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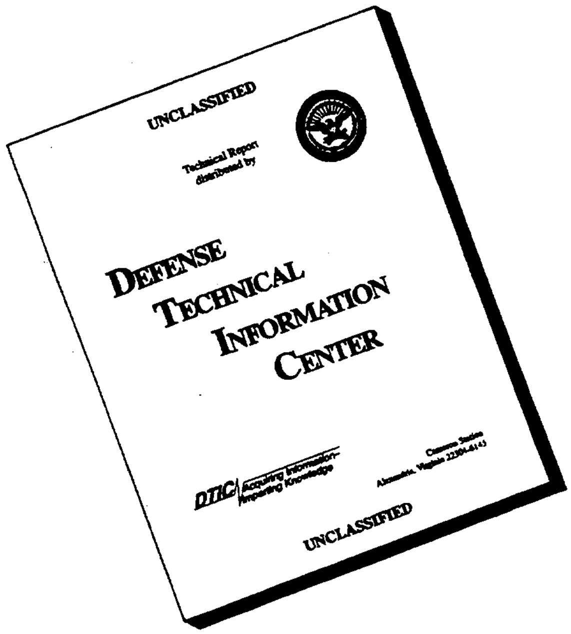

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A 40 W cw, TEM_{00} mode, diode-laser-pumped, Nd:YAG zig-zag miniature-slab laser

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ABSTRACT

We have built a cw, diode-laser-pumped, Nd:YAG slab laser that emits 72 W of multimode power when pumped with 235 W, or 40 W of TEM_{00} power when pumped with 212 W of diode laser power. The slope efficiencies are 36% for multimode operation and 22% for TEM_{00} mode operation. The laser uses the zig-zag slab geometry to reduce the thermal effects associated with high power operation, resulting in less than one wave of distortion at the full pump power. Reasonable efficiency for the side-pumped slab design was obtained by confining the pump power within a gold-coated box which surrounds the slab. TEM_{00} mode operation was obtained in a simple three-mirror folded cavity. The Nd:YAG slab acted as an aperture in the cavity and the astigmatism due to off axis incidence on a curved mirror corrected for a minor 1 meter cylindrical thermal lens. A significant advantage of our design over 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.

2. INTRODUCTION

Gravitational-wave interferometric receivers and high-power resonant non-linear optical interactions require an efficient laser that provides many tens of watts cw in a nearly diffraction-limited mode.[1] Previous attempts to build diode-laser-pumped high power cw lasers with high beam quality have typically used a rod laser design, with either end- or side-pumping.[2,3] However, at high powers thermal lensing, stress birefringence and biaxial focusing degrade laser performance.[4] The zig-zag slab design is known to reduce thermally induced effects,[5] but has been avoided because of slab fabrication and mounting difficulties. In addition, most zig-zag slab geometry lasers are designed to produce high power but in a multimode rectangular output beam that is many times diffraction-limited. In this paper we describe a diode-laser-pumped, cw, Nd:YAG zig-zag 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,[6,7] this is 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 several tens of watts with minimal thermal lensing and stress birefringence. By minimizing the thermal lensing, a simple resonator can be designed which operates well inside the stability region while still having a TEM_{00} mode size large enough to efficiently extract the power. Reducing the thermally induced stress birefringence will reduce cavity losses for the linearly polarized beam and improves the efficiency in a TEM_{00} mode. In addition, the laser head design is simple, making it easy to assemble and disassemble.

3. LASER DESIGN CHOICES

We chose to use diode lasers as the pump source. Compared to lamp-pumping, diode laser pump sources offer high electrical-to-optical efficiency, long lifetimes, and good spectral overlap with the absorption bands of solid-state lasers.[8] The narrow emission spectra of the diode lasers is also useful in high power laser engineering since it reduces the thermal loading of the slab. The emission wavelength of the diode laser can be tuned to the most efficent absorption band of the laser material, reducing the pump energy delivered to non-radiative transitions and hence the overall thermal loading of the slab. In addition, we have chosen to use fiber-coupled diode lasers rather than bare diode bars.[9,10] Although this reduces the overall system efficiency, it increases the reliability of the design as well as simplifying the engineering. The use of multiple pump sources provides a soft failure mode. If a single diode fails, the power will drop by a fraction, but the laser will remain in operation. Fiber coupling allows this failed diode to be replaced without disassembly of the laser head by either recoupling the fiber to a working diode or turning on a reserve diode to return the output power to the previous level.[11] In this way the laser could operate almost continuously with scheduled maintainence to replace failed diodes. Engineering of the system is simplified by mounting the diode lasers well away from the laser head, thus separating the heat loads. In our system, each

