HIGH POWER LASERS FOR 3RD GENERATION GRAVITATIONAL WAVE DETECTORS

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OUTLINE

Requirements on lasers for 3rd generation gravitational wave detectors

Experimental results:

- Fiber amplifier results: 1064 nm
- Fiber amplifier results: 1.5 µm
- Coherent beam combining

Summary

LASERS FOR 3RD GENERATION GWD

There is no final design for a 3rd generation gravitational wave detector.

There are no final laser specifications.

Development targets?

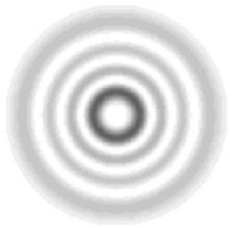
- Wavelength?
- Output power?
- Beam shape?

TWO LASERS!

Look in Einstein Telescope (ET) Design Study Document:

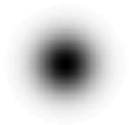
Laser 1:

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



Laser 2:

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



All power values after IMC!

But: Requirements might change with interferometer design:

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

Lasers @ 1064 nm

PART 1: LASERS @ 1064 nm

Long term design goal: 1 kW @ 1064 nm

At this stage: Mode shape TEM_{00}

Mode conversion from TEM_{00} to LG_{33} is treated as independent problem
(→ will not be covered in this presentation)

Approach:

- Single-frequency Master Oscillator Fiber Amplifier (MOFA) concept
  → NPRO + Ytterbium-doped fiber amplifier(s)
- All polarization maintaining (PM) fibers

- Also working on high power solid state amplifier systems
  (→ will not be covered in this presentation)

STATE OF THE ART OF PM-MOFAS @ 1064 nm

Power scaling of PM single-frequency MOFAs up to 500 W*

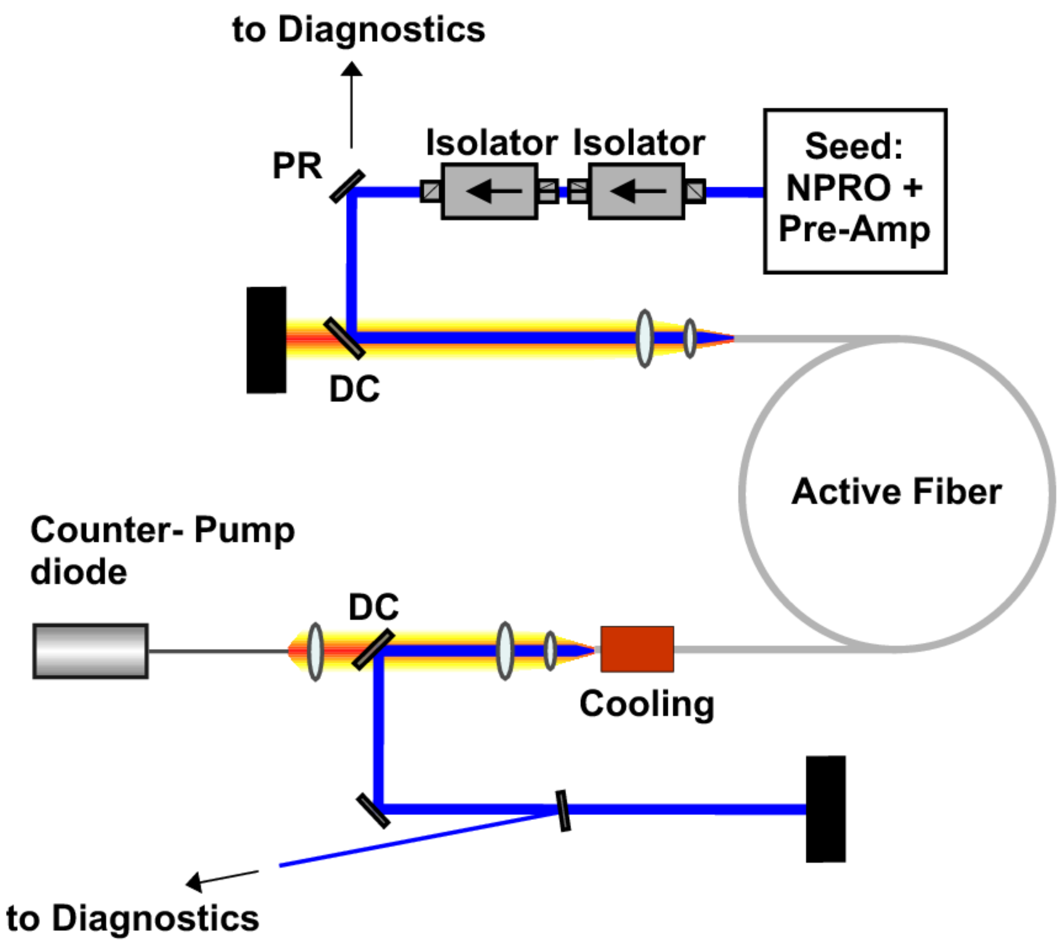
- Customized fiber designs: fiber designs tested for power scaling (SBS threshold), not yet commercially available
- Only M^2 measurements for beam quality characterization

TEM_{00}-mode content measurements only for system delivering up to 148 W of output power**

- Amplifier fiber: photonic crystal fiber with a MFD of 22 µm
- Pump- and seed-power limited (single-stage setup)
- Non-PM, though good PER
- TEM_{00}-mode content: 92.6 %

* Gray et al. (2007), Robin et al. (2011), Zhu et al. (2011)
** Hildebrandt et al. (2006)

