BLTS interferometers:
Big, Low-temperature Transparent Silicon Interferometers

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Concept came up here last year.

- **B**ig mass reduces effect of back action,
- **L**ow-temperature reduces thermal noise, often by big factors
- **S**ilicon has received more material development than any optical material.
- Choosing a longer wavelength, ~ **1.55 micron**, makes silicon **T**ransparent, perhaps extremely so.

Use the bench program to explore a few options.

– it tallies the *fundamental* (i.e. predictable) noise sources for a interferometric gravitational wave detector,

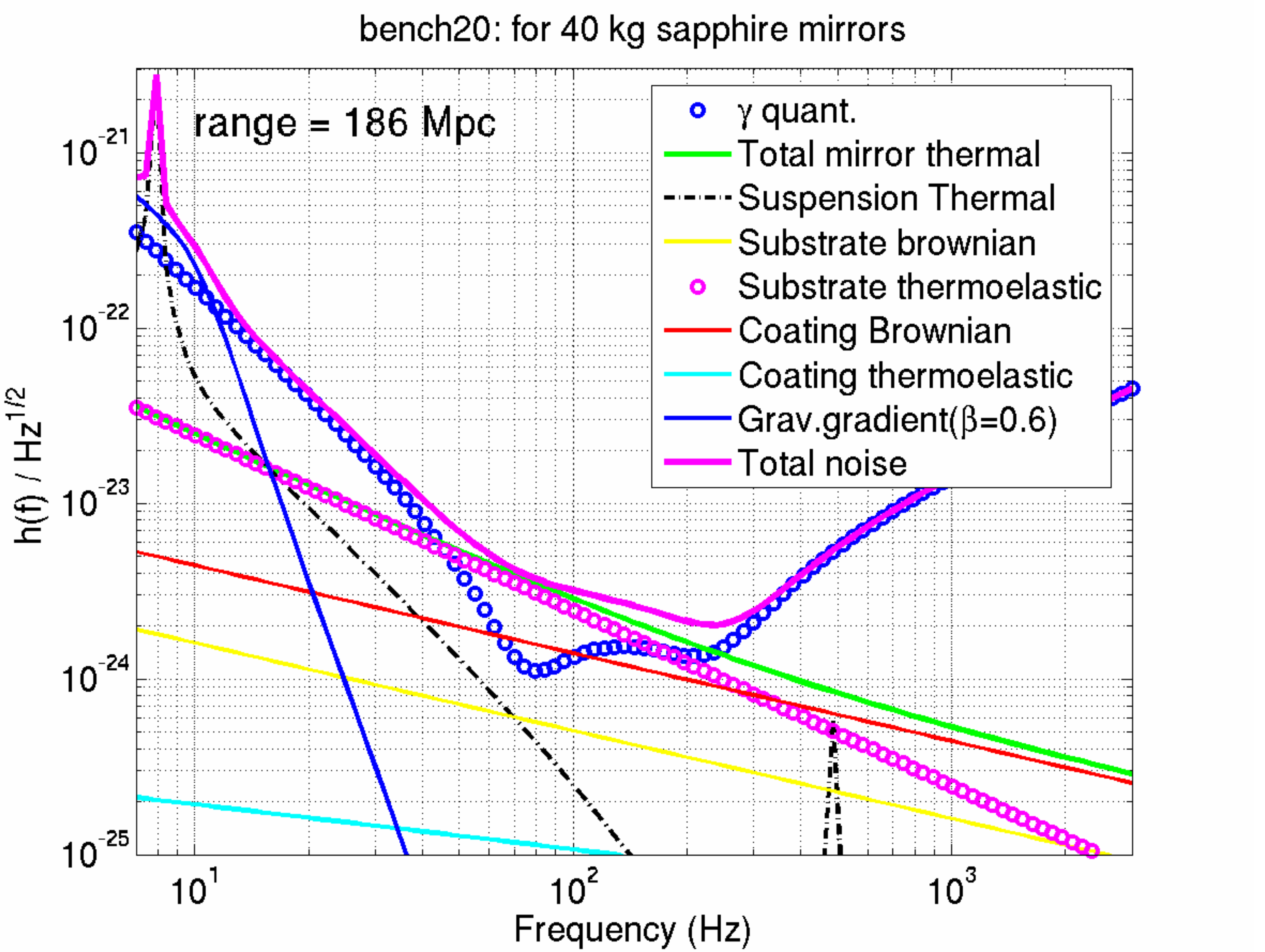
– calculates the (minimum) predictable noise of the detector, in the form of its amplitude spectral density (asd)

