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Technical Aspects of Using Nd:YAG(1064nm) Lasers instead of Argon Ion Lasers in the Initial LIGO Interferometers

Title

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Summary

The technical merits of using Nd:YAG lasers with a wavelength of 1064 nm for the initial LIGO interferometers are analyzed. The technical risk of implementing a Nd:YAG 1064 nm initial interferometers appears low, and there is promise for future improvements in laser sources.

1 INTRODUCTION

The current LIGO Baseline Concept employs Argon ion lasers, emitting 5 W of single frequency, single mode light at wavelength of 514.5 nm. In recent years, Nd:YAG technology has made impressive advances, and it appears that the components for 1064 nm lasers adequate for the initial LIGO interferometers are now available. For a variety of reasons, there is growing belief that the advanced interferometers will have to use 1064 nm light, thus a switch from Argon lasers to Nd:YAGs seems quite likely, raising the issue of finding the optimal point in time for this transition. Given the high cost[1] of rebuilding three operational interferometers operating at 514.5 nm to accommodate 1064 nm, it is natural to ask what the implications are of switching lasers and wavelength at an early stage, before the first LIGO interferometers enter the Operations phase. Accordingly, Abramovici and Shoemaker were asked to conduct a study addressing the technical and cost/schedule aspects related to using Nd:YAG (1064 nm) instead of Argon lasers. Following that study and the ensuing internal debate, LIGO management decided that the transition to Nd:YAG lasers be made immediately. The transition of the various parts of LIGO to Nd:YAG lasers is currently in the planning stage.

The following material contains a collection of technical information related to the Argon/YAG question. Section 2 summarizes the comparison between the two types of lasers, in the LIGO context. Appendix A presents the proposed modifications to the LIGO baseline needed to accommodate Nd:YAG lasers; Appendix B lists relevant activities in other GW laboratories; Appendix C contains a discussion of the effects of an Argon/YAG switch on the LIGO R&D effort. A draft specification for a Nd:YAG laser adequate for the initial LIGO interferometers is presented in Appendix D. References for the technical discussion are in Appendix E.

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[1] in money, manpower, and instrument down-time.

2 SUMMARY OF TECHNICAL ASPECTS

Nd:YAG is expected to be a light source which will be suitable for enhanced and advanced LIGO interferometers. In the laboratory, Nd:YAG and other solid-state lasers exist already which are suitable for engineering into 'enhanced' interferometers (with 40 W of power, equivalent to 20 W of Argon 514 nm light). In contrast, Argon lasers have no promise of more than 20% increases in power. Thus, we see a need to change to solid-state lasers shortly after commissioning of the initial LIGO interferometers.

To first order, then, we wish to start the initial LIGO interferometers with a light source and wavelength which would allow an adiabatic change to higher power. This can save schedule, and reduce the net cost, of arriving at an enhanced level of shot-noise limited sensitivity.

A second reason for switching to Nd:YAG lasers at 1064 nm at this time is to take advantage of possible performance advantages from the longer wavelength. Relaxed mirror specifications, and lower Rayleigh scatter in the substrates, are examples.

There do not seem to be any aspects of the interferometer performance or engineering difficulty which would be significantly adversely impacted by a change to 1064 nm and Nd:YAG for the initial LIGO interferometers, and all indications that higher power lasers will be in parallel development (driven by a rapidly growing industrial demand). There are a number of places where more in-house effort will be required, to characterize new components, but sharing with laser groups and other GW groups can reduce this burden.

The tables below summarize the differences between a Argon-514nm interferometer and a Nd:YAG-1.06μm laser. Points which can be clearly seen as disadvantages are indicated in *italics*. Most categories should be self-explanatory; by 'engineering status' we mean to give a one-line summary of the availability of a commercial solution, the engineering future, the rate of progress in the field, etc.

Table 2-1: Laser Technical Summary

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
power	initial power available, future power assured; *~2x power required for given sensitivity*	initial power available; *no further increases probable*
efficiency	several 10^{-2}	10^{-4}
mean time before failure	10,000 MTBF (commercial specification) 10-20,000 MTBF (Byer experience)	8000 MTBF (commercial specification) ~2000 MTBF (LIGO experience)
failure mode	~20% reduction in power	*no light*
raw frequency noise, 90 Hz	10^2 Hz/$\sqrt{\text{Hz}}$	10^5 Hz/$\sqrt{\text{Hz}}$
raw intensity noise, 90 Hz	10^{-6} $\delta I/I$ $1/\sqrt{\text{Hz}}$	10^{-4} $\delta I/I$ $1/\sqrt{\text{Hz}}$
raw intensity noise meets ~10 mW shot noise	3 MHz	~5 MHz
beam jitter	not yet characterized; reported to be small	characterized
engineering status	*~\$1M+ 1 year development*	ready
future development	growing market	*static to declining market*

Table 2-2: Modulator (Input Optics) Technical Summary

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
power handling	to 20 watts	to 5 watts
sensitivity	210 volts/π, 1.06 μm	1000 volts/π, 514 nm
frequency range	to 100 MHz	to 60 MHz (in pairs)
engineering status	commercial item	commercial item

