Open access • Journal Article • DOI:10.1109/JQE.1983.1072061

Reduced thermal focusing and birefringence in zig-zag slab geometry crystalline lasers — Source link

Thomas J. Kane, R. C. Eckardt, Robert L. Byer

Institutions: Stanford University

Published on: 01 Sep 1983 - IEEE Journal of Quantum Electronics (IEEE)

Topics: Slab, Solid-state laser and Birefringence

[4] J.W.M. Beisterbos and H.W.M. Salemink, "High-frequency intensity noise behavior during accelerated life tests of narrow-stripe proton-isolated DH AlGaAs lasers for optical communications," *Electron. Lett.*, vol. 18, pp. 300–302, Apr. 1982.
[5] J. A. Armstrong and A. W. Smith, "Intensity fluctuations in lasers," in *Progress in Optics*, vol. VI, E. Wolf, Ed. New York: Wiley, 1967.
[6] C. Freed and H. A. Haus, "Photoelectron statistics produced by a laser operating below and above the threshold of oscillation," *IEEE J. Quantum Electron.*, vol. QE-2, pp. 190–195, Aug. 1966.
[7] J. Perina, *Coherence of Light*. London: Van Nostrand Reinhold, 1971.
[8] R. J. Glauber, "Photon statistics;" H. Haken, "The theory of coherence, noise and photon statistics of laser light;" F. T. Arecchi and V. Degiorgio, "Measurement of the statistical properties of optical fields," in *Laser Handbook*, vol. 1, F. T. Arecchi and E. O. Schulz-Dubois, Eds. Amsterdam: North-Holland, 1972.
[9] S. O. Rice, "Mathematical analysis of random noise," *Bell Syst. Tech. J.*, vol. XXIV, pp. 46–156, Jan. 1945.
[10] I. P. Kaminow, L. W. Stulz, J. S. Ko, A. G. Dentai, R. E. Nahory, J. C. DeWinter, and R. L. Hartman, "Low threshold InGaAsP ridge waveguide lasers at 1.3 μm," *IEEE J. Quantum Electron.*, vol. QE-19, pp. 1312–1318, Aug. 1983.
[11] T. P. Lee, C. A. Burrus, P. L. Liu, and A. G. Dentai, "High-efficiency short-cavity InGaAsP laser with one high-reflectivity mirror," *Electron. Lett.*, vol. 18, pp. 805–806, Sept. 1982.
[12] T. P. Lee, C. A. Burrus, K. Ogawa, and A. G. Dentai, "Very- high-speed back-illuminated InGaAs/InP pin punch-through photodiodes," *Electron. Lett.*, vol. 17, pp. 431–432, June 1981.

Reduced Thermal Focusing and Birefringence in Zig-Zag Slab Geometry Crystalline Lasers

T. J. KANE, R. C. ECKARDT, AND R. L. BYER

Abstract—**Replacing the rod in a Nd:YAG laser with a zig-zag slab resulted in a very substantial reduction of the thermally induced optical distortion without sacrifice of output power or efficiency. This reduction was possible after simple measures were taken to eliminate end and edge effects.**

In this letter, we present interferometric measurements of the thermally induced optical effects in laser crystals cut in both the zig-zag slab and the conventional rod geometries. These measurements confirm the present understanding of zig-zag slab geometry lasers and demonstrate the significant advantages obtained by replacing the rod in a Nd:YAG laser with a slab. We describe simple measures to eliminate end and edge effects and present efficiency and threshold data for the Nd:YAG slab and the rod it replaced.

In conventional cylindrical rod solid-state lasers, both temperature and thermally induced stress change the index of refraction, and the laser beam is distorted. The rod becomes a nonuniform multiwave birefringent element and a strong and polarization-dependent lens. These effects have been thoroughly described and analyzed [1]-[4].

The zig-zag slab laser geometry, also known as the total internal reflection face pumped laser geometry, was invented by Martin and Chernoch at General Electric [5]. This geometry greatly reduces the thermally induced optical effects in the pumped laser [6], [7]. The zig-zag slab geometry is shown schematically in Fig. 1. Focusing is eliminated in the x-direction by the uniformity of the pumping and cooling in that direction, and in the y-direction by the averaging of temperature that takes place over a full zig-zag. The birefringence caused by the thermal stress in a slab is also much lower than that of a rod because the major component of stress averages to zero over a full zig-zag. Recently, we have built and tested