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diode is individually mounted on a thermo-electrically controlled (Peltier cooler) copper plate and is temperature tuned to match the 809 nm absorption line in Nd:YAG. Waste heat is removed from the diode plates by water cooling. We have noticed that the laser output power in our system is relatively insensitive to the actual diode temperature to within a few degrees. For this reason, it is possible to consider removing the thermo-electric coolers from the system to improve the overall electrical efficiency. In a system using a large number of diode lasers, the diode lasers could be binned into groups of 5 to 10 based on their operating temperature. The water temperature for each bin of diode lasers could be used to control the diode laser wavelength. Fiber coupling also simplifies the laser head design since no imaging or steering optics are needed to deliver the pump power to the gain medium. Two simple clamps hold all the fibers in the laser head assembly, creating a compact and simple laser head. The pump sources for our laser are twenty five SDL-3450-P5 fiber-coupled diode lasers (SDL, Inc.).[12] Each 600 μm core, 0.4 numerical aperture (N.A.) fiber emits 9.5 watts for a total of 235 watts at the slab. An additional fiber to fiber junction to provide easy disassembly accounts for a 5% power loss from each diode laser. At the beginning of this project, the diode laser cost made this project prohibitively expensive. However, during the three year course of this project, the cost of the diodes has been reduced by a factor of four while the output power has doubled. Even at this point the diode lasers remain a major cost of the system. After removing diode lasers which failed during a 24 hour burn-in performed under our supervision, this set of 25 diode lasers has operated reliably for a few hundred hours. Recently, though, we had our first diode laser failure. Assuming a binomial distribution of independent sources, the projected lifetime of a single diode laser based on this one failure is in the neighborhood of 7500 hours.

With a total diode laser pump power of 235 W available, thermal issues dominate the laser engineering At high pump powers, thermal lensing and stress birefringence become significant problems in rod laser designs, using either end- or side-pumping. It is possible to compensate for these problems. Thermal lensing is the easiest problem to compensate, especially if the rod is uniformly pumped throughout its volume and uniformly cooled from its side. For example, the rod can be ground with concave ends to compensate for the thermal lensing at a fixed operating point.[13] However, since most end-pumped designs do not pump with a uniform top-hat profile but rather with a gaussian profile to improve the pump and signal overlap, there will be higher order aberrations to the thermal lensing. Polishing concave ends onto the rod can make the laser more sensitive to these thermal aberrations induced in the rod. To avoid this problem, others have ground convex curvature onto the rod to dominate any thermal lensing.[14] In this design, the thermal lensing becomes a small perturbation on top of the convex curvature and reduces the effect of thermal distortions. However, both these designs compensate the thermal lensing at a fixed point. Careful resonator design can reduce the sensitivity of the laser to the variations in rod thermal lensing. An example of this is the dynamically stable resonator where the mode volume in the rod is kept under control by appropiate choice of mirror curvatures.[15] Similarly, it is possible to compensate for the stress birefringence by using a dual rod with a quartz rotator placed between the rods.[16] Assuming both rods are pumped identically, the thermally induced birefringence and bifocusing can be canceled by rotating the polarization of all rays by 90°. In practice at moderate power, this design has been used to reduce depolarization losses from over 6% to below 0.2%.[2] As the power is increased, this compensation may not work as well as pump differences in the rods become more significant. The ultimate limit to end pumping is stress fracture of the rod. This depends critically on the cooling mechanism and pump distribution. For a side cooled design, a pump power of 60 W has fractured a rod, while with face cooling as much as 140 W has been applied to a single end.[2,17] Near the stress fracture limit, it is difficult to obtain a diffraction-limited beam without going to extreme lengths to compensate for these various thermal distortions. Stress fracture related issues are less severe in a side-pumped rod since the power density per unit length can be reduced by distributing the pump power over a longer length. However, the problems of thermal lensing and stress birefringence are not avoided because these effects are caused by the cylindrical geometry of the gain medium and, in fact, thermal lensing is independent of length.[18] Nevertheless, it is possible to avoid all of these problems to first order by using a zig-zag slab geometry.[5]