Table 2-3: Core Optics Technical Summary

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
mirror size	*back mirror >27 cm*	<25 cm
figure requirements (sample requirement)	Argon *2 =$\lambda_{514}/300$	$\lambda_{514}/600$
required coating uniformity (random errors)	0.1%	0.1%
substrate scatter	1-2 ppm/cm	*10-20 ppm/cm*
substrate absorption	1-2 ppm/cm	1-2 ppm/cm
substrate homogeneity	same to 2x better	---
coating absorption+scatter	6 ppm	~20 ppm (1.5 reported)
metrology	commercial	*special interferometer must be fabricated*

Table 2-4: Suspension Technical Summary

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
end FP mirror	*possible additional design type required*	

Table 2-5: Photodetector (Length Control) Technical Summary

parameter/part	InGaAs Merit/*Demerit*	Si (Argon or YAG) Merit/*Demerit*
power handling	150 mA	*15 mA*
quantum efficiency	80-90%	60-70%
surface diameter	*0.5-2 mm*	10 mm
spatial non-uniformity	TBD	$<10^{-3}$
capacitance	15 pf	30 pf
engineering status	*in development*	commercial

APPENDIX A: BASELINE FOR ND:YAG IN INITIAL LIGO

This is a brief description, organized by Detector Subsystems, of the differences from the present baseline (Baseline1) for the initial LIGO interferometers for a sample configuration using a Nd:YAG laser at 1.06 μm as the light source. Additional technical information is included where appropriate.

A.1. Prestabilized Laser Source

A.1.1. Laser Configuration

The laser is a master-slave injection locked system based on modified commercial lasers. This configuration was first suggested as a light source for GW interferometers by Brillet (Man84) and demonstrated in that laboratory on Nd:YAG lasers (Cregut89). Several lasers have been described in the literature which more or less closely resemble this description. See Farinas94 (description also of some of the physics of injection locking), Shine95, and Freitag95. We propose that the laser system be built by an commercial laser manufacturer to our specifications, and that the stabilization then be done by LIGO and/or LIGO collaborators. (This would be the equivalent of contracting for the rebuilt Argon laser but without stabilization electronics.)

Figure B.1.1-1 is a schematic diagram of the laser (after Farinas94).

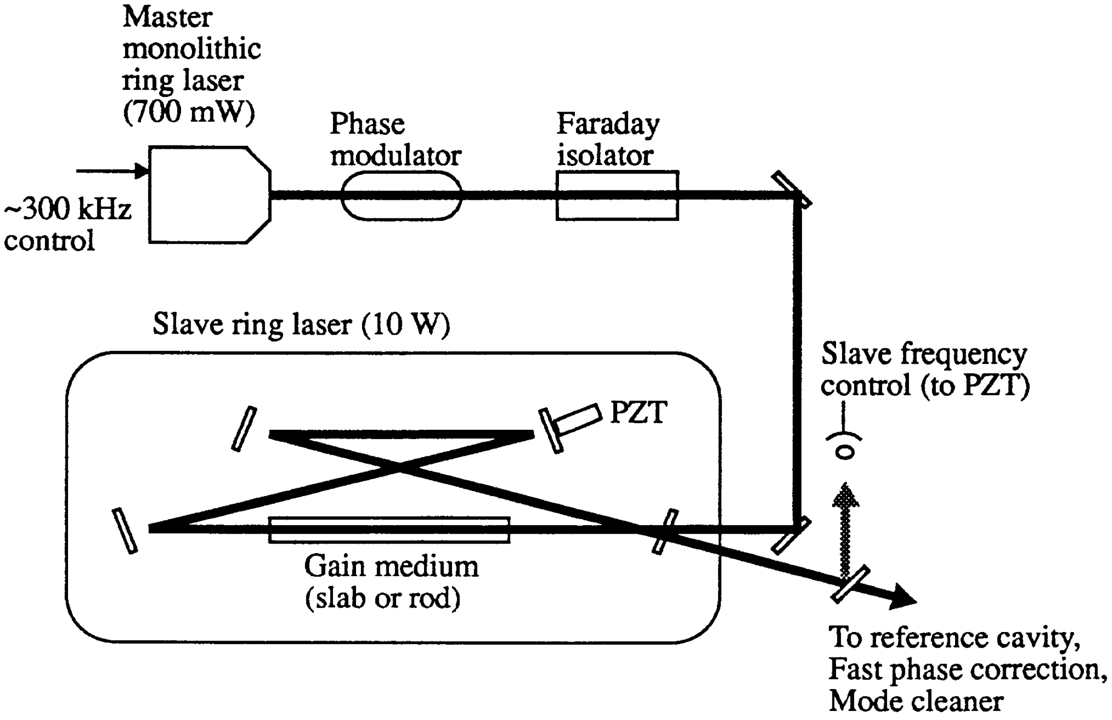

Figure B.1.1-1: Master-Slave Nd:YAG laser configuration

The **master** (low noise) laser is a standard Lightwave 126 non-planar ring oscillator or the equivalent. It produces 700 mW TEM_{00} single frequency 1.06 μ m light. It includes inputs for modulating the intensity of the pump diodes (for intensity control) and medium-fast frequency modulation (with roughly 30 kHz bandwidth, for frequency stabilization). See Kane85 for a description of this laser.