– makes use of the known NS-NS ***inspiral*** waveform, (which includes its <u>absolute</u> strain), and

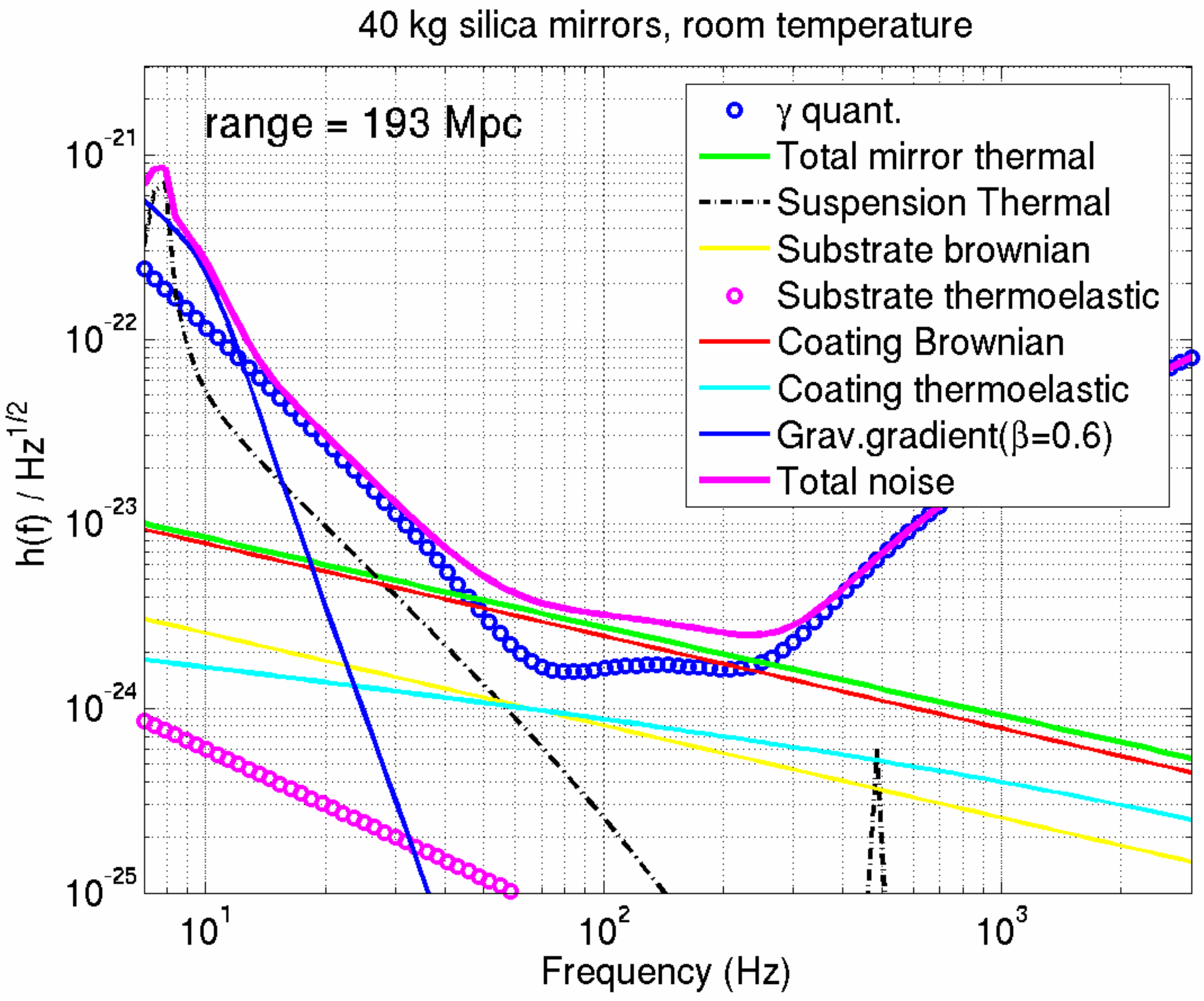
– calculates the farthest distance, or ***range***, at which the inspiral is detectable