We chose to use a Brewster-end, zig-zag slab design.[5,19] Stress-induced biaxial focusing and birefringence can be eliminated by using a rectilinear rather than a cylindrical geometry and if the slab is pumped and cooled uniformly on the correct surfaces. If the rectilinear slab is both uniformly pumped and cooled on two opposite surfaces, a one dimensional thermal profile is created and the isotherms and stress tensor remains aligned with the rectilinear axes of the slab. A linearly polarized signal beam experiences no birefringence effects or depolarization if it is aligned along one of the rectilinear axes, as it is in a Brewster-end design. In addition, the zig-zag optical path compensates for thermal lensing. The signal beam is confined by total internal reflection as it zig-zags across the thermal gradient in the slab. Since all portions of the signal beam experience the same thermal environment as it travels this zig-zag path, thermal lensing effects are avoided. We chose the geometry of the slab to have a straight resonator structure (zero angle between the ray outside the slab and the long axis of the slab) with Brewster angle incidence. With these constraints and the choice of Nd:YAG as the slab material due to its high thermomechanical properties, the apex angle and internal bounce angle of the slab are completely determined, 28.8° and 32.4° respectively.[19] Since these angles are not identical, there will be unfilled regions of the slab. Since the apex angle is less than the internal bounce angle, these unfilled regions occur at the entrance and exit faces of the slab reducing the useful aperture. Although the full slab is not accessible, rays that enter near the slab apex strike the entrance face after being totally internally reflected, a beam filling the useful aperture of the slab will sweep out the slab volume efficiently by double passing all points in the slab except those near the apex. This "unity fill factor" can make maximum use of the pumped region. In this design, it is important to avoid pumping within one slab width of the slab apex region to avoid end effects.[20] The slab apex is easily deformed if pumped, and this deformation can aberrate the beam. Recent designs have used AR-coated blunt-ended slabs to avoid end effects as well as for other reasons.[6,7] However, the Brewster-ended design does not need dielectric coatings on the entrance and exit faces and is less likely to suffer from parasitic oscillations. As a final note, the benefits of the zig-zag slab design depend critically on uniformly pumping and cooling the TIR surfaces and adequately insulating the unpumped surfaces to minimize thermal effects and beam distortion.

4. LASER DESIGN

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 and the slab aspect ratio. In most zig-zag slab designs, one wants to increase the slab aspect ratio, the width to thickness ratio, as much as possible since this more nearly approximates a semi-infinite slab and improves the thermal handling characteristics. In addition, this increases the cooling area of the slab and increases the pump power limit per unit length. However, since our system is to operate cw in a TEM_{00} mode, we must make some design compromises. The gain of the cw system is too low to operate as an unstable resonator efficiently.[21] This restricts our choice of slab cross section since we cannot use an unstable resonator to extract a large mode volume. In addition, we cannot use phase conjugate optics such as SBS cells to correct any phase aberration caused by the thermal load.[7] Losses must be minimzed in our cw system and it is difficult to find a phase conjugate system with near 100% reflection efficiency that works in the near-IR. For these reasons, we planned to use a stable resonator geometry. To avoid working near the edge of stability with relatively small resonators under 1 meter in length, we are limited to resonator modes smaller than 600 μm. To minimize diffraction effects while still extracting a significant portion of the pump energy the slab aperture should be roughly 3 to 4 times the mode radius.[22] The correct slab thickness is critical to managing the thermal gradient in the slab. A thin slab reduces the thermal gradient but also reduces the amount of pump power absorbed. By designing a reflecting geometry to double pass the pump light, the pump absorption can be increased without increasing the thermal gradient significantly. We chose a slab thickness of 1.7 mm such that a double pass was roughly one absorption depth for our diode-laser pump sources. Since we anticipated a slight cylindrical lens due to imperfect insulation on the top and bottom of the slab, we chose a slab width of 1.8 mm such that a simple resonator would clip equally in both directions while the slab acted as an aperture. The slab length does not affect the gain, so a long slab is favorable to reduce the chance of stress fracture. However, crystal scatter and absorptions losses do increase with length while the fabrication of the slab becomes more difficult. We chose a slab length such that the full pump power would be 50% of the stress fracture limit.[23] This length of 58.9 mm represents 22 TIR bounces in the slab. With this number of bounces, it is important to minimize the loss associated with each TIR bounce. Although this slab design does not take full advantage of the slab design because of the near unity aspect ratio, it minimizes the effects of stress birefringence and thermal lensing, and results in a nearly diffraction-limited TEM_{00} mode output with good slope efficiency.

