STANFORD UNIVERSITY

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FAX MESSAGE

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DATE: 9 Sept 96

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Message:

P.S. the head Ginzton bean counter says your plans for sending no equipment is just fine.

Stan,

Feel free to just scan this. the Last 2 sections are only half serious if they cause any political problems just cross them out. My Next step is to sit down with Bill Tulloch & Byer and have them do a serious edit. At which point everything will probably change.

High-Power Laser Development

Robert L. Byer and Martin M. Fejer

DRAFT

A. Diode-Laser-Pumped Nd:YAG Optical Amplifiers
    1. A 100 Watt TEM_{00} Slab Amplifier
    2. Advanced Slab Amplifier
B. Efficient Frequency Conversion of 1064 nm to 532 nm
C. Phase Noise Measurements

A. Diode-Laser-Pumped Nd:YAG Optical Amplifiers

One aspect of our proposed research program is to extend the laser development to meet advanced LIGO interferometer requirements. We describe in this section a proposed research program to amplify the output of a 10-watt diode-laser-pumped Nd:YAG laser to 100 watts while preserving the spectral and spatial mode qualities required for advanced LIGO, and to develop amplifier technology capable of scaling to hundreds of watts of output powers.

Solid-state lasers are limited in average power scaling by thermally induced stress which ultimately leads to the fracture of the laser gain medium. In the traditional rod geometry laser the radial heat flow from the rod leads to a radial index of refraction variation which in turn leads to thermally induced lensing. The thermally induced lens is correctable. What presents difficulties is the stress-induced changes in the index of refraction that have both radial and tangential components. The radial and tangential stress components introduce birefringence, and further, introduce a biaxial lens that is not correctable with simple optical elements. The highest average power demonstrated in a diode-pumped Nd:YAG rod laser is 90 W in a depolarized and noticeably degraded TEM_{00} mode. Above that power the rod fractured. ***(Reference)***

The solution to the thermally induced birefringence and focussing is to use the rectilinear geometry of the slab laser. If the slab is cooled and pumped through faces that are perpendicular to the laser axis, then the thermally induced stress aligns parallel to the optical polarization. Furthermore, if the laser beam propagates in a zig-zag optical path through the slab, using total internal reflection, then the thermally induced cylindrical lens is compensated. The slab geometry laser reaches an average power limit due to stress fracture proportional to the width and length of the slab-laser gain medium. The symmetry of the slab laser not only corrects for the thermally and stress induced optical distortions, but offers convenient average power scaling proportional to the cooled face area of the slab. This scaling enables slab geometry lasers to operate at average powers in excess of one kilowatt and will allow scaling to powers in excess of ten kilowatts. (Basu and Byer)

We have taken advantage of the slab geometry in high-power-laser research programs for more than a decade, including the recent research conducted at Stanford in support of LIGO. Shine (Shine 1995b) has demonstrated output powers of 75 W multimode, 40 W TEM_{00} mode and 20 W injection-locked, single-frequency from a diode-laser-pumped Nd:YAG minislab laser. These results represent the state of the art in cw, high coherence, Nd:YAG laser performance suitable for LIGO. Shine also demonstrated laser power up to 96 W of cw output power when pumped by 437 W of diode-laser power utilizing two diode-pumped Nd:YAG-miniature-slab laser-gain elements in a single resonator. In a separate experiment, Shine demonstrated a cw Nd:YAG slab amplifier. The amplifier operated with a small signal gain of $e^{0.9}$ or 240 % per pass. (Shine dissertation) For 40 W of input power the single pass amplifier generated 64 W of output power for a partially saturated single pass power gain of 60%. These preliminary dual-head oscillator and amplifier experiments show that 100 W average power operation is possible and set the stage for research on lasers that operate at the 100-watt level with the stability requirements necessary for the advanced LIGO interferometers.