SETUP OF TWO-STAGE Yb-DOPED FIBER MOPA

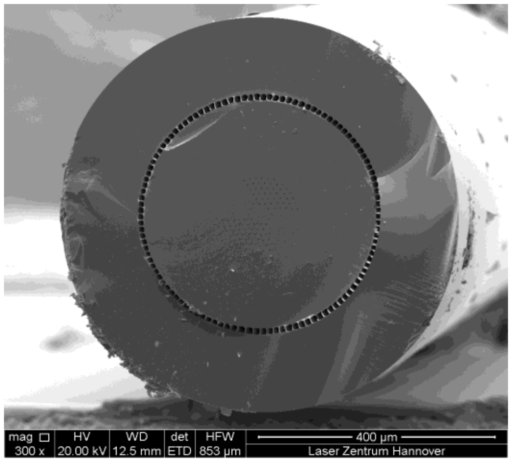


Seed
500 mW NPRO
With ~1 kHz linewidth

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

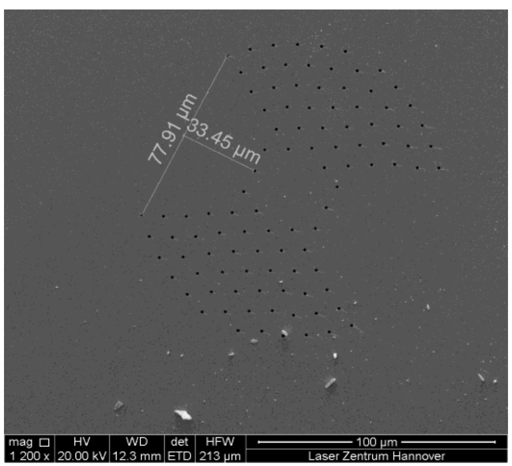
Pump modules
Fiber coupled,
Emitting at 976 nm

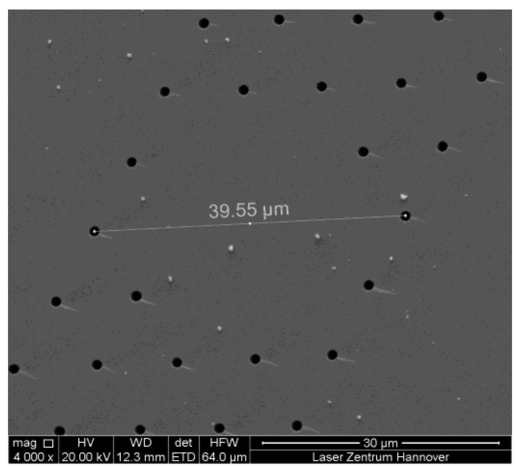
NKT PHOTONICS DC-400-40-PZ-YB



Outer cladding diameter: 700 µm

Pump cladding diameter: 400 µm
Pump cladding NA: 0.6
Nominal absorption at 976 nm: 2.4 dB/m



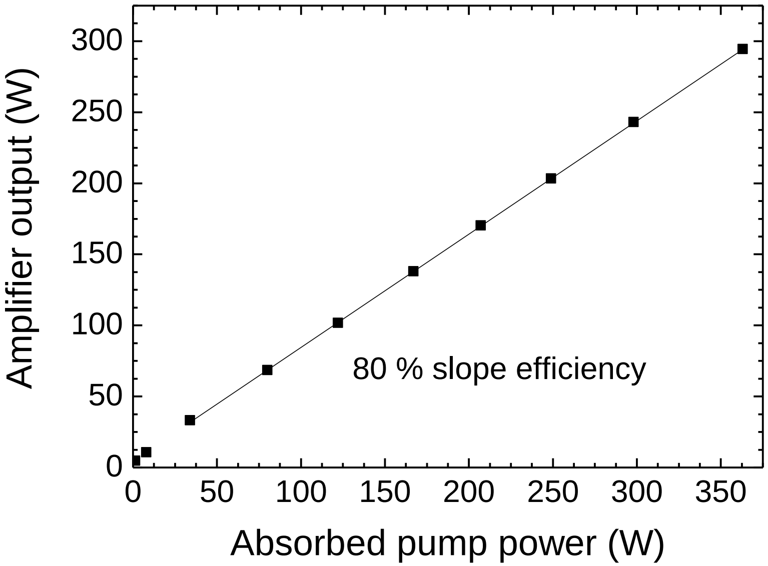


Core diameter: 40 µm
Core NA: 0.03
MFD: 29 µm

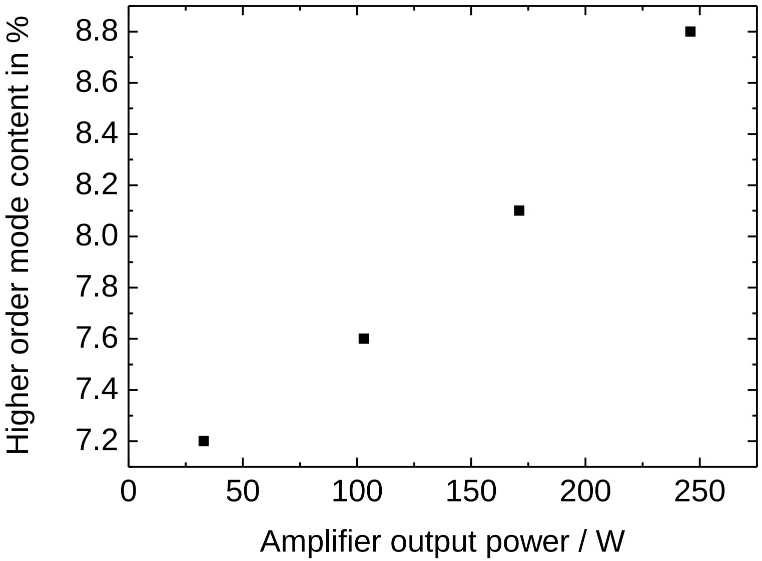
Pitch: 9.97 µm
d/pitch: 0.14

MAIN AMPLIFIER WITH 6.8 m PCF

Output power



Higher order mode content



- Maximum absorbed pump power: 363 W
- Maximum signal output power: 294 W
- Slope efficiency: 80 %
- PER: ~ 27 dB
- No evidence of SBS

