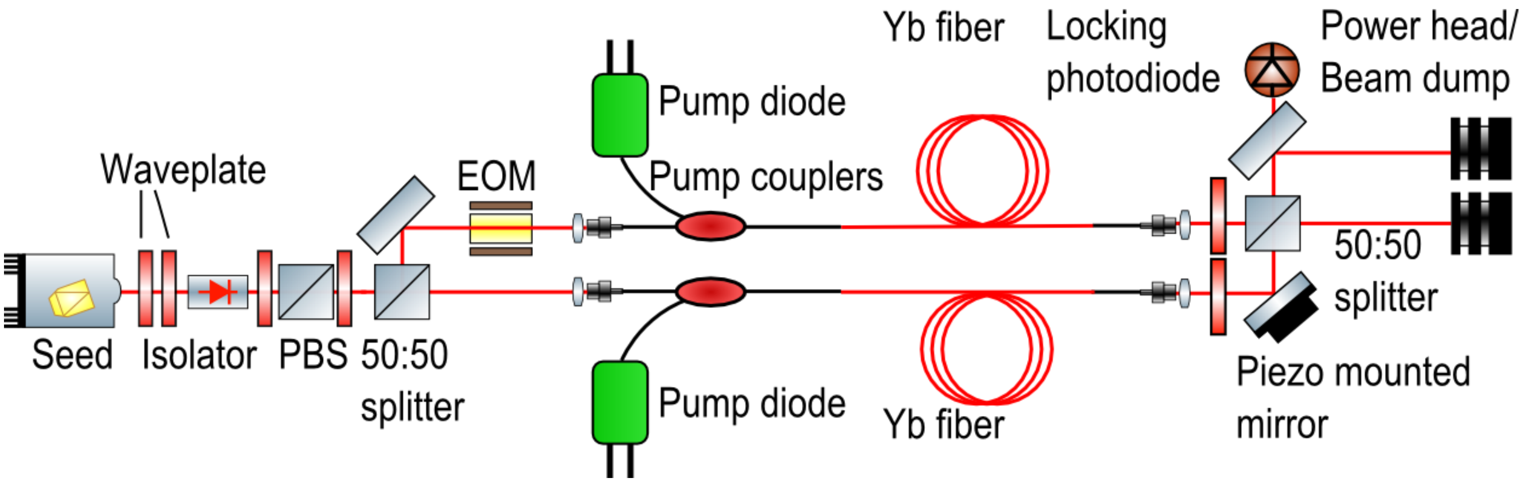
Power scaling becomes increasingly difficult at high output power

- 500 W in LG_{33}-mode may require even higher power fundamental mode operation due limited efficiency of mode convertors

- Several groups have encountered problems with the power scaling of single-frequency systems beyond 500 W at 1064 nm (*,**,***)
- kW-class systems may require combining techniques to reduce the thermal and optical loads of the individual amplifiers

* Gray et al., OE **15**, 17044 (2007)
** Jeong et al., IEEE J. Sel. Top. Quant. Elec. **13**, 546 (2007)
*** Robin et al., Proc. SPIE **7580**, 75801I (2010)