The **slave** (high power) laser is a Lightwave 220 or the equivalent. The commercial version is a cylindrical rod diode-laser side-pumped laser with a simple two-mirror linear cavity. It is designed to deliver 7 W TEM_{00} multi-longitudinal mode. By selecting pump diodes the power can be raised to 10 W without compromising the 10,000 hour MTBF. The rod is placed in a bow-tie ring cavity to allow injection locking; the injection locking ensures single longitudinal mode operation, and sets the frequency and intensity noise at the level of the low-noise master laser described below. See Shine94, Alfrey94, and Freitag95 for descriptions of similar lasers.

A.1.2. Power and Efficiency

A Nd:YAG laser for the initial LIGO interferometers must provide at least the same shot-noise limited performance as the planned Argon laser. The shot noise scales as $\sqrt{P/\lambda}$, and since $\lambda_{Nd:YAG}/\lambda_{Argon} \sim 2$ the laser power must be double that of the present 5 W, *all other aspects of the interferometer being equal*. This leads to a requirement of 10 W for the Nd:YAG laser output power. The optical performance of an interferometer at a longer wavelength is likely to be better (for example, a given surface error results in only half the phase error), as discussed below, allowing somewhat smaller powers for equivalent performance.

Nd:YAG lasers are much more efficient than Argon lasers, with input electrical power to output luminous power ratios of typically several percent: by comparison, Argon lasers have about 10^{-4} efficiency. This leads to lower operating costs, smaller power supplies and chillers, greater portability, and probable longer lifetimes. Most Nd:YAG designs will fail ‘gracefully’, leading to a reduction of power when a diode pump laser burns out rather than a complete and sudden loss of light. This may be quite a significant advantage; to avoid a ~6 hour loss of observation time with Argon lasers might require having two lasers running at all times, due to the extended warm-up period of the backup in case of failure.

The present (mid-95) Nd:YAG lasers with characteristics attractive for LIGO interferometers have maximum output power of 20 W (Freitag95), 26 W (Uehara95b) to 40 W (Shine95). No fundamental problems with significantly increased power are foreseen, and lasers with multi-mode output power of 175 W (Freitag95) are presently available with diode-pumped lasers (much higher power Nd:YAG and Nd:glass flashlamp-pumped lasers are also on the market, but their noise performance makes then unattractive for this application). Byer (Byer95) claims that 1kW diode-pumped lasers will be available by the year 2000. The industry is driven by laser machining needs, although high beam quality will probably continue to be primarily of interest to research.

The future of Argon-ion lasers appears to be limited. Spectra-Physics (Shawn Streeby, telecon28jul95) indicates that they have an engineering effort underway now, driven by LIGO, to produce more power from Argon laser via changes in the bore size and pressure. They anticipate 15-20% increases in the power from this effort, with probable increases in the lifetime of tubes and thus the reliability. There are no plans to make a 2x more powerful Argon laser (because of the maturity of the product, they do not see a technical means); instead, they expect solid-state sources to replace Argon lasers in the green as well as infrared in a 5-year time scale and their engineering is primarily in that direction. Lawrence Livermore proposed to Spectra several years ago to build a 100 W Argon laser, with LLNL providing the engineering funds; after consideration, Spectra decided that they did not want to contract for that goal.

Reliability is cited by manufacturers to be similar for Nd:YAG and Argon lasers. Byer says that his, and Lightwave's, experience with the diode pumped Nd:YAG lasers meet or exceed this specification. Experience in LIGO laboratories is very roughly that one of our six Argon lasers requires attention once a month, and this leads to an estimate of 1,000 to 2,000 hours before the system is unavailable (for a day or so).

The beam quality of the Nd:YAG laser influences the efficiency of the optical system by determining the coupling efficiency into the first cavity along the optical path, but gives some basis for comparison. The 'M' parameter is often used to characterize a beam, but does not lead to an unambiguous calculation of the coupling into the TEM_{00} mode. Since the available data is described by the 'M', we use it here. The Shine (Shine SPIE vol 2379) 40W slab (which has a basically 'square' geometry) laser has an M=1.3. The Uehara (Uehara OL preprint) 26 W laser has an M=1.01 and M=1.1 in x and y. A Spectra-Physics 7 W Nd:YAG has an M=1.1. These should be compared with the specification for Argon lasers; Inova quotes M=1.3 for their large-frame Argon lasers.

A.1.3. Frequency Stabilization

The basic techniques for stabilization are the same as those presently used for the Argon laser. The frequency is measured in a reference cavity (which can be identical to the present design but with mirrors coated for the Nd:YAG wavelength). Phase modulation and reflection locking are used to obtain an error signal, which is then applied to fast and slow actuators in a configuration similar to the Argon pre-stabilized laser. The laser described above is 2-3 orders of magnitude less noisy in frequency than the Argon, so unity-gain frequencies and dynamic ranges can be relaxed from the present requirements. The fast actuator is a Pockels cell (Magnesium-doped Lithium Niobate is recommended by New Focus (Shine)), probably at the output of the slave laser. The medium-speed correction is built into the master laser (a PZT which compresses the Nd:YAG material, changing the optical path in the master laser; this has a bandwidth of ~300 kHz, and a range of about 20 MHz). The slow correction is with PZT actuators on the mirror mounts of the ring-laser cavity of the slave laser to make the slave laser track the master, and temperature control of the master for long-term control. See Nakagawa94 and Nakagawa95 for frequency control of the master laser.

