A cw, high-power, conduction-cooled, edge-pumped slab laser

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ABSTRACT

We have developed a high average power zig-zag slab laser based on conduction-cooling and a novel pumping geometry called edge-pumping. The edge-pumping geometry decouples the cooling and optical pumping interfaces, simplifying the laser head design. The advantages of this design include efficient pump absorption, uniform conductive-cooling, high brightness fiber-coupled laser diode pumping, and power scalability. We have demonstrated this new design in a Nd:YAG zig-zag slab laser which operates at 104 W of multimode power for 340 W of pump power with a 40% slope efficiency. TEM$_{00}$ mode operation was demonstrated at 39.5 W for 250 W of pump power at a slope efficiency of 21%. Thermal lensing measurements indicate an effective focal length of < 0.5 m in both the zig-zag and the non-zig-zag planes for 340 W of pump power.

Keywords: Edge-pumping, slab laser, laser-diode-pumped, Nd:YAG laser, conduction-cooling, high power lasers

1. INTRODUCTION

High power laser-diode-pumped lasers are required for many applications such as laser interferometric gravitational wave detection, free space optical communications and industrial manufacturing. These lasers must be robust, and capable of delivering output powers above 50 W while maintaining good beam quality. Stress induced birefringence, thermal lensing, and the stress-fracture-limit makes scaling of rod lasers to high average powers difficult when good beam quality is required. The zig-zag slab geometry has demonstrated scaling to high average powers while maintaining good beam quality and polarization contrast. However, the development of slab lasers in the 20 - 100 W power range has been limited by the low slope efficiencies and the complexity of the pumping and cooling interface in typical slab laser designs. Our edge-pumped slab laser design incorporates conductive-cooling and a novel pumping scheme that represents a significant departure from conventional slab lasers. In the edge-pumped geometry the slab is uniformly cooled on the total-internal-reflection (TIR) faces and the pump power is incident through the non-TIR faces, along the slab width, transverse to both the thermal gradient and the direction of optical propagation. Pumped by fiber-coupled laser diode arrays this design takes advantage of the thermal characteristics of the traditional zig-zag slab design, while improving the efficiency by improving the pump absorption. There are three primary benefits of this design. First, both thermal stresses and pump absorption improve in this edge-pumped configuration as the width/thickness ratio is increased, while conventional face-pumped slab designs require a trade-off between these two properties. Second, the separation of the pumping and cooling interfaces simplifies the opto-mechanical design. Third, the ability to incorporate conduction-cooling, instead of direct water-cooling of the slab, provides greater mechanical stability and removes the failure mechanisms associated with direct water-cooling.

In this paper we describe the first implementation of the edge-pumped, conduction-cooled slab laser geometry. We present results which demonstrate the high slope efficiency and minimal thermal lensing possible in this pumping geometry. The development of a reliable conduction-cooling interface has led to a simple laser head design that is robust and can be scaled to kW average powers.

2. THE EDGE-PUMPED SLAB GEOMETRY

An ideal slab design requires the slab volume to be uniformly heated and uniformly cooled through the two total-internal reflection (TIR) faces. This cooling configuration creates a one-dimensional temperature gradient between the TIR faces. A zig-zag optical path through the slab averages out the first order thermal lens due to this thermal gradient. Conventional slab laser designs have realized the requirement of uniform heating of the slab volume by pumping the slab through the TIR faces (face-pumped). Figure 1a shows a cross-sectional schematic of the conventional face-pumping geometry. Using the same interface for pumping and cooling places significant engineering constraints on the slab laser design. Face-pumped designs

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typically require direct liquid cooling in order to provide uniform pumping and cooling of both faces, complicating the laser head design, and often leading to slab degradation or damage due to particles in the cooling fluid.

Figure 1b shows the cross-sectional schematic of the new edge-pumped slab geometry. The slab is still uniformly cooled on the TIR faces, providing the desired one-dimensional thermal gradient within the slab. However, the pump power is now incident from the non-TIR faces, along the slab width, transverse to the thermal gradient and the direction of optical propagation. The edge-pumped design has the potential for improved pump absorption efficiency and simplified conduction-cooling compared to face-pumping.

![Optical Pumping](image1.png)

**Figure 1:** a) Face-pumped slab geometry, optical pump is incident through the cooling interface. b) Edge-pumped slab geometry, pumping and cooling interfaces are decoupled. For both geometries the cooling interface is the total internal reflection surface.

The advantages of conduction-cooling were recognized early in the development of slab lasers. Cooling uniformity, mechanical stability, protection of the TIR faces, and the separation of the slab from the liquid interface are often sighted as benefits of conduction-cooling. Experimental demonstrations of conduction-cooling through a thin static layer of He gas in lamp-pumped Nd:Glass lasers confirmed these benefits. More recently, conductive-cooling of high power thin disk lasers, and one-sided conduction-cooling of slabs, have been demonstrated. However, the asymmetries of these cooling schemes lead to thermal stresses in the crystals that limit the power scaling. The symmetric cooling of the edge-pumped slab laser provides a design that can be scaled to very high power.