Careful thought must be given to the mounting problems of the zig-zag slab design. The surfaces which serve to confine the signal beam by total internal reflection are the same surfaces that are pumped and cooled. It is important to choose a mounting design where the signal TIR is not affected by the cooling mechanism. At high thermal loads, water cooling will provide a very high heat transfer coefficient to remove the waste heat. Turbulent water can increase the heat transfer coefficent by as much as a factor of five,[24] but can create phase distortions on the laser beam by coupling to the evanescent wave. Previous workers have avoided this problem by depositing dielectric coatings, such as SiO_2, on the TIR surfaces.[25] However, these thick coatings can be difficult and expensive to apply. We have developed a new coating technique based on a new fluorpolymer, Teflon AF® 1600, developed by DuPont.[26] 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.[27] 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 a protective coating from 3 to 15 μm thick, depending on the initial concentration. This coating prevents evanescent wave coupling at the TIR interface and permits direct water cooling of the zig-zag slab without wavefront distortion. It also eliminates the need to locate O-rings away from TIR bounce points when mounting the slab. 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 for months. During the optimization of the laser head, the Teflon AF® coating occasionally has 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 loss numbers are between 0.1 to 0.2% per bounce.

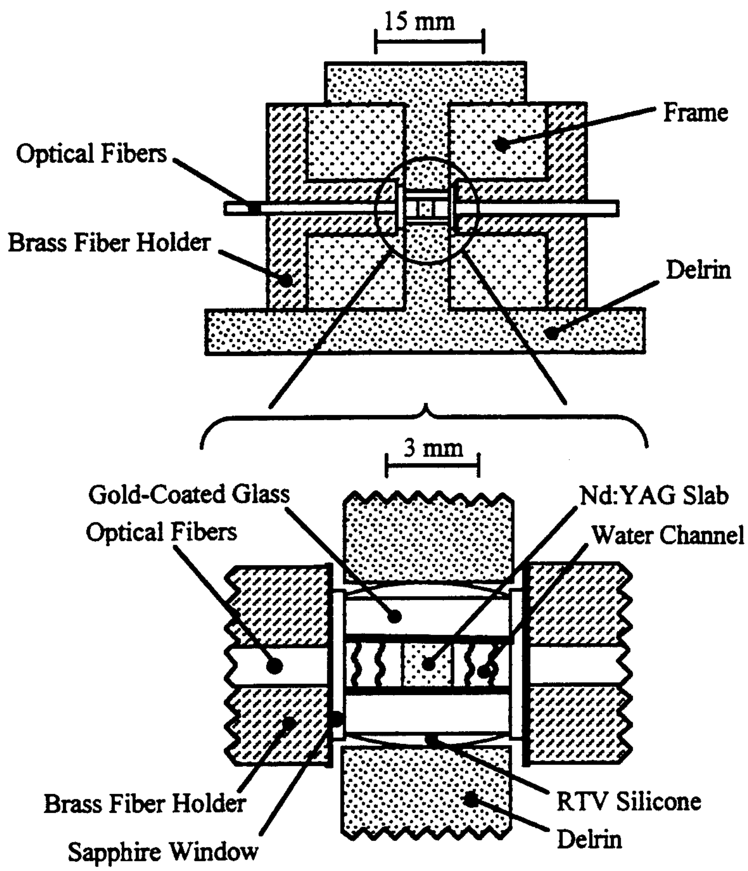

Figure 1. Schematic of laser head. The thick black lines on the glass slides and brass fiber holders represent gold coatings to confine the pump light.