A.1.4. Intensity Stabilization

The pump diode lasers both produce intensity noise (which then excites intensity fluctuations in the Nd:YAG) and provide a convenient actuator to suppress it. Modulation of the current in the pump diode lasers gives a very-wide bandwidth control over the intensity. Again, the noise level from the laser is smaller than that for the Argon laser, and lower loop gains can be used. See Harb94 for intensity control of this laser. The high-frequency intensity, extrapolated from Farinas95, looks like it will be shot-noise limited at frequencies greater than 10 MHz (for 5W of power in their case), allowing our present modulation frequencies to be used.

A.2. Input Optics

Most of the input optics can remain the same in design (size, radii of curvature, etc.). All optics must be coated for 1.06 μ m; such low-loss coatings are standard for REO and other coaters. See Core Optics, below.

A.2.1. Modulation System

The crystal used in the Pockels cells must be changed to one which is transparent at 1.06 μ m. Magnesium-doped Lithium Niobate is recommended by New Focus. Commercial units from New Focus can be used at 20W (Shine95), and have the same physical crystal size as the Gsaenger cells presently used. They are specified for a smaller beam diameter, because measurements show that this gives better uniformity of modulation (presumably also true for the Gsaenger cells presently used at 0.5 μ m).

A coincidental advantage of the MgO-doped LiNbO is that its loss tangent for RF modulation is much smaller than that of ADP or KDP (the presently used materials) and its electro-optic coefficient much larger (hundreds of volts per λ instead of thousands). This allows easier electronic design with probably greater phase stability with temperature, lower radiation from modulation circuits, and, most importantly, the possibility of employing higher modulation frequencies which may ease some interferometer configuration difficulties.

There is experience showing that the electro-optic to piezoelectric coupling is stronger for the Lithium-based modulators (Weiss85). The success of efforts to stabilize Nd:YAG lasers in frequency, using these modulators, suggest that these problems have been solved or are not relevant to practical applications.

A.2.2. Faraday Isolators

Faraday isolators for 1.06 μ m are commercially available. They are specified as >90% transmission, and >30dB attenuation (thus resembling 514 nm isolators), with <95% transmission and >35 dB attenuation observed in practice. The material itself (Terbium Gallium Garnet) absorbs 0.4%, with the remaining lost in AR coatings and polarizers. Devices with up to 45 mm free aperture are available (at 85% transmission) (Electro-Optics Technology, Inc.).

A.2.3. Other Optics

Many optics companies have a series of beamsplitters, polarizers, waveplates, etc. designed for 1.06 μm.

A.3. Core Optics

Size: This proposed configuration adopts the same *g=0.3* factor as the present 4 km arm-cavity design. This leads to beams $\sqrt{\lambda_{1.06}/\lambda_{0.514}} = \sqrt{2}$ larger everywhere in the interferometer. Because the present near test masses and recycling mirror are oversized, no change in diameter or thickness of those components is required. The far test masses and the beamsplitter must be made larger. All optics must be coated (Rmax, 3%, AR) for 1.06 μm, a standard wavelength for REO and other coaters.

Thermal noise: Saulson has pointed out that a larger beam radius-to-mirror radius can reduce the thermal noise contribution from internal modes, with a linear dependence (Raab95); however, a larger mirror will have lower resonances and a greater mass, so that the scaling is not simple. A test-mass size and aspect-ratio optimization (thermal noise from substrate and pendulum, diffraction loss, mode mixing by the edge, fabrication ease) should be performed for either a Argon or Nd:YAG design. The small changes in diameter proposed here will make small changes in the thermal noise, as the thermal noise goes as the square root or slower of most of the parameters.

Coating uniformity, scatter and absorption: Studies of the performance of mirrors at 1.06 μm show that the absorption and scatter performance available is as good or better than that obtained with coatings at 0.5 μm. Published measurements of loss (Uehara95) and informal reports (Boccara95, Brillet95, Willke95) indicate total losses < 6 ppm are achievable. Comparisons between 0.5 μm and 1.06 μm of measurements of correlations between substrate preparation and the scatter give mixed results, but show either similar or better (as would be predicted by simple theories of scatter as a function of wavelength for fixed workshop practice) performance for longer wavelengths (Hickman93, Watkins93). REO (Lalezari95, telecon 1Aug95) indicates that there are equally good results seen for their coating system at 1064 and 514 nm, and that they have no preferences for one wavelength. The coating errors tend to be proportional to the thickness, so that a fractional precision of (say) 0.1% is maintained independent of the wavelength of the coating. REO can coat right to the edge of the substrate, with errors growing to 1% in thickness at the edge of the coating (whether this is at the edge of the substrate or in from the edge a cm or so). Hiro Yamamoto (Yamamoto95, calcs) has shown that 0.1% uniformity of coating is sufficient for the initial LIGO if coating errors are random, and 0.02% if 'accordion'-like.

Note that the phase noise from a given level of stray light is 2x greater for the 2x longer wavelength. The net impact is due to a combination of factors, where the 10x reduced Rayleigh scatter in the substrate and the likely reduced mirror source scatter mitigate. No estimate has been made for the total.

Thermal distortions: The power level will be twice as high in a 1064 nm interferometer, leading to (for a given wavelength-independent coating absorption) larger thermal deformations from surface absorption. However, the net result cancels (Strain94): While the optical path distortion due to heating grows linearly with the power, and the required power linearly with the wavelength, the effect on the interferometer performance falls linearly with the wavelength, so that the two effects cancel. This, with the fact that at present the best 1064 nm and 524 nm mirrors show roughly the same absorption, makes for no difference from this effect.

