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High Power Lasers and Novel Optics for Laser Interferometric Gravitational Wave Detectors*

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Abstract

Research at Adelaide is directed towards the development of critical optical components for second generation long baseline gravitational wave interferometers. In particular, the development of high power, low noise lasers, and an investigation to determine the potential of holographic, diffractive and nonlinear optical components for solving some of the problems which could limit the sensitivity of second generation detectors. In this paper we will outline the proposed research and present some early results.

1. Introduction

The task of detecting gravitational waves using laser interferometers places stringent demands on optical and laser technologies (Danzmann *et al.* 1992; Brillet *et al.* 1993). For example, second generation long baseline interferometers will require the development of lasers that can produce ~100 W of output power and yet be single frequency, and have a nearly-diffraction-limited TEM_{00} mode, low beam jitter, low intensity noise and ultra-low frequency noise. They also require ultra-high quality optics (mirrors, beam splitter, etc.) which will minimise the aberration of the light field as it traverses the interferometer, as aberrations will reduce the light power stored in the interferometer arms and decrease the sensitivity of the interferometer.

First generation long baseline gravitational wave interferometers (LGWI) presently being constructed in the USA and Europe make use of existing technology with provisions for incorporating improvements as they emerge. However, some of the existing technology may not be scalable, in either performance or cost, to the parameters required for a practical gravitational wave observatory. Thus, experimental gravity research at the University of Adelaide is directed towards the development of some of the critical optical components for second generation LGWI. In particular, the development of the high power, low noise lasers and an investigation to determine the potential of holographic, diffractive and nonlinear optical elements to solve some of the problems presented by optical aberrations in LGWIs.

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2. High Power, Low Noise Lasers

An important consideration in the design of a long baseline interferometer is the choice of laser wavelength. At shorter wavelengths, the beam diffracts less and thus the diameter of the interferometer mirrors and the interferometer vacuum tube can be reduced; thereby reducing the cost of the interferometer. Also, since the shot-noise-limited strain sensitivity of an interferometer is $\propto \lambda^{\frac{1}{2}}$ (Edelstein *et al.* 1978; Winkler 1991), shorter wavelengths would allow a better sensitivity. Longer wavelengths, on the other hand, are scattered less by the residual gas in the vacuum and by imperfections in the optics. Other important factors in the choice of laser wavelength are the losses (absorption and scattering) in the mirrors and beamsplitter, and the availability of suitably quiet and powerful lasers.

Prototype interferometers use Ar-ion lasers operating at 514·5 nm. Such lasers can produce output powers of 2–5 W in a single frequency TEM_{00} mode, and their intensity and frequency can be stabilised. In prototypes that have Fabry–Perot cavity arms, the frequency stabilisation is accomplished using a two-stage nested servo loop in which the laser is pre-stabilised to a monolithic Fabry–Perot reference cavity and then this combination is stabilised to one of the high-finesse Fabry–Perot arms of the interferometer. Using this system, the free running frequency noise of the Ar-ion laser $S_{\mathrm{f}}{}^{\frac{1}{2}}(1\ \mathrm{kHz}) \approx 2\times10^{3}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ can be reduced to $S_{\mathrm{f}}{}^{\frac{1}{2}}(1\ \mathrm{kHz}) \approx 2\times10^{-5}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ (Hough *et al.* 1991).

However, the electrical 'wall-plug' efficiency of an Ar-ion laser is typically 10^{-4} and thus it would cost approximately A$440k per annum in electrical power costs alone to produce 100 W of laser power—assuming such a proposal were technologically feasible. The cost would be even further increased by the need to regularly replace the laser plasma tubes.

An alternative laser may be the diode-laser pumped Nd:YAG solid state laser which lases at 1064 nm, and can have an efficiency of up to 20–25%. The main cost associated with this type of laser is the replacement of the laser-diodes—expected to be less than A$40k per annum. Another advantage is that the free-running diode-pumped Nd:YAG laser is much quieter than the Ar-ion laser (Danzmann *et al.* 1992).

There are several possible techniques one might employ to produce a high power laser: (a) amplify a stabilised master laser (MOPA—master oscillator power amplifier), (b) stabilise a free-running high power laser, (c) injection-lock (phase-lock) a high power slave laser using a stabilised master laser, or (d) coherent addition of several phase-locked medium power slave lasers.

It is difficult to achieve efficient energy extraction in a compact device using a MOPA configuration due to the opposing requirements of gain saturation and large gain-length product.

The development of a free running high power laser could also be difficult because of the need to have intra-laser-cavity elements to select the TEM_{00} mode and ensure that the laser operates in a single frequency. These elements would have losses that would limit the output power and could degrade the stability of the laser.