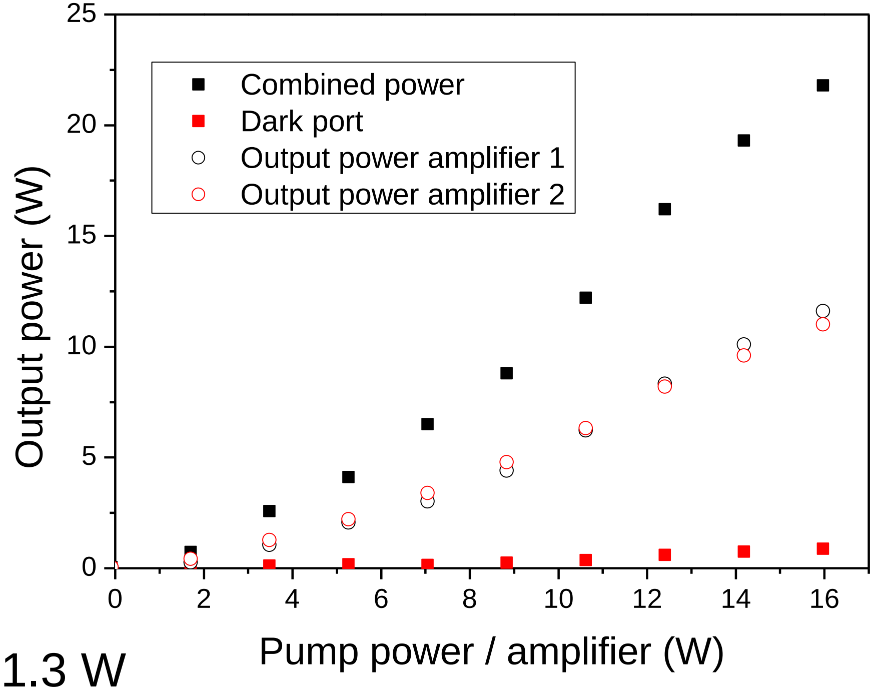
COHERENT BEAM COMBINING SETUP



- 2x 10 W single-mode Yb-doped PM amplifier @ 1064 nm
- Free space combining to avoid fiber coupler limitations
- Use proven actuators
  - Electro optic modulator (EOM)
  - Piezo mounted mirror

CBC RESULTS – POWER AND BEAM QUALITY

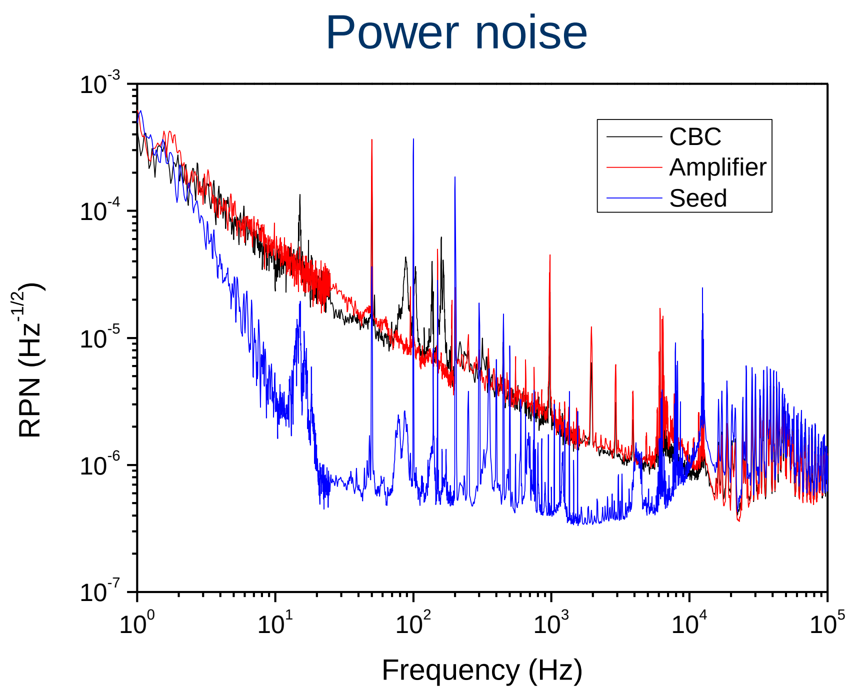
- Single amplifier output: 11.4 W
- Max CBC output: 21.8 W
- CBC efficiency: 95-97 %
  - Over the whole slope
- Stable under laboratory conditions

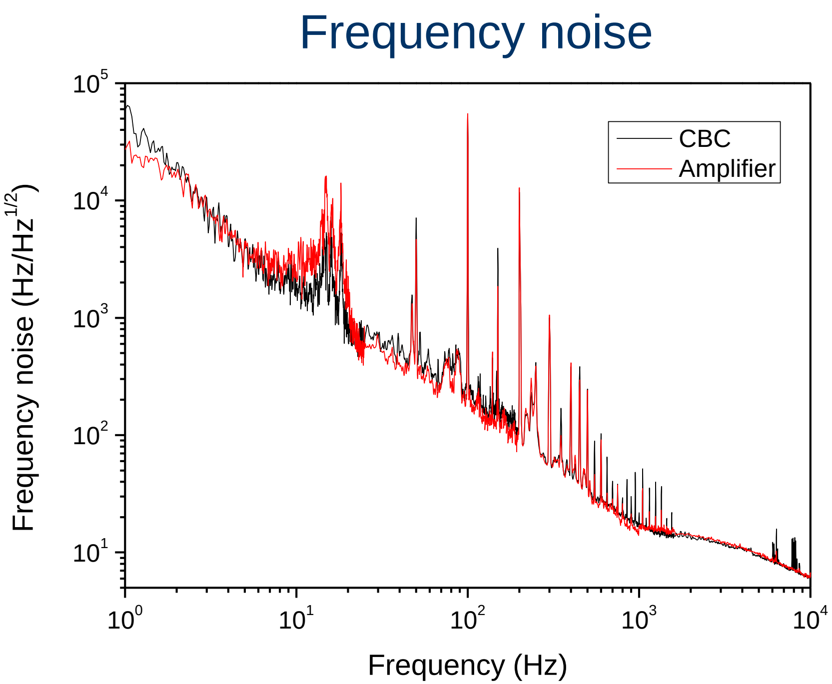


- TEM_{00} content: 97%
  - Both for single amplifier and combined signal
- Transmission through locked cavity: 21.3 W