Once the slab is coated, it is placed in the laser head, a schematic of which is shown in figure 1. The Nd:YAG slab is mounted in an aluminum frame and sealed at both ends. We place the O-rings on the slab just as one would place O-rings on a rod. No care taken to locate the O-rings away from a bounce point since the slab is protected by the low index coating. The top and bottom of the slab are insulated by placing gold-coated glass microscope slides in contact with the Nd:YAG slab. The glass slides are coated on the back with a thin RTV silicone layer to relieve stress. 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 liter per minute and the Reynolds number and flow geometry were selected to make the flow turbulent. The turbulent flow does not create phase distortions on the laser beam because the evanescent wave is isolated from the water flow by the protective Teflon AF® coating. The fibers are isolated from the water flow by a 0.5 mm anti-reflection (AR) coated sapphire window glued onto the brass mount. The inside surface of the brass has been polished and gold coated to reflect any unabsorbed pump radiation. The fibers positions are staggered in this brass mount both transversely to increase the unifomity of the pump distribution incident on the slab and longitudinally relative to the fiber positions on the opposite side to increase the pump reflection. The high N.A. of the fibers also acts to increase the uniformity of the pump illumination on the slab. Since the slab is only half an absorption depth thick, we have gold coated all the surfaces surrounding the slab to increase the pump absorption and to improve the overall efficiency. We have attempted to reduce any possible corrosion due to the use of dissimilar metal by hard anodizing the aluminum, gold electroplating the brass, and using deionized water. The assembly of this laser head is simple and typically takes less than 10 minutes.

5. EXPERIMENTAL RESULTS

Figure 2. HeNe interferometer fringe pattern of slab pumped with 125 W of unextracted power.

To test the effectiveness of our cooling design, we built a HeNe interferometer around the slab laser head and counted fringes as the pump power was varied. Average heating of the slab does not add any curvature to the fringe pattern but does change the path length in one arm of the interferometer. The average temperature rise in the pumped slab can be determined by counting fringes. In a previous conduction cooled design the slab temperature rose beyond 150° C due to poor thermal contact across the interface layers. In the water cooled design, the average temperature of the slab rises less than 30° C, demonstrating the effectiveness of heat transfer from the slab into the water. The interferometer also allowed us to measure any thermal non-uniformity 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 distorting the slab. When pumped, there is a minor cylindrical lens created by the non-ideal insulation. A picture of the interferometer fringe pattern with the slab pumped with 125 W is shown in figure 2. At this level, the fringe pattern shows a slight fringe curvature of less than 1/4 wave. 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 meter focal length which is easily compensated in the resonator design.

The laser was initially tested with a short confocal cavity. This cavity consisted of a 20 cm radius of curvature HR mirror placed 2 cm from one slab end and a flat 21% output coupler placed 11 cm from the opposite mirror. The diode laser input power was calculated by monitoring the current to all 25 diode lasers and converting to optical power using previous calibration measurements. At a pump power of 235 W emitted from the fibers, the zig-zag slab laser emitted 72 W in a square, multimode beam. The optical-to-optical slope efficiency was 36% with a threshold of 30 W. The gain was measured by probing the active volume with a Lightwave Electronics 300 mW laser. The small signal gain is $e^{0.9}$. At this level of gain, the laser should be analyzed with the Rigrod laser equation.[28] We have varied the output coupling from 15 to 30% with only small changes in output power, as expected.

