Development of Power Scalable Lasers for Gravitational Wave Interferometry

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The design approach for intermediate and high power lasers for gravitational wave interferometry including TAMA 300 is discussed with latest laser performance results.

§1. Introduction

Solid-state lasers capable of operating at significant power levels while maintaining single frequency and excellent beam quality are required for a number of scientific, technological and defense applications, including free space optical communications and remote sensing. One of the most demanding applications appears to be ground based interferometric detection of gravitational waves.[1),2)] In this application a laser emitting hundreds of watts, continuous-wave (cw), in a single frequency TEM_{oo} mode is required in order to reduce the laser shot noise in the detector at high frequencies.

§2. Laser design options

The current preferred laser technology for advanced gravitational wave interferometers (GWIs) is Nd:YAG, due to the suitable wavelength and the mature associated technology, including high quality crystals, efficient diode-laser pumping, high quality coatings, the availability of ultra-stable master oscillators (MOs) and the potential for scaling the power to the required level. The subsequent fundamental design issue is the choice between laser oscillators and power amplifiers. Due to detailed considerations discussed below, we have chosen our approach to be a chain of injection locked laser oscillators: Successive stages of optimized slave power oscillators are frequency locked to a MO, with each slave oscillator having been designed for good mode control and optimum power extraction. The alternative architecture, making use of a MO followed by power amplifiers (MOPA), although inherently simple, is the preferred approach only for very high power devices, where the amplifier is well saturated.

For intermediate power levels (10-100 W), we believe laser oscillators have distinct benefits over the MOPA because of their lower excess noise and superior mode control. The subject of excess (Petermann) noise has been discussed at length by

Siegman and others.[3] This noise arises from amplified spontaneous emission into all of the modes available to the laser. It can be controlled by ensuring that the laser gain medium is well saturated everywhere by the preferred mode. Siegman points out that for an injection locked unstable oscillator and an amplifier with a properly shaped injected signal, it is possible to recover quantum-limited noise performance. In practice, this is most easily achieved by mode matching an injected signal into a single eigenmode of an oscillator. It is rarely achieved in low power amplifier systems, unless great care is taken to match an injected saturating signal to the available gain. For Nd:YAG the saturation intensity is about 3 $\mathrm{kW/cm^2}$, and a well saturated medium should thus have intensities well above this value in regions of significant gain.

As mentioned, another essential requirement for the GWI laser is excellent beam quality for efficient mode matching into the interferometer. At high pump powers, however, the beam quality in Nd:YAG is limited by thermal stress induced birefringence and temperature dependence of the refractive index. The variations in refractive index often manifest themselves as thermal focusing, whereas the stress induced birefringence causes depolarization and losses at polarizing elements. These effects have traditionally limited the power scaling of rod lasers, and have led to the zigzag slab laser design.[4] However, recent progress on birefringence compensation of rod lasers may help reinstate this approach for medium power lasers.[5,6]

In zigzag slabs the wavefront distortion is significantly reduced as each part of the wavefront experiences the same optical pathlength in a sufficiently uniformly pumped gain medium. Thus, a strong thermal gradient in the zigzag plane does not result in a significant thermal lens. The effect of thermal stress induced birefringence can be reduced by using a large aspect ratio slab.[4] Zigzag slabs can be either side-pumped (the approach in this paper), edge pumped[7] or end-pumped.[8]

In solid-state laser amplifiers, pump and gain inhomogeneities lead to degradation in beam quality through wavefront distortions. In a laser oscillator, however, small wavefront distortions initially lead to only a reduction in power and not necessarily a reduction in beam quality as the resonator optics can dominate the wavefront shape. Thus, a well-designed resonator can ensure both improved beam quality due to the resonator transverse mode control and efficient coupling of the laser mode to the gain medium, thereby saturating the gain and minimizing noise.

We have tested these ideas in side pumped slab lasers ranging from 5 to 80 W and have successfully demonstrated very low phase noise and diffraction-limited beam quality in an injection locked 5 W laser.[9,10] Currently we are building an advanced 10 W version for use in the ACIGA[*] high power test facility and in a collaboration with TAMA 300. We have also demonstrated excellent spatial mode and single frequency control in an injection locked 30 W unstable resonator laser[11,12] and are currently working on scaling the concept to 100 W. In this work we have found some limitations due to stress birefringence in our side-pumped gain medium. We shall discuss these results, but emphasize that the basic concept of injection-locked

[*] Australian Consortium for Interferometric Gravitational Astronomy. http://www.anu.edu.au/Physics/ACIGA/

unstable resonators is sound.

§3. Laser results

The 10 W travelling-wave laser shown in Fig. 1 is a coplanar folded zigzag laser[13] optically pumped using 40 W total pump power. The diode-lasers are fast-axis collimated using Doric lenses, and pump only 400 μm of the 3.6 mm high slab. The slab is 29 mm long and 3.2 mm wide, and is cooled by conduction through the top and bottom surfaces, orthogonal to the collimated pump light. The cooling is via thermo-electric coolers, with the final heat exchanger being cooled by forced air to avoid vibrations from cooling water. The laser produced 12.8 W multimode output power from 40 W pump power in a standing-wave configuration, with a slope efficiency of 38%. As a travelling-wave oscillator (Fig. 1) it achieved single mode operation at 10 W output power.

The mirror positions and curvature for the single mode travelling-wave oscillator were optimized from the measured vertical thermal lens focal length of 6-7cm and negligible horizontal thermal lens. Figure 2(a) shows a zero fringe interferogram of the pumped slab along the zigzag path travelled by the laser mode. The corresponding phase information is shown in more detail in Fig. 2(b). The central (pumped) region of the interferogram was fitted to a parabola (Fig. 2(c)), giving a thermal lens focal length of 6.3 cm. Single longitudinal mode operation will be achieved by injection-locking. The frequency of the slave resonator is controlled using a combination of a low frequency, high dynamic range piezoelectric transducer (PZT) and a high frequency, low dynamic range PZT to provide sufficient bandwidth and dynamic range for long-term locking.

