Gravitational-wave detectors require a laser that provides single-frequency, polarized, fundamental-mode output at high power. Ideally, the laser would also be reliable and efficient, capable of being operated 24 hours per day for years. While argon-ion lasers have been used in gravitational-wave interferometry, they do not meet the reliability, output power, and electrical efficiency requirements of the next generation of gravitational-wave receivers.

In this Letter we describe a laser-diode-pumped Nd:YAG laser, designed with the source requirements of an advanced gravitational-wave detector in mind.

We selected laser diodes as the pump source because of their high electrical-to-optical efficiency and good spectral overlap with the pump bands of solid-state lasers. In addition, laser diodes have long lifetimes. One can gain additional reliability in laser-diode-pumped solid-state lasers by coupling multiple laser-diode pump sources to the gain medium with optical fibers. In such a scheme, failed laser diodes can be replaced without great affect on the operation of the solid-state laser. In addition, fiber coupling offers great flexibility, since the pump source and the laser head can be designed almost independently.

To test the fiber-coupling concept, we operated 56 1-W fiber-coupled laser diodes (Sony SLU-304-XR) as the pump source. The lasers operated at 90% of their rated maximum output power; therefore 50.4 W of pump power was available. The laser diodes were coupled into 300-μm core-diameter, 0.2-numerical-aperture optical fibers at an average coupling efficiency of 62%. The fiber ends were bundled together, placed in a fixture, glued into a single line, and polished flat. This line emitter measures 0.3 mm x 20 mm and emits 31.4 W of power. Each laser diode was independently temperature tuned to emit at 808 nm to maximize absorption in Nd:YAG.

In designing the laser gain medium, we chose a side-pumped, Nd:YAG, slab laser with direct contact cooling. Nd:YAG was selected as the laser material because of its good optical and thermomechanical properties, its low bulk scatter loss, and the relative ease with which it can be fabricated. We chose a side-pumped architecture because of the low brightness of our pump source. We employed direct-contact conduction cooling, as this simplifies the head fabrication, and we used a rectilinear geometry to minimize depolarization loss. In cylindrical geometry lasers, heat flow in the radial direction leads to a spherical thermal lens and radial and tangential stresses. These stresses lead to spatially dependent depolarization loss in a linearly polarized beam. A rectilinear geometry laser has a rectangular cross section, with heat removal from two opposing sides. In this geometry the thermally induced distortions include a cylindrical thermal lens and Cartesian stress components. These stress components do not lead to any depolarization in a linearly polarized beam. A zigzag slab laser is a rectangular geometry laser with a signal beam that bounces back and forth in the plane of heat removal. Therefore, in an ideal zigzag slab laser, all thermally induced beam distortions are eliminated by either the rectilinear geometry or averaging in the zigzag optical path. In our design, heat flows in the direction normal to the plane of signal propagation; hence our design is not a zigzag slab. We expect low depolarization losses and a thermally induced cylindrical lens.

Figure 1 shows a schematic of our miniature-slab laser. The gain medium is a 1.5 mm x 1.5 mm x 24 mm Nd:YAG parallelepiped. It is polished such that the signal beam enters at Brewster's angle, undergoes 10 total internal reflections, and exits again at Brewster's angle. The pump fiber bundle is held a few millimeters above the slab and shines directly onto the top of the gain medium, pumping the central third of the slab. After one pass, a gold-coated glass spacer reflects the pump light. We estimate a double-pass pump absorption efficiency of 70%. The gain medium is conduction cooled through the nonoptical side faces of the parallelepiped. We use a thin indium sheet to relieve strain between the gain medium and a water-cooled copper clamp that holds the Nd:YAG slab.

We tested the performance of the laser head in a standing-wave optical cavity. The cavity consisted of a 5-m radius-of-curvature convex high reflector and a 1-m radius-of-curvature concave output coupler placed 19 cm apart, with the gain medium...
Fig. 1. Schematic of the laser-diode-pumped Nd:YAG laser head. The laser is pumped from above by 56 300-μm core-diameter optical fibers. A gold-coated mirror is used to double pass the pump light. Heat is removed through a thin indium sheet in physical contact with the nonoptical side faces.

Fig. 2. Input–output plot for the standing-wave laser. Each point represents the addition of the pump power of a single laser diode. The maximum TEM\textsubscript{00} output power is 8.0 W. The linear fit corresponds to a threshold power of 8.3 W and a slope efficiency of 19%. Also plotted is the output power of the injection-locked ring laser.

centered between them. The laser operated in a linearly polarized TEM\textsubscript{00} mode. A maximum output power of 8.0 W was obtained with an output coupling of 9.8%. Figure 2 shows the output power at 1.064 μm versus the laser-diode output power. We generated each point by successively turning off a pump diode. A least-squares fit to the linear portion of the plot yields a threshold power of 8.3 W and a slope efficiency of 19%.

