40-W cw, TEM_{00}-mode, diode-laser-pumped, Nd:YAG miniature-slab laser

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We have built a diode-laser-pumped Nd:YAG slab laser that emits 40 W of cw power in a TEM_{00} mode and 72 W of power in multimode operation when pumped with 235 W. The slope efficiencies are 22% for TEM_{00}-mode operation and 36% for multimode operation. The laser uses a zigzag slab geometry to reduce thermally induced distortions and operates at less than one wave of distortion at the full pump power. A significant advantage of our design over those of previous slab lasers is a new Teflon AF protective coating on the slab total-internal-reflection surfaces, which greatly simplifies the mounting and cooling of the slab laser medium.

Gravitational-wave interferometric receivers and high-power resonant nonlinear optical interactions require an efficient laser that provides many tens of watts in a nearly diffraction-limited mode. Previous attempts to build high-power, high-beam-quality lasers have typically used a rod laser design, with either end or side pumping.[1,2] However, at high powers thermal lensing, stress birefringence, and biaxial focusing degrade laser performance. The zigzag slab design is known to reduce thermally induced effects[3] but has been avoided because of slab fabrication and mounting difficulties. In addition, the zigzag slab geometry typically produces a multimode rectangular output beam that is not useful for applications requiring high beam quality. In this Letter we describe a diode-laser-pumped, cw, Nd:YAG zigzag slab laser that efficiently produces a TEM_{00} mode with a simple water-cooled laser head design. Although the slab laser design has been used successfully in diode-laser-pumped pulsed laser systems,[4,5] this is to our knowledge the first implementation of a uniformly face-pumped, face-cooled, cw, diode-pumped slab laser.

The goal of our design is to produce a laser operating at many tens of watts with minimal thermal lensing and stress birefringence. By reduction of the thermal loading effects at these high pump powers, the laser should operate with good efficiency and reliability in a TEM_{00} mode. By minimizing the thermal lensing, we can design a simple resonator that operates well into the stability region while still having a TEM_{00}-mode size large enough to extract the power efficiently. In addition, the laser head design is simple, making it easy to assemble and disassemble.

Figure 1 shows a schematic of the laser head. The Nd:YAG slab is mounted in an aluminum frame and sealed at both ends. We place the O-rings just as one would place O-rings on a rod with no care taken to locate the O-rings away from a bounce point since the slab is protected by a low-index coating. We insulate the top and bottom of the slab by placing gold-coated glass microscope slides in contact with the Nd:YAG slab. The glass slides are coated on the

The last two sides of the frame contain the fiber pump modules. The Nd:YAG slab is water cooled with 2-mm-thick water channels flowing between the slab surfaces and the brass fiber holders. The water flows at a rate of 1 L/min, and the Reynolds number and flow geometry were selected to make the flow turbulent. The fibers are isolated from the water flow by a 0.5-mm antireflection-coated sapphire window glued onto the brass mount. The assembly of this laser head is simple and typically takes less than 10 min.

Compared with lamp pumping, diode-laser pumping offers high electrical-to-optical efficiency, long lifetimes, and good spectral overlap with the absorption bands of solid-state lasers.[6] This last feature is especially useful because it reduces the thermal

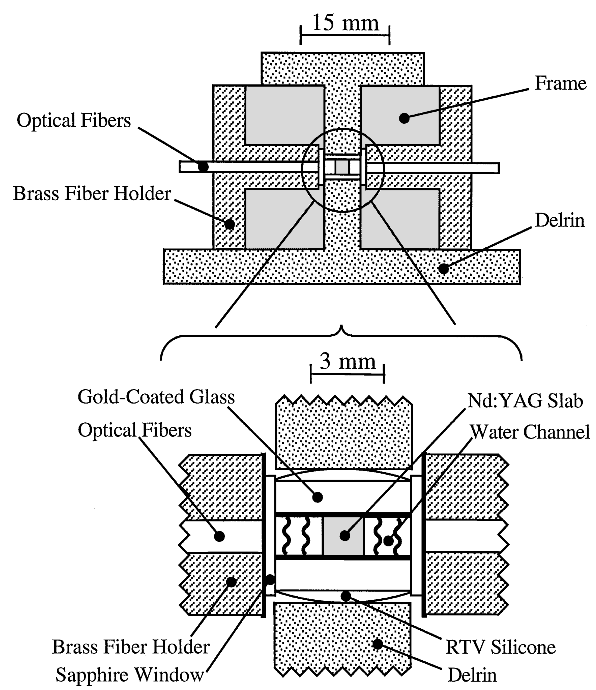


Fig. 1. Schematic of the laser head. The thick black lines on the glass slides and the brass fiber holders