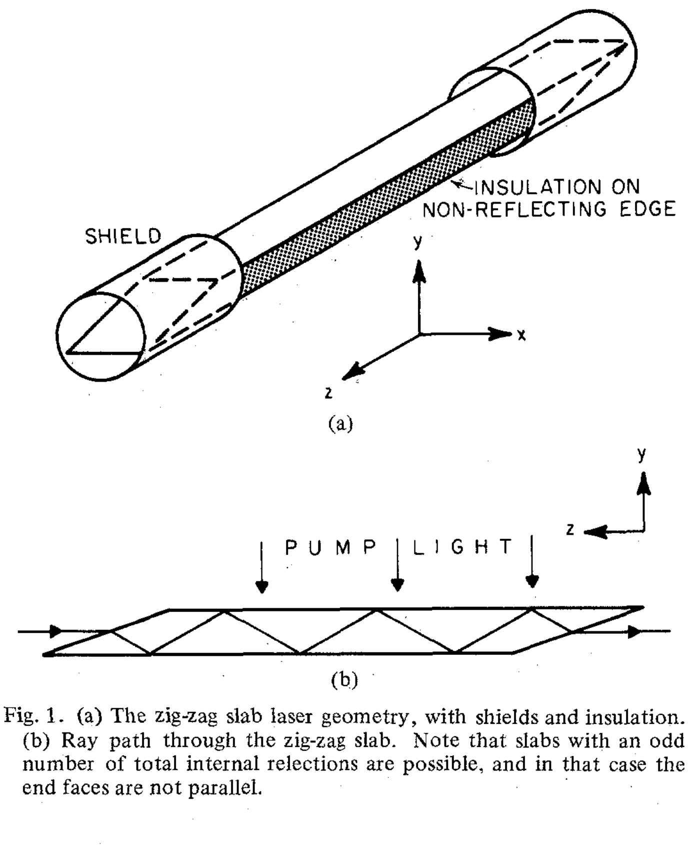

Fig. 1. (a) The zig-zag slab laser geometry, with shields and insulation. (b) Ray path through the zig-zag slab. Note that slabs with an odd number of total internal relections are possible, and in that case the end faces are not parallel.

Manuscript received February 4, 1983; revised April 4, 1983. This work was supported by the U.S. Army under Grant DAAG29-81-C-0038 and NASA under Grant NAG1-182.

The authors are with Ginzton Laboratory, Stanford University, Stanford, CA 94305.

0018-9197/83/0900-1351$01.00 © 1983 IEEE

a zig-zag geometry neodymium doped glass laser, developed a computer model of the thermally induced optical effects in slabs, and successfully tested the model [8], [9].

For the crystal slab tests described in this letter, we fabricated zig-zag slabs of Nd:YAG and Nd:GGG (gadolinium gallium garnet). The material Nd:GGG is of interest because its large change in index of refraction with temperature has been a major reason for its infrequent use in rod geometry lasers. In the slab geometry, thermal focusing is fully compensated, so it is possible to take advantage of the superior crystal growth properties and greater resistance to thermal fracture of Nd:GGG. We achieved stable CW operation of the Nd:GGG slab, but a meaningful efficiency comparison is not possible until more highly doped material is available. The Nd:GGG and Nd:YAG slabs were tested in a commercial CW laser system. The laser head contained a single 6 mm inner-diameter krypton arc lamp, with 76 mm of radiating length. A gold coated elliptical cavity focused the pump light into the slab. The slabs were mounted from the ends, and two simple procedures, described below, were used to approach the ideal slab thermal boundary conditions.

To approach the ideal slab limit of zero thermally induced optical distortion, it is necessary to avoid cooling the nonreflective edges, and thus avoid creating a temperature gradient in the x-direction. We achieved adequate insulation by the simple means of attaching silicone rubber to the nonreflecting edges of the slab. Dow Corning Sylgard 186, with a thermal conductivity of 0.0017 W/cm·K [10] has 84 times higher thermal resistance than Nd:YAG. Thus, a relatively thin layer (about 1 mm for our 4 × 8 mm slabs) effectively insulated the surface.

The ideal slab appears optically flat in the y-direction because all zigzag segments have the same average index of refraction. This is not true near the ends of a finite slab. We observed strong negative focusing in the y-direction when the entire slab, including the ends, was pumped. Again, a very simple procedure consisting of slipping opaque tubes over the ends of the slab to shield the entrance face from the flashlamp radiation greatly reduced the negative focusing. In order to use the pump light efficiently while shielding the ends of the slab, it is necessary that the slab be longer than the radiating length of the lamp. Our slab was 100 mm from tip to tip, although the lamp radiating length was 76 mm.