Substrate homogeneity, scatter and absorption: Silica substrates have Rayleigh scatter at 1.06 μm on the order of 2 ppm (Boccara95), as compared with scatter at 0.5 μm of 10-20 ppm (Winkler93, Shoemaker93). The absorption in substrates appears to be similar for the 1.06μm and 0.5 μm, at 1 to 2 ppm; this will not be a factor in the initial LIGO interferometers, where deformation from the surface absorption will dominate the thermal focussing budget (which itself is expected to be negligible). Homogeneity and birefringence effects in the substrate will be smaller for the longer wavelength for the part due to density variations; index variations will lead to the same effect on the two wavelengths.

Contamination: We do not have experience with contamination of mirrors at 1064 nm. In general, the lower energy per photon will probably lead to less destructive contamination (Byer, talk 1Aug95), but unfortunate resonances could make contamination at 1064 nm worse than 514 nm. We feel that we do not have a thorough understanding of contamination at 514, and have planned to study it; this certainly holds true for 1064 nm as well. Groups familiar with low-loss 1064 mirrors (JILA) may be able to help us with this.

Effect of surface figure: The change in optical phase for a given mirror surface error (from the substrate surface or the coating) is 1/2 as large at 1.06 μm as at 0.5 μm. This advantage may be offset by the fact that larger beams sample longer spatial wavelengths on the optical surface, and this is in general a rapidly growing spectrum toward longer spatial wavelengths.

Using the FFT optics propagation code and standard LIGO FFT optics model to explore the impact using 'real' mirrors (the statistically duplicated HDOS reference flat), the optical power throughout the interferometer and the signal-to-noise ratio has been calculated for 1.06 μm light (Bochner95). No re-scaling of the substrate surface errors was made, in the assumption that the polishing techniques for a 28 cm mirror would be the same as for a 25 cm mirror. For mirror diameters kept at their nominal 12.5 cm diameter (as for the 0.5 μm runs, the net effect of larger beams is an improvement in the contrast (because given surface errors are less at the longer light wavelength) and a consequent reduction in the power on the photodiode for a given input power.

Another run was performed for the mirror diameters here proposed for 1.06 μm: We assume effective coated diameters of 23 cm for the near FP mirrors and the recycling mirror, and 28 cm for the end mirrors and the beamsplitter (an aperture of 19.8 cm was used for the beamsplitter, due to the 45 degree incidence; this refinement was not used for the Argon run, which had a very large effective beamsplitter). Several key parameters are shown in the table; the 'bottom line' is that somewhat better performance is obtained with Nd:YAG (once the power is doubled for the shot-noise equivalence). The improvement is due to better optical performance of surfaces and coatings at the longer wavelength leading to a smaller contrast defect, lower modulation index, and less power on the photodetector per input watt of light.

Table A.2-6: FFT Optics model results for 1.06μm

Parameter	Nd:YAG	Argon
Laser wavelength	1.06 μm	532 nm
Mirror radii: recycling, flats	11.5 cm	12.5 cm
beamsplitter	9.9 cm	12.5 cm
FP back mirrors	14.0 cm	12.5 cm
Laser power (at recycling mirror)	5 W	2.5 W
Assumed loss/bounce on all mirrors	100 ppm	100 ppm
Optimum recycling gain	34	31
Contrast defect $(1\text{-}C) \sim 2\,(I_{min}/I_{max})$	3×10^{-4}	1.3×10^{-3}
Optimum modulation	0.34	0.47
Photodetector power	260 mW	240 mW
h (below cavity pole frequency)	$5.7\times10^{-24}/(\sqrt{Hz})$	$6.2\times10^{-24}/(\sqrt{Hz})$

Metrology: It may be less expensive to hire and easier to find precision metrology houses for the 1.06 μm wavelength, as some commercial manufacturers (Zygo, Wyko) offer interferometers for this wavelength as standard items.

A.3.1. End Test Masses

The end test masses should be increased from 25 to at least 27 cm diameter (28 was used in the FFT analysis). This leads to 2 ppm/bounce diffraction loss (Spero92, Spero95) if the surface to the edge is usable (to be compared with the nominal present requirement of 1 ppm/bounce, which is exceeded by 25 cm mirrors). The additional loss is not important from the point of view of lost power; the impact due to additional scatter needs to be evaluated, but since reduced scatter from microroughness is anticipated, no net impact is expected. No difficulties in polishing the larger masses is anticipated; the coating chamber must be large enough to hold the larger diameter, but the coating requirements can be relaxed at the edges (true for Argon and 25cm as well, of course).

A.3.2. Beamsplitter

A minimum 26 cm beamsplitter is recommended to meet the above diffraction requirement and to allow walkoff beams to be separated (Abramovici95). To ease manufacture of substrates and coatings and suspensions, the same size beamsplitter and end test mass are recommended, thus 28 cm is the point-of-departure baseline. Note that the beamsplitter for the Argon case must probably be larger than the present nominal 25 cm test mass design.

A.3.3. Baffle Reflectivity and Scatter

The scatter from the mirrors can be reflected or backscattered from the tube walls and baffles and then recombine to make excess phase noise. The prospective baffle materials and the tube walls have been characterized at both 0.5 μm (Whitcomb95) and at 1.06 μm, and preliminary results show that the backscatter for baked stainless steel is lower by roughly a factor 2 at 1.06 μm, but that the reflectivity is higher by about the same factor. There may be a compensating lower scatter from 1.06 μm mirrors, but neither the baffle data nor the scattering data are yet definitive.