loading of the slab. In addition, we have chosen to use fiber-coupled diode lasers rather than bare diode bars.[7,8] Although this reduces the overall system efficiency, it increases the reliability of the design as well as simplifying the engineering. The diode lasers can be mounted on a water-cooled block well away from the laser head, thus separating the heat loads. Two simple clamps hold all the fibers in the laser head assembly, reducing the laser head size and complexity. The pump sources for our laser are 25 Spectra Diode Laboratories SDL-3450-P5 fiber-coupled diode lasers. Each 600-μm, 0.4-N.A. fiber emits 9.5 W of power for a total of 235 W at the slab. An additional fiber-to-fiber junction to provide easy disassembly accounts for a 5% power loss from each diode laser.

The anticipated pump power levels and desired gain can be used to determine the slab dimensions. The slab cross-sectional area determines the laser gain, while the pump power per unit length is limited by stress fracture of the material. Other factors to consider include the thermal gradient created by the pump absorption, the Nd:YAG absorption depth, and resonator designs for efficient TEM_{00}-mode operation. Given these criteria, we chose a slab with a thickness of 1.7 mm, a width of 1.8 mm, and a centerline length of 58.9 mm. This length corresponds to 22 total-internal-reflection (TIR) bounces and is chosen to operate at 50% of the stress fracture limit at the full pump power of 235 W.[9] Although we do not take full advantage of the slab design because of the small aspect ratio, we still minimize the effects of stress birefringence and thermal lensing and obtain a nearly diffraction-limited mode with good efficiency.

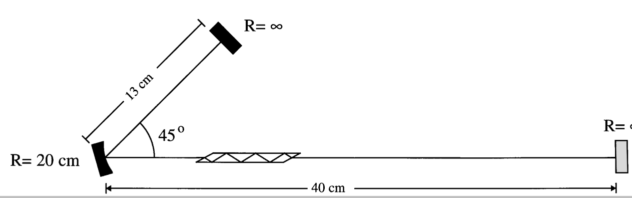
For the benefits of the slab design to be obtained, the laser gain medium must be efficiently and uniformly pumped. The interior surface of the brass fiber holder has been polished and gold coated. The fiber locations are chosen to increase both the reflectivity of the unabsorbed pump power from the opposite fiber holder and to increase the pump uniformity. The 2.5-mm space between the fiber ends and the slab face and the high N.A. of the fibers also act to improve the uniformity of the pump power deposition within the Nd:YAG slab. The glass insulator is gold coated to confine the pump light and increase the absorption by the Nd:YAG slab. We anticipated a minor cylindrical lens because of nonideal insulation on the top and bottom of the slab laser.

To overcome the difficulty of mounting a zigzag slab laser created by the TIR bounce points, we have developed a new coating for these surfaces.[10,11] Previous workers have used dielectric coatings, typically SiO_2, as a protective coating.[12] However, these thick coatings can be difficult and expensive to apply. The coatings we use is a new fluoropolymer, Teflon AF 1600, developed by duPont. This polymer is optically clear throughout the visible and near-IR regions of the spectrum, has a refractive index near 1.3, and is soluble in perfluorinated solvents. We apply this protective layer to a cleaned Nd:YAG slab surface by painting the surface with the Teflon AF solution. The solvent evaporates within a few minutes, leaving initial concentration. This coating prevents evanescent wave coupling at the TIR interface and permits direct water cooling of the zigzag slab without wave-front distortion. It also eliminates the need to locate O-rings away from TIR bounce points. In addition, the coating appears durable; we have noticed no degradation in laser operation even though the Teflon AF-coated slab has been continuously submerged in cooling water. During the optimization of the laser head, the Teflon AF coating occasionally had higher losses than expected. When this happens, the laser head is disassembled and the slab is recoated. Complete disassembly, cleaning, recoating of the slab, and reassembly can be done in less than an hour. Finally, this coating introduces minimal loss at the TIR bounces; typical losses are 0.1–0.2% per bounce.