The optical quality of the pumped slab was measured with a Mach–Zehnder interferometer. A 633 nm helium–neon laser was used as the light source. The location of each fringe was measured on horizontal and vertical cuts through the center of the interference pattern and the fringe number was plotted as a function of distance from the center. A least-square fringe-fitting procedure determined the focal length of the pumped slabs and rods and also gave the residual distortion.

The most complete set of interferograms was taken for the Nd:GGG slab. Interferograms were recorded for four cases: 1) with no thermal insulation and no shielding, 2) with insulation but no shielding, 3) with shielding but no insulation, and 4) with both shielding and insulation. Fig. 2 is a reproduction of these four interferograms at a lamp pumping power of 4.2 kW. Table I summarizes the results for the Nd:GGG slab. In the x-direction, shielding and insulation changed the thermal focusing from 1.35 to −0.26 diopters. Most of the change in the x-direction was due to the insulation. In the y-direction, the change was from −2.34 to −0.46 diopters, with almost of all the improvement due to the shielding. The Nd:GGG measurements clearly show that the slab boundary conditions are critical to the reduction of thermal focusing. The difference between the focusing power in the two directions, a parameter of key importance to resonator stability, was reduced to 5.4 percent of its original value.

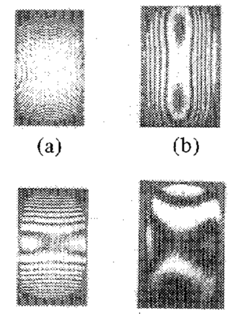

Fig. 2. Interferograms of the Nd:GGG slab pumped at 4.2 kW CW power, showing the importance of end and edge effects. (a) No edge insulation, no end shields. (b) Edge insulation, but no end shields. (c) End shields, but no edge insulation. (d) Edge insulation and end shields.

TABLE I
EFFECTS OF SHIELDS AND INSULATION ON FOCAL POWER AND DEPOLARIZATION FOR Nd:GGG SLAB AT 4.2 kW

Shields		No	Yes	No	Yes
Insulation		No	No	Yes	Yes
Focal Power (Diopters)	X	1.35	1.05	-0.54	-0.26
	Y	-2.34	-0.40	-2.82	-0.46
Depolarization (percent)		4.5	0.5	1.5	0.2

Data for the Nd:YAG slab were recorded for the case where both shielding and insulation were in place. The 4 × 8 mm slab used had almost the same cross-sectional area as the 6.4 mm diameter rod it replaced, so a comparison is possible. The interferograms of the Nd:YAG slab and rod at 4.2 kW of lamp power are reproduced in Fig. 3. Table II summarizes the Nd:YAG interferometry results. For a rod, the y-direction is defined as the direction parallel to the polarization of the probe beam. In the y-direction, the focal power of the slab and rod were −0.18 and 2.71 diopters, respectively. In the x-direction, the values were −0.47 and 2.31 diopters. The difference in focal lengths is also less for the slab, at −0.29 diopters as compared to 0.40 diopters for the rod. The focal lengths of the rod for the two directions differ because the thermal stress creates birefringence. The ratio of focal lengths has been calculated for a uniformly pumped rod by Koechner [3]. Our observed ratio of 1.17 is close to his theoretical value of 1.2. The thermal effects in the slab are well described by an elliptical lens, as is shown by the fact that the root-

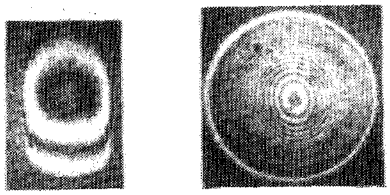

Fig. 3. Interferograms of Nd:YAG rod and slab pumped at 4.2 kW CW show substantial advantages of zig-zag slab geometry.

TABLE II
FOCAL POWER, DISTORTION, AND DEPOLARIZATION FOR Nd:YAG SLAB AND ROD AT 4.2 kW

	Direction	Slab	Rod
Focal Power (Diopters)	X	-0.47	2.31
	Y	-0.18	2.71
Residual Distortion (HeNe Wavelengths)	X	0.03	0.16
	Y	0.10	0.36
Depolarization (percent)		0.2	25.0

mean-square deviation from an ellipsoidal surface is no more than one-tenth wave at 663 nm.

