Piezo-tuned nonplanar ring oscillator with GHz range and 100 kHz bandwidth

Tom Kane Tom.Kane@ieee.org www.KaneOE.com

Kenji Numata and Anthony Yu, NASA Goddard Space Flight Center

Julia Majors and David R. Demmer, AVO Photonics

KANE OE

Avo Photonics

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The “Nonplanar Ring Oscillator” (NPRO)

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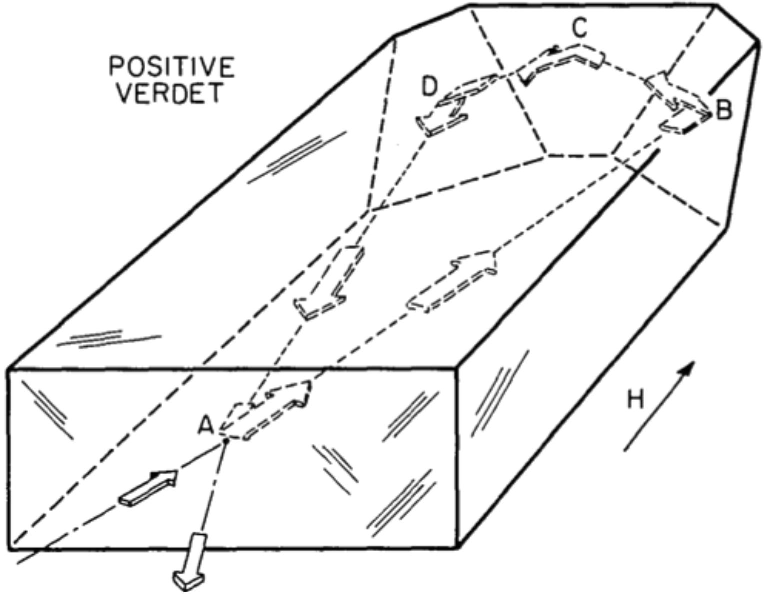
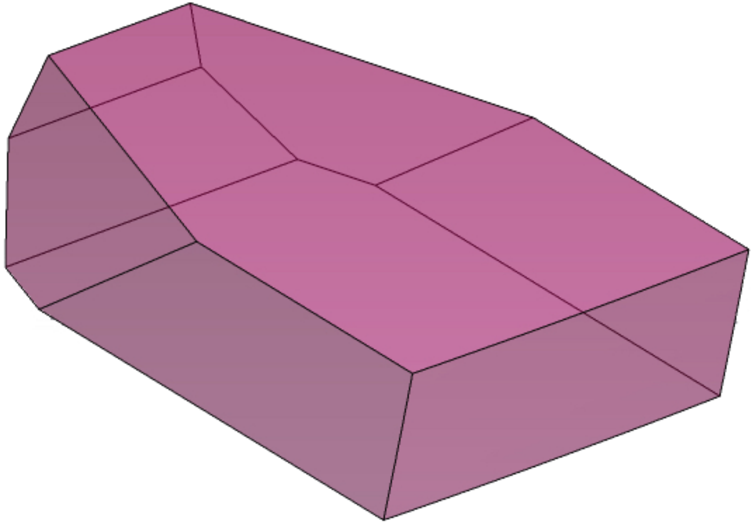
Monolithic, unidirectional single-mode Nd:YAG ring laser

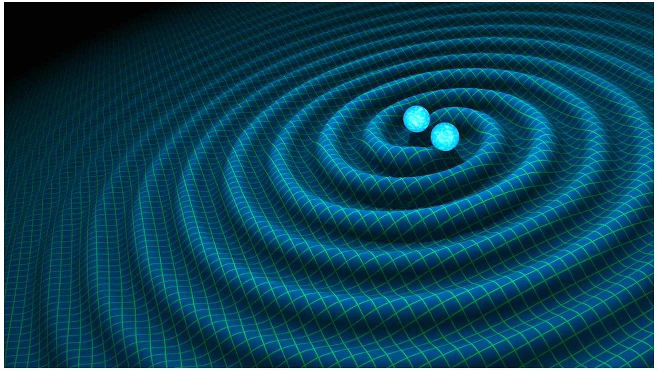
Thomas J. Kane and Robert L. Byer

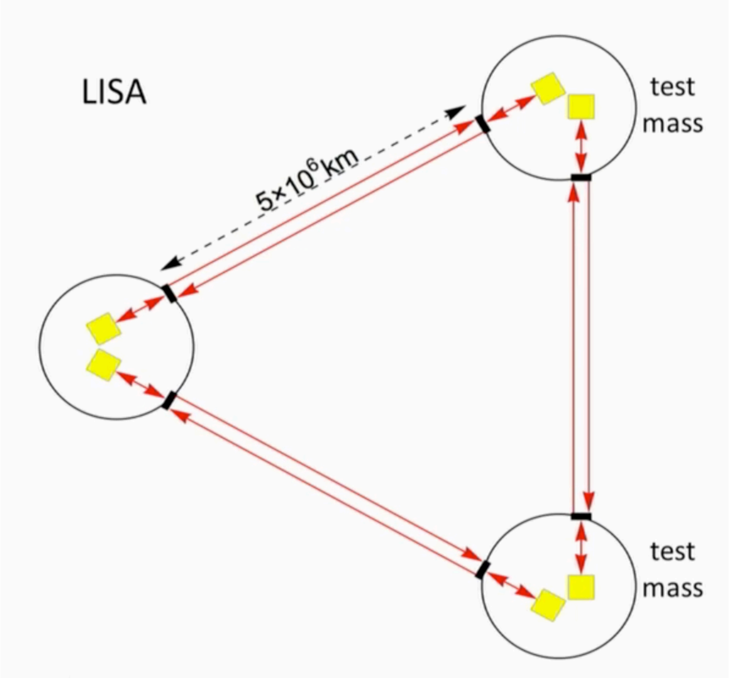
Ginzton Laboratoory, Stanford University, Stanford, California 94305





