Status of lasers for next generation cryogenic silicon optics

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for the LAWG/LSC

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Outline

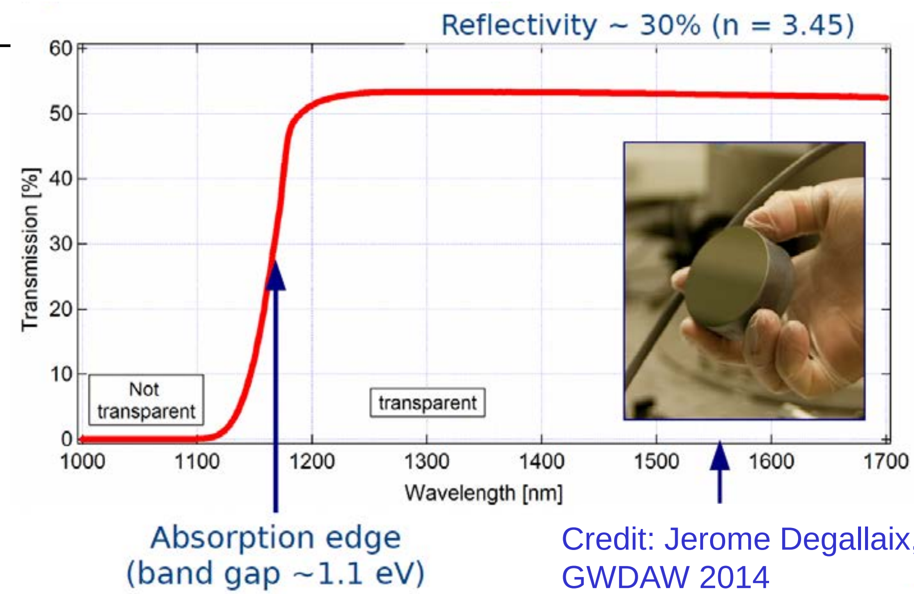
- What wavelength is needed for cryogenic silicon GW detectors
- Current status and problems
- Future plans

Why a new wavelength

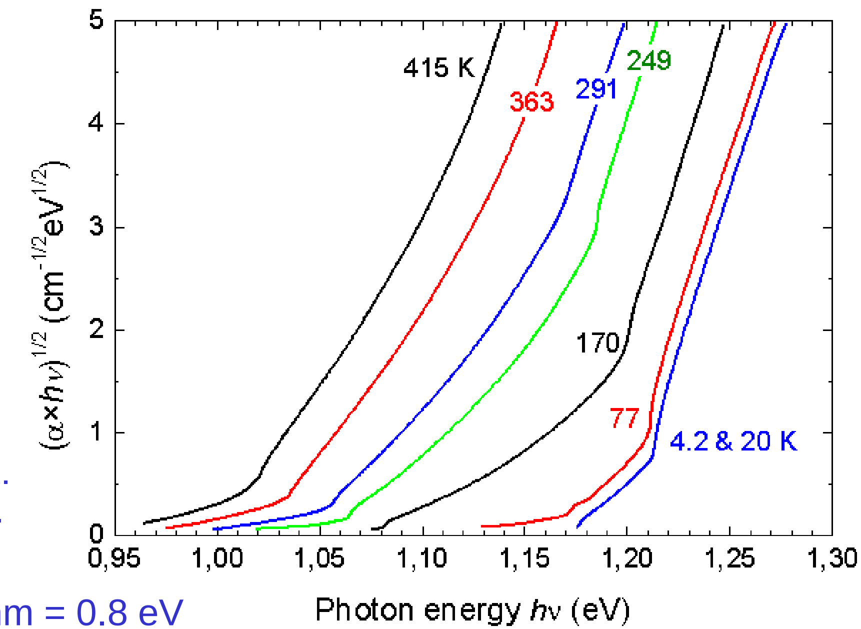
- The absorption of silicon decreases for lower temperatures and longer wavelengths
- Above 1.5µm it virtually vanishes

- The absorption of silicon coatings is significantly lower at longer wavelengths and that scattering losses scale with $1/\lambda^2$

LSC presentation: R. Adhikari, "Voyager: Laser Wavelength Choice", Presentation for LSC lasers and auxiliary optics working group