To test the effectiveness of our cooling design, we built a He–Ne interferometer around the slab laser head and counted fringes as the pump power was varied. The interferometer also allowed us to measure any thermal nonuniformity by observing the curvature of the fringe pattern. The fringes for the unpumped slab are flat to better than 1/10th wave and demonstrate that there is no net polishing error or mounting stress. There is a minor cylindrical lens created by the nonideal insulation. However, even at the full pump power, the fringe curvature is less than 1 wave of distortion. This curvature corresponds to a weak cylindrical lens of approximately 1-m focal length, which is easily compensated by the resonator design.

The laser was initially tested with a short confocal cavity. This cavity consisted of a 20-cm radius-of-curvature highly reflecting mirror placed 2 cm from one slab end and a flat 21% output coupler placed 11 cm from the opposite mirror. We calculated the diode-laser input power by monitoring the current to all 25 diode lasers and converting it to optical power using previous calibration measurements. At a pump power of 235 W, the zigzag slab laser emitted 72 W of power in a square, multimode beam. The optical-to-optical slope efficiency was 36% with a threshold of 30 W.

The laser was then operated in a TEM_{00}-mode configuration. We obtained the best performance by using a three-mirror folded cavity, as shown in Fig. 2. The asymmetric thermal lens is compensated by the astigmatism from an off-axis concave mirror. A 20-cm radius-of-curvature mirror was chosen to dominate the thermal lensing in the cavity, and the fold angle necessary to produce TEM_{00}-mode operation at full power was 45°. The mode size in the Nd:YAG slab is 500 μm and can be changed by small displacements in the short, 13-cm leg. It is adjusted so that clipping around the Nd:YAG slab



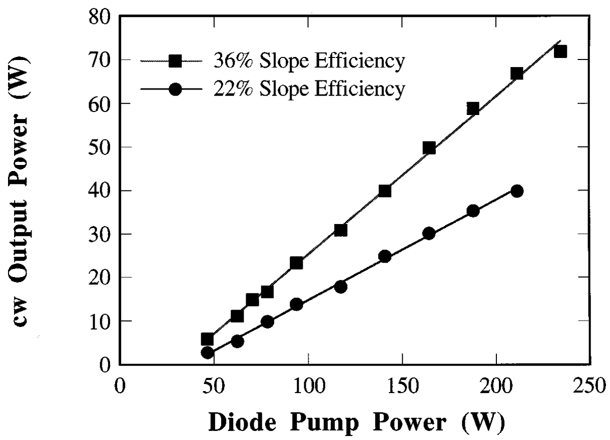


Fig. 3. Input-versus-output curve for multimode (squares) and TEM_{00}-mode (circles) operation.

prevents higher-order modes from oscillating. We confirmed TEM_{00}-mode operation by displaying the beat note from a fast photodetector on a spectrum analyzer as well as monitoring a portion of the output beam with a scanning slit. At most power levels, 55% of the multimode power could be obtained in a TEM_{00} mode by appropriate cavity adjustment. We obtained 40 W of power in a TEM_{00} mode at a pump power level of 212 W. The slope efficiency for TEM_{00}-mode operation was 22%. Figure 3 shows the Nd:YAG cw output power versus diode-laser input power for both multimode and TEM_{00}-mode operation. The M^2 value was measured with the knife-edge technique and was found to be less than 1.3 in both directions. The output is polarized as a result of the Brewster slab faces, with a polarization ratio of better than 100:1.

In the future we plan to convert the standing-wave cavity to a ring cavity and injection lock the laser to obtain stable, single-frequency operation.[13] The laser can then be used as a source for nonlinear optics experiments, which may include resonant doubling to the green, pumping a degenerate optical parametric oscillator to the mid-IR, and gravitational-wave interferometry studies.

In summary, we have built and demonstrated a zigzag slab laser that emits a power of 72 W cw multimode when pumped with 235 W and a power of 40 W TEM_{00} when pumped with 212 W of diode-laser power. We obtained reasonable efficiency for the side-pumped slab design by confining the pump power within a gold-coated box around the slab. This also created a uniform thermal loading profile in the slab laser and contributed to the good fringe pattern. The mounting and cooling problems of the slab laser design were overcome by development of a new coating technique to protect the slab TIR surfaces. This simplified the laser head design and allowed us to design a simple water-cooled structure with less than one wave of distortion at full pump powers of 235 W. The slightly nonideal loading and cooling of the slab laser created a minor cylindrical thermal lens that is compensated by an off-axis concave mirror. Because of the thermal handling benefits of the slab laser design, this laser can be scaled to higher output powers with appropriate scaling of the laser gain medium.

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