- Higher order mode content increases slightly with increasing amplifier output power

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Lasers @ 1.5 µm

PART 2: LASERS @ 1.5 µm

Long term design goal: >> 100 W @ 1.5 µm

Design approach: Single-frequency master laser + fiber amplifier

Active dopants: Erbium *or* Erbium/Ytterbium

BASIC COMPARISON OF 1.0 µm AND 1.5 µm

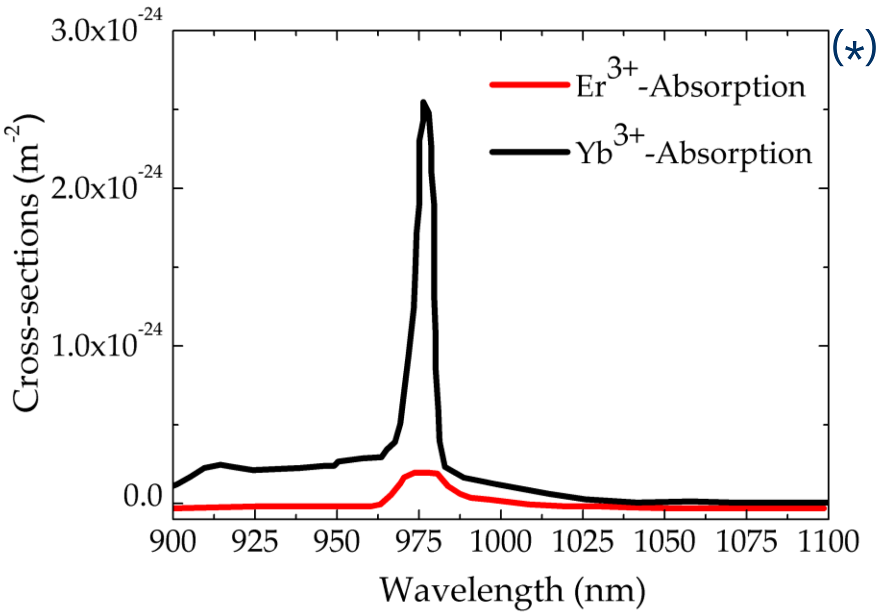
Wavelength	1.0 µm	1.5 µm
Dopant	Yb	Er/Yb, Er
typ. Efficiency	up to 85%	up to 30%
Quantum defect	~10%	30-70%
rel. absorption cross section	~10	1
rel. dopant concentration	~10	1
Highest Output Power	~ 500 W (SBS limited)*	~ 150 W (high NA fiber, Yb-ASE limited)**

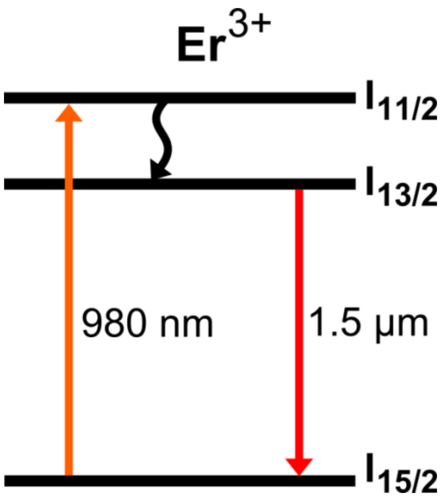
* Jeong et al. , IEEE JSTQE 13, 546 (2007)
** Jeong et al., OL 30, 2997(2005)

At 1.5 µm:

- More pump light is needed for same output power
- Far more heat is generated

CHALLENGES TO POWER SCALING / Er-DOPING





- Absorption cross sections and possible doping concentrations lead to about two magnitudes lower absorption compared with Yb-doping
- Er fibers need higher pump brightness due to smaller pump claddings
- Upconversion and ESA processes can increase the quantum defect to about 70 %

* Laroche et al., JOSA B 23, 195-202 (2006)

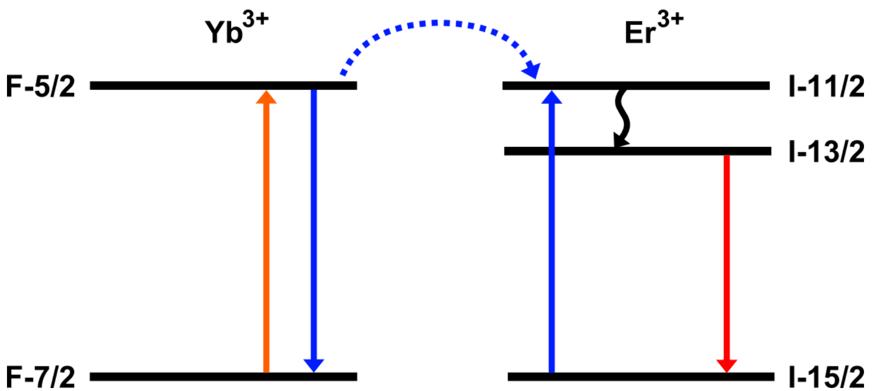
ALTERNATIVE: Er/Yb CO-DOPING

Concept & Advantages:

- Pump light absorption mainly by Yb
- Transfer from $F_{5/2}$ to quasi-resonant Er-$I_{11/2}$ level
- Significantly higher absorption cross sections
- “Classic“ double-clad high power approach possible
- Far less pump brightness required due to smaller required core-to-cladding-ratio