The fundamental limit to scaling slab lasers to high average powers is the thermal stress fracture limit. The stress fracture limit is a function of the slab dimensions and the material thermal shock parameter, Rs. Stress fracture will occur for absorbed pump powers per unit length exceeding

$$\frac{P_{\text{abs}}}{l} = 12 \, R_s \, \frac{w}{t}$$

where $P_{\text{abs}}$ is the absorbed pump power, $l$ is the slab length, $w$ is the slab width, and $t$ is the slab thickness. The material shock parameter, $R_s$, is given by

$$R_s = \frac{(1 - \nu) \, k \, \sigma}{\alpha \, E}$$

where $\nu$ is the Poisson ratio, $k$ is the thermal conductivity, $\sigma$ is the fracture stress, $\alpha$ is the coefficient of thermal expansion, and $E$ is Young’s modulus. The material shock parameter for Nd:YAG is 7.9 W/cm$^2$.

A key advantage to the edge-pumping geometry can be seen by examining the effect of slab dimensions on the thermal stress fracture limit and the pump absorption efficiency. Efficient pump absorption requires a long pump absorption path. For face-pumped geometries the pump absorption is a function of $t$, the slab thickness. In the edge-pumped geometry the pump absorption is a function of $w$, the slab width. Equation 1 shows that the stress fracture limit scales proportionally with $w$, but...
and is inversely proportional to \( t \). Therefore, in the face-pumped geometry there is a trade-off between pump absorption and thermal stress induced on the slab. In the edge-pumped design, both higher pump absorption efficiency and lower thermal stress can be achieved by increasing the slab width. This is a critical advantage for a design that is scalable to kW power levels.

3. LASER DESIGN

Figure 2 shows a cross-sectional view of the initial design for the edge-pumped laser head. The Nd:YAG slab is clamped between two polished aluminum surfaces with a layer of indium foil placed between the aluminum and the Nd:YAG slab to improve the thermal contact. The aluminum blocks are water-cooled for efficient heat removal from the laser head. Optical pumping is incident from one side, a diffuse Spectralon reflector on the opposite side of the slab provides double-pass pumping for efficient pump power absorption. Figures 3a and 3b show the engineering drawing and a photograph of the edge-pumped laser head.

The laser diode pump module consists of 35 Spectra-Diode Laboratories SDL-3450-P5 fiber-coupled laser diode arrays, each package delivers a maximum power of 10 W through the 600 μm diameter, 0.4 N.A. fiber. Each laser diode array has a thermoelectric cooler for wavelength control. The laser diode fiber output is connected to a short pigtail fiber. The cleaved output ends of the 35 pigtail fibers are clamped into a Spectralon holder, creating a closely packed linear fiber-array for pump power delivery to the slab. This fiber array is close coupled to the top of the slab, which is antireflection coated. Fiber-coupled laser diode arrays were chosen because they provide easy access for replacing pump diodes without disturbing the fiber array at the laser head, and the remote location of the laser diodes separates the temperature control requirements of the laser diode and the heat removal requirements of the gain medium.

Figure 3a is the engineering schematic of the conduction-cooled, edge-pumped slab laser design. Figure 3b shows a photograph of the aluminum laser head and the 1.55 × 1.8 × 58.9 mm Nd:YAG slab. The fiber optic array assembly that delivers the pump power to the top of the slab is not shown.
The dimensions of the Brewster-end face Nd:YAG slab are 1.55 mm thickness, 1.8 mm width, and 58.9 mm centerline length, corresponding to a 24 bounce TIR path in the slab. Protection of the Nd:YAG slab TIR interface is of critical importance to ensure low loss reflections and long term robust operation. The TIR interface also acts as the conductive cooling interface, therefore, the coating material must have a low index of refraction compared to Nd:YAG, good thermal conductivity, and durability. A 2.5 μm thick SiO₂ coating effectively prevents evanescent wave coupling loss at the TIR interface. The hard SiO₂ coating allows the laser head to be assembled and disassembled without risking damage to the TIR interface. Typical losses in a new slab are 0.1 - 0.2% per bounce for an uncoated slab in air. The losses do not change when the SiO₂ coated slab is clamped into the laser head.

4. EXPERIMENTAL RESULTS

Optical pumping in the edge-pumped geometry causes a nonuniform absorbed pump power profile, which produces a thermal gradient in the non-zig-zag plane of the slab. This thermal gradient will create thermal lensing effects that are not corrected by the zig-zag optical path. A measurement of the 1064 nm fluorescence from a pumping plane within the slab provides a measure of the pump absorption profile. A Spiricon CCD-based beam analyzer was used to image the fluorescence from the slab. The image plane was located within the slab, directly below a pump fiber at the near the end of the slab. Figure 4 shows the fluorescence profile recorded when a single pump laser located at the end of the slab was operated at 8 W of pump power. The profile was averaged over the center 25% of the slab thickness.