Results for one adv Ligo design

Sapphire test masses at room temper-ature



Silica



40 kg silica mirrors, room temperature
range = 193 Mpc
γ quant.
Total mirror thermal
Suspension Thermal
Substrate brownian
Substrate thermoelastic
Coating Brownian
Coating thermoelastic
Grav.gradient(β=0.6)
Total noise
h(f) / Hz^1/2
10^-21
10^-22
10^-23
10^-24
10^-25
10^1
10^2
10^3
Frequency (Hz)

Silicon : **the** most advanced material

- The industrial investment in silicon crystal development is orders of magnitude larger than for any other material
  - Higher purity
  - Much bigger crystals
    - Diameter <= 22 inches **(52 cm**)
    - **Mass <= 300 kilograms**
  - Techniques for near perfect surfaces

LSU

SILICON CRYSTALS INC.

Products

E.g., the diameter and polish claimed by one company

Optical Industry . . .

Infrared Transmitting

- Windows
- Lens
- Prism

Mirrors

- High Power: Weapons and Welders
- Low Power: Instruments

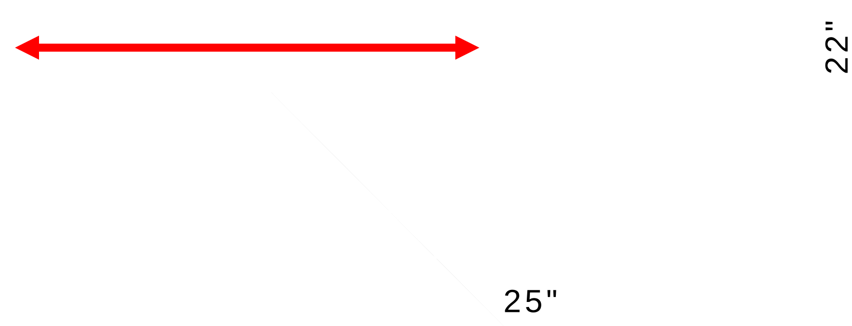
Ultra-high purity single or semi-single [polycrystalline] silicon blanks, up to 22" diameter in single crystal form and 24" diameter in semi-single crystal form, reflecting or transmitting grade.

These blanks are capable of being polished into mirrors with surface finishes free of work damage and having an extremely high resistance to high power pulses. When polished with the "semiconductor" silica sol process, it is possible to achieve RMS of less than 3 angstroms combined with extremely low BRDF and BTDF scattering figures.

Composite mass is possible

- Several techniques could be used to “weld” together ~300 kg silicon crystals for bigger mass
  - Metal film deposition, then vacuum furnace fusion
  - Stanford “silica bonding” technique
- One possible configuration:

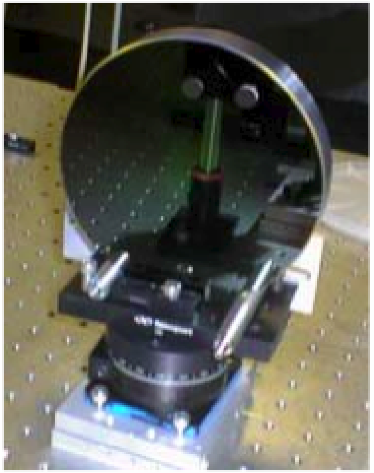
a disk bonded to annuli



Rowan and collaborators have emphasized possibilities of silicon

- **Thermal noise** from test masses and suspensions important below few 100 Hz
- **Silicon** has various desirable material properties (optical and thermal noise)
-
  - High thermal conductivity, κ
  - Available in large pieces (~100kg)
  - Can be polished and coated to form high quality dielectric mirrors
  - Measurements suggest intrinsic mechanical loss (and **thermo-elastic loss***) comparable to sapphire at room temperature
  - Can be silicate bonded to silica (and by extension to itself)

Coated silicon mirror



- At room temperature, thermo-elastically driven displacement noise forms hard limit to detector sensitivity
- **By cooling test masses, expect significant gains in thermal/thermo-elastic noise performance**

* **Braginsky et al**

Gone at Low-temp: substrate thermoelastic noise, and thermal deformation

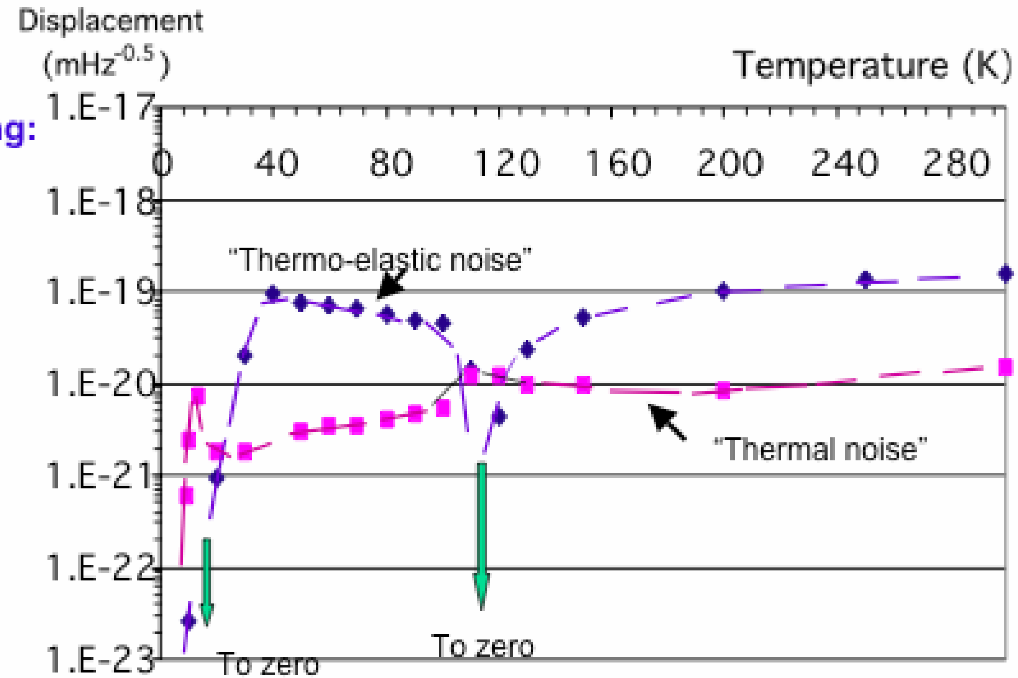
– Silicon: unique material properties on **cooling:**
  - Intrinsic mechanical loss decreases
  - Two zero's in coefficient thermal expansion, α, at ~130K and ~20K

Dual benefits:

– thermal deformation proportional to α/κ

– thermo-elastic noise proportional to α

– **both should vanish as α tends to zero**



"Thermo-elastic" displacement noise and "thermal" noise in a silicon test mass as a function of temperature

– **silicon substrates opens avenues for significant thermal noise improvements at low temperatures but material properties need further study**

Previous proposals for silicon have assumed it is opaque

- Crucial ideas from Stan Whitcomb
  - ‘Silicon is nominally transparent above the band edge, ($\lambda > 1.2$ microns), so regular (transmissive) optics can be used’, just like LIGO
  - ‘There exist high power laser systems, at ~1.5 microns’, under development for “telecom” use.
  - ‘There are reasonably efficient photodiodes at this wavelength.’