Credit: Jerome Degallaix, GWDAW 2014

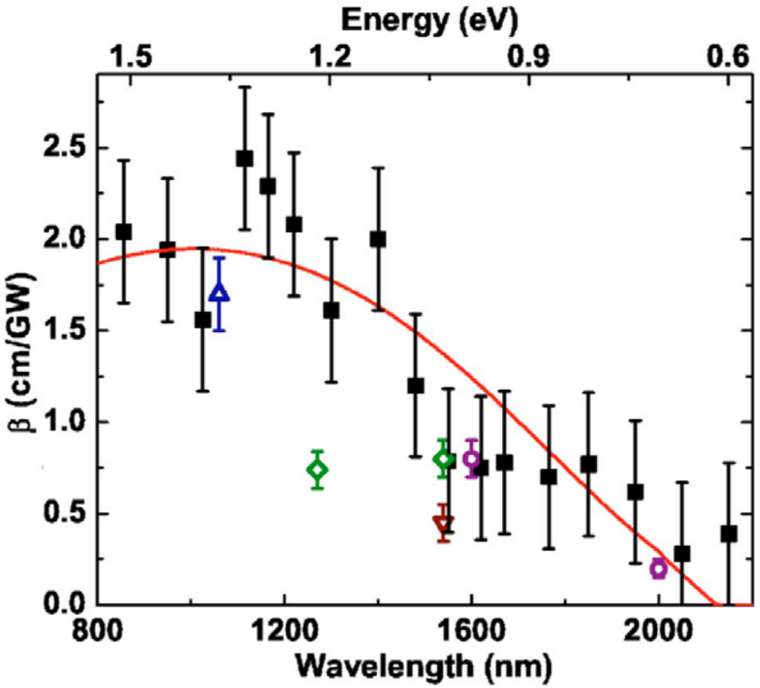


Credit: Macfarlane, G. G., T. P. McLean, J. E. Quarrington, and V. Roberts, J. Phys. Chem. Solids 8, (1959) 388-392

1550 nm = 0.8 eV

Possible issue at high powers

- Two photon effects become possible
- Move close to half the bandgap energy ~0.6eV, i.e. 2µm
- Not likely an issue for future detectors, as transmissive optics are not likely to see high power densities



Credit: Bristow, et.al. (2007). Two-photon absorption of silicon for 850-2200 nm. *Appl. phys. lett*, *90*(19), 191104

Current plans

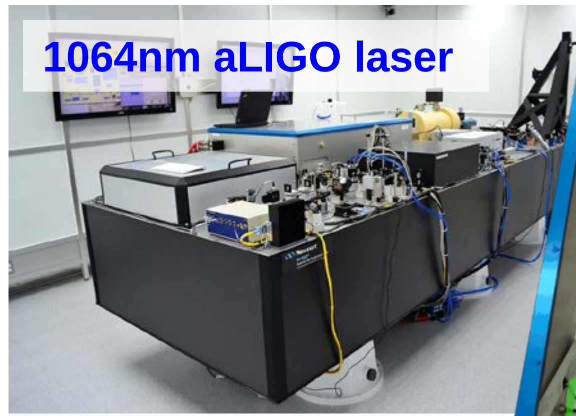
- Einstein Telescope (low frequency)
  - ET-LF: silicon mirrors
  - cryogenic (10K), 3W @ 1550nm
- ET (high frequency)
  - ET-HF: fused silica mirrors, 500W @ 1064nm in LG_{33} mode
- LIGO Voyager
  - Cryogenic? Likely silicon, 200W @ 1.5µm or longer
- Cosmic Explorer
  - Most probably cryogenic, silicon, very high power @ 1.5µm or longer