Drawbacks:

- Heavy phosphorous codoping needed for depletion of backtransfer
  → typically high core NA (~ 0.2)
- Yb pump rate increase beyond Er-Yb-transfer rate causes large gain values at 1.0 µm



Er/Yb – FIBER DESIGN ISSUES

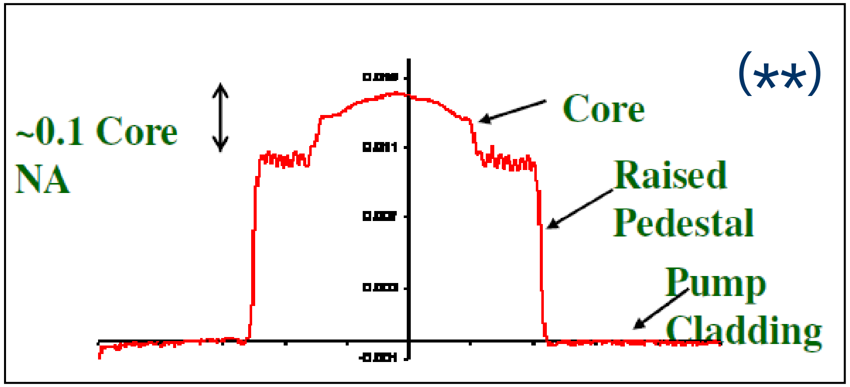
High core NA due to phosphorous-codoping

- Can be reduced by making a Ge-pedestal
- Use of fiber tapers and targeted single-mode excitation*

  → To be tested for large-core fibers

Low core-to-cladding ratio might lead to preferential operation at 1535 nm (Er emission maximum)

Fiber drawing and processing is especially difficult



* Morasse et al., Photonics West 2009
** Nufern, Photonics West 2009

TESTED CONFIGURATIONS

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 LMA fibers
- Novel multifilament-core (MFC) fibers
- Specially designed photonic crystal fibers (PCF)

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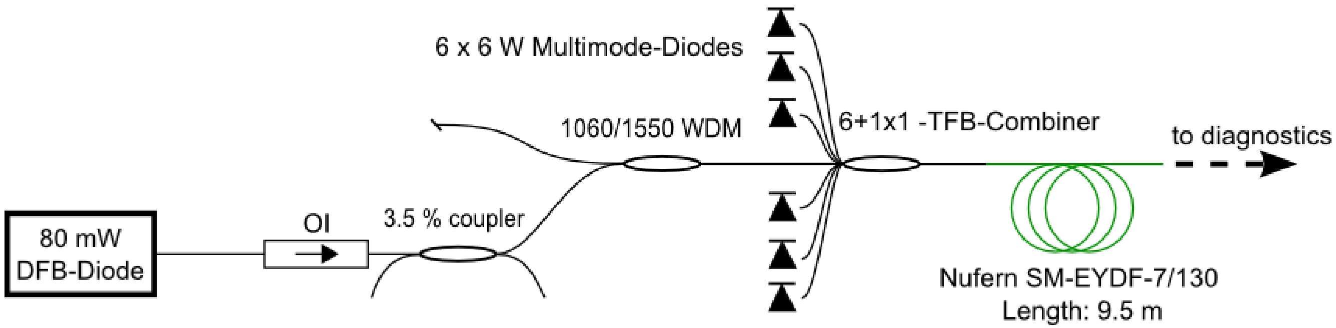
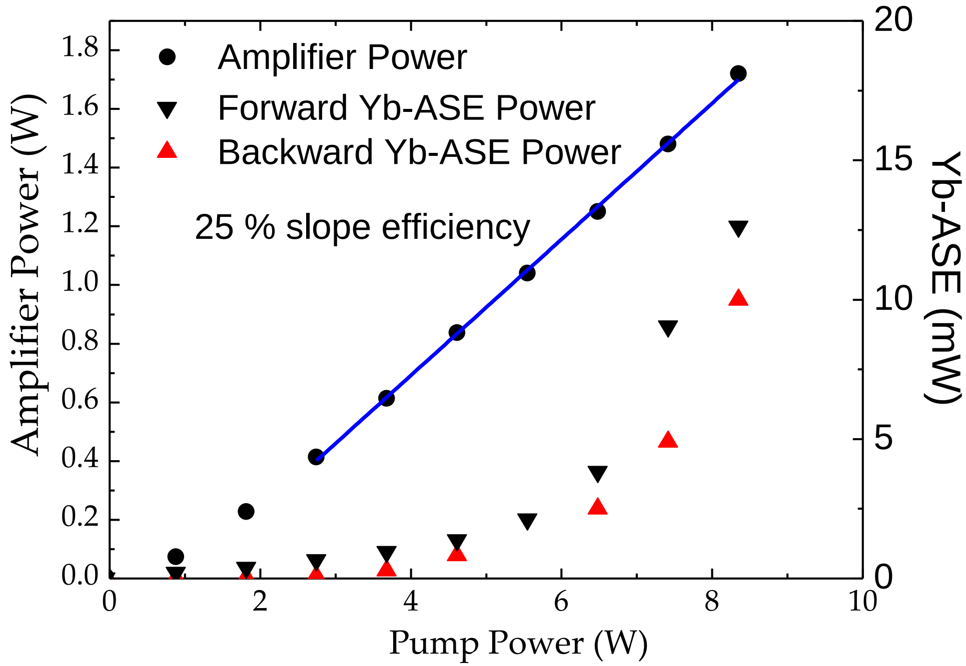
How to handle parasitic gain and emission at 1 µm?