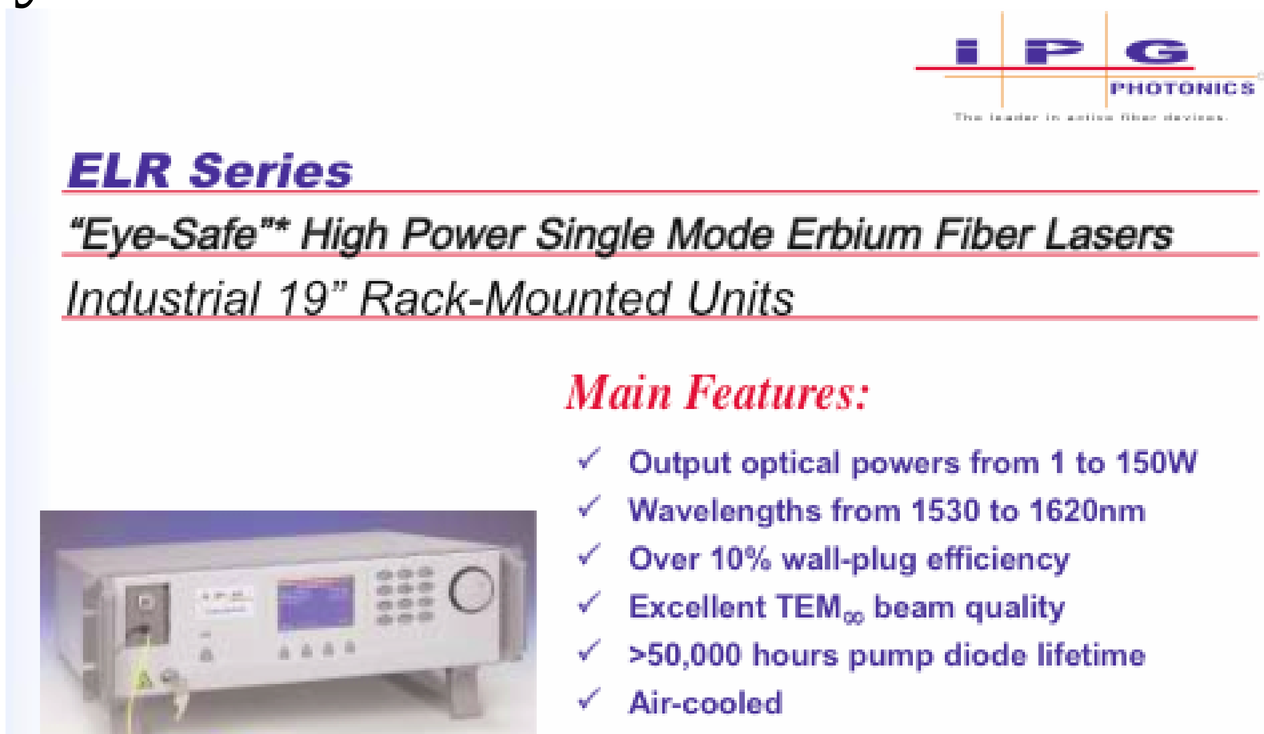
Silicon transparency at 1.5 microns

- There has been preliminary measurements, <u>verbally communicated</u>, of < 5ppm/cm, much better than sapphire.

- But it remains to be seen whether such results can be replicated, and whether required conditions on purity, temperature, power density, etc are practical for large crystals.