H. Tünnermann et al. OE, 19(20), 19600-19606 (2011)

CBC RESULTS – POWER AND FREQUENCY NOISE





Combined power and frequency noise dominated by single-amplifier
→ Promising approach for further power scaling

H. Tünnermann et al. OE, 19(20), 19600-19606 (2011)

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SUMMARY

Fiber amplifier system @ 1.5 µm

- Suppression/stabilization scheme for 1 µm parasitic emission demonstrated
- Maximum output power of PCF amplifier system > 70 W
- TEM_{00} content ~ 80%

Fiber amplifier system @ 1064 nm

- Maximum output power: 294 W
- TEM_{00} content > 90%

Coherent beam combining testbed

- Combining efficiency of 2x 10 W amplifier ~ 97 %
- TEM_{00} content ~ 97%
- No degradation of power and frequency noise compared to single amplifier

FUTURE RESEARCH TOWARDS GWD LASER SOURCES

Fiber amplifier system @ 1064 nm
- Power scaling design goal: 1 kW
- All-fiber implementation
- Conversion to LG_{33}-mode

Coherent beam combining
- Low-noise all-fiber CBC
- Testing of novel actuators and couplers
- Power scaling

Fiber amplifier system @ 1.5 µm
- Power scaling design goal: 100 – 200 W
- All-fiber implementation
- TEM_{00} content >90% @ high thermal loads

Major technology to be further developed

- Advanced active fibers
- Fiber components for rugged all-fiber implementation
- Components for higher order mode generation

ADVANCED FIBER DESIGNS

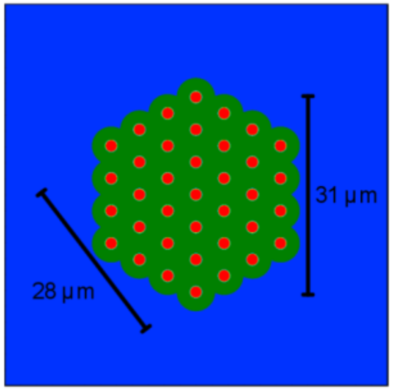
Especially for Yb-doped fibers at 1 µm

SBS mitigation for power scaling

- Acoustic anti-guiding
- Filamented cores
- … increased SBS thresholds for further power scaling

Higher order mode suppression

- Leakage channel designs
- Chirally-coupled core designs
- … efficient HOM suppression to avoid beam quality degradation at high power levels



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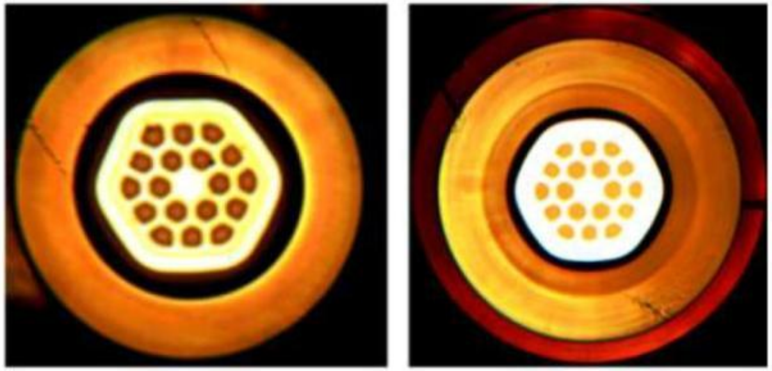
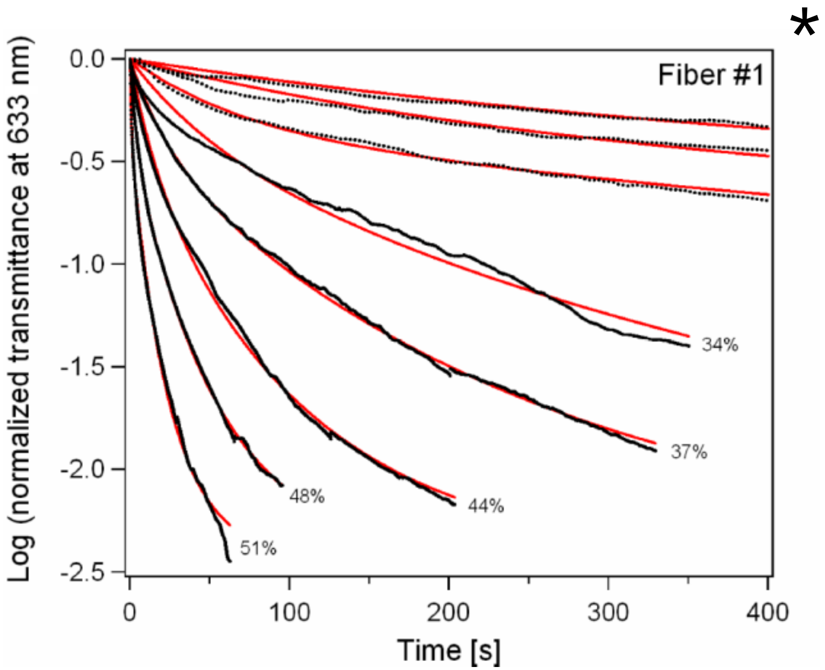