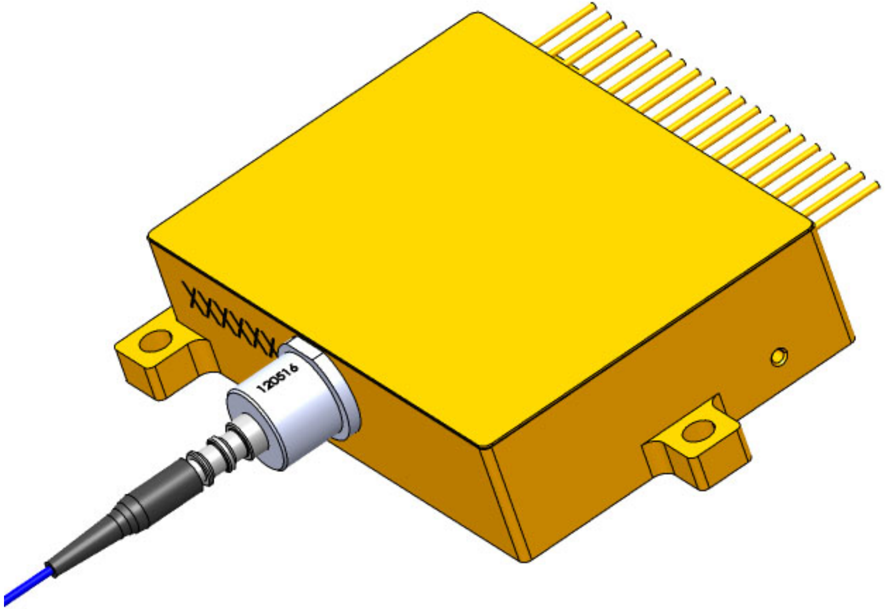
Gravitational Wave Detection





NASA Goddard / AVO / Kane collaboration

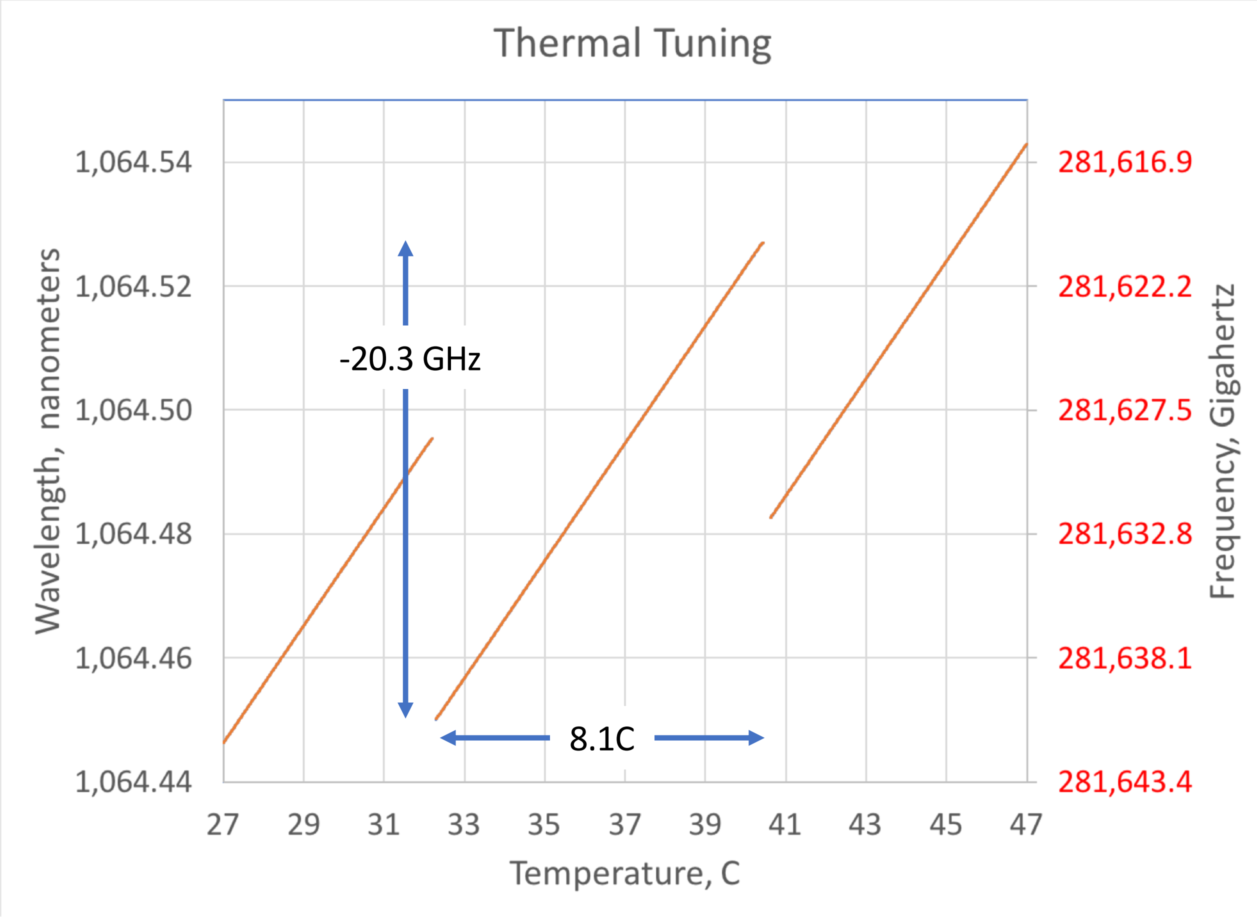
- "μNPRO"
- Welded PM single-mode fiber coupling
- Dual polarization-combined pump lasers
- 700 mW @ 1064 nm
  - 10X what LISA needs to saturate YDFA Stage 1