The proposed amplifier research follows the traditional master oscillator, power amplifier (MOPA) design approach for extending laser power. This design takes advantage of the stability of the master oscillator while allowing the amplifiers to be designed for optimum efficiency at increasing output powers. The proposed amplifer research program will take place in two stages. In the first stage, a TEM_{00}-mode laser will be amplified in two successive Nd:YAG slab amplifiers with the goal of preserving the TEM_{00} mode while testing the performance of the slab amplifiers. In the second stage, an amplifier configuration suitable for scaling to kilowatt powers will be investigated. This advanced amplifier configuration will incorporate an active mirror for wavefront correction, and relay imaging optics for transverse mode control. Isolation is provided by faraday isolators. Isolation from back reflections is particularly important because the laser illuminates LIGO, interferometers which act as variable-phase high-reflectivity mirrors.

1. A 100 Watt TEM_{00} Slab Amplifier

We propose to design, test and evaluate a diode-laser-pumped Nd:YAG slab amplifier for application to the advanced LIGO. The amplifier gain elements are based on the fiber coupled, diode-pumped, miniature-slab laser demonstrated by Shine ***(Shine A)***. The slab amplifier will be used to amplify one of the 10-W Nd:YAG lasers being developed by Lightwave Electronics for LIGO as shown in **Figure 1.4**.

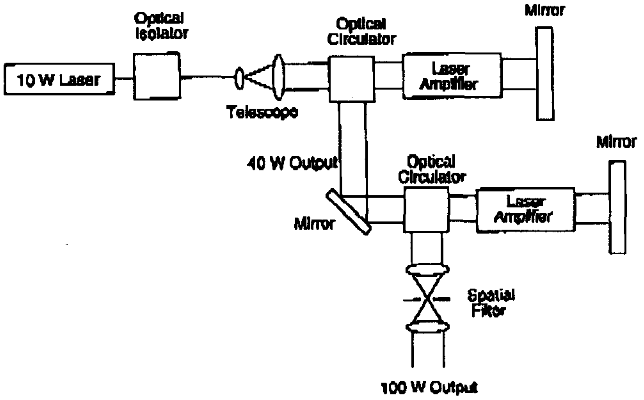

Figure 1.4 The amplifier uses two stages of amplification each of which is double passed. The forward and backward going passes are separated with circulators and the output is spatially filtered if necessary. The amplifiers are standard Stanford cw minislab heads.

The operation of a laser amplifier is well understood and is described in detail by the Franz-Nodvik amplifier equations (Siegman). For efficient power extraction, the laser amplifier must operate at near the saturation intensity of the gain medium, I_{sat} = 2 kW/cm^2 for Nd:YAG. Thus the current Nd:YAG-slab gain elements, with an area of 1.7 x 1.8 mm or 0.03cm^2, require 60 W of input power to reach I_{sat}. The demonstrated amplifier power gain from 40 watts to 64 watts illustrates the operation of the slab amplifier near the saturation intensity. The 62 % single pass gain is well below the unsaturated single pass gain of $e^{0.9}$ or 240 %. When operated in saturation, the output power of a laser amplifier increases linearly with the length of the amplifier. However, a saturated amplifier distorts the spatial mode of the input beam and thus use in power scaling for Gaussian input beams requires additional spatial mode correction.

We propose as a first step in the amplifier studies to test the existing minislab heads in a double pass amplifier configuration. The existing minislab heads, with an unsaturated single pass gain of $e^{0.9}$, will be configured with one minislab gain element operating as a single-frequency 10-W oscillator and the second gain element operating as a double-pass amplifier; an output power of 35 W is expected. These demonstrations should confirm the efficient operation of the amplifiers in a double-pass configuration. After the characterization of the amplifier is completed the minislab gain elements will be redesigned to reach the 100 W output power level in a similar double-pass, dual-amplifier configuration as shown in **Figure 1.4**.

