Argon and Nd:YAG Lasers: Comparative information

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Title

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Objective

to give background information which can aid in the choice between Argon Ion and solid-state lasers (example: Nd:YAG)

point of departure:

- alternative lasers will be needed for later LIGO interferometers
- one alternative, Nd:YAG is (close to) ready
- it is not too early to make a plan for integration of Nd:YAG

branch points to be addressed:

- Nd:YAG for initial LIGO interferometers or later
- at 1.06 μm, or at the doubled frequency of 532 nm

structure of the discussion:

- characteristics of Nd:YAG and (for reference) Argon lasers
- Impact on the optics
- Impact on length sensing system
- possible paths for LIGO

Characteristics of the basic laser

Configuration

- Argon: rebuilt commercial unit; single, or possible addition
- Nd:YAG
  - › laser diodes for pumping (preferable to discharge lamps)
  - › monolithic ring master laser
  - › ~100 mW, intrinsically quiet
  - › slab slave laser, ring configuration, injection locked
  - › slave follows frequency, amplitude noise of master laser
  - › at normal wavelength (1064 nm) or doubled (532 nm)

Efficiency

  - › electrical power in to luminous power out
- Argon: 10^{-4}
  - › about 55 kW/laser, another 55kW for cooling
  - › initial LIGO requires about 4 lasers, or 440 kW
  - › if run 2 full time, about 100k$/year (.06 $/kW-hr)
- Nd:YAG 1.06: 10^{-2} to 10^{-1}; typ 1/2 this for 532 nm
  - › say 10 W laser, 1 kW for heating and cooling
  - › initial LIGO requires 4 kW
  - › advanced LIGO would require maybe 40 kW

Characteristics of the basic laser

Reliability

- Argon
    - › shakedowns/initial design (multi-mode problems)
    - › incorrect installations (magnet/tube incompatibility)
    - › normal tube lifetime
    - › power supply breakdowns
    - › chiller problems
    - › slow service
    - › net: about 1 of 6 down, 6 months; maybe 2000 hrs
- YAG
    - › 1.06: 7 W Lightwave, 10,000 hrs MTBF
    - › 532: no good statistics, but 1000 hrs for a 5-10 W seen

Availability

- will Argon lasers continue to be manufactured?
    - › entertainment
    - › medical uses (tuned dyes)
- are commercial YAG lasers available now?
    - › ingredients for 1.06 stabilized laser, 10W or so, yes
    - › 532: not really.

Characteristics of the basic laser

Output power

- Argon
  - › roughly 5 W useful power
  - › little prospect for more powerful lasers in future
- Nd 1.06
  - › 20 W, 40 W TEM_{00} single freq. in recent research papers
  - › continued industrial development, mostly multimode
- Nd 532 nm
  - › non-linear material (e.g., BBO) in external ring resonator
  - › efficiency of the doubling is reliably about 0.5
  - › state of the art 20 W 1.06 -> 11.5 W 532
  - › no MTBF data for this, though

initial cost: similar for hardware

- Argon rebuilt as PSL
  - › 110k$ in materials and fabrication
- Nd:YAG at 1.06: 33k$ for 7 W, another 25k$ for quiet master
- Nd:YAG doubled to 532 nm:
  - › 33k$ for pump laser, 25k$ for master
  - › probably 20-40k of other stuff

Characteristics of the basic laser

Intensity noise

- Argon
  - plasma and mechanical excitation
  - shot-noise limited intensity noise roughly 5 MHz
  - $\sim 10^{-4}\ \delta I/I$ at 90 Hz
- Nd:YAG (1.06, probably 532)
  - relaxation oscillation driven by pump diode noise
  - can be reduced through pump intensity servos
  - intensity noise spectrum like a white-noise driven oscillator
  - shot noise at roughly 1 MHz
  - low-frequency plateau at $\sim 10^{-7}\ \delta I/I$

Characteristics of the basic laser

Frequency noise

For both lasers, the intensity noise and frequency noise spectra resemble each other, due to common causes.

- Argon: $10^4\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 90 Hz.
- Nd:YAG 1.06 master (and thus slave) lasers: $70\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$
- relatively easy to convert present system of frequency stabilization to YAG; done, shows $3\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ down to 1 Hz
- Nd:YAG 532:?, but probably similar to 1.06

Beam jitter

- Few measurements, little experience with Nd:YAG
- 20 W 1.06 'similar' to Argon (limited by measurement tech)

Impact on the Optics

distinguish green (514 or 532 nm) vs. 1.06 μm

- can make dual-wavelength coatings for both 514 and 532
  - beamsplitter is probable exception
- appears impossible for 1.06 μm dual with any green color

substrate size for 1.06

  - for same flat-curved geometry, goes as $\sqrt{\lambda}$
- flat-curved: only back mirror is in question
  - some 16 ppm diffraction loss out to r=12.4 cm
  - not used in transmission, may allow different material
  - can use different g-factor, reduce beam at BS
- curved-curved: present substrate is fine
  - beamsplitter may need to be larger

substrate optical properties

- 532/514: 10-20 ppm/cm scatter measured
- 1.06: 1-3 ppm/cm measured
- homogeneity probably smaller phase by ratio of λ