58 x 41 x 14 mm

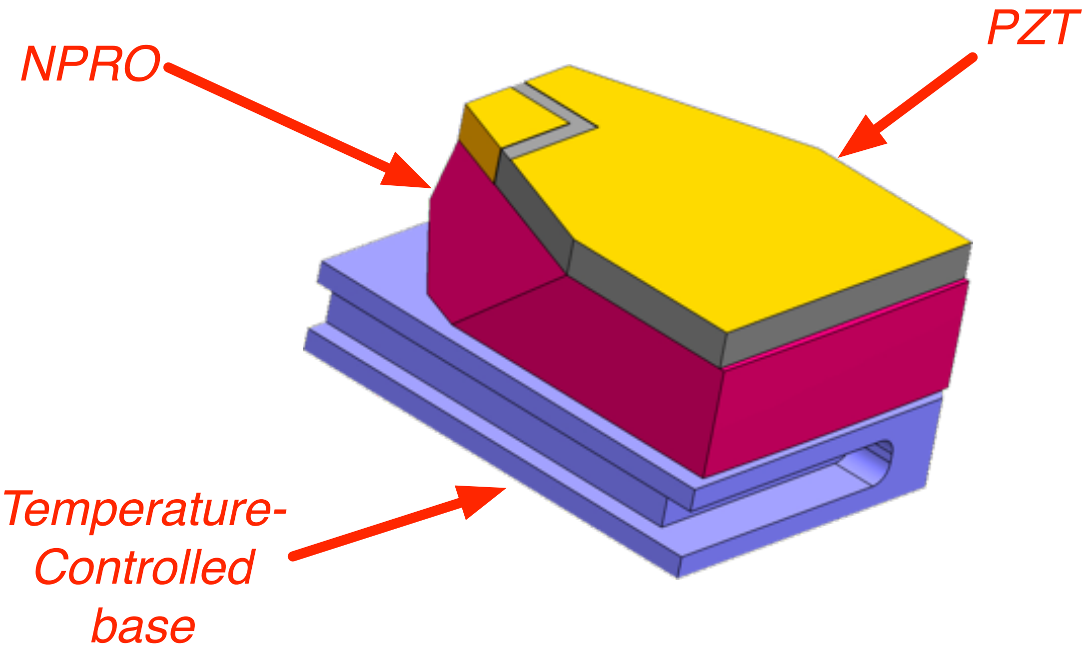
NPROs are Tunable – Thermal: Slow, Wide Range

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\text{optical path length}}{\text{optical path length}} \approx \frac{-\Delta f}{f}$$



Strain tuning – fast, narrower range

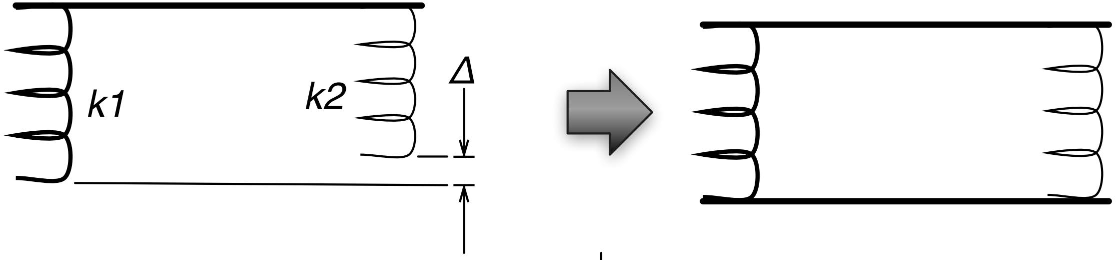
- "Prior art" response:
  - 1 MHz/Volt
- ESA Requirement for LISA
  - ±100 MHz
- NASA Goal
  - ±12 volt drive
  - >8.33 MHz/volt

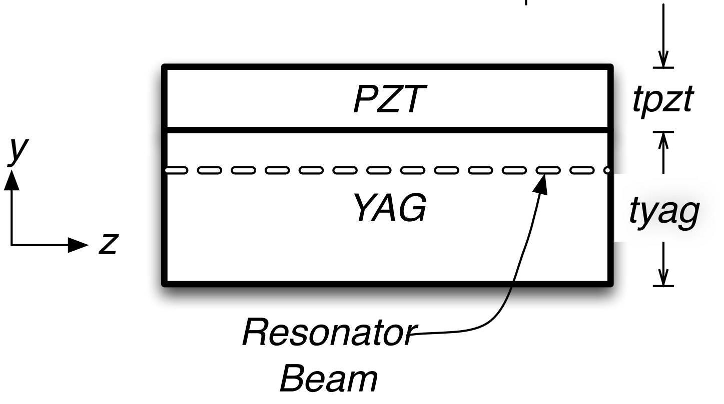


Demonstrated: 18.2 MHz/Volt

- Design changes:
  - Make the NPRO small. With proportions maintained, the MHz/volt coefficient scales inversely with linear dimension
  - Maximize the product of the Young's Modulus *Y* and the charge constant d_{31} of the PZT material
  - Make the internal beam as near as possible to the PZT
  - Make the PZT is thin as practical