Injection locking of cw lasers is a technique of coherently coupling a low power master and a higher power slave oscillator resulting in a high power output with

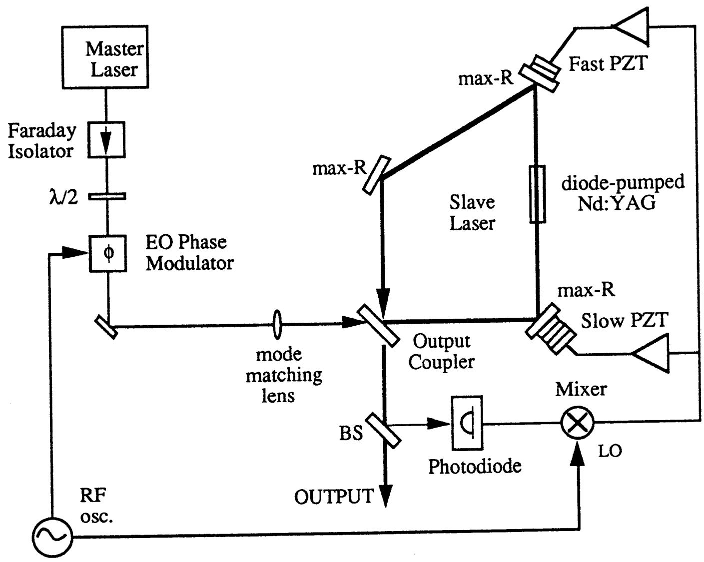

Fig. 1. Schematic for injection locking of two lasers.

the frequency characteristics of the master (Buczek *et al.* 1973; Siegman 1986). As shown in Fig. 1, this is accomplished by injecting the output power from the master laser into the slave laser's resonator, and adjusting the frequency of one of the slave laser's modes, by varying the position of the slave's mirrors, so that

$$|\, f_{\text{master}} - f_{\text{slave}}\,| \;\leq\; \Delta f_{\text{lock}} = \eta\,\frac{T \times \text{FSR}}{\pi}\left(\frac{P_{\text{master}}}{P_{\text{slave}}}\right)^{\frac{1}{2}} .$$

Here η is a parameter that indicates how well the light field from the master laser overlaps with the slave laser mode, T is the transmission of the slave output-coupler, FSR is the free spectral range of the slave laser, and P_{master} and P_{slave} are the output powers of the master and slave lasers respectively. The injected light is then regeneratively amplified by the slave gain medium until it saturates the gain and thereby prevents lasing of any of the slave's free running modes. The output of the slave laser is phase-locked to the master as long as the frequency of the slave's free running mode remains within the locking range, Δf_{lock}. The spatial mode of the output is determined by the resonator of the slave oscillator.

An error signal that indicates the difference between the frequency of the master and slave is developed using the rf-reflection-locking or Pound–Drever system (Drever *et al.* 1983). The error signal is used to control the position of the slave laser's mirrors and maintain the phase lock.

An architecture that attempts to balance the complexity associated with high-power pumping of a large slave laser, and the complexity associated with injection locking several slave lasers and coherently adding their outputs, is shown in Fig. 2. Each detector monitors one output of an 'addition-beamsplitter': if that output is non-zero then the detector generates an error signal which is applied to a piezoelectric actuator which adjusts the position of the previous beamsplitter such that the two beams being added are in-phase. Investigations into the coherent addition of two injection-locked Ar-ion lasers have been reported by Man and Brillet (1984), and Kerr and Hough (1989). A potential problem with the coherent addition scheme is wavefront distortion in the beamsplitters as this will affect the addition process.

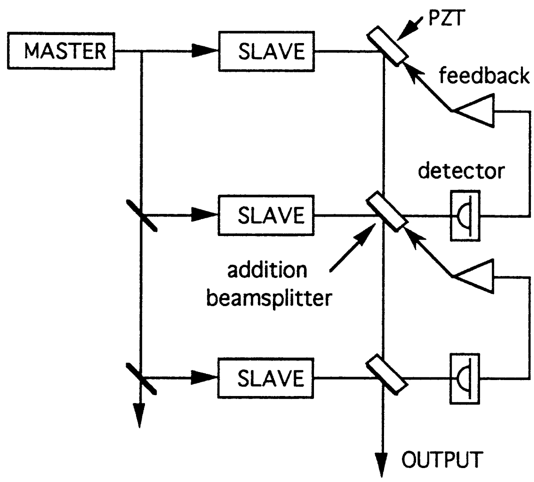

Fig. 2. Schematic for the coherent addition of several phase locked lasers.