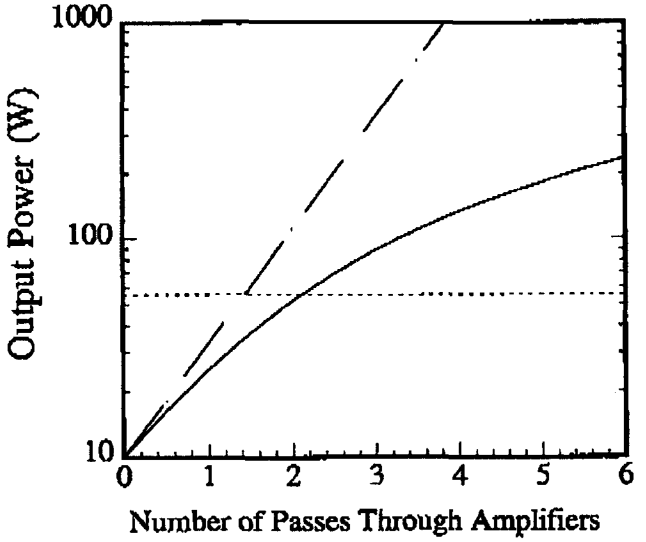

Figure 1.5. Amplifier output power in watts as a function of the number of gain element passes through an upgraded Stanford cw minislab head. (1 corresponds to the first pass through the first head, 2 the second pass through the first head, 3 the first pass through the second head, etc.) The top curve is the output power if exponential gain is assumed and the lower curve is the calculated power if saturation is assumed. The saturation power (saturation Intensity * beam aperture) is shown for reference as a horizontal line. The calculation assumes three identical amplifier modules, each module is double passed and is polarization insensitive. The amplifier heads are similiar to the present Stanford minislab head design with an additional 30% more pump light corresponding to 300 W of pump light from the fiber coupled diodes and a 1.7 x 1.8 x 58.9 mm Nd:YAG slab with a small signal single pass gain of $e^{1.2}$.

We propose to use the 10 W TEM$_{00}$ mode Nd:YAG laser as the input oscillator for a Nd:YAG slab amplifier. The amplifier module will be an upgraded Stanford minislab gain element with an unsaturated single pass gain of $e^{1.2}$. This can be accomplished with the addition of 30% more diode pump power per minislab gain element. With the 10 watts of input oscillator power, the two stage double pass amplifier configuration shown in **Figure 1.4,** we predict 50 W output power after double passing the first amplifier stage. The output power after the double-passing the second amplifier stage is 130 W. After spatial filtering to a TEM$_{00}$ mode, the available power is 100 W. **Figure 1.5** plots the amplifier output power in watts as a function of passes through the upgraded Stanford cw minislab head. The goal of this phase of the program is to confirm the minislab amplifier gain and power extraction efficiency at the 100 W output power level. The experience with these Nd:YAG slab amplifiers will allow optimization of the advanced amplifier configuration designed for power scaling to the kilowatt level with spatial mode control.

A second goal is to use this high power laser source for harmonic generation studies and for illumination of interferometers to study the thermal loading of the optical components and the interactions between thermal loading and active control of the optical components.

2. Advanced Slab Amplifier

We propose the development of an advanced amplifier design that can be operated at power levels of 50-100W and can be reliably scaled to kilowatt power levels. The advanced amplifier design incorporates relay imaging to preserve the spatial mode through the amplifier, active mirror technology to correct beam tilt and low order beam distortion, and a Faraday rotator to isolate the amplifier from back-reflected beams. The advanced amplifier module will be designed for power scaling to the kilowatt level without the need to change the basic design. Thus, if the amplifier is developed at the 100 W power level, scaling to hundreds of watts and beyond involves increasing the volume of Nd:YAG and the power of the diode-laser-pump module but does not require a change in the configuration of the amplifier module.