Simple-minded Calculation: Uniform Strain



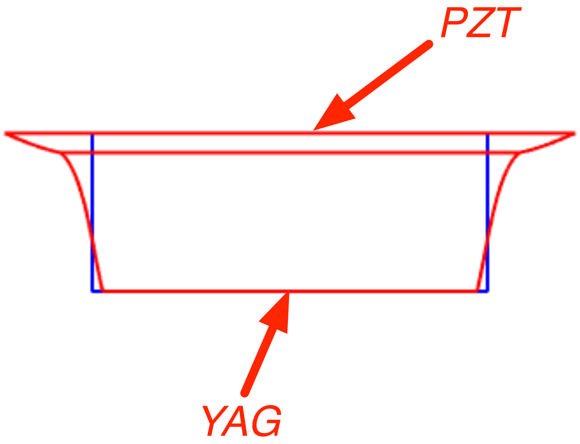


Simple 2-spring “lumped element” model

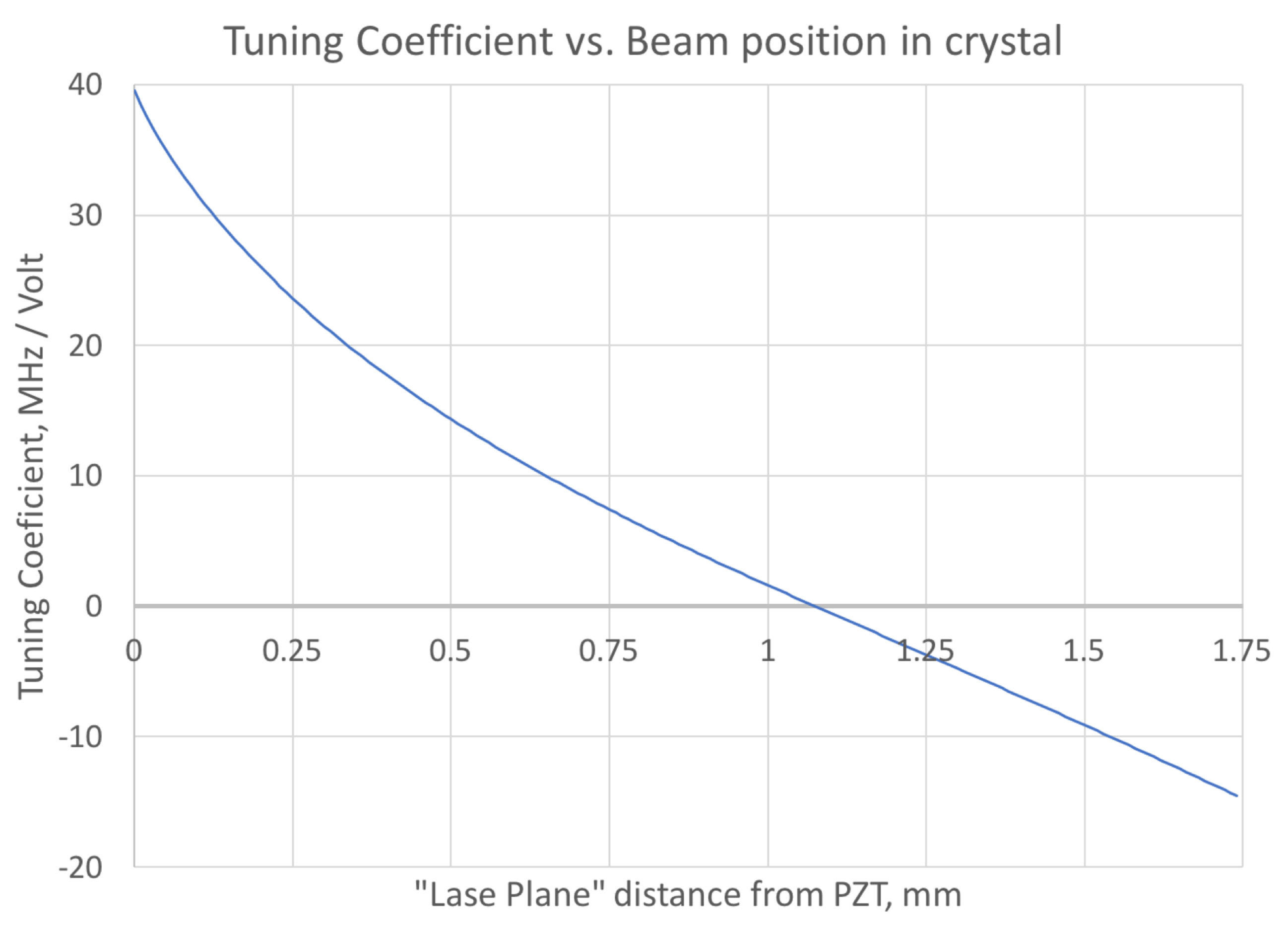
$$\text{Tuning coefficient} = \frac{f\, Y_{PZT}\, d_{31}}{(Y_{YAG} t_{YAG} + Y_{PZT} t_{PZT})}$$

- 3 predictions
  - Figure of Merit for PZT
    - $Y\, d_{31}$
  - Inverse Linear scaling
  - Thin PZT beneficial, to a point
- For µNPRO parameters
  - 14.3 MHz/volt
- *This neglects the elasto-optic effect*