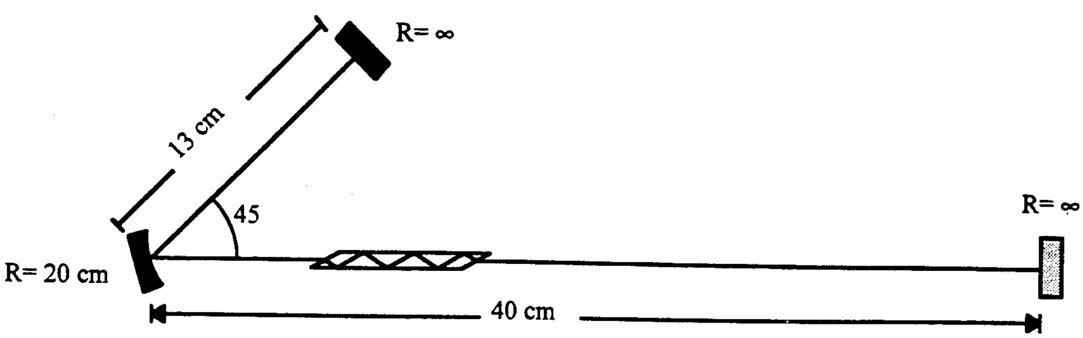

Figure 3. Cavity design for TEM_{00} mode operation.

The laser was also operated in a TEM_{00} mode configuration. The best performance was obtained by using a three mirror folded cavity as shown in figure 3. The asymmetric thermal lens is compensated by using 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 obtain TEM_{00} mode operation at full power was 45^{o}. 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 prevents higher order modes from oscillating. TEM_{00} mode operation was confirmed 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 in a TEM_{00} mode at a pump power level of 212 W. The slope efficiency for TEM_{00} mode operation was 22%. Figure 4 shows the Nd:YAG cw output power vs. diode laser input power for both multimode and TEM_{00} mode operation. The M^2 value was measured using the knife edge technique and was found to be less than 1.3 in both directions. The output is polarized due to the Brewster slab faces with a polarization ratio better than 100:1.

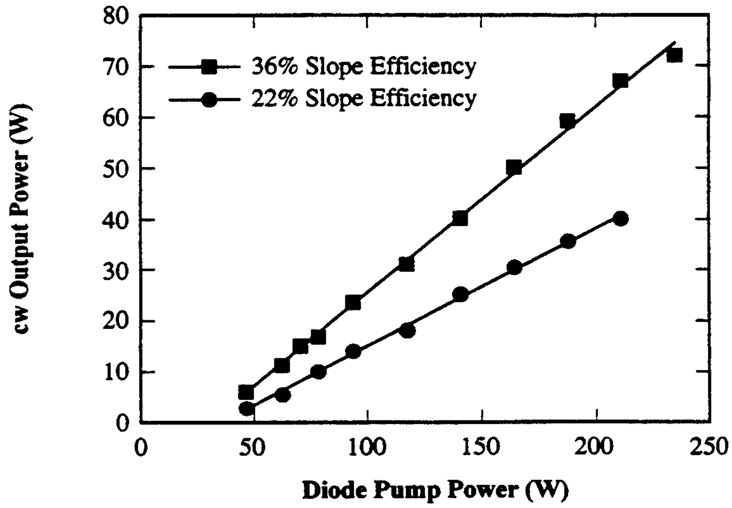

Figure 4. Input vs. output curves for multimode (squares) and TEM_{00} mode (circles) operation.