We are committed to making the LIGO installation compatible with near-infrared light, independent of our initial configuration, and the initial interferometer will not be limited by this scatter (in either the Argon or Nd:YAG wavelengths). Mirror technology is expected to improve, and the influence of scattered light falls with the square of the mirror scatter, leading to optimism that changing the mirrors will allow significant changes in the LIGO system sensitivity to scattered light when more sensitive interferometers are installed.

A.3.4. Suspensions

A.3.4.1 End Test Masses

The larger end test mass mirrors will require a larger suspension. The same design rules used to generate the present two (or three) suspension designs are extended to a ~10% larger diameter; we can contemplate reducing the mirror size for the near test masses and the recycling mirror. Again, the beamsplitter in the Argon design will probably require a larger mount; the beamsplitter and end mirror design could be the same.

A.4. Length Control System

A.4.1. Photodetector

The same silicon photodetectors now used for Argon can be used at 1.06 μm, with a change in the doping and silicon wafer thickness to improve the quantum efficiency (the absorption length for 1.06 μm light is of order 1 mm in Si, making it more difficult to simultaneously require good conversion efficiency from photons to electron-hole pairs, and to collect those pairs before recombination takes place). The EGG part YAG-444 has very similar specifications to the presently used SGD-444, with a lower capacitance (helping signal to noise in the diode-amplifier combination) and a greater responsivity (0.45 A/W at 1.06 μmm compared to 0.2-0.25 A/W at 0.5 μm). The net quantum efficiency is similar at both wavelengths. We will probably use several photodiodes in a shared aperture configuration with cascaded photodetectors (electrical parallel, before or after conversion to voltage) to collect the approximately 300 milliwatts of light at the interferometer output. If the light not converted is reflected, the later photodiodes can be used to increase the efficiency of the total photodetector (Fox93). We may choose to place the detectors at a non-optimum Brewster angle to intentionally distribute the current collection uniformly over a number of photodiodes.

Alternative photodetectors exist (InGaAs) which have a high quantum efficiency, and some devices with higher power-handling have been developed (Harris95, Intevac Advanced Technology Division). The higher quantum efficiency and lower energy per photon lead to roughly 0.7 A/W for InGaAs diodes at 1.06μm, and present devices are linear to 140 mA (1 dB compression); they have an inconveniently small active area (0.5 mm diameter). Most of the industrial interest is in 1.3 μm, and one manufacturer of InGaAs (Olsen95, Sensors Unlimited) recommends staying (at least presently) with Si for the Nd:YAG wavelength. The VIRGO effort reports that the InGaAs specifications are conservative, and that present detectors are perfectly satisfactory at currents of up to 100 mA.

APPENDIX B: ACTIVITY IN OTHER RESEARCH GROUPS

Short descriptions of some of the other efforts to produce laser sources, optics, and detection systems for GW interferometers is given below. At present, all of the plans for moderate- or long-baseline interferometers call for laser-diode pumped Nd:YAG lasers at 1.06μm using the master-slave approach describe above.

B.1. STANFORD

B.1.1. Laser

There is a great wealth of experience with solid-state lasers at Stanford (Gustafson95). The Lightwave NPRO monolithic laser used widely as a master laser comes from this laboratory. A slave laser using a zig-zag slab geometry has been made and characterized (Shine95) which produces 40W in a linear cavity (multi-longitudinal-mode). Injection locking of a 5W slab laser to a NPRO showed very good agreement with the theory of injection locking, with the frequency noise and intensity noise of the injection locked slave laser being effectively identical to the master (Farinas94).

B.1.2. Input Optics

No detailed information.

B.1.3. Core Optics

No detailed information.

B.1.4. Length Sensing/Control System

There is activity in fundamental research (Harris95) and in device development (Yamamoto, in conjunction with Hamamatsu) in the domain of InGaAs photodiodes for high quantum efficiency, high current handling capability.

B.2. VIRGO (France, Italy)

B.2.1. Laser

A description is found in the VIRGO design document, section 4100; further details from Brillet95. The Master Laser is manufactured by Laser Zentrum Hannover (See GEO-600 below). The Slave laser is manufactured under contract by BMG and is designed in collaboration with the Orsay group and is to be delivered in August 95. Presently, the plan is for the injection locking to be performed in the Orsay lab, with a completed laser by October 95. The initial goal ('VIRGO 97') is for a 10W 1.06 μm laser, with a plan for 20 W in 1999. Frequency stabilization is as described for the LIGO Nd:YAG baseline, with particular attention paid to the mechanical properties of the triangular rigid reference cavity. The present low-power system delivers 10^{-2} Hz/$\sqrt{\text{Hz}}$ at 100 Hz, measured with an external cavity; this is well in excess of the LIGO laser requirements.

B.2.2. Input Optics

Modulators are as described for the LIGO Nd:YAG baseline.

B.2.3. Core Optics

The optics will be manufactured by some combination of REO and the Lyon coating group of Mackowski, where the goal is to apply a variable-thickness final coating to correct for surface, coating, and substrate errors. The metrology is to performed largely in-house by Boccara in Paris.