* L. Dong et al., OE, **17**, 8962 (2009)

FIBER LONG TERM RELIABILITY

Fibers have to be long term tested with respect to GWD requirements:

- Photodarkening
- Coating degradation
- Effects of humidity
- … all other kinds of fiber aging



*J. Koponen et al., Appl. Opt., **47**, 1247 (2008)

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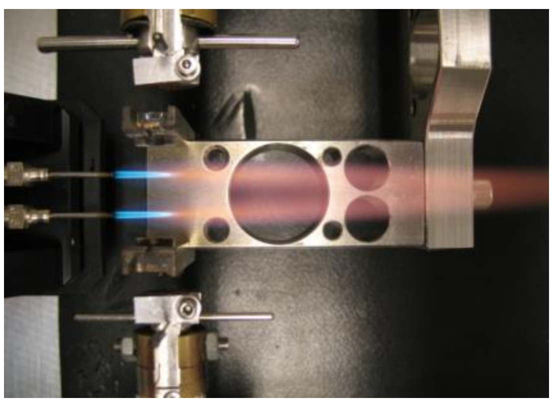
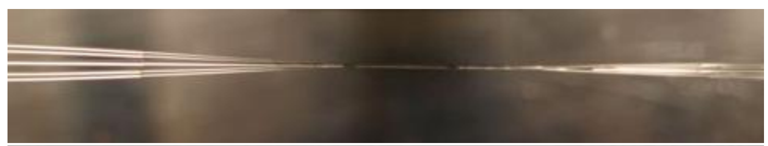
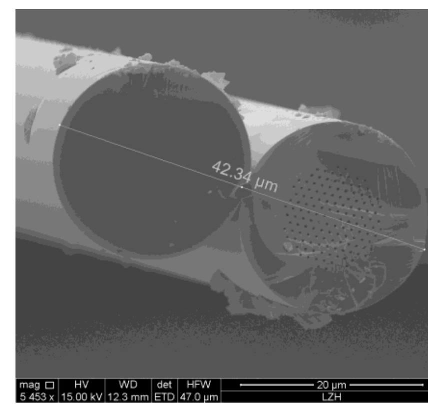
FIBER COUPLERS / PCF COUPLERS

Further research is required for

- Long-term qualification of fiber components
- Very high power couplers for several 100 W of pump and signal power
  (400 W pump coupler for backward pumping recently demonstrated by LZH*)
- (High power) PCF couplers for monolithic photonic crystal fiber setups