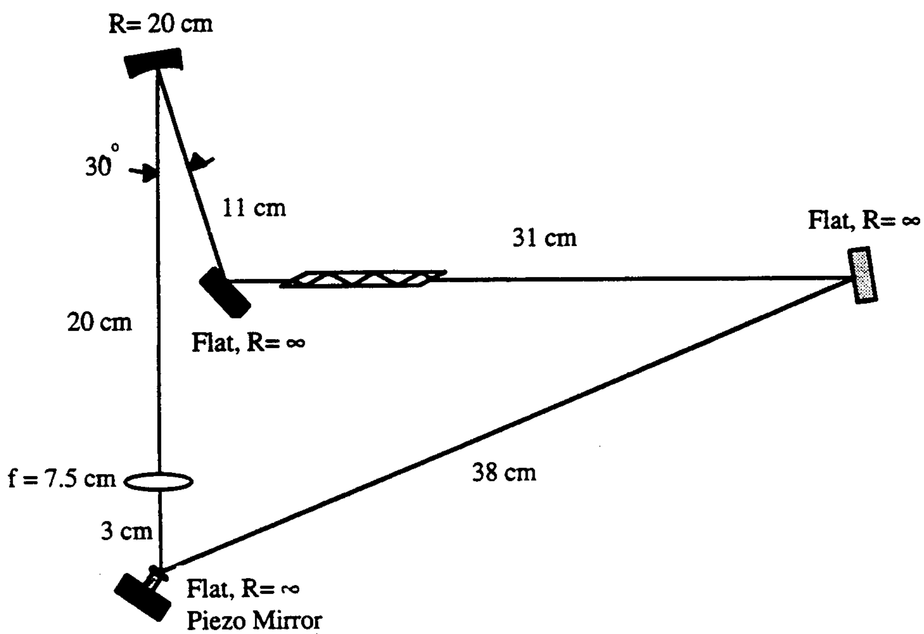

Figure 5. Ring laser cavity used for injection locking.

Finally, we injection locked the laser using the Pound-Drever-Hall FM sideband locking technique.[29,30] In the linear cavity described by figure 3, a waist occurs at each of the flat end mirrors. We have closed the cavity into a ring by transforming one waist to the other using an intracavity lens. The cavity diagram is shown in figure 5. The top half of the cavity is identical to the linear cavity run previously. The flat mirror placed next to the slab is used to steer the cavity beam away from the diode-laser pump fibers. Since there is no astigmatism in the bottom half of the cavity, a 7.5 cm focal length spherical lens was used in place of an off-axis concave mirror and the ring was closed using a flat mirror. This cavity runs in a TEM_{00} mode but at lower power than the linear cavity due to additional clipping at the slab mount. We believe optimization of the intracavity lens focal length and position will improve the output power. We have operated at 165 W of pump power because the cavity has not yet been optimized at the full pump power. At this pump power level, we obtained a single frequency output of 20 watts.

We have injection-locked the laser using a Lightwave Electronics model #122-1064-300-F laser as the master oscillator with the slave laser cavity length stabilized using the FM sideband locking technique. The piezo-mounted mirror has a resonant frequency of 30 kHz, and only this one moderately fast piezo element was needed for stable locking. To compensate for slow temperature drifts in the cavity and to keep the piezo element away from the limits of its throw we have built a feedback circuit to control the master oscillator temperature. This circuit uses the pole in the Lightwave Electronics laser temperature response near 1 Hz and does not affect the much faster cavity servo lock used in the FM sideband technique. Single frequency output was confirmed by using a scanning confocal interferometer, as shown in figure 6. Using both feedback circuits we have observed stable locking over periods greater than an hour at 20 watts of output power. In the future we plan to use this laser as a source for nonlinear frequency conversion.

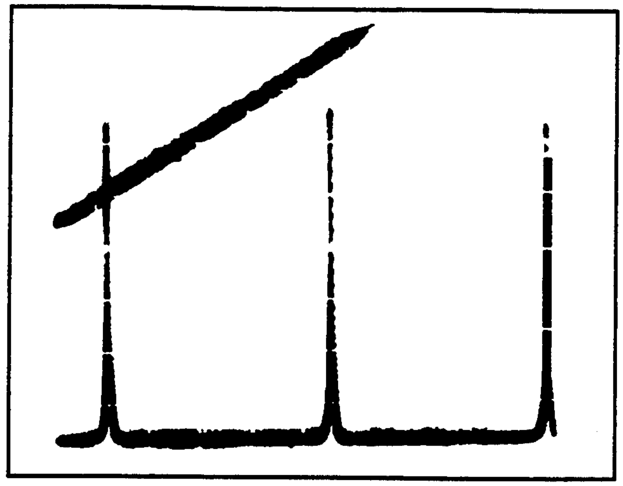

Figure 6. Confocal interferometer trace displaying single freqeuncy output. Upper line displays ramp voltage to interferometer.

6. CONCLUSION

In summary, we have built and demonstrated a zig-zag slab laser that emits 72 W cw multimode when pumped with 235 W or 40 W TEM_{00} when pumped with 212 W of diode laser power. Reasonable efficiency for the side-pumped slab design was obtained by confining the pump power within a gold-coated box containing 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 developing 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 non-ideal loading and cooling of the slab laser created a minor cylindrical thermal lens which is compensated by an off axis concave mirror. In addition, we have injection locked the laser to obtain a single frequency output of 20 watts at a pump power of 165 watts. 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.

7. ACKNOWLEDGMENTS

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