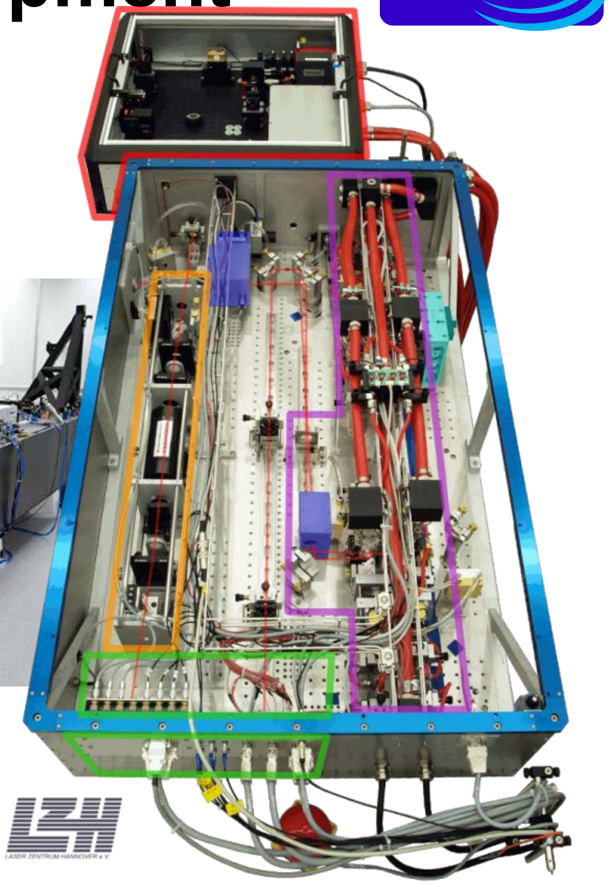
Requirements

- The actual requirements of the next-generation GWDs on the laser sources are TBD
- Minimum requirements, at least as good as current GW detectors for:
- Power output, single mode oeration, linear polarization, beam quality, reliability, intensity and frequency stability
- Either show that the requirement is satisfied or that the laser has actuators to allow to control the parameter

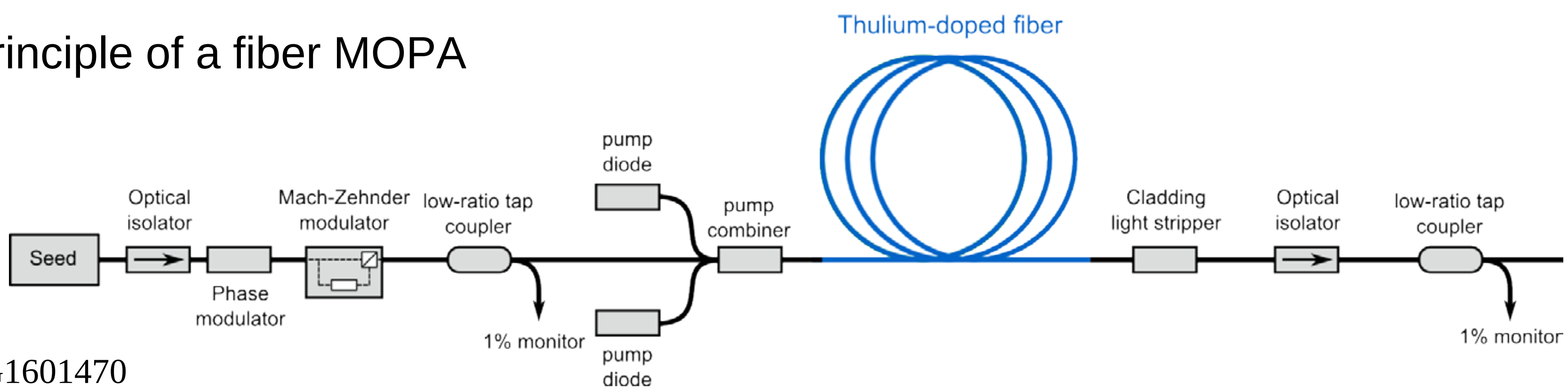
Trends in laser development

- From master/slave oscillator systems to master oscillator power amplifier (MOPA) systems