Er/Yb – MANAGE 1µm EMISSION – SETUP (1)



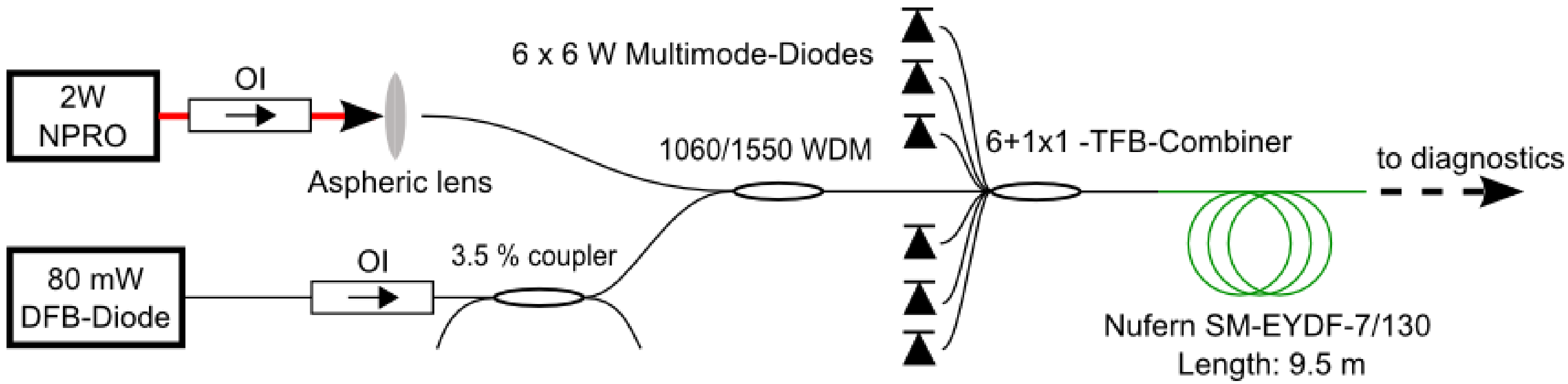
- 80 mW seed power at 1556 nm, linewidth < 10 MHz
- Co-propagating pumping configuration with 6+1 x 1 TFB-coupler
- 6x6 W of pump power at 976 nm
- Active fiber: 9.5 m of double-clad 7/130 µm Er:Yb-codoped fiber (Nufern)
- 1060/1550 WDM coupler to protect seed from Yb-ASE

Er/Yb – MANAGE 1µm EMISSION – RESULTS (1)



- Slope Efficiency: 25 %
- Yb-ASE rises strongly for pump power > 6 W
- Limitation set by necessity to avoid parasitic lasing at 1.0 µm

Er/Yb – MANAGE 1µm EMISSION – SETUP (2)

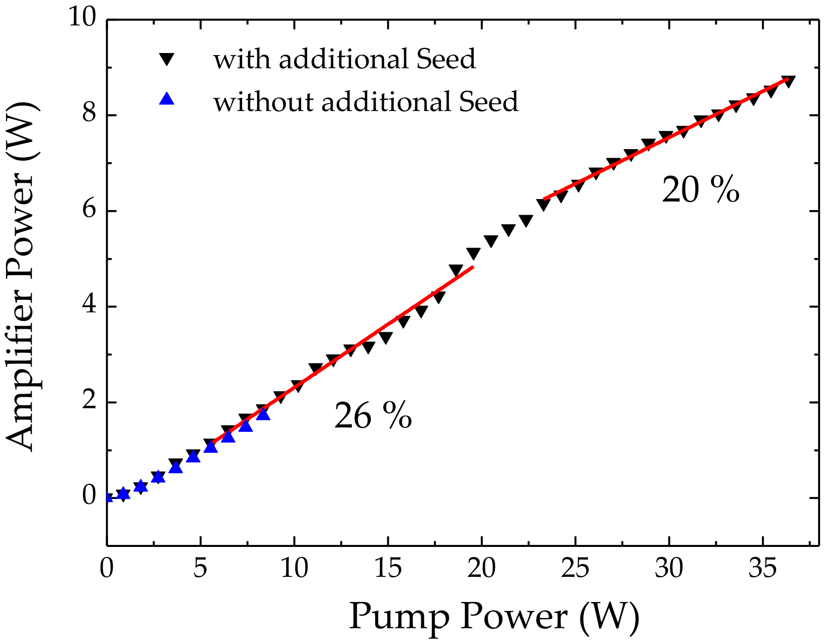


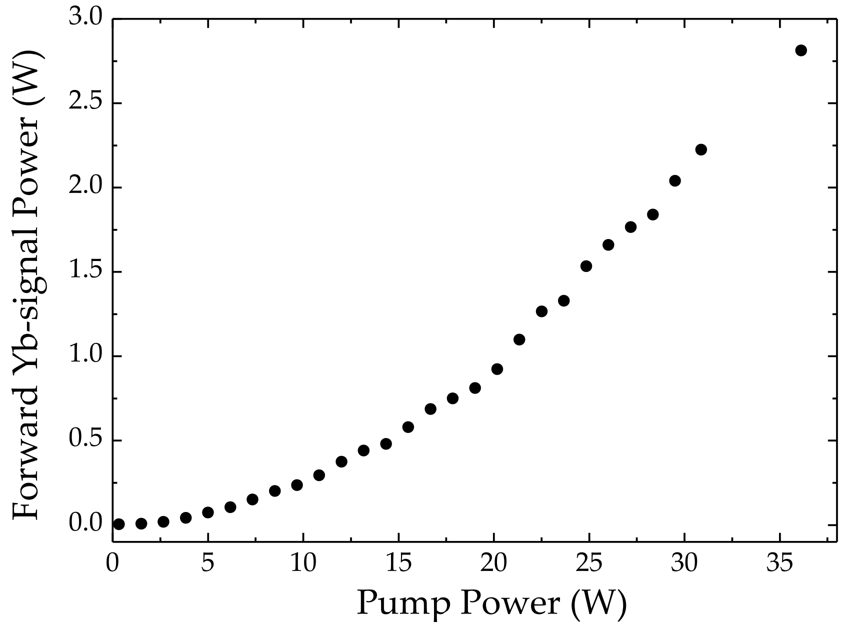
Inject 2nd seed signal at 1064 nm simultaneously

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
- Potential efficiency depletion at 1.5 µm by competing signal?