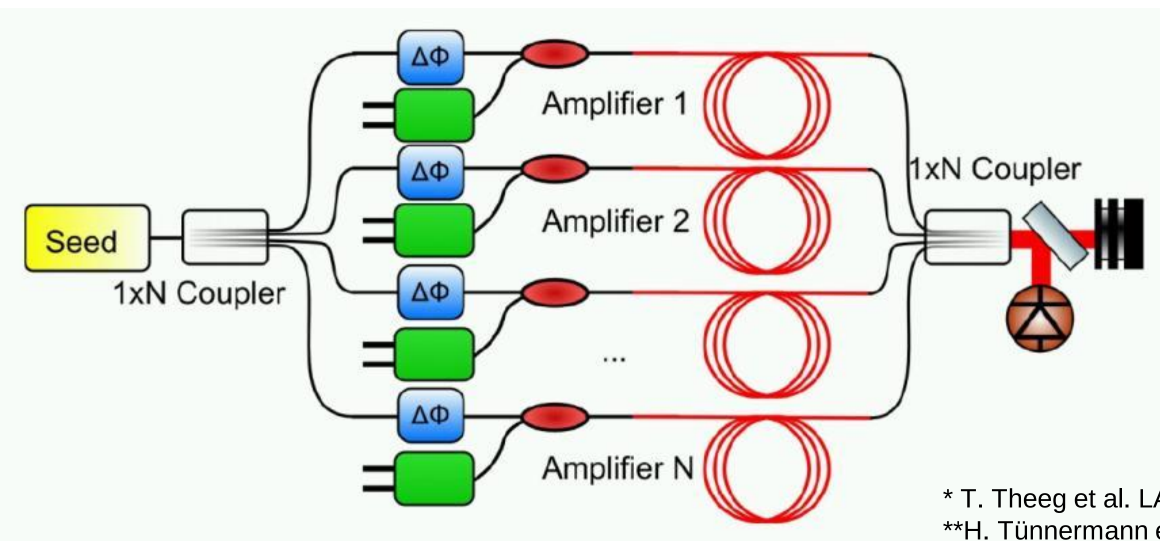


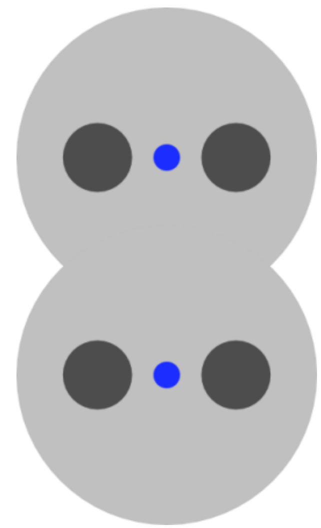


* T. Theeg et al. LASE/Photonics West 2012, Paper 8237-55 (accepted)

COMPONENTS FOR ALL-FIBER CBC

- High power fiber tap couplers for all-fiber beam combination*
- Ideally high power polarization maintaining components for better long term stability through decreased drifting effects
- Identification of fiber-based actuators for stabilization**
- Low loss electro-optic modulators for fast signal modulation directly inside of the Mach-Zehnder-interferometer



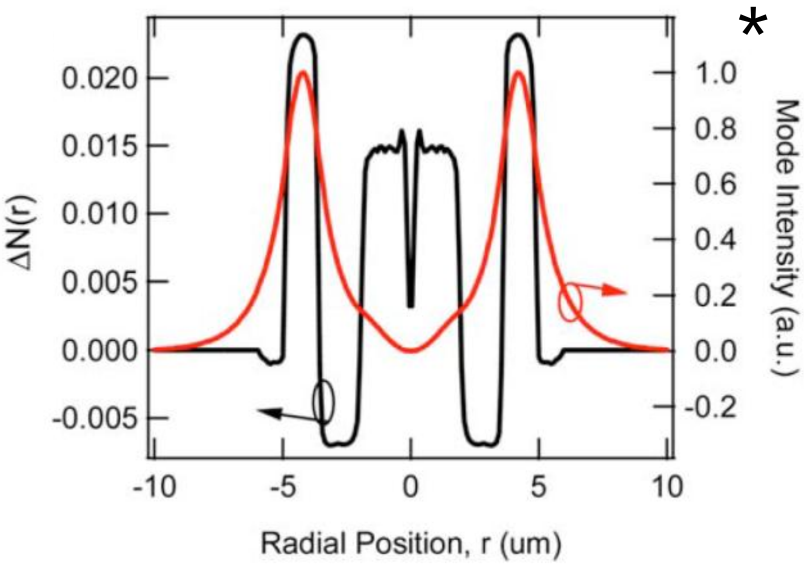


* T. Theeg et al. LASE/Photonics West 2012, Paper 8237-89 (accepted)
**H. Tünnermann et al., OL 36(4), 448-450 (2011)

HIGHER ORDER MODES

Direct generation of higher order modes in specialty fibers

- Can modes without center-lobe be (stably) generated?
- How robust is the generation against fiber strain and heating?
- Achievable power levels?



*Ramachandran et al., OL, **34**, 2525-2527 (2009)

Mode conversion

- Diffractive optical elements
- Fiber-based mode convertors (long period Bragg gratings)

- What power levels can be reached/tolerated?
- What are the maximum conversion efficiencies?
- Environmental and long-term stability?

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VolkswagenStiftung

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THANK YOU FOR YOUR ATTENTION!

Laser Zentrum Hannover, Germany

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