![Fluorescence Profile](image)

Figure 4: 1064 nm fluorescence power profile in the pumping direction as imaged by a CCD. This provides a measure of the absorbed pump power uniformity along the pumping axis. The theoretical fit is based on the 1-sided pumping in a double-pass pumping geometry.

As expected there is a small absorbed pump power gradient in the pumping direction, this gradient can lead to beam steering and thermal lensing in this plane. A theoretical fit based on double-pass pumping predicts an absorption coefficient of 3.8 cm⁻¹, close to the directly measured value of 3.4 cm⁻¹. A 2-sided pumping geometry would result in a symmetric absorbed pump power profile with the lowest point in the center of the slab and the maximum absorbed power points at the edges.

Thermal lensing is a critical concern when designing laser resonators and amplifiers, and the thermal lens generated by the thermal gradient shown in figure 3 is not reduced by the zig-zag optical path. The effective focal length of the thermal lens was measured using a HeNe laser probe beam and Photon, Inc.'s BeamScan laser beam measurement system. The effective focal length of the thermal lens in the pumping direction was longer than 0.5 m at all pump powers. Additionally, the zig-zag path removes first order lensing effects in the zig-zag plane, however, a thermal lens is possible in this plane due to nonuniformities in the pumping or cooling of the slab. The magnitude of the effective focal length of the thermal lens in the zig-zag plane was larger than 0.5 m at 310 W of pump power, and larger than 1 m for all other pump powers. These levels of thermal lensing indicate that the slab cooling and pumping are relatively uniform. Most importantly, scaling to higher laser powers can be accomplished without making this thermal lens worse by scaling the area of the cooled slab surfaces proportionally with the increase in pump power.

Multimode laser operation was demonstrated in a 16 cm long cavity consisting of a 10 cm radius-of-curvature highly reflecting mirror, a flat 23.5% transmitting output coupler, and a 10 cm focal length lens located inside the cavity 2 cm from the output coupler. Figure 5 shows the multimode performance of the slab laser. The laser operated with a 41% slope efficiency with a threshold pump power of 35 W. The multimode beam filled the square aperture slab, generating a square beam with a measured M² value of 30 in both the x and the y-axis. The single-pass loss of the slab was measured to be 5%, due to high scatter loss at the TIR interface. This high loss value has a significant effect on the slope efficiency, reducing the single-pass loss to 2% from 5% would increase the slope efficiency from 40% to 50% in this system.

The roll-off of the slope efficiency at high pump powers was observed to be dependent on the average temperature of the slab. It is possible that this effect is related to the "dead sites" phenomenon described by Fan, depolarization losses, or 1064 nm
absorption losses due to thermal population of the lower laser level. Experiments to determine the cause of this effect are underway.

TEM\textsubscript{00} mode operation of the laser was demonstrated using a flat/flat laser resonator with a pair of intracavity crossed cylindrical lenses to compensate for the cylindrical lensing in the laser slab. Figure 5 shows the TEM\textsubscript{00} performance of the slab laser. The $M^2$ was measured to be less than 1.3 for all output powers.

Figure 5: Output power-versus-pump power for the conduction-cooled, transverse-pumped slab laser in multi-mode and TEM\textsubscript{00} mode operation. The multi-mode slope efficiency of 40% demonstrates efficient pump power absorption. The TEM\textsubscript{00} mode laser operated with an $M^2$ below 1.3 for all pump powers. The pump power was measured at the output of the fiber array.

5. CONCLUSIONS

The goal of our research program is to develop a 100 W, TEM\textsubscript{00}, low noise laser for use in advanced laser interferometric gravitational wave detectors. The edge-pumped slab design head is the first step in designing a high power master-oscillator power-amplifier laser system for this application. Based on the oscillator results described in this paper, an edge-pumped amplifier design using slabs with a 3:1 aspect ratio (width/thickness) has been completed. Experiments using these slabs will provide the ability to study the thermal characteristics and confirm the power scaling properties of edge-pumped slab amplifiers.

Models based on the performance of this Nd:YAG laser indicate that the combination of high brightness fiber-coupled laser diode arrays and high pump absorption efficiency show promise for edge-pumping of Yb:YAG slab lasers.

In summary, we have demonstrated the operation of a 100 W, multimode, cw, laser-diode-pumped, conduction-cooled, Nd:YAG slab laser in the new edge-pumping geometry. Absorbed pump power profiles and thermal lensing measurements indicate that small non-uniformities in the optical pumping due to the edge-pumping geometry result in small thermal lenses that can be compensated in resonator and amplifier designs. This new laser design provides a robust device that takes advantage of the thermal and power scaling properties of slab lasers, improves the pump absorption efficiency, and greatly simplifies laser head design and fabrication.

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REFERENCES


