HP Lasers for future GW detectors

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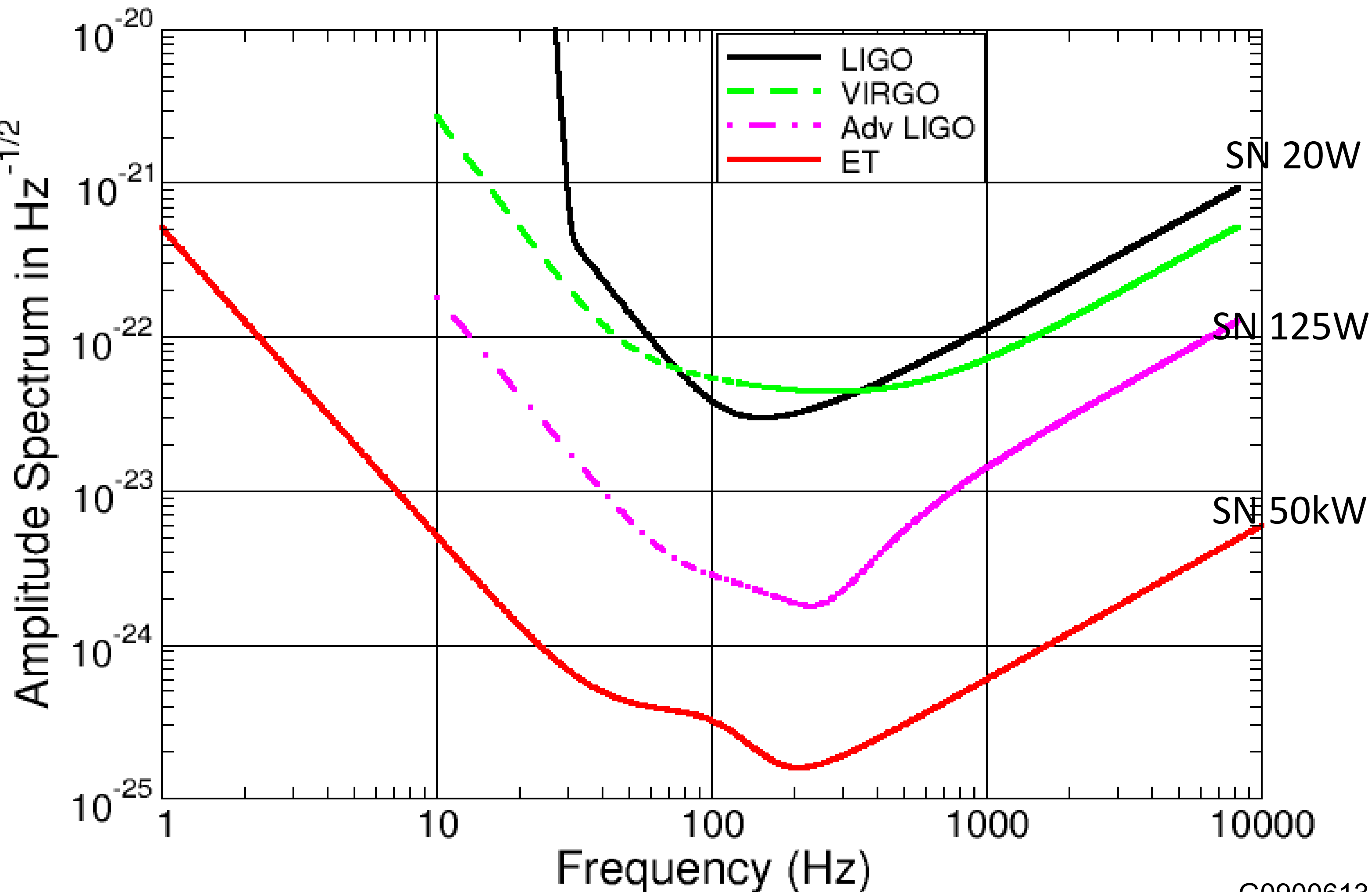
- Starting from Sensitivity
- Specifications for laser source
- The laser's story
- What could be done to prepare the future?
  - Fiber lasers
  - Disk lasers
  - Ceramic lasers
  - Other wavelengths
- What are the limits to HP extrapolation ?
- Discussion

Sensitivity curve



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First specifications of the laser

- Laser power: 10 kW – 50 kW, easy to get but difficult to handle
- Reliability in long term operation

Easy and rare maintenance

- Easy controllable through rapid and large dynamical transducers
- Weak thermal effects (beam geometry and polarization))
- Wavelength : 1 μm to 1.55 μm, depends on test-mass material
  - ✓ 1.06 μm linked to SiO_2 , known but absorbing & heating
  - ➢ 1.55 μm to enjoy telecom developments, use Silicon optics,

    to improve mirror figures (scatter goes as $1/\lambda^2$)

.

Laser Frequency Noise specifications

Origin of laser noise's influence comes from interferometer (ITF) imperfections:

$$\frac{\delta\tilde{f}}{f} = \frac{\tilde{h}}{\beta}$$

β Contrast defect

$\delta\tilde{f}$ around $10^{-8}\ Hz/\sqrt{Hz}$ for $\beta = 10^{-2}$, $h \approx 3\times10^{-25}$

Like in Virgo/LIGO today, the laser needs a few stabilization stages:

-pre-stabilization on rigid cavity

-stabilization on the common-modes

-stabilization on differential mode

In any case, need a quiet free-running laser

and improve the mirror figures to sub nm rms.

Laser RIN specifications

Amplitude Fluctuations couples to ITF:

- Via non perfect dark fringe contrast
- via radiation pressure
- Via rad. press noise: quantum noise can be reduced by squeezing techniques and QND

Frequency [Hz]	Rel Intensity Noise [1/Sqrt[Hz]
10	? $< 2 \times 10^{-8}$
$10 < f < 500$	? $< 2 \times 10^{-9} f$
$f >= 500$	? $< 1 \times 10^{-7}$

A low level requirement at 10 Hz is very tough to get

In case of RF readout in the range above the limit of *UGBW* of servos, passive control can be done with filtering .

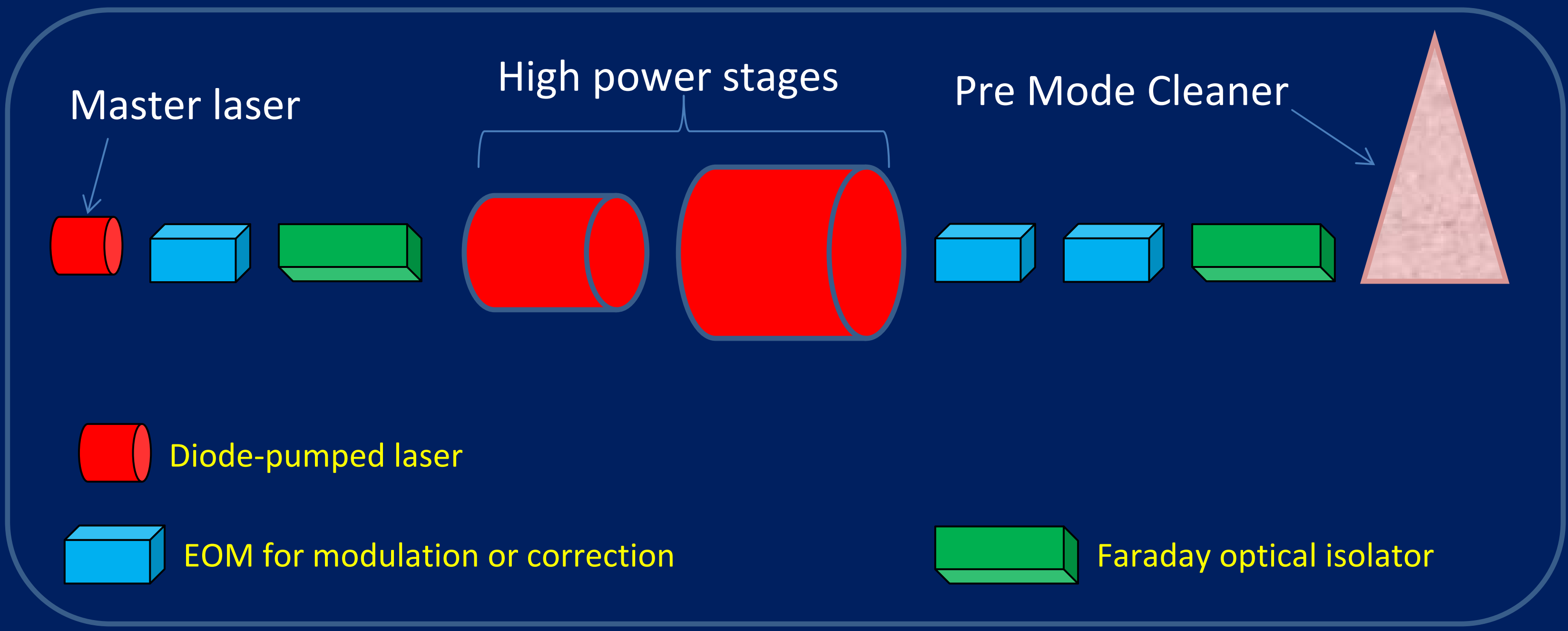
In any case the stabilization level is limited by the shot noise of the photodetector:

DC power on photodetector	**35mW**	**23 W**
RIN [1/Sqrt[Hz]	2.5×10^{-9}	10^{-10}

Photodiode with such HP standing and such dynamic range?

Injection locking and Amplification schemes

To avoid operating HP laser in single-frequency mode by inserting losses inside:
- Use a low power single frequency master laser
-- injection-lock a HP single-mode laser
--- amplify a HP stage in saturated regime
-- use more than one HP stage to go to very HP



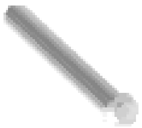
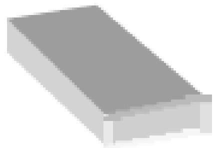
Initial GW detectors' solution: SSL

=> Diode-pumped Solid-State lasers rod geometry (mm x cm): Nd:YAG, Nd:YVO4

Power scaling to kW is restricted by many thermo-optical problems if want good beam quality (less than 10% out of gaussian mode)

- stress fracture
- birefringence / depolarization
- spatial distortions
- cavity stability / thermal lens
- spurious oscillations in high gain material

SSL gain medium

Challenge	 Rod	 Slab (zigzag)	 Disk
Thermal Lensing	Significant (can be compensated except for bi-axial focusing)	None in y-z plane (zigzag path averages out $\nabla_{\perp}T$), weak in x-z plane	None (1-D heat flow eliminates $\nabla_{\perp}T$)
Stress Birefringence	Significant (can be compensated)	None (for ideal slab with 1-D heat flow)	None (1-D heat flow)
Mode Control	Generally good at lower avg. power	More difficult with increasing aspect ratio	Good
Modal Fill Factor for TEM_{00}	up to ~80% (95% goal)	up to 78%	up to ~95%
Best Power with Good BQ	500 W @ M^2 ~ 1.5 [2]	3 kW @ M^2 ~ 2.4 [5]	13 kW @ M^2 ~ 4 [11]

Principal configuration of SSL gain medium and their comparison (Boeing Cie 2002)

Do we try to look ahead for other kind of lasers? Other wavelengths?

distributed gain available from a long length of fiber enables efficient thermal management.

Observatoire de la CÔTE d'AZUR

Fiber lasers

ARTEMIS

Promising alternative to bulk SSL are rare-earth doped fibers:

1.large ratio of surface-to-active volume : good heat dissipation

2.distribution of thermal load on a longer length

3.beam quality depends on the physical design of the fiber

4.Wall-plug efficiency > 28% while bulk YAG is between 10-20%

5.Fixed spot size at all power levels

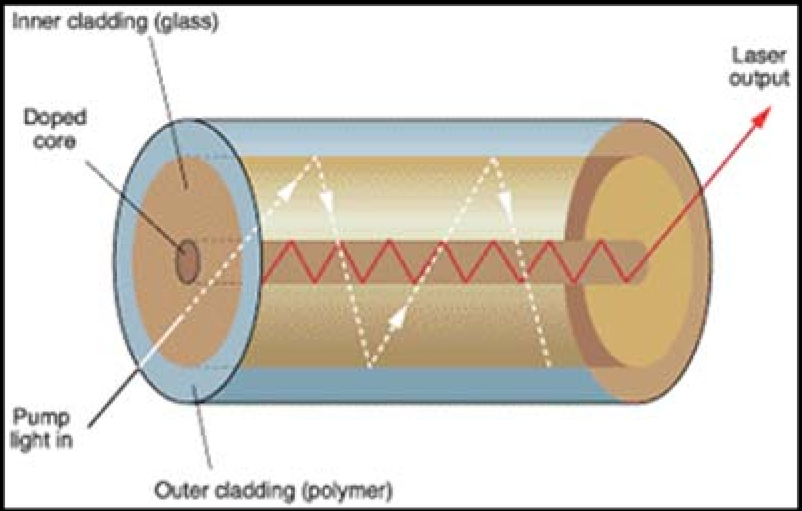
6.Minimum spare parts, low maintenance operation

7.pumping diodes at 980 nm has MTBF > 100,000h of operation better than 808nm pumping diode of Nd:YAG, better quantum defect

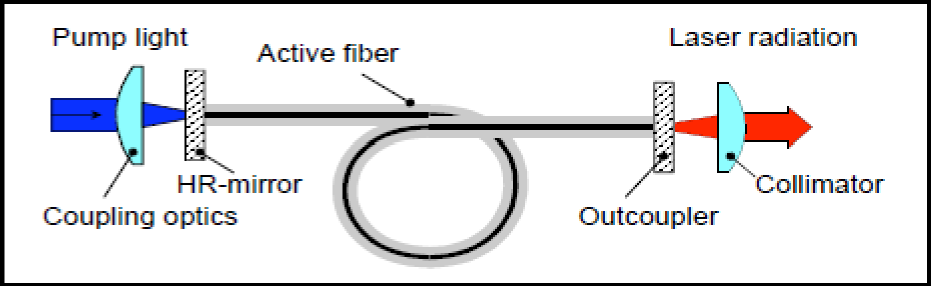
* Fiber laser setups need fewer mechanical components, which can make them significantly cheaper and smaller than bulk lasers.

Erbium doped Silica (1.55 micron)
Ytterbium doped all glass (1.06, eff > 80%)
Ytterbium doped Silica (1.06, eff 85%)