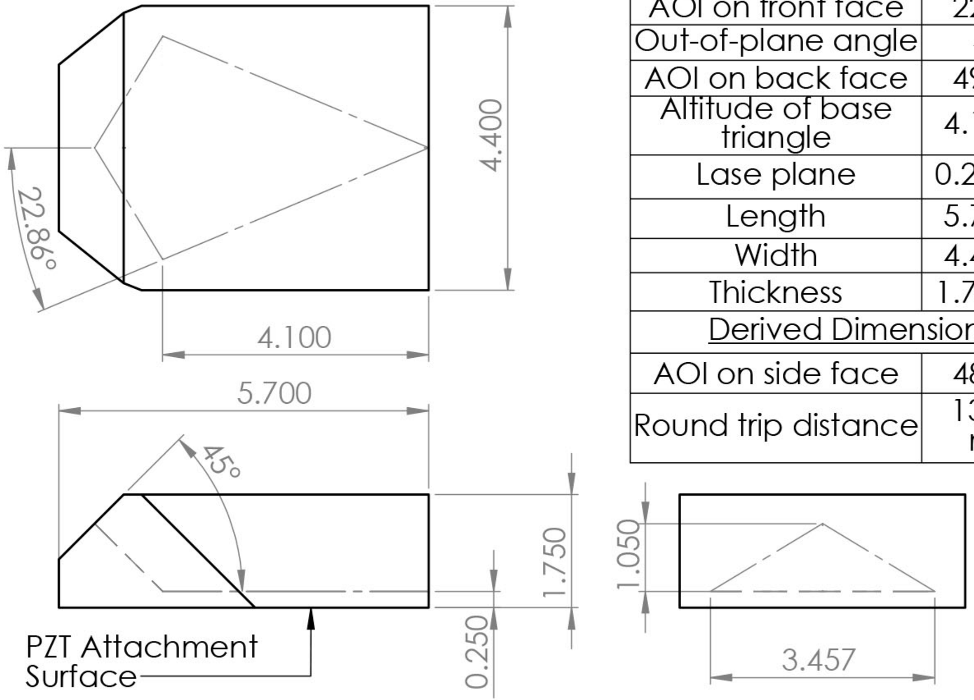
Effect of non-uniform strain



2-dimensional numerical solution



µNPRO Fabrication

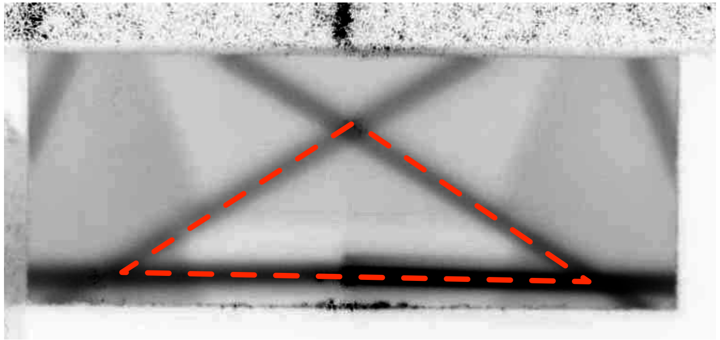


Controlling Dimensions	
AOI on front face	22.86°
Out-of-plane angle	45°
AOI on back face	49.34°
Altitude of base triangle	4.1 mm
Lase plane	0.25 mm
Length	5.7 mm
Width	4.4 mm
Thickness	1.75 mm
Derived Dimensions	
AOI on side face	48.73°
Round trip distance	13.456 mm

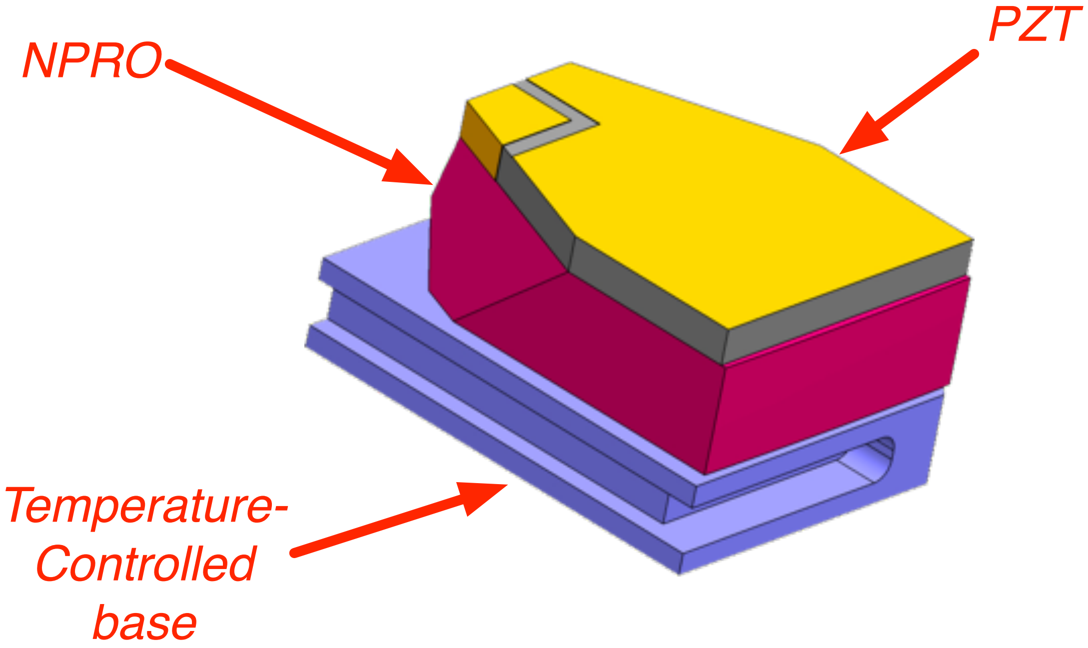
Control of beam position demonstrated

µNPRO Fab	# tested	Average (0.25 mm by design)	Standard Deviation
#1	7	0.26 mm	0.02 mm
#2	62	0.20 mm	0.06 mm
#3	4	0.24 mm	0.03 mm