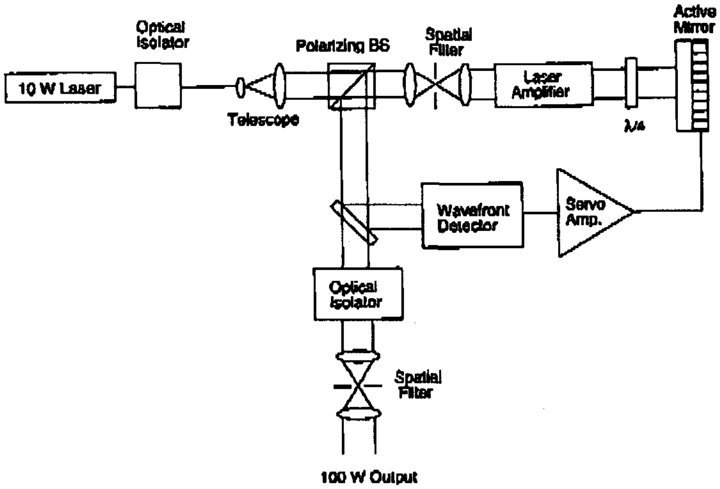

Figure 1.6 Diode laser pumped Nd:YAG amplifier module. The laser beam passes through a Faraday isolator, is expanded and spatially filtered before entering the double pass amplifier. A small part of the output beam is picked off and enters a wavefront measuring interferometer the signals from which are used to control an active mirror. The output passes through a second optical isolator and is spatially filtered a second time.

Figure 1.6 shows a schematic of the advanced amplifier module. The input power is assumed to be a 10-W TEM_{00}-mode beam from the single-frequency Nd:YAG laser. This beam is expanded, transmitted through a Faraday isolator and then transmitted through a rectangular spatial filter that produces a super-Gaussian-shaped roll-off at the edges of the rectangular, flat-topped beam. The rectangular aperture is the input aperture of the amplifier module. This aperture is relay imaged by a telescope onto the input face of the Nd:YAG slab amplifier. The rectangular beam nearly fills the aperture of the slab. The relay imaging is essential to preserve the near-field flat-topped beam shape, and is used in all optical systems that follow this input aperture.

The Nd:YAG slab amplifier has normal-incidence faces with an antireflection coating. The angle of incidence relative to the center line of the Nd:YAG slab is designed to maintain the zig-zag optical path within the slab. The normal-incidence slab allows polarization rotation for double-pass power extraction from the amplifier element.

A quarter-wave plate following the amplifier rotates the polarization of the return beam so that the amplified beam can be separated from the incoming beam by a polarizing beamsplitter. Following the waveplate is the active mirror which is controlled by information from a wave front interferometer at the output of the slab amplifier. The active mirror need only correct low order distortions including tilt and cylindrical and spherical distortion in the x and y directions. The thermal time constant for these distortions in Nd:YAG is 0.1 seconds so that the bandwidth of the control loop is low. The separated beam is then transmitted through the Faraday isolator and onto the output aperture of the amplifier module. The relay imaging optics assure that the input aperture is relayed onto the output aperture of the module.

We propose to design and test the advanced amplifier module using the available diode-pumped Nd:YAG-slab-laser head with a normal-incidence, antireflection coated slab. The 10-W Nd:YAG laser beam is spatially filtered to 5-W flat topped beam, and after a single pass through the Nd:YAG amplifier, yields 11.5 W of power. On the second pass this beam is amplified to 24 W which is then available at the output port of the amplifier module. A second Nd:YAG slab amplifier module of the same design will amplify 24 W to 40 W and then to 65 W at the output. This output beam has planar phase fronts with the spectral characteristics of the Nd:YAG power oscillator. This initial testing of the modular relay-imaged amplifiers should provide the experience required to design higher power systems by scaling of the slab amplifier dimensions.

The operation of amplifiers in the efficient but highly saturated mode brings spatial mode distortion. A Gaussian beam profile is flattened at the top and steepened at the edges by the saturated amplifier. This is well known and designs have been invented to maintain the spatial beam coherence during amplification. For high peak power amplifiers, such as those used in the Nd:Glass laser amplifier chain for laser fusion studies, relay imaging of the near-field beam profile is used to maintain beam-spatial-mode coherence. Additional spatial filtering is applied to eliminate Fresnel fringing from apertured beams. High-peak-power laser amplifiers also allow the use of phase conjugation to correct beam phase distortion due to effects in the amplifier. An example is the use of Stimulated Brillouin Scattering (SBS) by the TRW group as a phase conjugate mirror to correct the optical distortion of a three stage Nd:YAG slab amplifier system that is diode-laser-pumped and produces close to 1 kW of average output power at near 10% electrical efficiency. Unfortunately, cw laser power levels are well below the threshold power for SBS scattering. Therefore, a new approach to beam-spatial-mode correction is needed. We propose using active mirror technology, now under development for astronomical telescopes, as the phase correcting element in the advanced amplifer design.