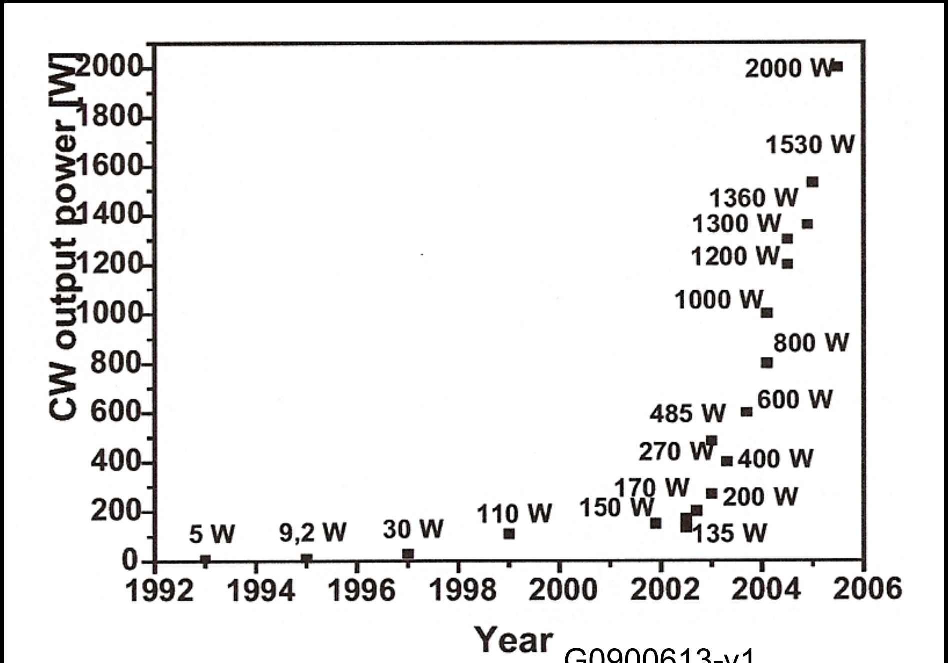
Fiber lasers' concept and evolution



Double-clad fiber concept



-the core contains a rare-earth element that provides laser gain,
-the 1rst inner cladding layer confines laser light in the core but in addition it transmits the pump light.
-The outer cladding layer has a refractive index lower than the inner cladding, confining the pump light and reflecting it many times through the core



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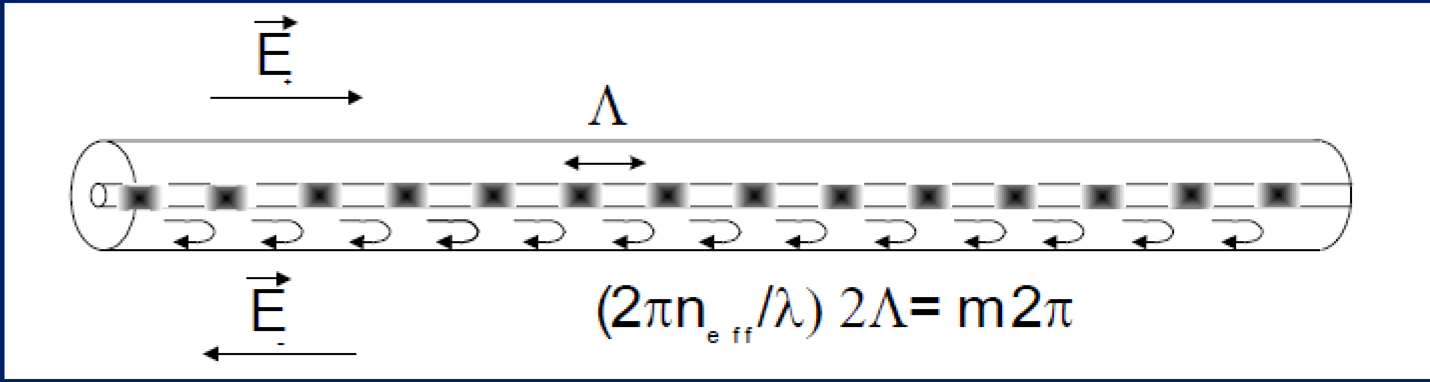
Fiber technologies

Bragg gratings as reflector

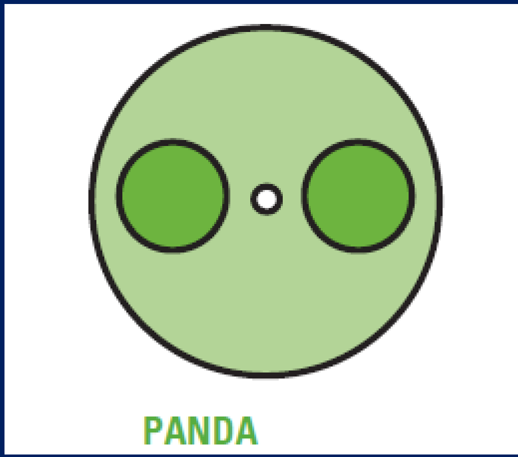


aperiodic perturbation of the effective refractive index in the core over a few mm/cm reflection of light (propagating along the fiber) in a narrow range of wavelengths, for which a Bragg condition is satisfied (→ Bragg mirrors).

Polarisation-maintaining fiber (commercially available)

The 20 µm (NA 0.065) core diameter is Ytterbium doped and surrounded by 2 borosilicate rods to induce birefringence as high as $3.\ 10^{-4}$.

The fiber has an inner cladding with a diameter of 400 µm



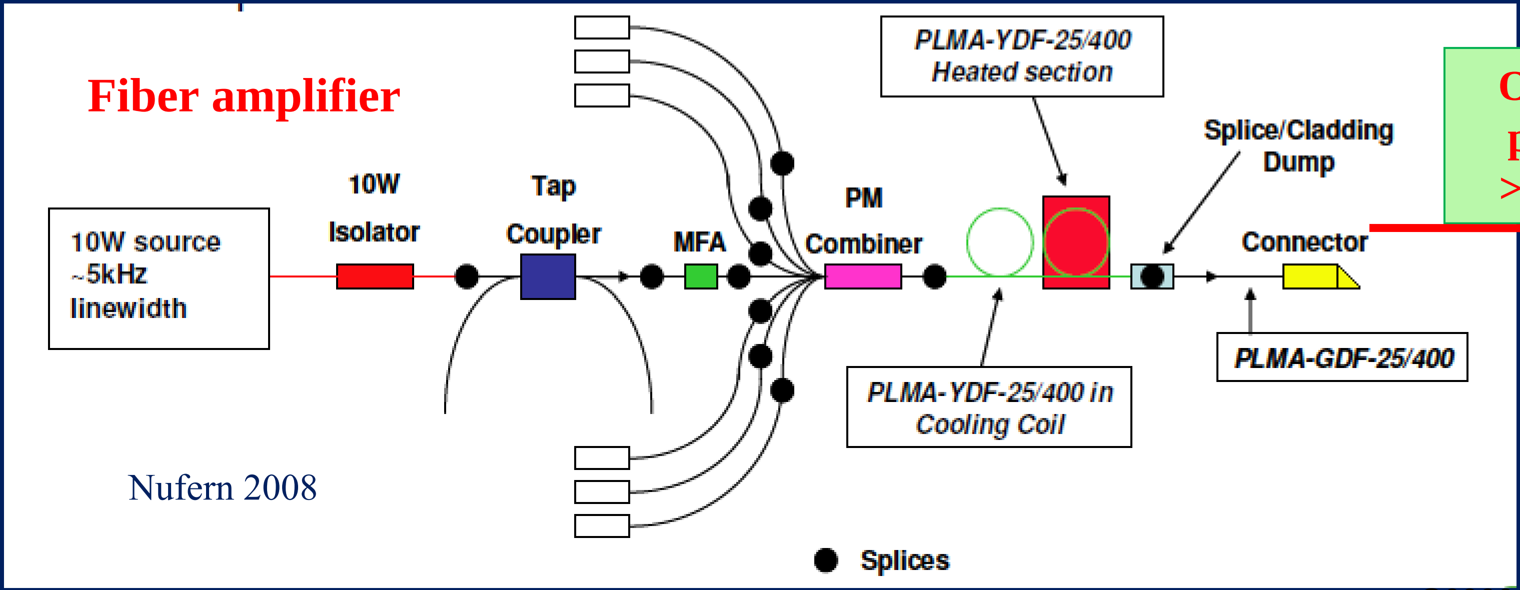
State of art on fiber laser and amplifier

Single-mode fiber laser

IPG: Yb Fiber lasers based on rare-earth doped silica delivers up to 5 kW single-mode (March 2009) [557950.htm]