Solid state lasers for LGWI are presently being developed for VIRGO at Laboratoire de l' Accelerateur Lineaire (LAL) in Orsay, for LIGO at Stanford University and for GEO600 at the Laser Zentrum Hannover (LZH) using a variety of techniques. At LAL, injection locking of a high power, diode pumped, Nd:YAG, stable resonator, ring laser to a single frequency monolithic, non-planar ring oscillator (NPRO) is being investigated. The pumping scheme uses four 10 W diodes which side-pump the Nd:YAG slab. An output power of 5 W, single frequency TEM_{00} has been produced with a beam quality parameter $M^2 = 1\cdot1$ (Durand *et al.* 1993; Brillet, personal communication 1994).

At Stanford, injection locking of a high power, diode pumped, Nd:YAG, stable resonator, ring laser to a MISER is being investigated. The pumping scheme uses 56 1 W fibre-coupled diodes which side-pump the Nd:YAG slab. An output of 5·5 W, single frequency, 'nearly diffraction limited', TEM_{00} power was produced using 50·4 W of pump power. As expected, the frequency noise of the unstabilised master laser $S_f{}^{\frac{1}{2}}(1\ \mathrm{kHz}) \approx 20\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ was reproduced at the output of the slave. The relative intensity noise at the output of the slave $S_{\mathrm{RIN}}{}^{\frac{1}{2}}(1\ \mathrm{kHz}) = 1\cdot7\times10^{-6}/\sqrt{\mathrm{Hz}}$ was 10 times higher than that at the output of the master (Farinas *et al.* 1994).

At LZH, injection locking of a high power, diode pumped, Nd:YAG, stable resonator, ring laser to an NPRO is being investigated. The pumping scheme employs 28 10 W diodes that are grouped together in stacks and side pump a cylindrical Nd:YAG rod. An output of 15 W, single frequency, TEM_{00} power has been obtained (Golla *et al.* 1993). Intensity noise on the output of injection locked diode-pumped Nd:YAG lasers has also been investigated (Freitag and Welling 1994). It was found that (a) the relaxation oscillation in the slave laser was suppressed by the injection locking process, (b) the intensity noise of the master was amplified by the same factor as the injected carrier, so that $S_{\mathrm{RIN}}{}^{\frac{1}{2}}$ remained constant, and (c) additional audio-frequency intensity noise could be produced by introducing fluctuations in the slave pump power. Thus, to ensure that the relative intensity noise of the injection-locked slave output is no worse than that of the master at frequencies of interest to LGWI, the pumping of the slave must be sufficiently quiet.

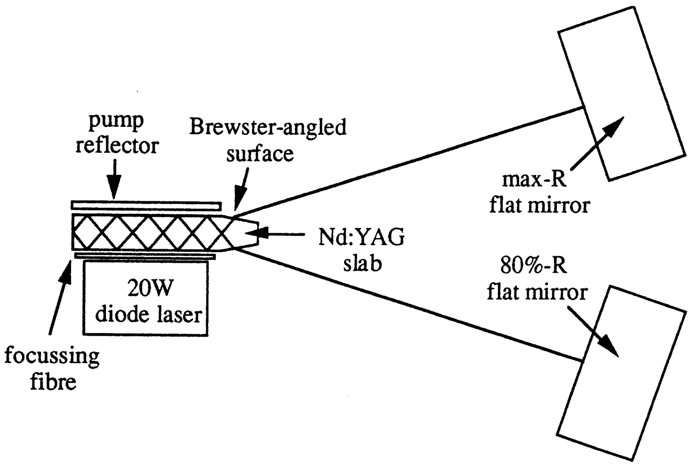

Fig. 3. Schematic of the standing wave laser. The Nd:YAG slab is 15 mm long and the flat mirrors are 33 mm from the Brewster-angled faces.

At Adelaide we are developing an efficient, medium power, diode-pumped Nd:YAG slab, stable resonator, ring laser based on a new diode-pumping geometry (Richards and McInnes 1995). In a standing-wave configuration with flat mirrors spaced 33 mm from the output faces of the slab, see Fig. 3, we have achieved a TEM_{00} output power of 5·8 W using 18 W of absorbed laser diode power (20 W diode output power). The output beam was asymmetric; with waist diameters of 260 and 690 μm, and M^2 values (determined using a Spiricon M^2-101 Beam Propagation Analyser) of 1·1 and 1·9, in the sagittal and tangential planes respectively. This laser will soon be reconfigured as a compact ring laser and injection locked using a NPRO.