Our relay imaging system emphasizes the use of rectangular beams for maximum energy extraction from the amplifiers. However TEM_{00} modes are possible through relay imaging and spatial filtering schemes, at a cost of a factor of two in the available output power from the amplifier chain. The advantage of the flat-topped beam compared to a Gaussian beam is not only the factor of two in extraction efficiency from the amplifier, and the ability to preserve the beam shape even during amplification in a highly saturated optical amplifier, but the preservation of a planar wavefront at the output. A further advantage is increased efficiency for harmonic conversion from near 60% for the Gaussian beam to in excess of 80% for the flat topped beam. Finally, the flat-topped beam, when combined with spot tiling on the mirrors, is ideal for high-power interferometry since it allows one-dimensional cooling of heat deposited onto the optical elements thus eliminating thermally induced beam distortion and birefringence. This in turn should improve the contrast ratio of the advanced interferometer which will operate at approximately 10 kW of circulating power on the beam splitter.

Power scaling of this amplifier module is straightforward. The amplifier output power increases with the input beam area of the amplifier. The amplifier average power can be increased, at a fixed thickness, proportionally to the area of the cooled TIR faces of the amplifier. The diode-laser-pump power must be increased as the volume of the Nd:YAG slab to maintain the same single-pass gain. The current Nd:YAG slab amplifier operates at 50% of the stress fracture limit for a 1.8 x 1.7 x 56 mm slab with 230 W of diode pump power. A slab amplifier of dimensions 3.6 x 3.4 x 110 mm will generate an output power of greater than 250 W for approximately 1000 W of diode pump power at the stress fracture limit. The slab can be lengthened to reduce the stress at the same diode pump power without altering the single pass gain. The 1/4 kilowatt Nd:YAG slab amplifier still fits into the palm of one hand.

A factor of four increase in power amplification per amplifier module is near optimum for power extraction efficiency. Thus to reach the 1 kilowatt amplifier module the Nd:YAG slab must have the dimensions of 3.6 mm x 7 mm x 220 mm which is well within current crystal growth capability. The thickness of the slab was kept at 3.6 mm because the diode pump radiation is completely absorbed in that thickness. The 1 kilowatt slab amplifier requires 4 kW of diode pump power. The electrical efficiency is expected to be 1/4 of the diode laser electrical efficiency of 40% or 10%. Because of increased pump light absorption, the design of a kilowatt Nd:YAG slab amplifier is an easier task than the design of the 100 W scale cw Nd:YAG laser.

The goal of our research program is to design Nd:YAG sources that meet the spectral and spatial coherence requirements of LIGO and to assist with the knowledge and technology transfer to commercial companies so that products can be engineered to meet the reliability and engineering performance goals required for advanced interferometers.

B. Efficient Frequency Conversion of 1064 nm to 532 nm

A possible enhancement of the LIGO interferometer is to operate at a shorter wavelength than 1064 nm. The most obvious choice is to frequency double the laser to 532 nm. This has the obvious advantage of improved shot noise sensitivity and a less obvious advantage for an advanced interferometer using delay lines. The mirrors can be made smaller for shorted wavelength beams which suffer less diffraction less diffraction. Rather than a complex resonant harmonic generation scheme ***(Yang)*** we propose single pass second harmonic generation in periodically poled Lithium Niobate.

Progress in the development of nonlinear optical materials has lead to increased optimism about the nonlinear frequency conversion of the Nd:YAG laser to 532 nm output . We have recently prepared a 0.5 mm thick, 10 mm wide and 56 mm long, periodically-poled $LiNbO_3$ crystal and demonstrated second harmonic conversion of 5.6 watts of 1064 nm power to 2.25 watts of 532 nm radiation. This required 6.5 micron pitch domain reversal grating over the entire 56 mm of the sample We have initiated a research effort, in cooperation with the GEO Project, to explore high-average-power frequency doubling of the diode-laser-pumped Nd:YAG slab laser and the amplitude noise characteristics of such a source. Our goal is a single pass conversion efficiency in excess of 60% with operational reliability and noise consistent with the advanced LIGO requirements and to understand the damage effects that will ultimately limit performance.