- Principle of a fiber MOPA



Comparison of solid-state and fiber technology

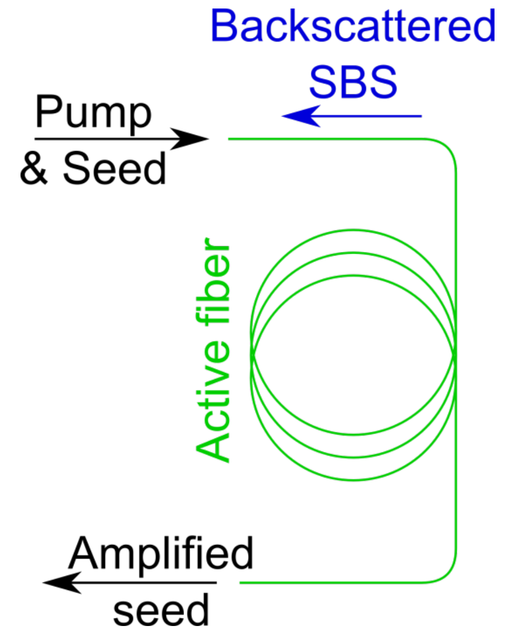
- Solid-state systems
  - Low single-pass gain
  - Long amplifier chains
  - Injection-locked oscillators
  - Maximum diffraction-limited output power per crystal limited by thermal lensing aberrations
    - Limits power scaling of injection-locked schemes
- Fiber-based systems
  - High single-pass gain
  - Single amplifiers are already promising
  - No injection-locking required
  - No thermal lensing but modal instabilities
    - Limits power scaling of fiber amplifiers
  - No free beam
    - Typically less alignment
    - Typically, small footprints

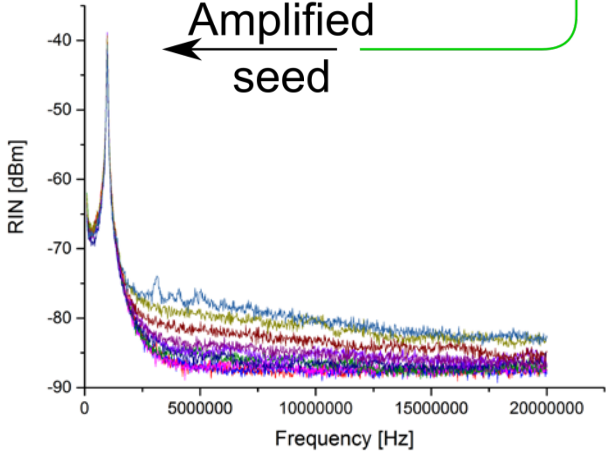
Limitations of fiber amplifiers - SBS

- Stimulated Brillouin scattering (SBS)
  - Scattering on acoustical phonons
  - Threshold scales with the linewidth but saturates for linewidths < ~MHz

- Limits the maximum output power and can lead to parasitic pulses
- Imprints a frequency-independent broadband intensity noise (on top of the shot noise)

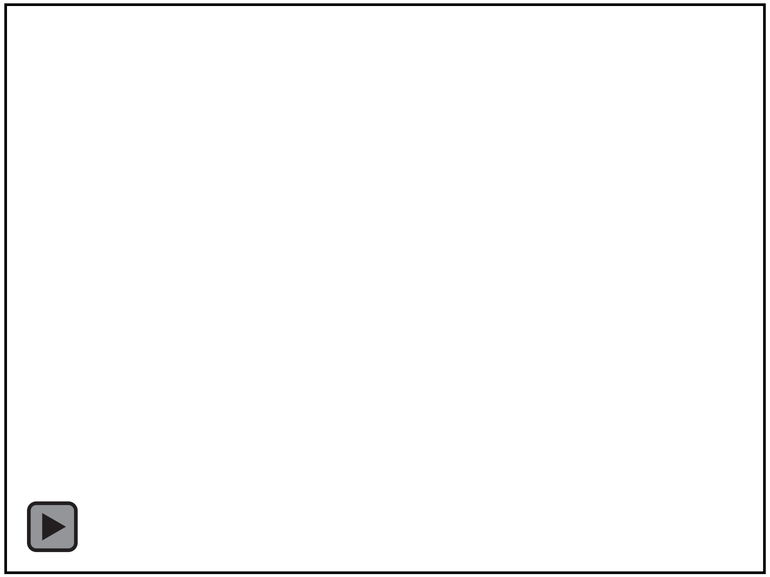
- Can be suppressed by using large mode area (LMA) fibers (tradeoff with beam quality / modal instabilities)