B.2.4. Length Sensing/Control System

A Hamamatsu InGaAs photodiode is used, and although only specified by the manufacturer to be useful to 3 mW, performs to their satisfaction at 100 mW (or about 70 mA of photocurrent).

B.3. GEO-600 (Germany, Great Britain)

B.3.1. Laser

Laser Zentrum Hannover produces a monolithic ring laser similar to the Lightwave design, with

700 mW available. It uses temperature and PZT tuning. See Freitag93, and Harb94, for details; intensity stabilization has been successfully researched, but no data on frequency stabilization. The Slave laser is also made in-house at LZH using a rod (not slab) geometry with radial pumping; it produces 20W single-frequency. A complete injection-locked system has been characterized, but no published results on frequency-stabilized high-power operation exist.

B.3.2. Input Optics

No detailed information.

B.3.3. Core Optics

Laser Zentrum Hannover has coating facilities which have produced 2 ppm absorption and 5 ppm scatter 1.06 μm mirrors on small substrates.

B.3.4. Length Sensing/Control System

No detailed information.

B.4. TAMA (Japan)

B.4.1. Laser

There are active groups at the University of Electro-communications (Ueda et al.) and at the University of Tokyo (Nakagawa et al.) doing laser development and characterization for GW ifos. The master lasers used are Lightwave. Using pairs of suspended cavities in vacuum, very good frequency stability has been achieved and independently measured (Nakagawa94, Nakagawa95) for the master laser.

B.4.2. Input Optics

Careful studies of the loss of mirrors for 1.06 μm manufactured by the Japan Aviation Electronics Industry have been made (Uehara95). They show 6±6 ppm of total loss ($L = 1 - (R + T)$ for mirrors of 1.4×10^{-3} transmission; the cavity formed of two such mirrors showed a transmission on resonance of 99.14±0.86 % for the TEM_{00} mode. These mirrors will be used to form a mode cleaner for the 20m interferometer at the National Astrophysics Observatory.

B.4.3. Core Optics

No detailed information.

B.4.4. Length Sensing/Control System

Multiple InGaAs photodiodes in optical series (using beamsplitters) has been used to collect high total photocurrents (Uehara 94a) in a shot-noise limited locking of a Fabry-Perot cavity.

APPENDIX C: IMPACT ON LIGO R&D

We break down this description by the major R&D installations.

C.1. Phase Noise Interferometer

The Phase Noise Interferometer (PNI) research program is designed to test both the phase measurement system (modulator, photodetector, pre-amplifier) and the laser source (frequency, intensity, and beam position noise) as well as sources of excess phase noise (e.g., mirror scatter). A test of a 1.06 μm Nd:YAG system on the PNI appears to be the shortest route to verification of this technology for LIGO's needs.

Many problems and solutions along the path to a successful experimental demonstration will be similar for the Argon and Nd:YAG cases, so that adding a test of Nd:YAG at the end of the Argon effort will allow problems specific to Nd:YAG to be solved. Should we choose to abandon the Argon demonstration in favor of Nd:YAG, the exact time of switch-over to the other wavelength is not critical.

A number of components would need to be changed.

- The Nd:YAG laser with stabilization of frequency and intensity must be in place. The laser should be given pre-installation tests to minimize down-time on the PNI.
- New optics for all suspended masses would need to be fabricated, setup for suspension, and suspended. As this is in-vacuum, delicate work, this presents the largest configuration change. In addition, optics fabrication often suffers longs delays compared to promised delivery, so that these components should be ordered, and then tested, well in advance---these can be test pieces for the coating process.
- The modulator (presently external to the vacuum system) would need to be switched with any changes in the drive system implemented.
- The high-power photodetector system for Nd:YAG must be put in place.

The test program once the system is together will resemble the one for the argon laser, but with no need for the staged approach planned for the Argon; one would immediately use the full recycled system with Mode Cleaner in place. This would also represent the test of a 1.06 μm Mode Cleaner.

The Byer group has expressed interest in being involved in such a test, and has proposed to contribute manpower both to get the hardware prepared and to aid in the installation and experimentation.

A crude timetable for such a test program is:

- laser source to be ordered as early as possible; frequency and amplitude stabilized (in the OTF, or possibly at Stanford) and characterized off-line
- Mirrors:

  mirror substrates to be ordered ~ 9 months before the start of installation
  precision metrology on the polished substrates to follow
  coating and repeat precision metrology, other off-line tests
  preparation for hanging (magnets, fins, baking)

- other components ordered to allow initial off-line tests
- Installation of laser and mirrors, other optics: 3 months
- Tests: 6 months

If we assume that the present PNI research is completed as planned in mid-96, and that the preparations are timely, then the research would be wrapping up in March 97; the information on the research would come later than the optimal time for a choice of wavelengths for the full-scale LIGO mirror coatings. The delivery time for a full-power laser source does not allow the schedule to be shifted much earlier.

An alternative would be to use a master laser alone for the initial research. This would make the primary delay the acquisition of suitable optics, with the frequency stabilization of the master laser in parallel. The present PNI research schedule concentrates on measurements without a mode cleaner until December, 95; it is possible to consider a switch at that time to Nd:YAG. This would lead to significant experience with Nd:YAG by mid-96 at the cost of extending the overall PNI program.