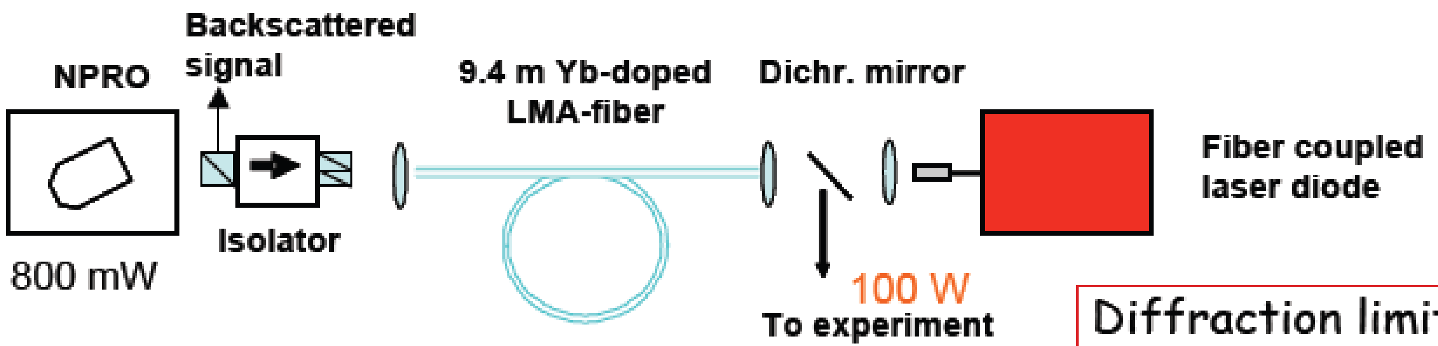
Single frequency Fiber laser

IPG: single frequency (line width ~100kHz) linearly polarized Ytterbium fiber lasers 150 W cw output power [http://www.ipgphotonics.com/products_1micron_lasers_single.htm]

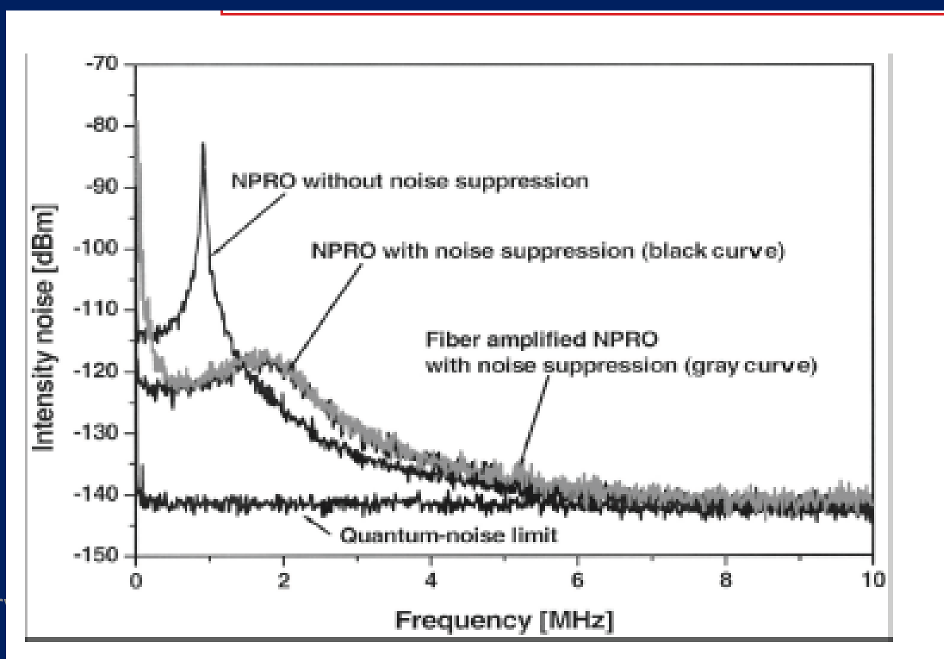


Intensity noise of a 100W amplifier

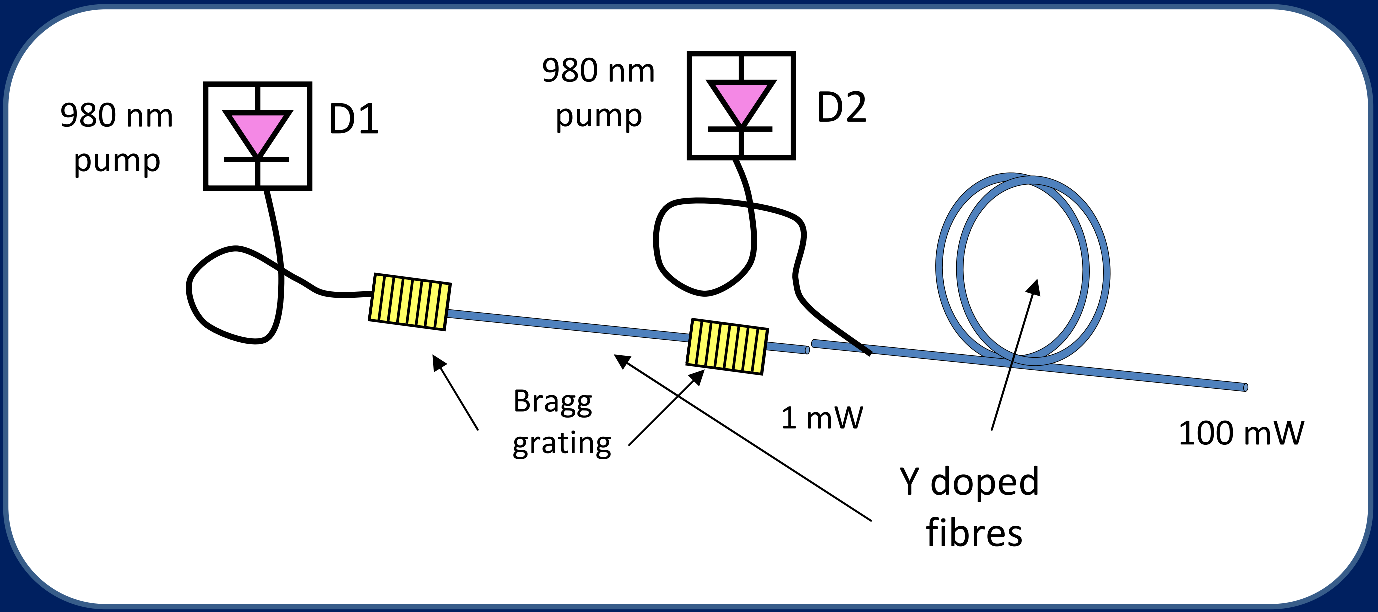
(Hofer et al, 2001)



Diffraction limited ($M^2 < 1.3$)
• Polarization 82% (10:1)



Monitoring and control of a fibre oscillator



Thermal effects:
D1 current affects laser frequency Freq stab with Diode D1
D2 current affects gain and intensity of laser RIN with D1 + D2 controls