Limitations of fiber amplifiers – MI

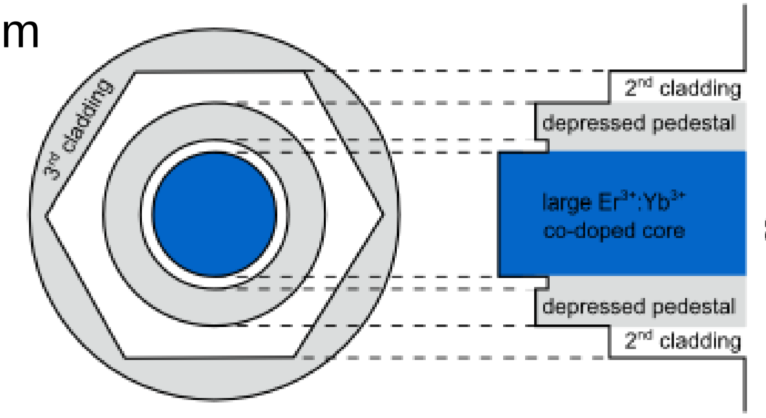
- Modal instabilities (MI)
  - Threshold-like onset of modal instabilities in high-power fiber amplifiers
  - Hot topic regarding the power scaling of fiber amplifiers at 1.0µm
  - So far (at 1064nm), not a limitation for single-frequency amplifiers but possible at higher output power levels and also for 1.5µm and 2.0µm



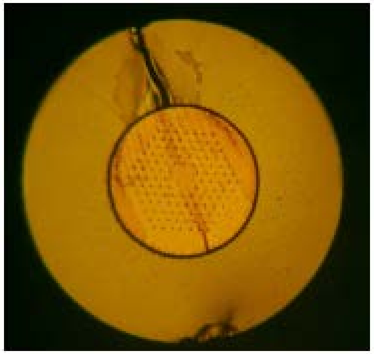
Eidam et al., Optics express 19 (14) 2011

State of the art: Erbium @ 1.5µm

- Er^{3+} emits efficiently between ~1.5µm and ~1.6µm
- Development driven by the telecommunication industry
  - Very reliable fiber- and components-technology at low power levels
  - Low absorption & inefficient
- Commonly codoped with Yb^{3+} to increase absorption



Output power		
207W*	Monolithic	Non-PM, no M^2 (few-mode fiber)
61W**	TEM_{00}>91 %	not monolithic, non-PM, specially designed triple-clad fiber
70W***	TEM_{00}~80 %	not monolithic, non-PM, specially designed PCF, pointing instabilities



* Photonics West 2016, Fiber Lasers XIII: Technology, Systems, and Applications, proceedings to be published

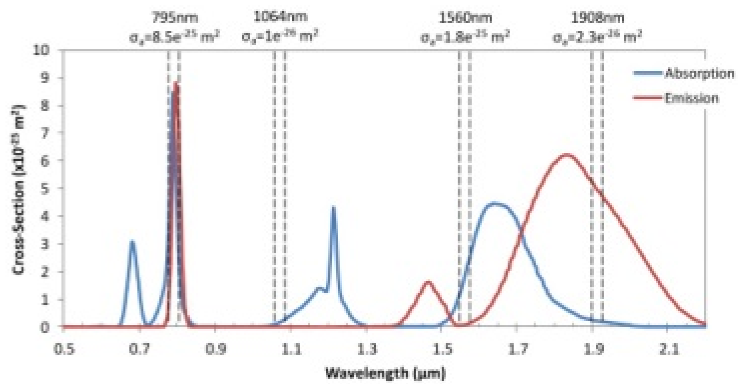
** M. Steinke et al., Optics Express 22 (14) 2014, *** V. Kuhn et al., Optics Letters 36 (16) 2011

Challenges : suitability @ 1.5μm

- High power is possible, but no commercial alternatives for GW detector requirements
- Develop frequency/amplitude stabilization using fiber components
- Quality and stability of seed sources. Single-mode, single frequency?