View looking into front face of µNPRO while lasing, negative image



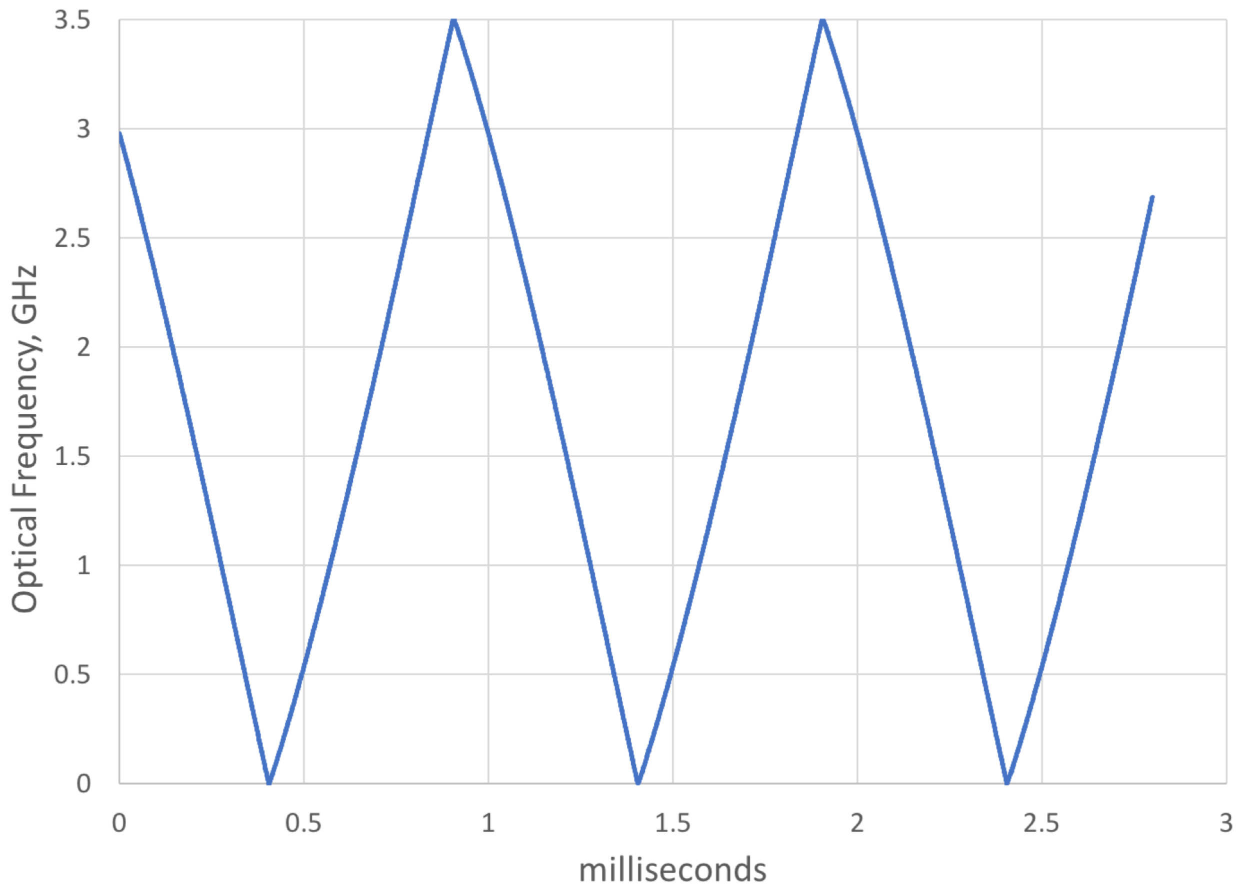
PZT Material



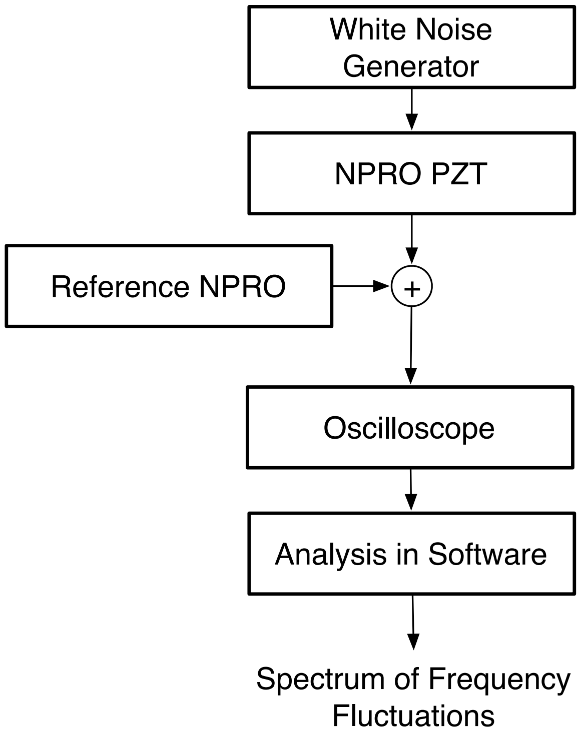
- 3265HD available from CTS Corporation
  - Y^{E}_{11} = 69 Gpa
  - d_{31} = -370 pm/volt
- 0.25 mm thick
- Max safe voltage ±125 volts