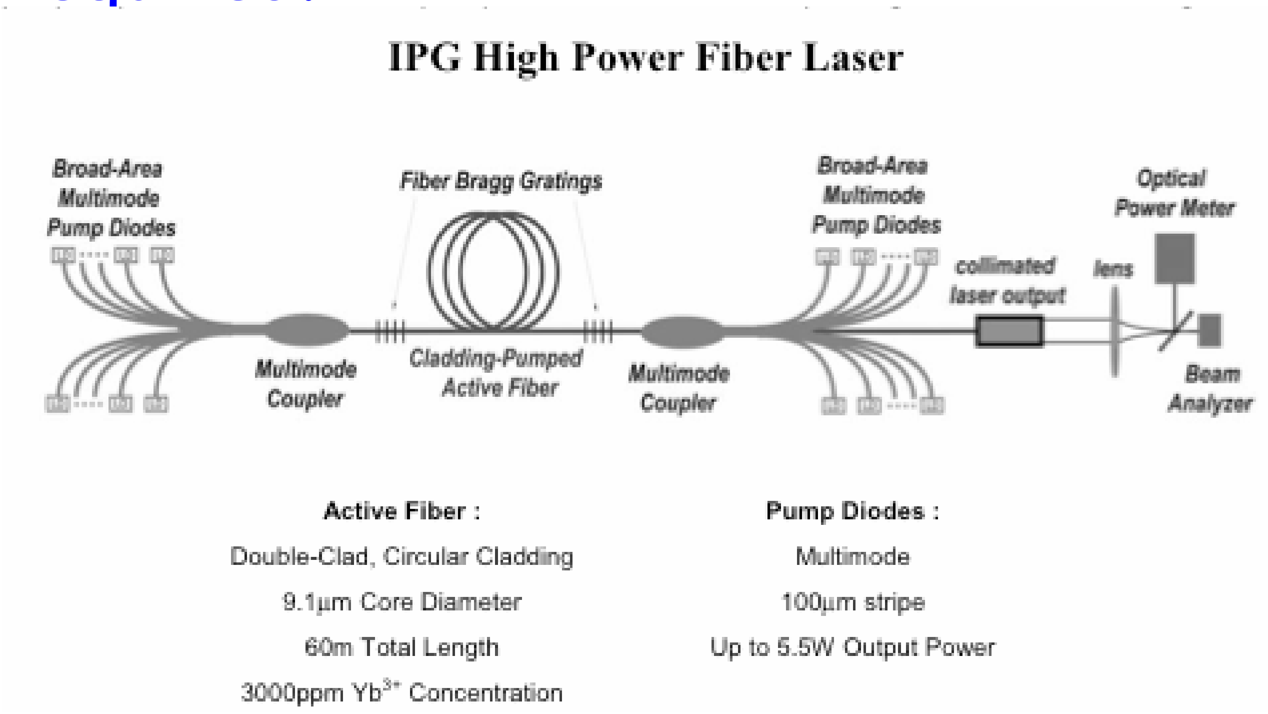
High power lasers -1

- For example, IPG Photonics has <u>erbium fiber laser</u> with power =100 Watts at 1.55 microns.
- Power likely to increase.



High power lasers -2

- BUT, it remain to be seen if this type of laser can be made with the high amplitude and frequency stability required.