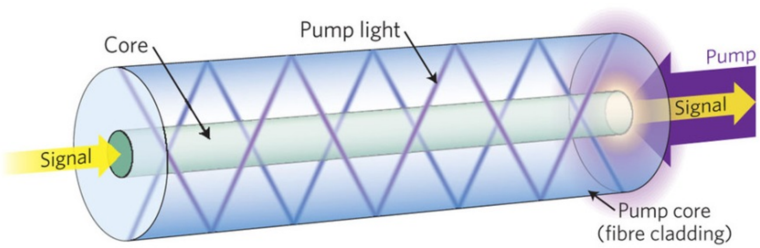
State of the art: Thulium @ 2.0µm

- Thulium (Tm^{3+}) emits efficiently between ~1.9µm and ~2.0µm
  - Very attractive for commercial (e.g. LIDAR) applications
  - Eye-safe
  - Efficient (>50% if pumped at 793nm due to cross-relaxations)



Output power	👍👍👍	👎👎👎
608W*	M^2~1.05 (few-mode fiber)	Non-PM, not monolithic
310W**	Monolithic	Non-PM, no M^2 (few-mode fiber)
210W***	Monolithic, PM (PER>17dB)	M^2~1.6 (few-mode fiber)

- Based on few-mode step-index fibers
- No TEM_{00} measurements or tests of reliability



nature.com

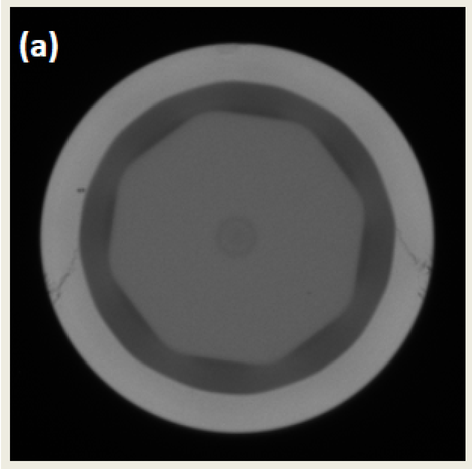
* Goodno et al., Optics Letters 34 (8) 2009
** Wang et al., IEEE Photonics Technology Letters 27 (6) 2015
*** Liu et al., Optics Express 22 (11) 2014

Challenges: suitability @ 2.0μm

- High power is possible
- Fiber technology at ~2.0μm is evolving significantly (driven by commercial interests)
- Mode quality (modal instabilities) needs investigation?
- Single-frequency seed sources at ~2.0μm?
  - Fiber lasers (e.g. from NP Photonics or AdValue Photonics)
  - Whispering gallery mode lasers (e.g. from OEwaves)
  - What about their noise levels etc.? Are they already appropriate?

State of the art: Holmium @ 2.1µm

- Holmium (Ho^{3+}) emits efficiently at ~2.1µm
- So far, no demonstration of single-frequency fiber amplifiers
- Record CW output power: 407W* (monolithic fiber laser, cladding-pumped)
- Drawbacks (narrow/selective absorption profile)**:
  - Can only be pumped at
    - ~1.9µm (by Thulium-doped lasers/amplifiers)
    - ~1.15µm (Ytterbium-doped laser/amplifiers and/or Raman fiber lasers)
  - Most high-power demonstrations relied on all-glass fibers
    - High absorption of polymer coating
  - Experimental slope efficiencies are rather low
    - Background infrared silica losses, absorption by OH- groups, re-absorption and non-radiative decay processes
- Single mode seed lasers???



Improved Ho doped pedestal fibers (DSTG)***

* Hemming et al., CLEO 2013, OSA Technical Digest, paper CW1M.1

** Jin et al., Journal of Electronic Science and Technology, 13 (4) 2015

*** Hemming et al, 2013. High power operation of cladding pumped holmium-doped silica fibre lasers. Optics express, 21(4), pp.4560-4566.

Plans for the future

- Projects at 1.5µm with
  - Benno Willke (AEI Hannover) / Peter Wessels (LZH)
- Projects at 2.0µm with
  - Peter Wessels (LZH) / Volker Quetschke (UTRGV)

- Other GW related laser projects*
  - Rana Adhikari (Caltech)
  - Peter Veitch, Jesper Munch (The University of Adelaide)
  - …

- The field is wide open for the next generation GW detectors!

* Incomplete list