The scalability of the top and bottom cooled zigzag laser is limited to output powers of tens of watts, as the focal length of the vertical thermal lens is related to the pump power density and the pathlength of the mode within the laser crystal. Increased pump powers result in a very short thermal lens (see Fig. 2) causing a poor coupling to the gain region and hence a decrease in laser efficiency. This problem can be avoided by cooling the sides rather than the top and bottom, and

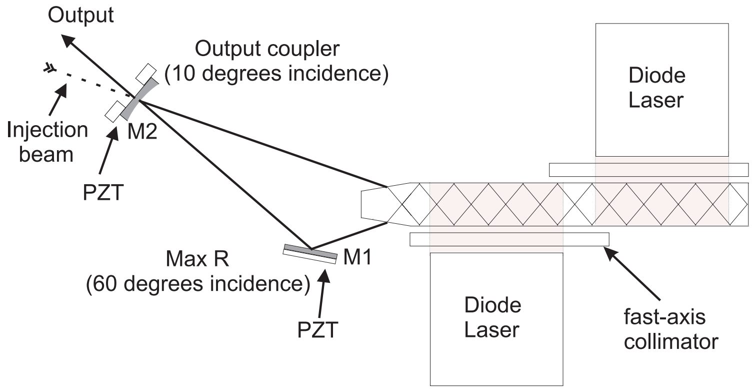

Fig. 1. 10 W travelling-wave oscillator configuration.

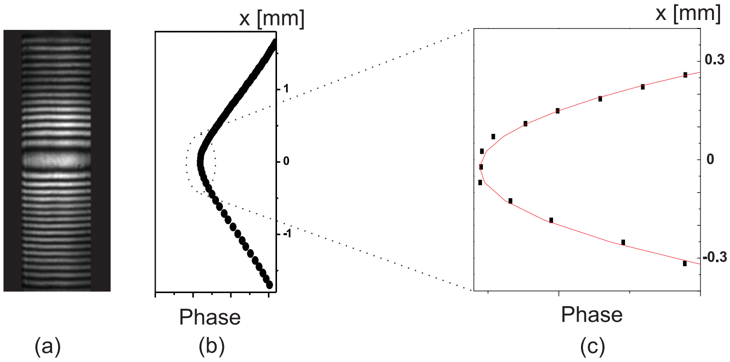

Fig. 2. (a) Zero fringe interferogram, (b) data from tilted interferogram, and (c) extract from the pumped region within the slab showing a parabolic fit to the lens data (thermal lens focal length 6.3 cm).

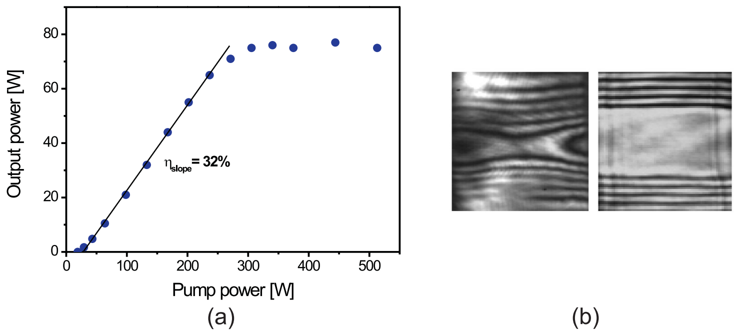

Fig. 3. (a) Laser output power as a function of pump power, slope efficiency of 32%, and (b) horizontal negative lensing within pumped region due to pump non-uniformity (left) and improved pump uniformity with negligible horizontal lens (right).

results in a power scalable geometry as it is pumped and cooled through the same area. For example, at 40 W pump power side pumping and side cooling allows the focal length of the thermal lens to be increased from 6 cm to several metres,[11)] and this reduced lensing can be maintained for pump powers of hundreds of watts. The output power of the laser is increased by increasing the height of the pumped zone within the crystal while maintaining constant pump density. The increased pumped region and minimal thermal lens allows a large mode size which is ideally suited to an unstable resonator. We have demonstrated injection-locked performance of an unstable resonator with 20 W output power.[12)]

Our efforts to power scale the side-pumped, side-cooled multimode laser is currently limited to 80 W as shown in Fig. 3(a). The power saturation above pump powers of 250 W is believed to be due to two phenomena. One of these is pump inhomogeneity in the horizontal pump profile which induces a horizontal negative thermal lens (shown in the zero fringe interferogram in Fig. 3(b), left). This lens increases clipping loss at the Brewster-angled window apertures and reduces the energy extraction efficiency of the horizontal laser mode. It was eliminated by improving the homogeneity of the pump distribution; the reduced wavefront distortion is shown in Fig. 3(b), right. The second limitation causing saturation is thermally induced stress birefringence which results in regions of depolarization at the outer edge of the pump distribution. This depolarizes the higher-order stable modes thus saturating the output power. The birefringence arises from the non-ideal vertical pump distribution and because the aspect ratio of our laser slab is not sufficiently large.[4] We are currently improving the pump distribution and aspect ratio of the slab in a separate experiment.

§4. Conclusion

The development of the 10 W slave laser has been completed and it will be injection locked using techniques developed for the 5 W laser. We have also invented a new zigzag gain medium design which we expect will enable us to increase the output power of the unstable resonator laser to beyond 80 W.

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