Er/Yb – MANAGE 1µm EMISSION – RESULTS (2)



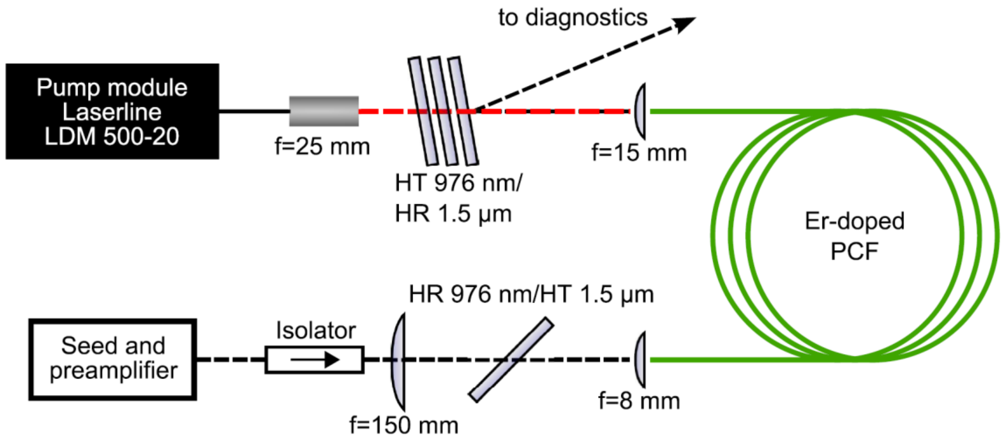


- Er slope efficiency not degraded by co-seeding
- Slight rollover at > 6 W power at 1556 nm
- 3 W of Yb output

  → Increased efficiency by fiber length optimization seems feasible (reabsorption of 1 µm signal → pump source for 1.5 µm signal)

Power scaling with specially designed photonic crystal fiber (PCF)

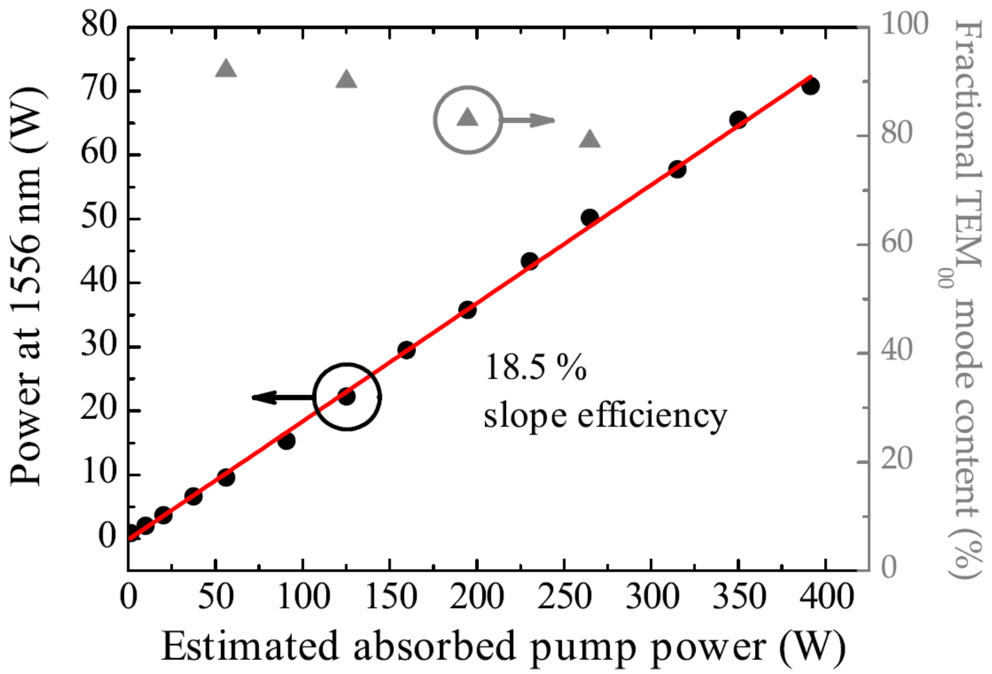
AMPLIFIER SETUP



- 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

AMPLIFIER RESULTS

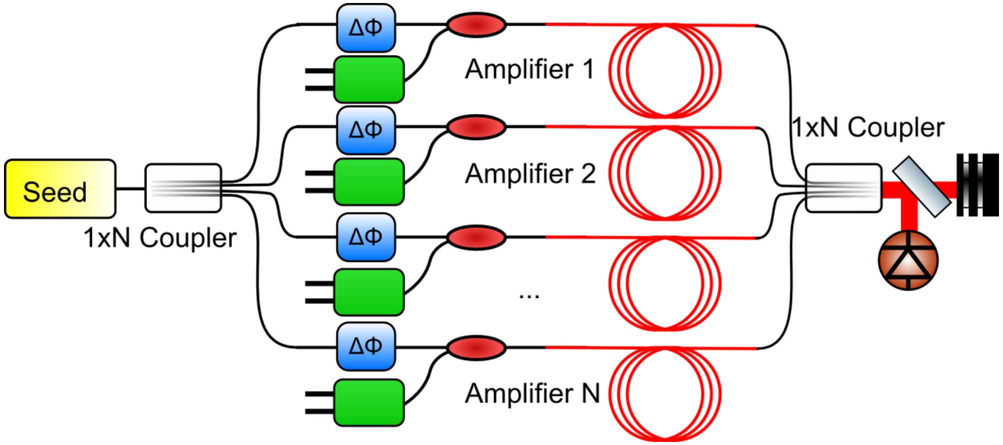


- Maximum output power: 70.8 W
- Slope efficiency: 18.5 %
- Limited by available pump power / amplifier efficiency
- ASE suppression: 44 dB