➡ Fast easy feedback

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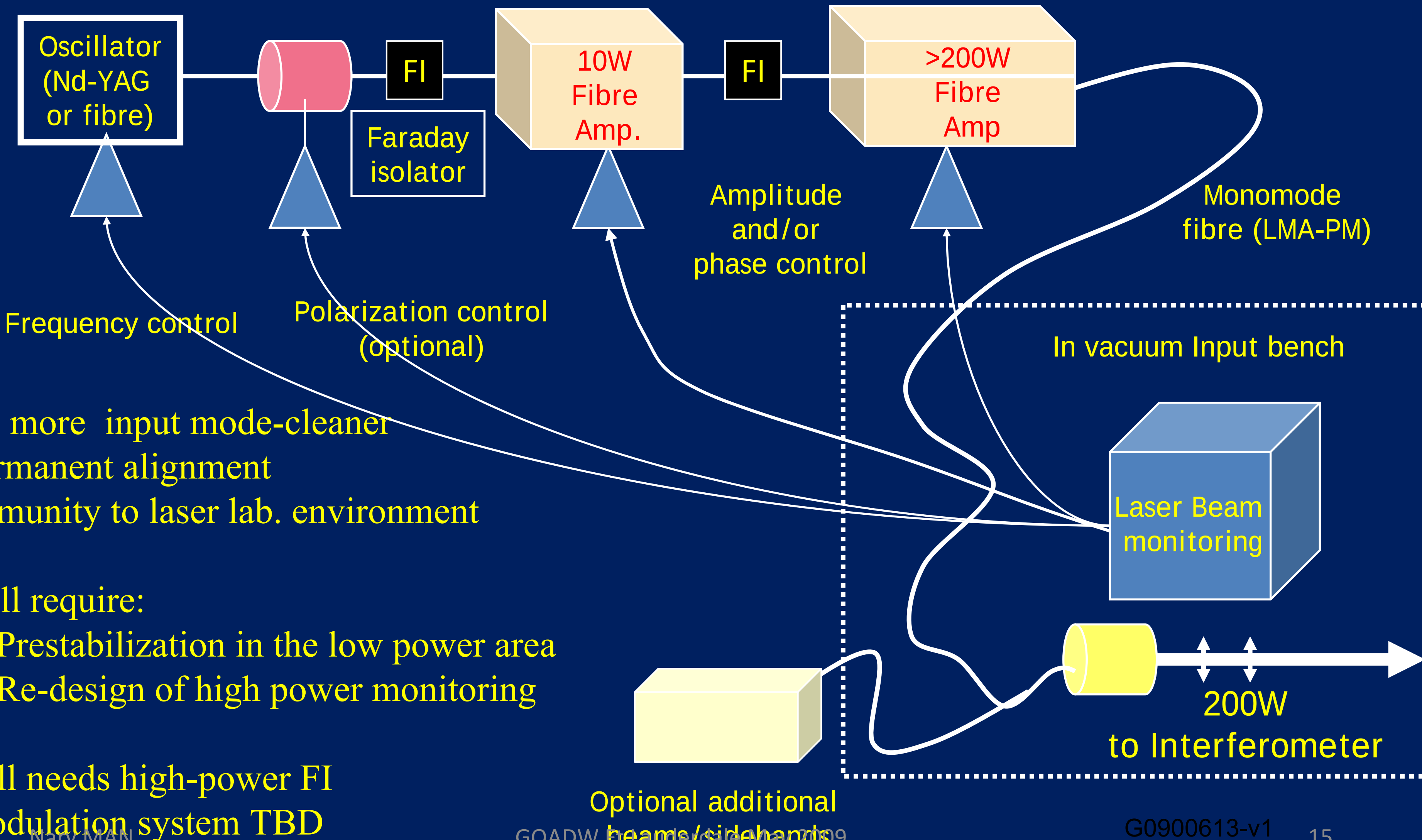
Stabilisations scheme for Advanced detector laser source



No more input mode-cleaner
Permanent alignment
Immunity to laser lab. environment

Will require:
- Prestabilization in the low power area
- Re-design of high power monitoring

Still needs high-power FI
Modulation system TBD

Limitations of fiber lasers/amplifiers

- Brillouin scattering: gain proportional to the length of the fiber and to the power (has been overcome for 264 W Jeong264WYbdopedFiber.pdf)

- Raman scattering: negligible because gain is about 100 times smaller

- Photodarkening

Fibers in which optical mode occupies a large modal area, and hence is less intense ➔ large mode area fiber ➔ multimode , except excite a single high order mode and use HOM High Order Mode Fiber Laser

Other geometries/types

Geometry of fibers = their built-in *waveguide* effect eliminate disturbing thermal effects (such as e.g. *thermal lensing*➔ possible to achieve an excellent **beam quality** even at very **high power** levels.

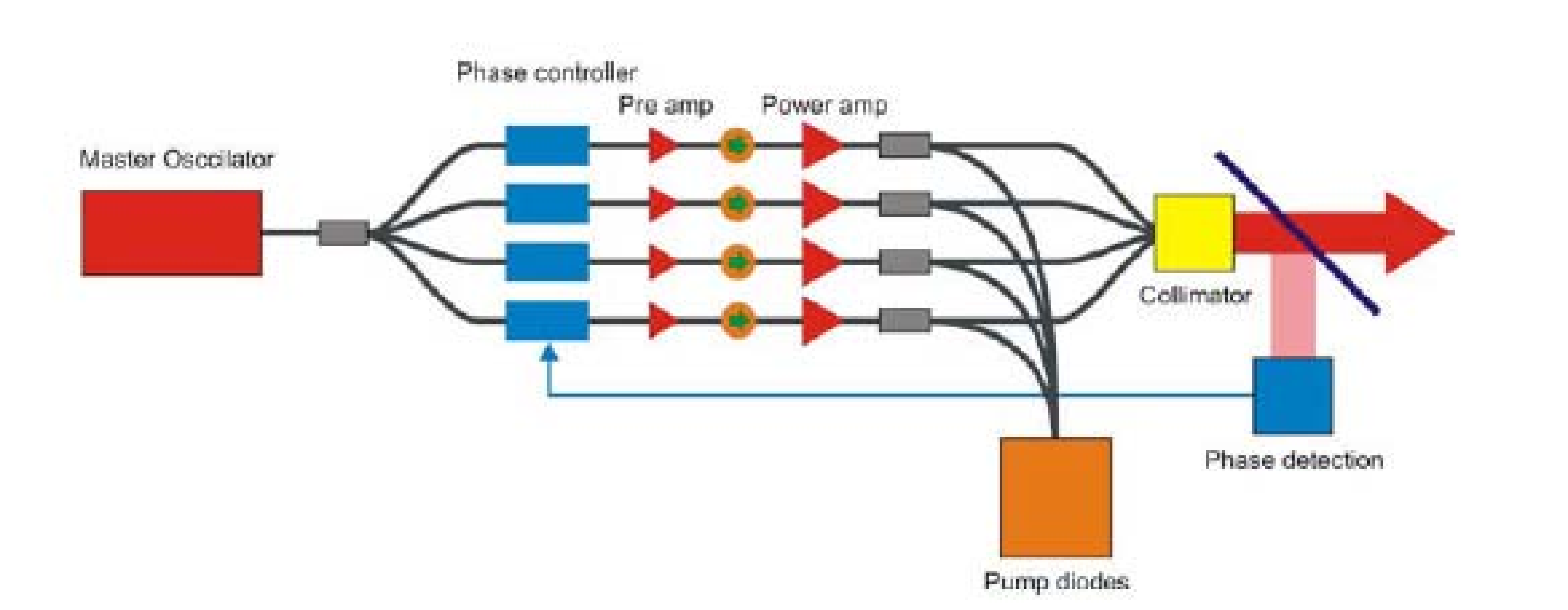
More difficult with bulk lasers, although some concepts (the thin disk laser, the ceramic laser) can also enable great achievements with bulk lasers.

- **1.55 µm laser**, Erbium doped fiber laser, developed eagerly for telecomm application
- Color coupled with Silicon test-mass?
- Smaller gain than Yb (10 dB/mW pumped at 980 nm)
- Best reported today is 48W with Er:Yb Fiber (Nova techno & Army Res Lab),
- Possible to scale up to higher power ?
  - HP Laser Diodes 2kW multimode exists
  - Monomode with HP ?

Where are they today? Development speed? What are their limits ?