Photodiodes -1

366 IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 14, NO. 3, MARCH 2002

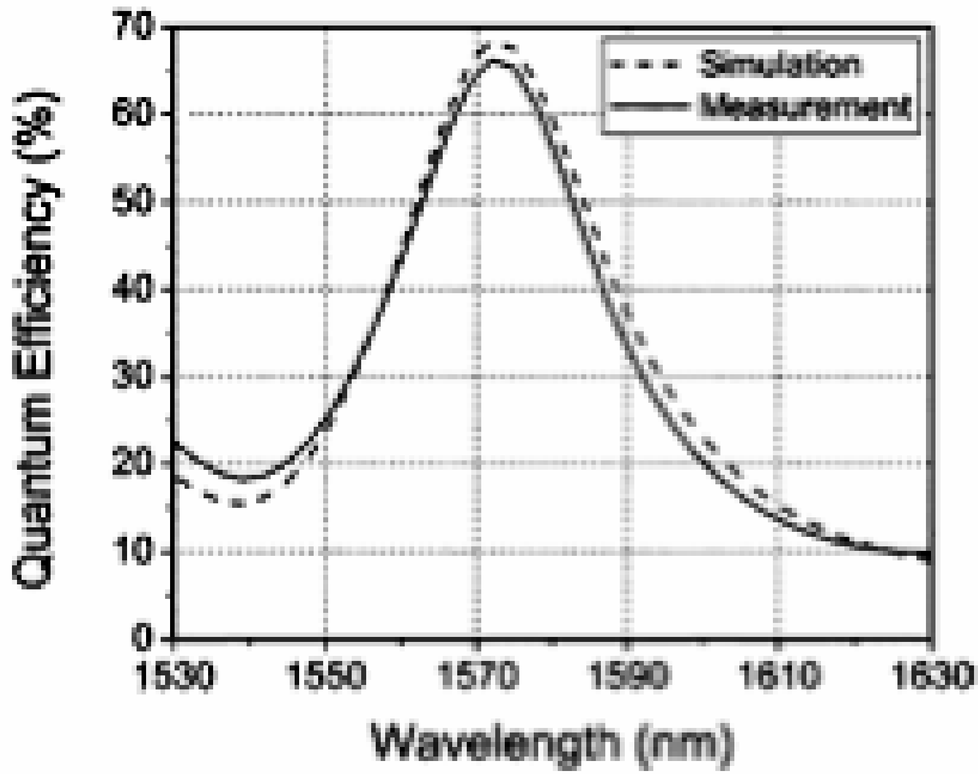
InGaAs-Based High-Performance p-i-n Photodiodes

Ibrahim Kimukin, *Student Member, IEEE*, Necmi Biyikli, *Student Member, IEEE*,
Bayram Butun, *Student Member, IEEE*, Orhan Aytur, *Member, IEEE*, Selim M. Ünlü, *Senior Member, IEEE*, and
Ekmel Ozbay, *Member, IEEE*

Photodiodes- 2

- BUT, it remains to be seen if such diodes can handle the required optical power.

(a)