Coherent Beam Combining (CBC)

PART 3: COHERENT BEAM COMBINING

Coherent Beam Combining (CBC) architectures:



- Split seed into N channels
- Amplify each channel separately
- Use phase actuator to stabilize relative phase in each path
- Coherently combine in the end
  - Tiled aperture (beam quality is limited)
  - **Collinear combining (best possible beam quality)**

WHY COHERENT BEAM COMBINING?

Single frequency fiber amplifier power scaling limited by

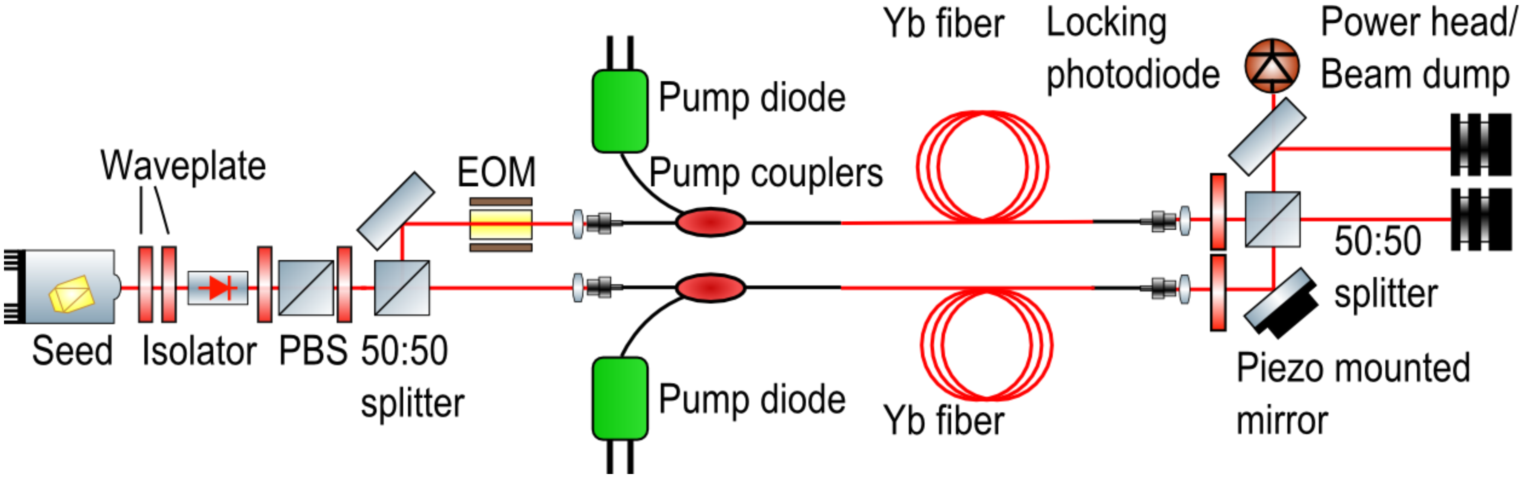
- Stimulated Brillouin Scattering
- Thermal effects

Coherent Beam Combining allows to overcome these limits

- Add coherently multiple (power limited) beams
- Scalable by increasing number of channels

But: Beam quality and noise properties of combined beam?