The output power of the laser was measured as a function of the lamp power for both the YAG slab and rod and for both multimode and TEM_{00} operation. In all cases, the output coupler was a 10 percent transmitting mirror. The parameters of a linear least-square fit gave the threshold and the slope efficiency for each case. Table III lists these values, as well as the output power achieved at the maximum lamp input power of 5.1 kW. The multimode slab power was corrected to take into account the fact that the beam was filling only 69 percent of the pumped volume. This correction was used only for multimode operation and is discussed more fully later. The slab was nearly as efficient as the rod it replaced. The slope efficiencies for slab and rod were 2.25 and 2.36 percent, respectively, for multimode operation. For TEM_{00} operation, the values were 0.47 and 0.51 percent. The extrapolated threshold for the rod was about 10 percent more than that of the slab, in both cases. This is probably the result of the fact that the zig-zag geometry results in the path through the slab being 15 percent longer than the path through the rod, with the gain correspondingly increased.

A key factor in the efficiency of a laser is the geometric filling factor, given by the ratio of the volume effectively swept by the laser beam to the total pumped volume. When total laser power is the only concern, a multimode beam may be used, which expands to fill any aperture. Under these conditions, the rectangular aperture is not a disadvantage. The 69 percent filling factor used for correcting multimode data was the result of the restricting aperture of the slab holder. The pump cavity was designed for rod use and it was not possible to access the full rectangular aperture of the slab without extensive modifications. No filling factors were used to correct data for

TABLE III
THRESHOLD, SLOPE EFFICIENCY, AND POWER FOR Nd:YAG SLAB AND ROD

		Threshold (kilowatts)	Slope Efficiency (percent)	Output, lamp at 5.1 kilowatts (Watts)
Multimode	Slab	1.55	2.25	83
	Rod	1.70	2.36	88
TEM_{00}	Slab	2.03	0.47	13.0
	Rod	2.25	0.51	13.8

TEM_{00} operation. The portion of the slab blocked by the holder was outside the Gaussian beam. Similar efficiencies were observed, even though the slab with 2:1 rectangular cross section had a smaller filling factor than the rod. This is a result of reduced birefringence in the slab. The complex pattern of birefringence in the rod made necessary a smaller aperture to restrict oscillation to the TEM_{00} mode.

Slabs with an aspect ratio of two have been used because we initially believed that depolarization and nonelliptical focusing would be severe near the edge of the slab, and that the edge region was not useful. This was not observed to be the case. The measurements of depolarization and residual distortion previously described, as well as recent theoretical work, show that it is possible to use the entire slab aperture. In the future, we will be reporting on theory and measurements using slabs with an aspect ratio of one.

The birefringence of the pumped slab and rod was found by measuring the transmittance of 633 nm light through crossed polarizers with the pumped slab or rod between the polarizers. Table I describes the depolarization of the GGG slab in each of its configurations, and Table II includes data for the Nd:YAG slab and rod. The GGG data show that depolarization in the slab was reduced from 4.5 to 0.2 percent when insulation and shielding were added. At all pump powers greater than 2 kW, close to 25 percent of the 633 nm light passing through the YAG rod changed polarization. The corresponding value for the YAG slab, with shield and insulation, was 0.2 percent at 4.2 kW of lamp power.

The degree of polarization of the Nd:YAG slab laser output was measured for both multimode and single transverse mode operation. We used an analyzer with an extinction ratio of 1000 to 1 and observed only single polarization output up to the maximum pump power of 5.1 kW. It was not possible to control the polarization of the rod. In the multimode rod case, power was present equally in both polarizations. The single mode rod output was 90 percent in one polarization, but an attempt to control the direction of the polarization with a Brewster plate reduced the power drastically.

The same compensation that reduces depolarization due to thermal stress in slabs also reduces depolarization in slabs cut from highly stressed crystals of Nd:YAG. Often, crystals of Nd:YAG show unacceptable birefringence even when not pumped, due to stress in the crystal that results from the growth process. We obtained two Nd:YAG rods that showed depolarization in stressed regions of 17 and 10 percent, respectively, for light of wavelength 633 nm. These rods were first cut into slabs with a simple straight-through path. Depolarization was reduced very slightly, to 14 and 9 percent. When the ends were cut to allow a zig-zag path with seven internal reflections, the depolarization of each was 0.3 percent or less, for light polarized along the axes of the slab.

We conclude that the zig-zag slab laser geometry has very significant advantages which are easily available after small modifications to an existing Nd:YAG laser system. The only disadvantage is a small increase in cost due to the more difficult fabrication of the slab and the greater amount of Nd:YAG which is needed to allow the ends to be unpumped. We predict that YAG slabs will show similarly reduced thermal focusing and birefringence up to the fracture limit of the material. The fracture limit of a Nd:YAG slab or rod is near 500 W of output power from a 15 cm long crystal.