Spectral and Coherent beam combining

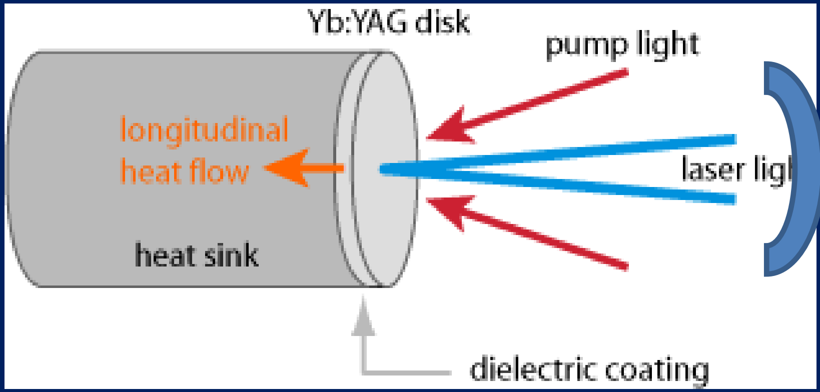
Crystal Fibre, white paper 2006



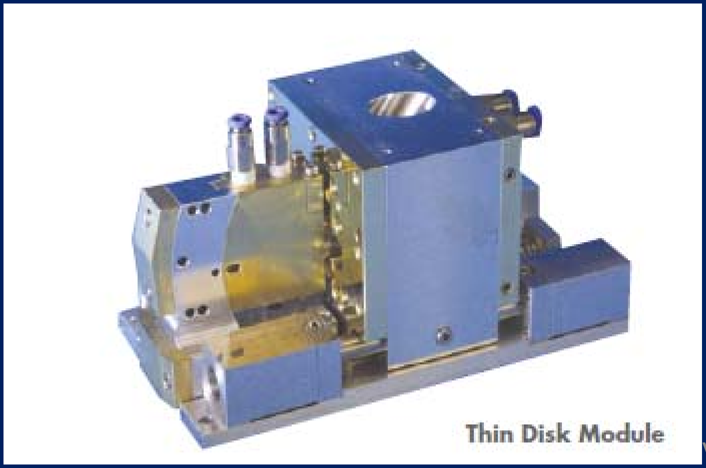
Schematic illustration of one configuration for coherent beam combining. A single-frequency seed laser (master oscillator) is amplified through a phase-controlled amplifier array. The output is a single high-power beam. The coherent nature of this beam allows steering to a much greater extend than multi-wavelength spectrally combined beams.

High Power Disk lasers

- Introduced in 90s by Giesen (U of Stuttgart):
- Laser xtal = thin disk, thickness < laser beam ϕ
- Heat extracted through end face
- Cooled end face is mirror
- Disk thickness 100-200 μm, temp rise small
- Temp gradients perpend to the disk ➔ small thermal lensing, high beam quality
- Power Scalability in adding pump power

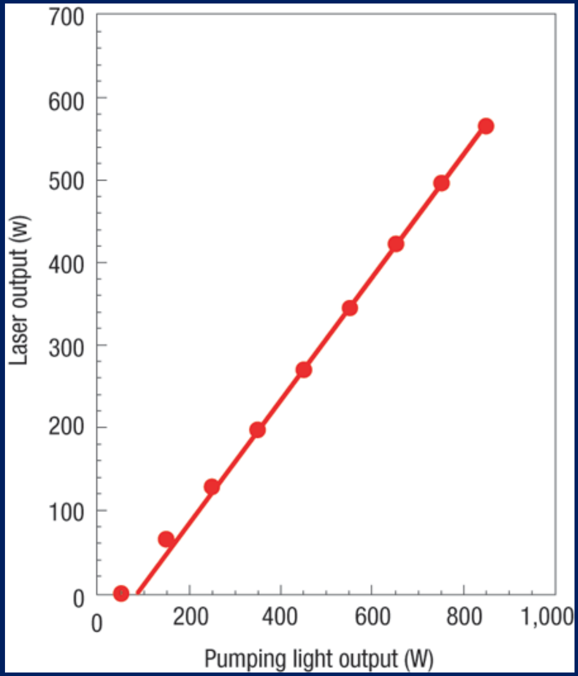


230W, M^2< 1.1



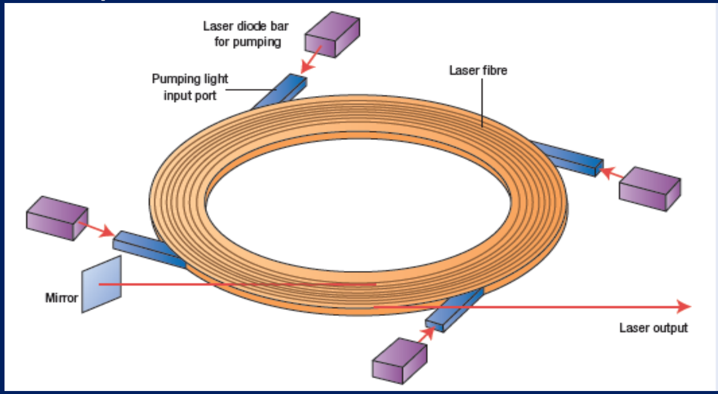
Limitations of gain due to ASE in transverse direction, but composite disk can push ASE limit to kW ?

HP Disk lasers



Boeing 25kWhtml.htm

Yb doped fiber disk



High power lasers: ceramic lasers

Ceramic laser : any size (23 cm long max for xtals, twice this length for ceramic), any shape, high Nd doping, mass production…

Possibility of having Nd:Y2O3 ceramic where thermal conductivity twice of YAG with similar thermal expansion coef.

98 in Japan, development of highly transparent Nd:YAG ceramic: efficiency comparable to single xtal lasers , 1.5 kW cw output (Ueada et al, 2001)

Lasing also at 1.3µm

Direct pumping to laser upper levels to get 1.06 wavelength

Wavefront quality, ? ….

Discussion

Do we try to look ahead for other kind of lasers? Other wavelengths?

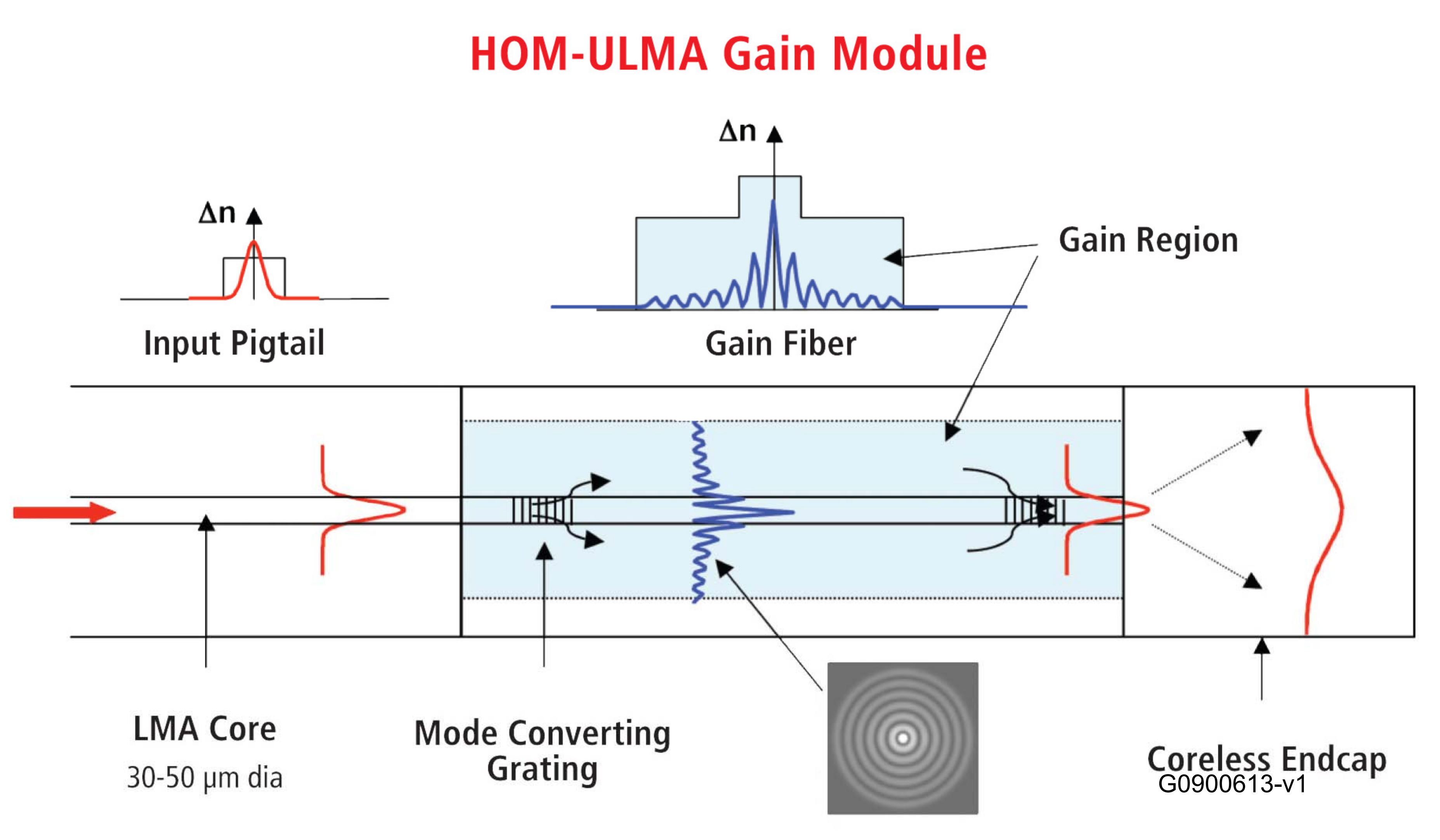
criteria to be fulfilled?