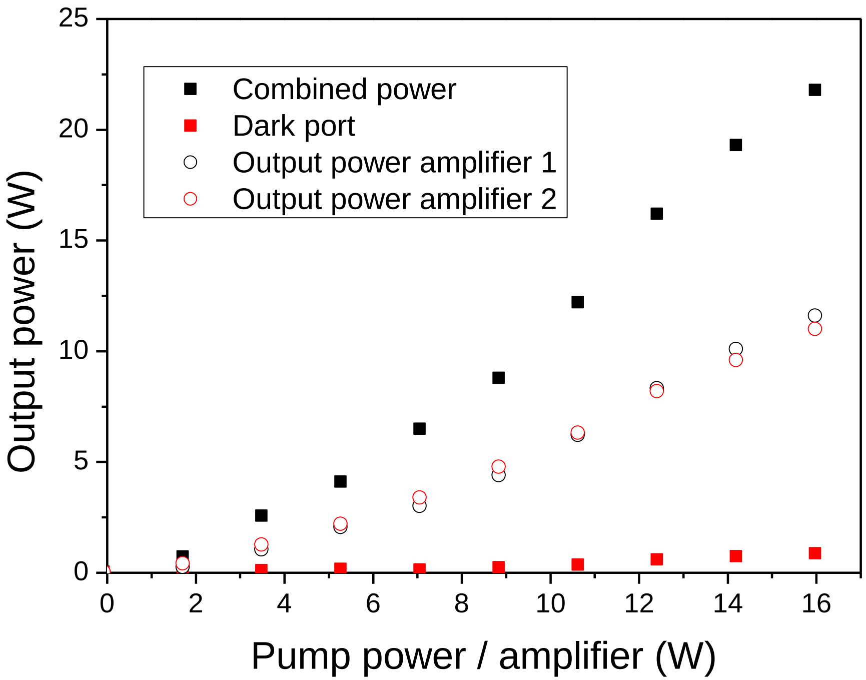
CBC SETUP



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

CBC RESULTS – POWER AND BEAM QUALITY

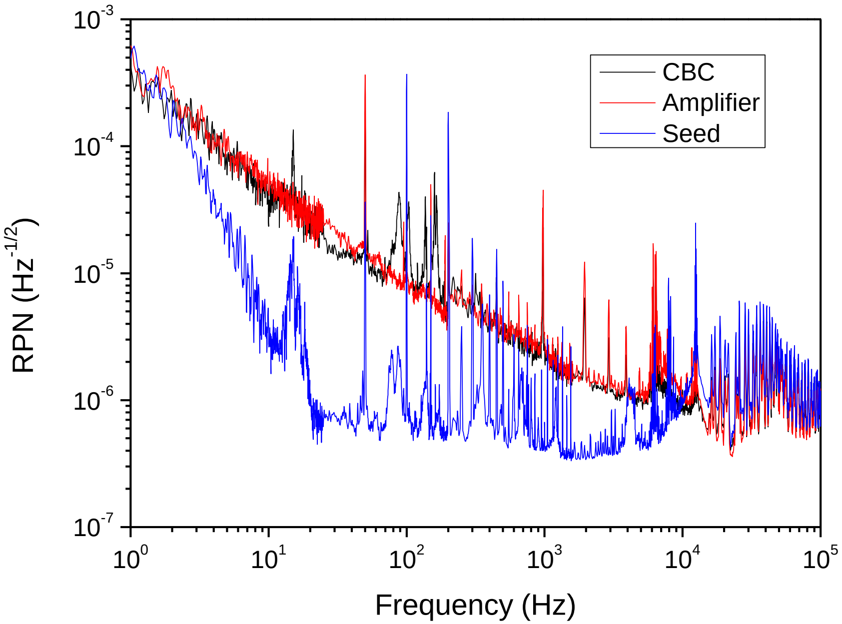
- Single amplifier output: 11.4 W
- Max CBC output: 21.8 W
- CBC efficiency: 95-97 %
  - Over the whole slope
  - Pump power was fine-tuned to maximize combining efficiency
- Stable under laboratory conditions



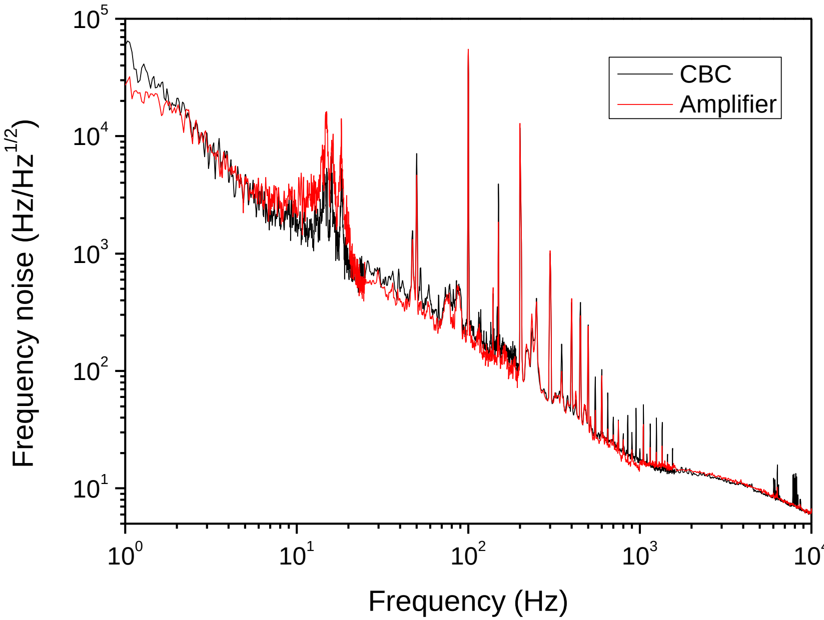
- TEM_{00} content: 97%
  - Both for single amplifier and combined signal
- Transmission through locked cavity: 21.3 W

POWER AND FREQUENCY NOISE

Power noise



Frequency noise



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

SUMMARY

Fiber amplifier system @ 1064 nm

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

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%

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

ACKNOWLEDGEMENTS

3rd generation laser development team:

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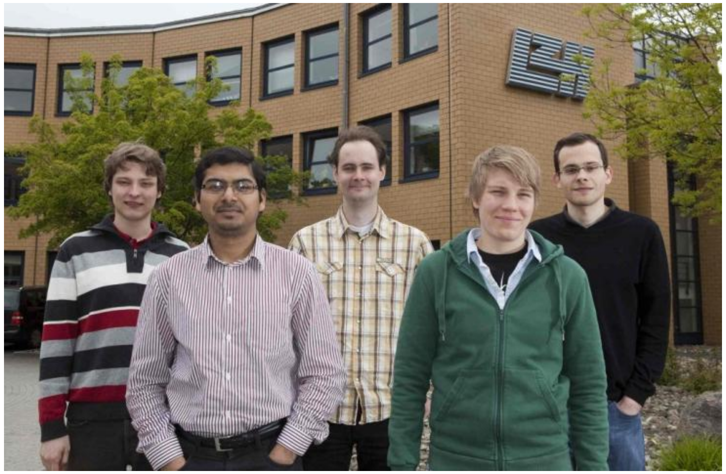
Malte Karow
Vincent Kuhn



DFG Deutsche Forschungsgemeinschaft

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