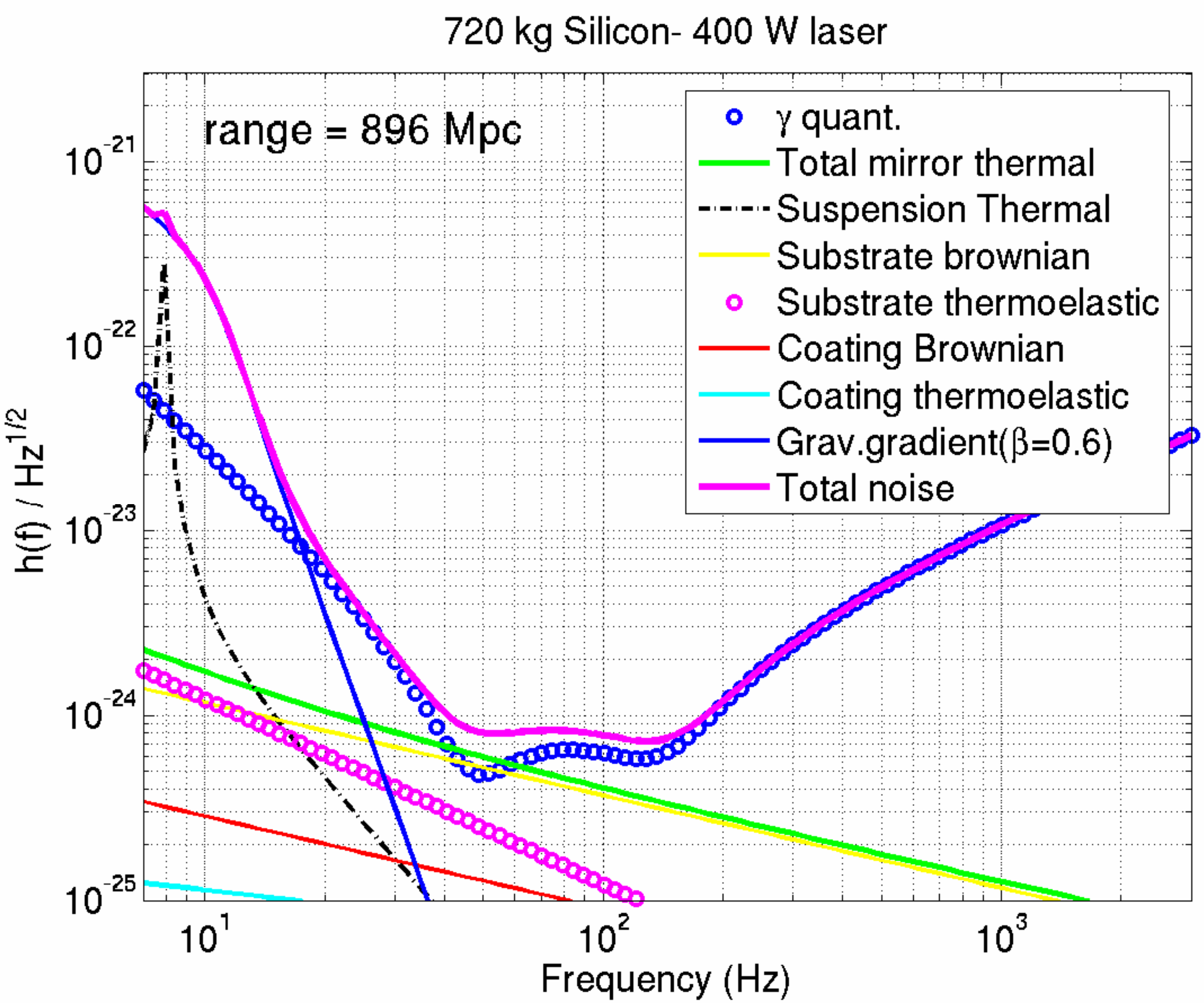
(b)

Fig. 1. (a) Spectral quantum efficiency measurements of the fabricated detectors after consecutive recess etches. (b) The theoretical calculation and experimental quantum efficiency measurement of a detector whose resonance had been tuned to 1572 nm.

Possible BLTS

- Increase mass to ~700 kilograms
- Increase power to ~ 400 Watts
- Assume that coating losses become smaller, (a miracle happens)
  - either because of new materials for the coatings, or
  - because of low temperature.

‘optimistic’ result



‘Optimistic’ result

- *Range* increases by factor of 896/186 ~ **5**
- Volume of space sampled increases by ~**100**

Cryogenics is our friend

- Some good things
  - Makes high vacuum much easier
  - Freezes out many types (?) non-gaussian mechanical noise.
    - No creep
  - Can use superconductors for some electrical parts.
  - Much more efficient eddy current damping. (conductivity of copper is 100 times higher)
  - Extremely low drift in springs
    - dk/dT -> 0 at low temp
    - ΔT is much smaller

There are some issues

- Takes special design to make thermal cycle times small. (Neon exchange gas and cold remote-operation beam port).
- Will require careful ballasting to compensate for thermal stiffening of springs.
- Will want to make a compact, actively isolated superattenuator. (I have a concept: “add” an inverted and a regular coupled pendulum to get a VLF horizontal Isolation. Use combine torsion lever with anti-spring for vertical isolation.)

Issues -2

- Will want to use single-crystal-silicon flexures as heat links to silicon mirror. (How much heat flux can and should be accommodated?)
- I know almost nothing about optical coatings on silicon. May be hard to find good ones, OR it may be much easier. (This is an oppurtunity to explore a whole new set of possible coatings.)