- *fulfill the specs of stability, reliability*
- *good efficiency, high power scaling possibility*
- *easy maintenance/ number of components, soft failure mode*
- *simplicity of implementation*
- *(in)sensitivity to environment …..*
- *transducers for laser controls (pzt, heater, polariser etc…….)*

What kind of limitations?   -Technical?   - fundamental?

distributed gain available from a long length of fiber enables efficient thermal management.

High Order Mode Fiber Laser



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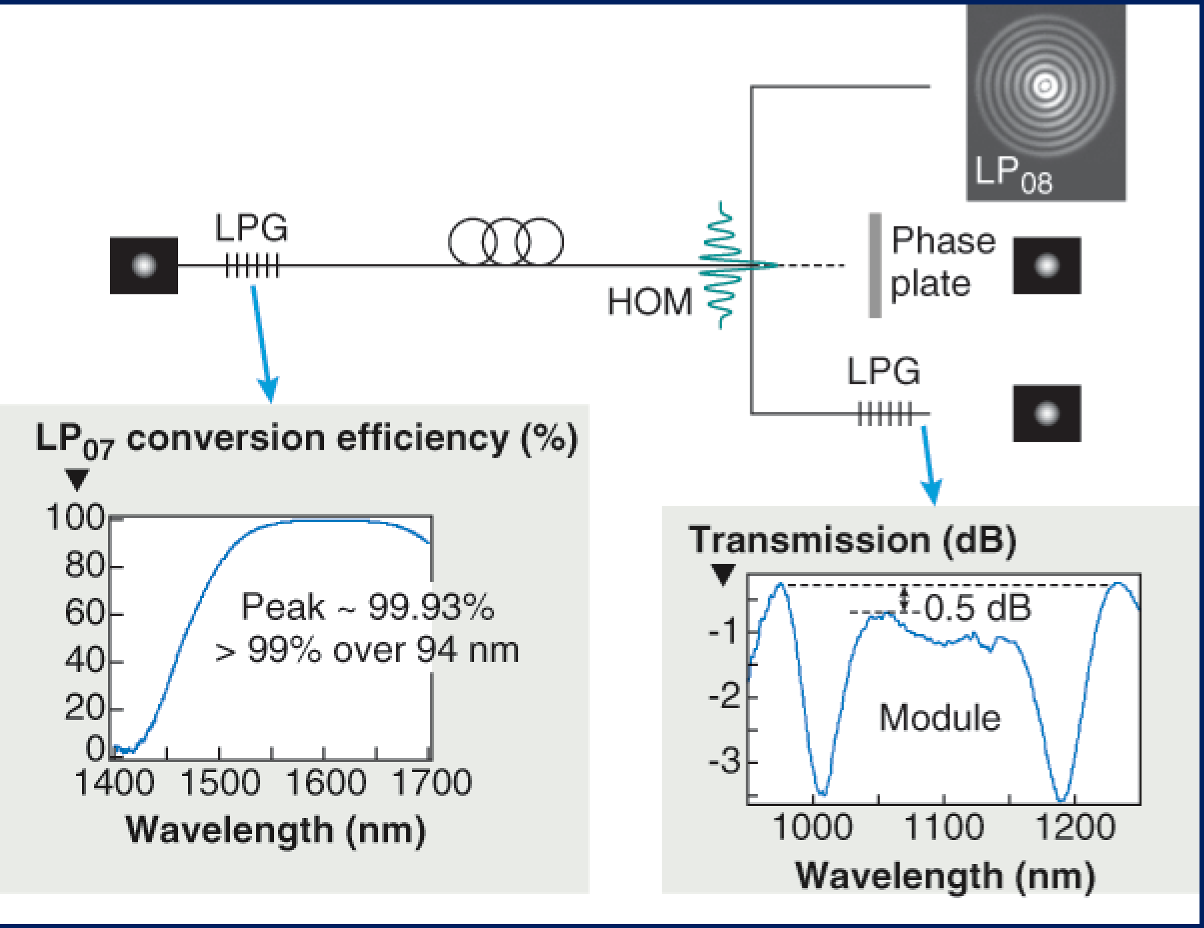
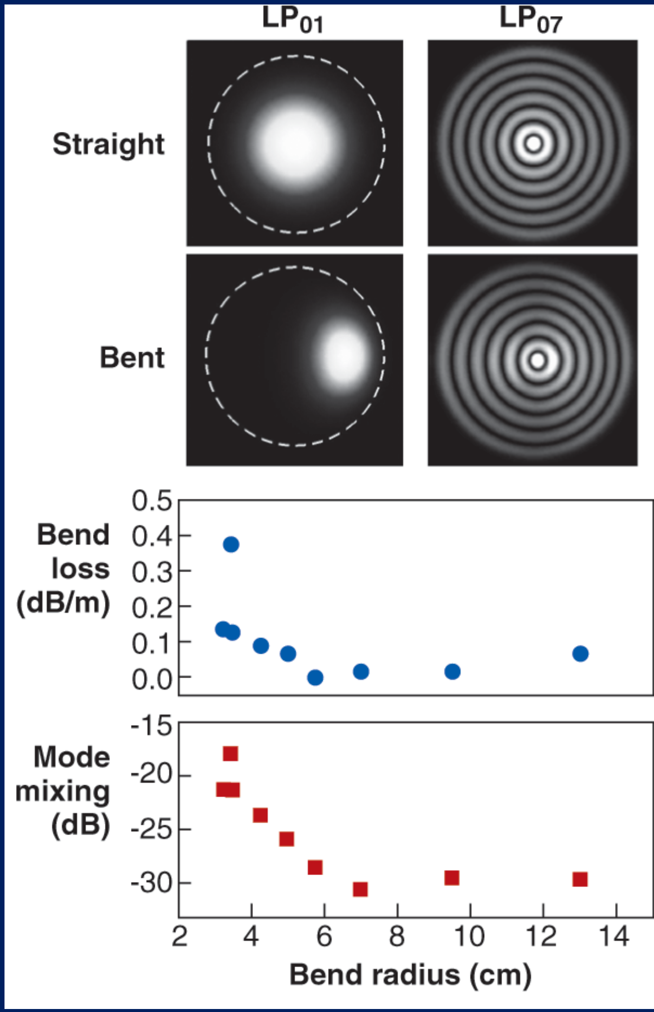
Few Moded Fiber