C. Phase Noise Measurements

The Caltech 40 meter Mark II interferometer has obtained the displacement sensitivity required for the initial LIGO interferometer by using, in the arms of the Michelson interferometer, Fabry-Perots with a finess of several thousand. However, it does not have the optical phase sensitivity of 10^{-10} rad/$\sqrt{\text{Hz}}$ at 100 Hz required for the initial LIGO interferometer because there is not sufficient optical power on the beamsplitter. To date, the best phase sensitivity obtained, 1.5×10^{-9} rad/$\sqrt{\text{Hz}}$, was with the 30 meter interferometer in Garching (Shoemaker 1988). Currently experiments towards improving the phase sensitivity are being carried out at MIT using a power recycled 1 meter Michelson interferometer like that shown in **Figure 1.2.** Demonstrating the initial LIGO phase sensitivity requirements in a simple Michelson interferometer requires approximately 75 watts of optical power on the beamsplitter. This power will ultimately be obtained using the 10 watt Lightwave laser and power recycling. Preliminary measurements will be carried out at MIT with a 700 mW NonPlanar Ring Oscillator (NPRO) single frequency Nd:YAG laser.

To make the phase measurement at the shot noise limit requires a suspended mass interferometer in which the physical displacements of the optical components that make up the interferometer result in phase noise small compared to the measurement goal. The MIT group has constructed a 1-meter, differential-arm-length (L_1-L_2=15 cm), power recycled (6 meter recycling arm) Michelson interferometer with the passive vibration isolation and control systems necessary for a phase-noise measurement with a spectral density of phase noise of 10^{-10} rad/√Hz at 100 Hz. Initial measurements will be made using a 700 mW NPRO and a recycling factor of about 100. When the first 10 watt diode-laser-pumped Nd:YAG laser is delivered in the summer of 1996 the recycling factor will be reduced and the measurements will be repeated. We plan to assist in the integration of the 10-W laser into the phase-noise measurement system and then in the phase noise measurements at MIT and in this way we will gain experience for the construction of a 10 meter suspended mass interferometer at Stanford.

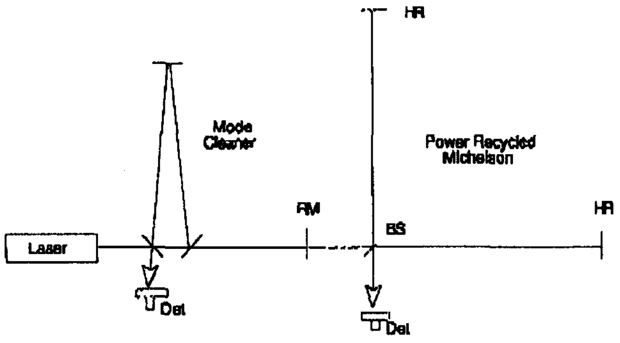

Figure 1.2 The measurement of phase to 10^{-10} rad/√Hz will be accomplished using a suspended mass differential arm length (L_1-L_2=15 cm) Michelson interferometer with low displacement sensitivity (no Fabry-Perot's in the arms) and power recycling to bring the 10 watt laser power up to the required 75 watts. The laser frequency, amplitude and modal noise will be supressed using a 12 meter suspended mass mode cleaner. High Reflecting end mirror (HR), Beamsplitter BS, and power Recycling Mirror (RM).

We propose to collaborate with LIGO in an experiment to measure phase to ***$3x10^{-11}$*** rad/√Hz within the LIGO frequency band using an optical amplifier and the 10 watt Lightwave laser to produce 100 watts of optical power. The goal of these experiments is to understand the sources of optical measurement noise that limit the measurement of optical phase at these high powers and to provide a measurement to confirm unequivocally the suitability of the amplified 10-W, stabilized, diode-laser-pumped, Nd:YAG laser for advanced gravitational wave interferometry.