The laser input–output efficiency, defined as the ratio of maximum output power to maximum pump power, is 16%, and the measured dc electrical efficiency is 1.4%. We calculate the dc electrical efficiency by taking the ratio of the laser output power and the dc electrical power consumed by the laser-diode current sources, the laser-diode temperature controllers, and the laser-head temperature controller. We ignore the power consumed by the recirculating water chiller that maintains the laser-diode heat sinks at 3°C. We also performed a Findlay–Clay analysis\textsuperscript{8} to determine the intracavity losses. We calculate an intracavity round-trip loss of 5.6%, which we estimate to be divided as follows: 3% total internal reflection and bulk scatter loss in the gain medium, 2% residual depolarization loss, and 1% mirror scatter loss and clipping loss. The low depolarization loss shows that our rectilinear geometry successfully eliminated this problem.

We verified single-transverse-mode operation of the laser by measuring the output amplitude on an rf spectrum analyzer. The spectrum showed no evidence of transverse-mode beating within the experiment's dynamic range of 55 dB. The uncompensated cylindrical focusing in the gain medium, whose equivalent focal length is estimated to be 8 cm, leads to an asymmetric and astigmatic output beam with Gaussian beam diameters of 310 and 140 μm at the output coupler.

Single-frequency operation was achieved by injection locking.\textsuperscript{9,10} Figure 3 shows a schematic of the experiment, which is similar to that described by Nabors et al.\textsuperscript{10} The laser head described above is placed in a four-mirror ring cavity consisting of a 5-m convex radius-of-curvature high reflector, a 10%-transmitting flat output coupler, a 1-m concave high reflector, and a flat high reflector mounted on a piezoelectric transducer (PZT). We use a monolithic, single-frequency, Nd:YAG, nonplanar ring laser (Lightwave Electronics Model 122-1064-300-F) as the master laser and Pound–Drever–Hall locking\textsuperscript{11} to derive an error signal that an active loop filter uses to drive the intracavity PZT. This feedback keeps the two laser frequencies within the injection-locking range. When it is injection locked, the ring laser produces 5.5 W of output power in a single direction. We believe that the reduction in output power in the ring geometry compared with that in the standing-wave geometry is due mainly to an unoptimized cavity spatial mode.

Amplitude and frequency noise in the laser are important parameters in the design of a gravitational-wave detector. Table 1 compares the spectral density of intensity and frequency noise of our injection-locked ring laser, an argon-ion laser,\textsuperscript{12} and a stabilized nonplanar ring laser\textsuperscript{13} (our master laser).

Fig. 3. Schematic of the injection-locking experiment. A loop filter (not shown) uses the Pound–Drever–Hall error signal to generate the control signal that drives the ring cavity PZT-mounted mirror. This feedback loop keeps the diode-pumped laser cavity locked to the single-frequency laser. LPF, low-pass filter.
Table 1. Summary of Laser Amplitude and Frequency Noise

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative Intensity Noise (1/\sqrt{Hz})</th>
<th>Frequency Noise (Hz/\sqrt{Hz})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At 100 Hz</td>
<td>At 1 kHz</td>
</tr>
<tr>
<td>300-mW Master oscillator(^a)</td>
<td>1.8 \times 10^{-7}</td>
<td>100</td>
</tr>
<tr>
<td>5.5-W, Injection-locked power oscillator</td>
<td>1.7 \times 10^{-6}</td>
<td>6 \times 10^{-7}</td>
</tr>
<tr>
<td>Argon-ion laser(^b)</td>
<td>2.0 \times 10^{-5}</td>
<td>3 \times 10^{3}</td>
</tr>
</tbody>
</table>

\(^a\)Ref. 13.
\(^b\)Ref. 12.

In summary, we have built a laser-diode-pumped Nd:YAG laser as a first step toward meeting the laser requirements for gravitational-wave detectors. We use fiber coupling of multiple laser-diode pump sources to increase the reliability of the design and a rectilinear laser geometry to achieve low-loss operation at high pump power. We have obtained 8.0 W of power in a TEM\(_{00}\), linearly polarized output mode from a standing-wave cavity. We have also demonstrated an injection-locked ring laser that produces 5.5 W of single-frequency radiation. The relative intensity noise and spectral density of frequency noise of the laser are more than an order of magnitude lower than those of an argon-ion laser at audio frequencies.

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References