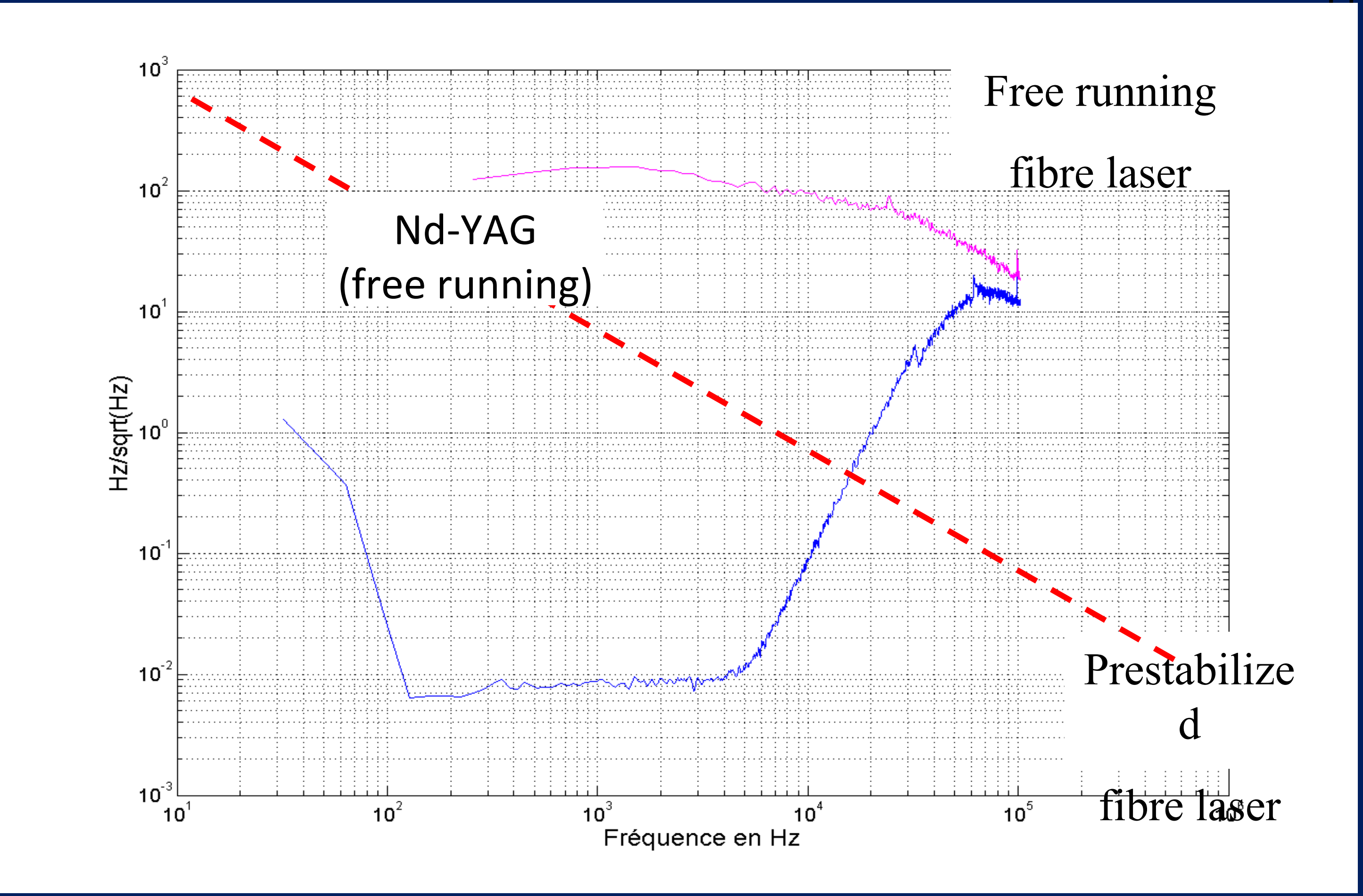




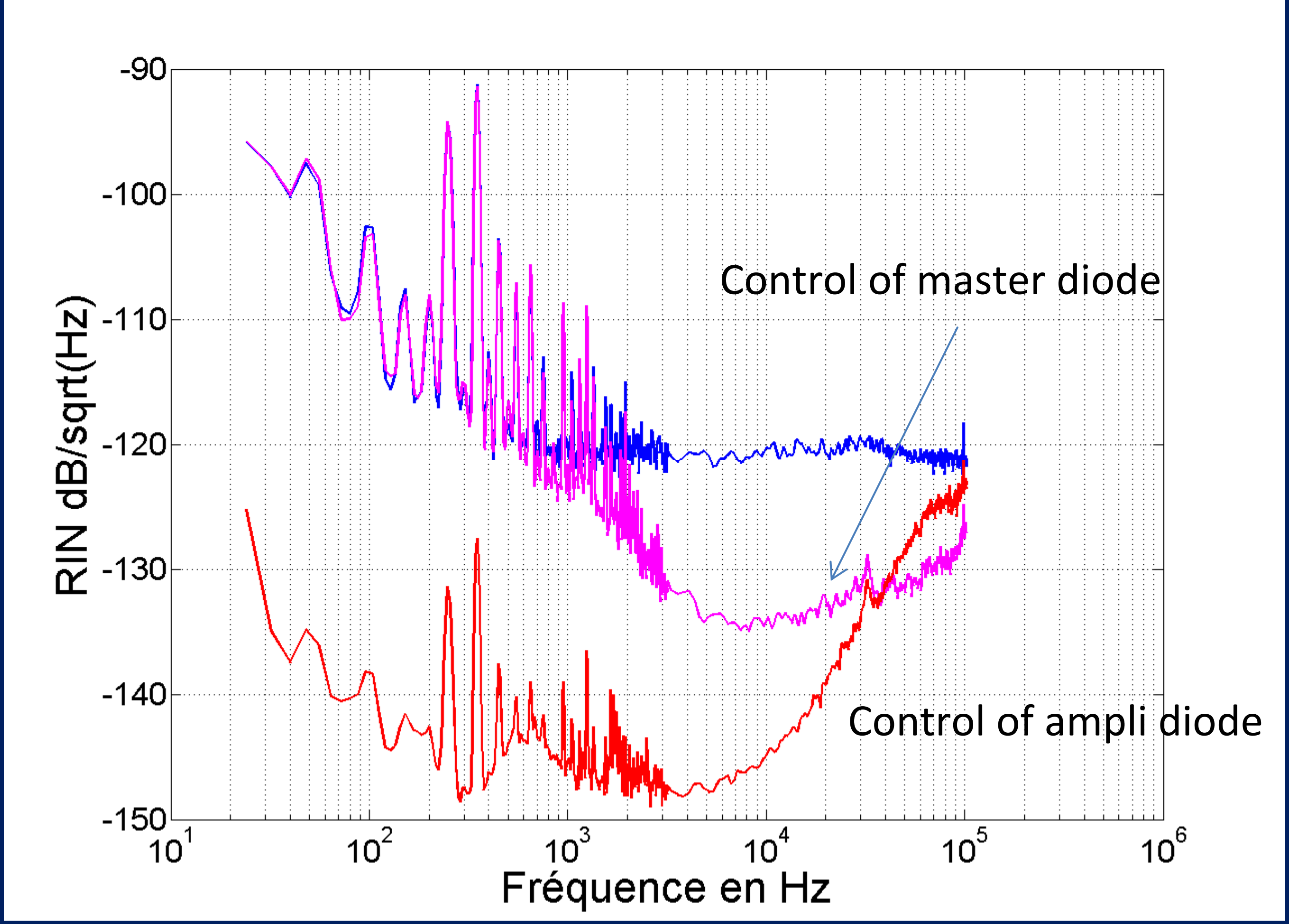
[Other geometries/types]()

Freq stab with Diode D1

Free-running



RIN with D1 + D2 controls



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