All of the above development is concentrating on the use of stable resonator slave lasers, an approach which is derived from low power laser technology. It is unclear whether these techniques can be used to produce a laser that has an output of 100 W, diffraction-limited TEM_{00}. For example, since the mode volume within the gain medium is small in a stable resonator, the pumped region within the gain medium must also be small and this region must be intensely pumped to produce a high power laser. This will necessarily lead to increased thermal stresses in the gain medium which could produce increased thermal lensing and unwanted thermal birefringence.

An alternative approach is to use an unstable resonator slave laser since this allows one to use more distributed pump regions. Unstable resonators have been found to be useful as resonators for high gain, high power lasers and can be injection locked. They have good transverse mode discrimination, can efficiently extract power from extended gain media, and can produce collimated outputs that are very close to diffraction limited (Siegman 1986). Despite these potential advantages, the use of injection-locked unstable-resonator lasers to produce low noise, high power lasers for LGWIs has not been investigated.

Since the architecture of the unstable-resonator laser will be significantly different to that of the stable-resonator lasers, we will need to investigate the inter-dependence of the choice of gain host material, resonator design and pump configuration. The final design will depend on both the physical and optical properties of various host materials (YAG/YLF/YVO/YAP...), and on the availability of required shapes (e.g. large cylindrical rods, hollow cylindrical shells).

The matching of the output of the unstable resonator to the TEM_{00} mode required by LGWIs will be addressed concurrently with the design of the resonator. One attractive approach is to use a variable reflectivity out-coupler, designed to give a near Gaussian beam, instead of the conventional annular beam profile of an unstable laser employing a scraper mirror.

3. Holographic, Diffractive and Nonlinear Optical Elements

A separate and critical issue for the successful realisation of LGWI is the quality of the optical components. In order to achieve the required sensitivity, components of $\sim$0·3 m in diameter must retain a figure of $\lambda/100$ or better, and have extremely low losses and scatter ($\sim 10^{-4}$ or better) while being able to handle stored powers of several kW. Although continuing advances in optical components may succeed in producing suitable optics, holographic and diffractive optical components offer the potential for correction of aberrations and thermal distortions in the whole system, thus resulting in high effective fringe visibility.

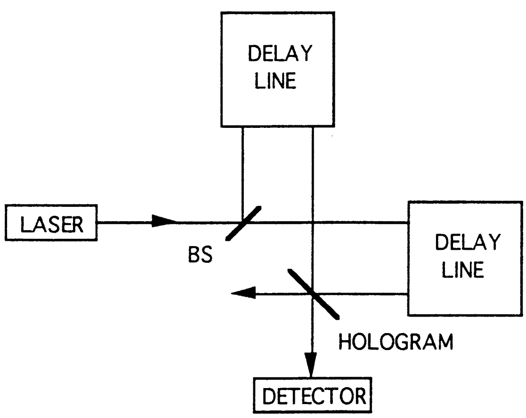

Fig. 4. Schematic of the use of a holographic beam splitter in a Michelson interferometer.

While the use of holographic interferometers to remove optical aberrations is not new (Brooks *et al.* 1965; Heflinger *et al.* 1966; Collier *et al.* 1971; Munch *et al.* 1989, 1990), we believe that the University of Adelaide group is the only one presently investigating the application of this technique to LGWI.

A simple example of the use of a holographic beam splitter in a Michelson interferometer is shown in Fig. 4. By recording a hologram of the interfering, but aberrated, wavefronts and using this hologram as a subsequent beam combining element, interference between two waves with identical wavefronts is assured, thus guaranteeing high fringe visibility and more importantly, complete destructive interference at the detector even in the presence of aberrations (Munch 1993).

We have initiated a pilot program to investigate the potential and limitations of this technology. Issues to be addressed include diffraction efficiency, useful wavelength regime, scatter, noise, useful wavelengths, power handling ability, as well as choice of materials for conventional and possibly real time, phase conjugated optical elements.

Results from early work (Greentree 1994) include the demonstration of aberration correction using silver halide holographic plates and a HeNe laser (632·8 nm), and using dichromated gelatin holographic plates and an Ar-ion laser (514·5 nm). The dichromated gelatin holograms have significantly lower loss than the silver halide holograms, due to the absence of speckle from the emulsion grain. Diffraction efficiencies ranging from 38% to 70% have been achieved using different techniques, leading us to expect that the recording technique can be adjusted to produce the ideal diffraction efficiency of 50%. Residual scatter by the holograms limited the maximum fringe visibility to 0·96, and work is presently in progress to improve this value. Thus, preliminary investigations are encouraging but further work is required to select the preferred holographic medium.

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