ACKNOWLEDGMENT

The authors thank F. Bruni of the Materials Progress Corporation for providing the Nd:GGG crystal.

REFERENCES

[1] L. M. Osterink and J. D. Foster, "Thermal effects and transverse mode control in a Nd:YAG laser," *Appl. Phys. Lett.*, vol. 12, pp. 128-131, 1968.
[2] J. D. Foster and L. M. Osterink, "Thermal effects in a Nd:YAG laser," *J. Appl. Phys.*, vol. 41, pp. 3656-3663, 1970.
[3] W. Koechner, "Thermal lensing in a Nd:YAG laser rod," *Appl. Opt.*, vol. 9, pp. 2548-2553, 1970.
[4] —, *Solid State Laser Engineering.* New York: Springer, 1976, ch. 7.
[5] W. S. Martin and J. P. Chernoch, "Multiple internal reflection face pumped laser," U.S. Patent 3 633 126, 1972.
[6] W. B. Jones, L. M. Goldman, and J. C. Almasi, "Performance characteristics of two face pumped face cooled glass laser," General Electric Research and Development, Schenectady, NY, Tech. Rep. AFAL-TR-72-233, 1972.
[7] G. J. Hulme and W. B. Jones, "Total internal reflection face pumped laser," in *Proc. Soc. Photo-Optical Inst. Eng.*, 1975, vol. 69, pp. 38-45.
[8] J. M. Eggleston, T. J. Kane, J. Unternahrer, and R. L. Byer, "Slab-geometry Nd:glass laser performance studies," *Opt. Lett.*, vol. 7, pp. 405-407, 1982.
[9] J. M. Eggleston, "Theoretical and experimental studies of slab geometry laser," Ph.D. dissertation, Stanford University, 1982.
[10] *Selection Guide to Electrical/Electronic Materials from Dow Corning.* Dow Corning Corporation, Midland, MI.

An Approximate Expression for the Effective Refractive Index in Symmetric DH Lasers

KUO-LIANG CHEN AND SHYH WANG

Abstract—**Using a variational method and an approximate equation for the confinement factor, a simple expression for the effective refractive index of the TE_0 modes in a symmetric double heterostructure (DH) laser is obtained. The relative error is smaller than 1.2 percent. Its applications are discussed.**

MOST double heterostructure (DH) diode lasers have a strong refractive index guiding in the transverse direction and a weaker index or gain guiding in the lateral direction. In the designing process we frequently need to know the electric field distribution for this two-dimensional problem. An often used approach is the effective index method [1]-[3]. This requires the calculation of effective index of refraction n_e for a slab waveguide, defined in [4] as

$$\beta = k_0 n_e \tag{1}$$

where β is the propagation constant and k_0 is the wavenumber in vacuum. Finding n_e involves solving a transcendental equation [4] which has no closed form solution. However, for a symmetric three-layer dielectric slab waveguide, we will show that a simple accurate approximate expression exists. A symmetric DH laser as a waveguide is a system where a uniform slab with index n_1 is embedded in an infinite medium with a smaller index n_2. The slab has a thickness t in the x direction while extending to infinity in the y and z directions. We are interested in finding the lowest order transverse-electric mode (TE_0) which is uniform in the y direction and propagates in the z direction. The field satisfies the following equation.

$$\frac{\partial^2 E_y}{\partial x^2} + (k_0^2 n^2 - \beta^2) E_y = 0 \tag{2}$$

where E_y is the electric field of the TE_0 mode, n^2 is the dielectric constant, and x is in the transverse direction. Suppose we vary the index by $\delta n(x)$. There are accompanied variations of $\delta E_y(x)$ and δn_e. They are related by

$$\frac{\partial^2 \delta E_y}{\partial x^2} + (n^2(x) - n_e^2) k_0^2 \, \delta E_y + (\delta n^2(x) - \delta n_e^2) k_0^2 E_y = 0. \tag{3}$$

Let us multiply both sides by E_y and integrate over x. After integrating by parts twice and dropping the surface integral, we have

Manuscript received March 18, 1983; revised April 29, 1983. This work was supported by the U.S. Air Force Office of Scientific Research under Contract F49620-79-C0178.

The authors are with the Department of Electrical Engineering and Computer Sciences and Electronic Research Laboratory, University of California, Berkeley, CA 94720.

0018-9197/83/0900-1354$01.00 © 1983 IEEE