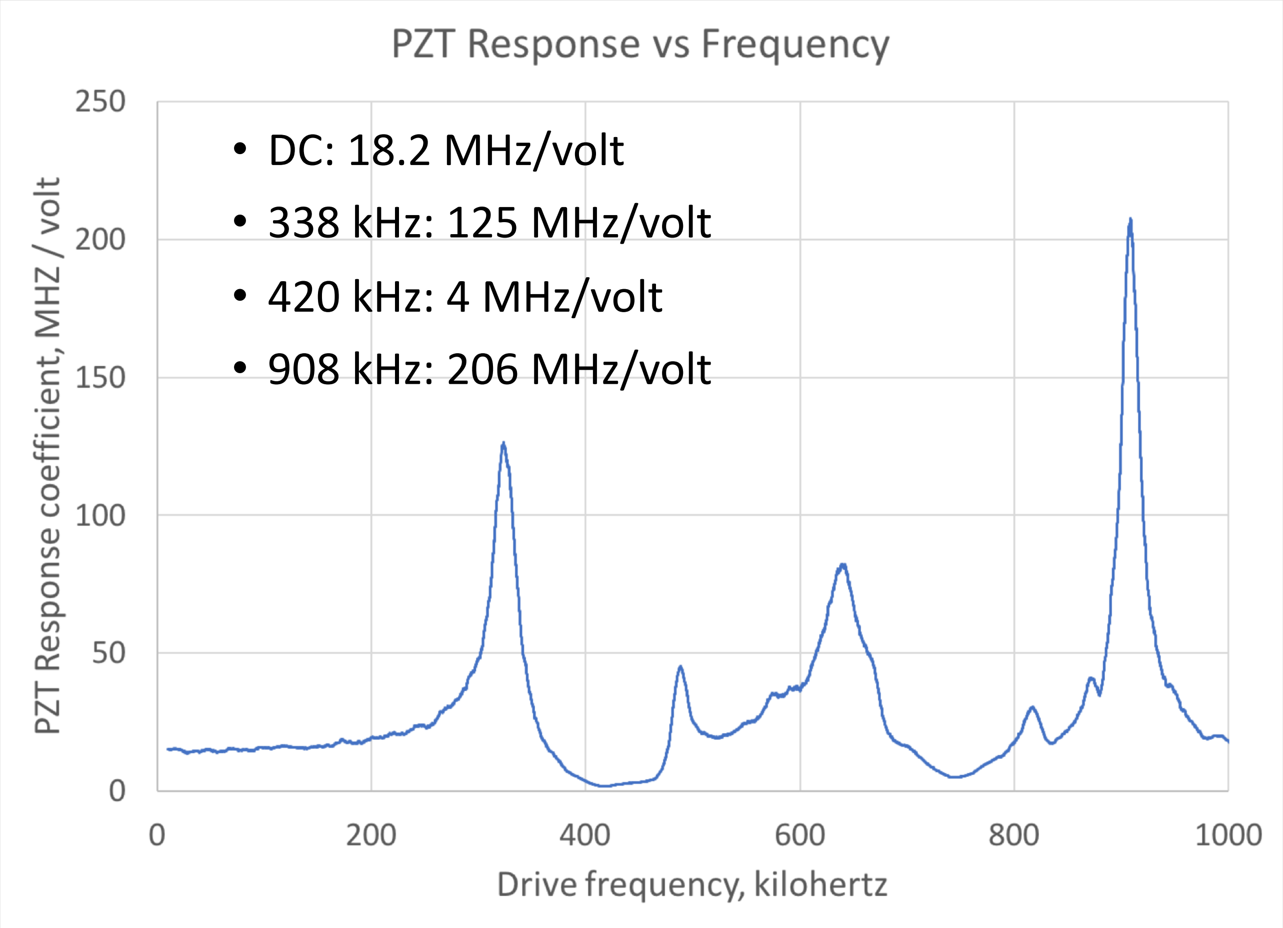
Performance driven by 192 volts, peak-peak

- 1 kHz triangle
  - ±96 volts
- 3.5 GHz peak-peak
- 18.2 MHz/volt
- Beat-note measurement