Impact on the Optics

scaling with wavelength, continued

- in general for scattering, beam distortion: $(x_{rms}/\lambda)^2$
- microroughness $(532/1064)^2 = 0.25$ less scatter for 1.06 µm
- medium and large-scale: several competing factors
  - › for a given beam size, as above
  - › for beams larger by $\sqrt{\lambda}$, sample longer spatial wavelengths
  - › if surface spectrum grows as $1/\nu^2$, no real change
- FFT run (Bochner) shows net effective improvement at 1.06
  - › used same HDOS-derived imperfect substrates, 1/900
  - › same 12.5 cm radius
  - › same assumed 100 ppm dead loss (not fair!)
- arm power drops to 0.92 of Argon case
- contrast defect smaller for 1.06 µm - 0.25 of Argon case
  - › longer wavelength 'wins' over larger beam
- less power on photodetector for YAG - 0.5 of Argon case
  - › 125 instead of 250 mW

Impact on the Optics

figuring and polishing

- probably no new territory, were we to make $\sqrt{2}$ bigger optics
- HDOS reference flat is measured to 20 cm...

coating (and losses)

- absolute error in coating thickness less important as λ_1/λ_2
- great (and growing) expertise in industry at 1.06
- total losses of ~<3 ppm measured at 1.06

metrology

- commercial Zygo/Wyko ifos available at 1.06
- requires special instrument for Argon
  - could 532/514 coatings be characterized only at 532?

baffles

- smaller backscatter but larger diffraction (by λ) for 1.06
- probable lower absorption in black materials at 1.06
  - and tube walls less effective
- change in ϕ per tube motion less by λ (but also for GWs!)
- not a problem for initial LIGO, and
- obligated to engineer for 1.06 in any case

Impact on length sensing system

shot noise limited strain sensitivity

- all things equal, goes with P/λ (thanks, FJR)
- requires 2x the effective power for 1.06 (roughly 10 W at laser)
- FFT run: Nd: YAG 1.50 less sensitive than Argon
  - requires $(1.5)^2$=2.25 more power for 'real' 25cm mirrors

photodiode quantum efficiency

- Argon or Nd:YAG at 514 nm: Si photodiodes, $\eta \approx 80\%$
- Nd:YAG 1.06: InGaAs photodiodes, $\eta \approx 98$
  - 1 W power handling

modulators (Pockels cells)

- Argon or Nd:YAG at 532 nm: KDP/ADP
  - maximum modulation frequency ~60 MHz
  - transmitted light power limit ~1 W
- Nd:YAG 1.06: $LiNbO_3$/$LiTaO_2$
  - GHz modulation possible
  - much higher powers; experience at 20W

Paths to use of Nd:YAG

Continue with Argon for initial LIGO ifo

- disadvantages:
  - › reliability/reparability
  - › operating costs
  - › built-in obsolescence
- advantages
  - › requires least up-front effort
  - › external YAG research and industrial efforts continue
  - › re-assess for 'enhancements'

Paths to use of Nd:YAG

Choose Nd:YAG for initial LIGO ifo

- disadvantages of either 1.06 or 532:
  - › internal manpower demands now
  - › R&D cycle required to gain confidence, experience
  - › rework of stabilization system
  - › probably requires partner (industrial/research)
- advantages of either 1.06 or 532:
  - › up-front power and operating costs lower than Argon
  - › forward-looking
  - › possibly better performance (frequency, intensity noise)

Specific to doubled YAG at 532 nm:

- › - doubling technology still quite new; lifetime, reliability?
- › + minimal impact on present optics, length readout systems

Specific to YAG at 1.06:

- › - possible increases in optic sizes
- › - some impact on length readout
- › + share more problems/solutions with VIRGO, GEO, others
- › + initial power levels pretty straightforward (10 W)
- › + enhanced levels (40 W) presently in labs, most sure future

Implementation

R&D tests

- some independent measurements possible
- most confidence from a phase noise measurement
- nominal plans for collaboration with Byer
    - › present experiment planned wrap-up mid '96
    - › Byer/Gustafson develop Nd:YAG in parallel
    - › they prefer 1.06, open to 532
    - › install optics and laser, test in early '97
- could push these dates and ordering around if needed
    - › PNI must/will fulfill goals, whether with Argon or YAG

Detector schedule

- PSL: would delay PSL schedule to go with (any) YAG solution
    - › PSL planned to be ready in advance of installation
- COC: same-size optics for (either) YAG solution no problem
    - › larger optics ripple through system (suspension...)
    - › if just back mirror, probably ok
- LSC/ASC: modulator, photodiode changes small

Your votes?