C.2. 40m Interferometer

We do not anticipate that the change of laser would impact either the operational length control system or the lock-acquisition strategy (assuming either that no fast servo look to the frequency is central to the locking scheme, or that the servo behavior of the laser can be characterized adequately separately from the interferometer). It is possible the it would impact the test-mass displacement in ways which are not evident, or that the complete system with Fabry-Perot cavities would show up shortcomings or interactions not seen in the Phase Noise Interferometer. A more important purpose for a 1064 nm test of the 40m is for system integration test of the Nd:YAG PSL. The timing of such a change has not been studied.

C.3. Optics Test Facility

A number of off-line tests can be performed in the OTF for Nd:YAG-1.06 μm components and assemblies to gain experience and to qualify components. This could be done under the rubric of R&D or Detector.

- 1.06 μm mirror tests: loss, scatter, uniformity, susceptibility to contamination
- modulator tests: transmission, efficiency, uniformity
- photodiode tests: uniformity, linearity, damage threshold
- stabilization of Master and/or or complete Nd:YAG lasers

A crude estimate of the manpower involved is 0.5 FTE for one year of scientist and a full-time graduate student. For a *complete* change-over of the OTF from 514 nm to 1064 nm, FJR provides an estimate of 15 MM scientist and 15 MM engineer. Note that in addition to components specifically purchased for tests, there is the additional cost of establishing an infrastructure (at both east and west coast LIGO) to allow experiments at 1.06 μm: lenses, mirrors, waveplates, polarizers; CCD cameras, infrared viewing scopes, fluorescent cards; safety glasses.

Note that many of these tests could be performed (and/or may have already been performed) at other laboratories working with Nd:YAG lasers. This worldwide activity is one of the strong arguments for adopting this laser in preference to the Argon laser.

APPENDIX D: YAG LASER SPECIFICATIONS

D.1 GENERAL

The present specification for a 10 W, single frequency Nd:YAG laser is intended to support the procurement of a laser appropriate for the initial LIGO interferometers, to be installed at the LIGO sites beginning in June, 1998. The resulting laser should be a self-contained turn-key system, with a minimum level of required adjustment and maintenance. It is desirable that the design ensures easy maintainability, by technical personnel with average training level in operating and maintaining lasers.

D.2 LASER LIGHT

D.2.1 General Properties

1. Wavelength: 1064 nm, single frequency
2. Output power: >10 W in TEM_{00} mode
3. Beam quality: less than 1 W in higher order modes
4. Polarization: linear, within 1^{o} of vertical, extinction ratio >500:1

D.2.2 Reliability

1. MTBF: >10,000 hours.
2. Minimum stretch of continuous operation, between required maintenance events: 500 hours.

D.2.3 Stability

1. Warm-up time: <1 hour. Stability specs Points 2,3,4 below refer to warmed up laser.
2. Power: long term variation < 5%
3. Frequency drift $<10^{-6}/^{o}C$, free running
4. Pointing drift $<10^{-5}rad/^{o}C$ p.t.p., free running
5. Beam diameter stability: within 5%

D.2.4 Noise

1. Relative power fluctuations $<10^{-5}/Hz^{1/2}$, above 100 Hz
2. Relaxation oscillation: critically damped or overdamped
3. Frequency fluctuations: $<10^{4}Hz/Hz^{1/2}$ at 100 Hz, $<10^{3}Hz/Hz^{1/2}$ at 1 kHz
4. Pointing: TBD

D.3 OUTPUT CONTROL

1. Frequency control:
    1. Slow tuning over >1 GHz range, over time spans corresponding to room temperature changes
    2. Fast tuning over >10 MHz range, at rates up to 100 kHz
2. Output power control: TBD by vendor

D.4 INTERFACES

D.4.1 Electrical

1. Mains: 110V-60Hz, single phase
2. Controls and inputs
    1. Local and remote (TTL) ON/STAND-BY/OFF switches
    2. Local and remote output power control
    3. Local and remote output shutter operation
    4. Local LOCAL/REMOTE switch selector
    5. Inputs for frequency control signals 3.1.1 and 3.1.2 above.

3. Outputs
    1. ON/STAND-BY/OFF status
    2. Output shutter status
    3. Power level
    4. Head temperature

4. Connectors:
   Items which are commercially available from multiple sources are strongly preferred. To be selected by vendor, subject to consultation with and approval by LIGO.

D.4.2 Mechanical

1. The laser beam will be 14 cm above the plane defined by the support points.
2. The laser will be supported on three legs, attached to the rigid resonator frame.
3. The rigid resonator frame will extend 10 cm outside laser enclosure, 10 cm below the output beam, parallel to the beam and horizontally centered on it. This extension will be provided with 1/4-20 threaded utility holes, number and pattern TBD.
4. Support points for lifting and other handling will be provided.

D.4.3 Cooling

1. Cooling capacity and type (air, water) to be set by interaction with vendor.
2. The laser cooling unit will be separate from the laser head.
3. The cooling unit will be operated on 110 V, self-contained, and connected to the facility only through the power cord.

D.5 MAINTENANCE AND SERVICEABILITY

Laser subsystems that need periodic maintenance will be designed as modules, kinematically attached to the frame whenever needed, and easy to access, remove and replace.

D.6 SAFETY

1. The laser will be provided with all safety arrangements required by applicable regulations, e. g. an output shutter.
2. All control inputs will be internally protected against overload damage.

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