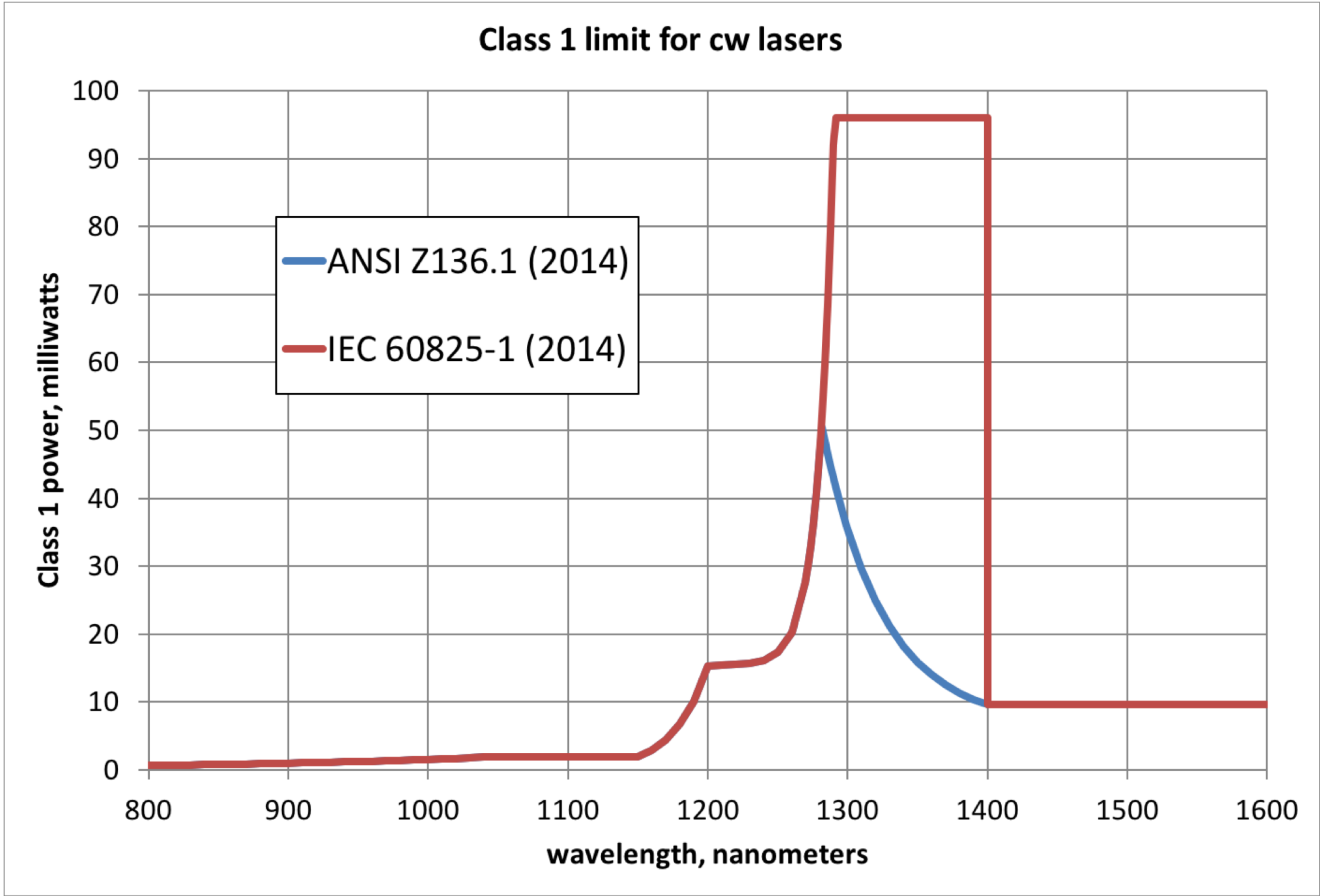


Bandwidth of response limited by resonances



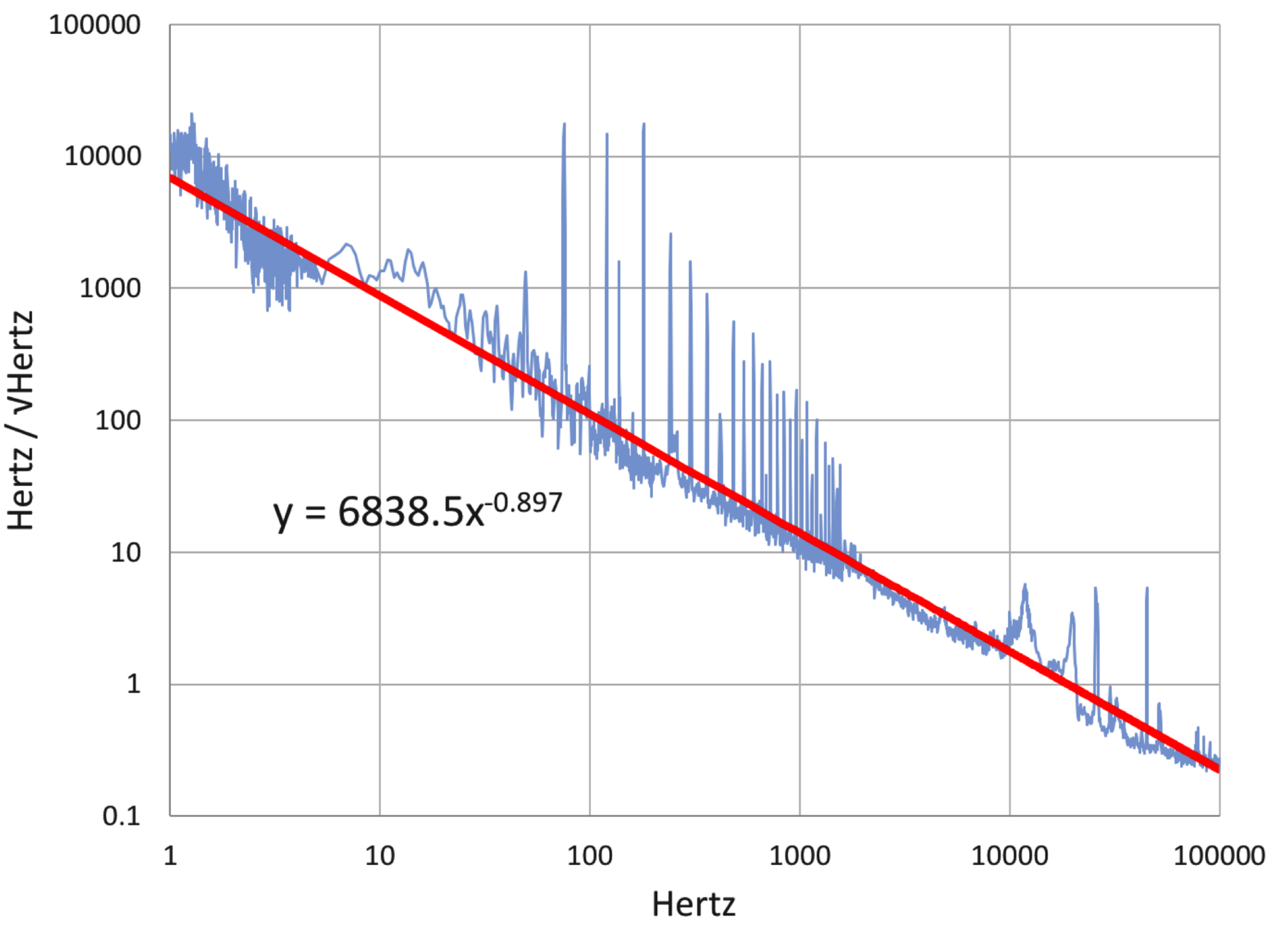


FMCW LIDAR? 1319 nm best λ for eye-safety



Unsurpassed low phase noise of NPRO

- NASA tested competing designs, NPRO best for LISA
- Sub-kHz linewidth
- 1/f spectrum



Conclusion

- High Power (~watt)
- Narrow linewidth (kHz)
- Broad and fast tunability
  - GHz per µsec
- Two standard wavelengths
  - 1064 nm – can amplify to 100 watts
  - 1319 nm – best eye-safety
- With proper tooling, fab cost is dominated by Nd:YAG raw material
- Further progress is possible – please challenge me!

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