

# YAG

YTTRIUM ALUMINUM GARNET LASER MATERIALS



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## Introduction

Yttrium Aluminum Garnet (YAG, with chemical formula  $Y_3Al_5O_{12}$ ) has emerged as the most widely produced laser gain host and has enjoyed recent popularity as a substrate material for optical components. The YAG host is a stable compound, mechanically robust, physically hard, optically isotropic, and transparent from below 300 nm to beyond 4 microns. YAG single crystals are able to accept trivalent laser activator ions from both the Rare Earth and Transition Metal groups, and can be grown with very low strain.

Crystal growth of the YAG host material was initially achieved in the late 1950s and early 1960s at various locations, including the National Lead Company,<sup>1</sup> the Linde Company,<sup>2</sup> and the Bell Telephone Laboratory.<sup>3</sup> Initial support of the growth and development of these materials was through internal research funds at these companies, and through the Department of Defense.<sup>4,5</sup> The first reported lasing of the YAG host with a rare earth ion (trivalent Neodymium,  $Nd^{3+}$ ) occurred at Bell Telephone Laboratories in 1964.<sup>6</sup> Other parallel research was reported by researchers at RCA Laboratories the same year, with lasing reported with a co-doped material consisting of trivalent Chromium ( $Cr^{3+}$ ) and  $Nd^{3+}$ .<sup>7</sup>

The Nd:YAG laser did not become a widely accepted tool until the 1970s, finding its first important application in the laser rangefinder arena. These YAG systems could be run at higher repetition rates, higher output energies, and operate more covertly than the first generation ruby systems, primarily because of the thermal stability and robust nature of the Nd:YAG material. After gaining acceptance within the military community, the scientific, industrial, and medical markets were explored. Nd:YAG lasers quickly gained recognition in new market applications due to their increased reliability and flexibility in delivery of the laser beam via fiber optics.

Additional applications, many of which also utilize fiber delivery systems, have been expanded to include cutting, welding and drilling of metals for the automobile industry, marking and repairing of semiconductor materials, and medical and dental procedures. These have been implemented utilizing lasers that operate from the ultraviolet (UV) to the mid-infrared (IR), through the substitution of other rare earth and transition metal ions, including Holmium ( $Ho^{3+}$ ), Thulium ( $Tm^{3+}$ ), Erbium ( $Er^{3+}$ ), Ytterbium ( $Yb^{3+}$ ), and Chromium ( $Cr^{3+}$ ).<sup>8,9</sup>

Another recent use of the YAG material is for optical components in laser and beam delivery systems. The undoped YAG single crystals can be polished to a high quality laser finish, thus making an ideal substrate for robust dielectric optical components, lens ducts,<sup>10</sup> prisms, and mirrors. In these applications, YAG is favored for its high optical transmission, ability to handle high fluences without damage or significant wavefront distortion, excellent thermal conductivity, and uniform index of refraction. These components are also physically more durable than glass or fused silica. They exhibit isotropic expansion and compression and their high index of refraction allows for durable dielectric coatings to be applied for either partial or complete reflectivity.

## Neodymium-doped YAG Applications

In YAG, the rare earth dopant ion substitutes for Yttrium ( $Y^{3+}$ ) in the crystal lattice, while the transition metal ion substi-

tutes for Aluminum ( $Al^{3+}$ ). For laser gain applications, YAG is typically doped with  $Nd^{3+}$  at the 0.2 to 1.4% (atomic) level. Nd:YAG is an efficient 4-level laser material and may be used in both pulsed and CW operation.<sup>11,12</sup> The principal Nd:YAG emission is at 1064.14 nm.

In combination with nonlinear optical (NLO) components, sum frequency or difference frequency output can be produced. This approach can be easily used to create frequency-doubled laser output at 532 nm and various other nonlinear processes spanning the UV to mid-IR bands.<sup>13</sup>

## High Power Continuous Wave Operation

High power laser output is required for many industrial applications, and often continuous wave operation is employed, with Nd concentration typically specified in the 0.4 to 1.0% range. In such a laser system, power is limited by the steady state temperature and thermal gradient of the laser gain material. The maximum continuous power depends upon the volume of the laser gain component, and is achieved by optimizing the dopant concentration according to system cooling efficiency and the spectral characteristics of the excitation radiation. Surface to volume ratio becomes an important consideration in the design of such laser gain components. (Refer to Koechner<sup>11</sup> for an excellent treatment of this topic.) Although Nd:YAG is most commonly employed in rod form, slabs are also utilized.

Because the heat is removed at the rod surface, the temperature distribution in an isotropic laser rod is typically radially symmetric. At high power levels, thermal expansion and temperature-induced changes in the index of refraction cause the rod to behave like a convex lens, focusing the beam more tightly as the power level increases. This is called thermal lensing, and it is one of the first evidences of excess heat load and restricted extraction of the thermal power within the laser rod. Sustained operation at levels above the thermal load capacity can lead to damage to the laser gain material and its optical coatings.

To minimize thermal effects, slabs are increasingly specified for highest power applications. This configuration gives the advantage of higher cooling surface to volume ratio and results in lower thermal stresses and beam distortion.

## High Intensity Q-switched Operation

For many industrial and military applications, where high energy intensity or peak power is required in short pulses, Q-switched operation is employed. In this case, energy is stored by populating the  $^4F_{3/2}$  electronic levels and then stimulating a rapid depopulation. Laser components for lamp-pumped, Q-switched operation are normally Nd-doped in the 1.0 to 1.2% range. The fluorescence lifetime of this excitation state is approximately 230 microseconds, declining somewhat with higher dopant concentration.

## Single Mode Operation

For applications where TEM<sub>00</sub> single mode operation is required, it is necessary to reduce or eliminate the variations in the bulk material and in the absorption of the pumping radiation throughout the component. In addition, wavefront distortions due to geometric imperfections and thermal gradient effects such as thermal lensing must be minimized. In this case, Neodymium concentration in the 0.4 to 0.8% range is typically specified.

## Laser Rod Quality Characteristics

Geometric and material imperfections in an Nd:YAG laser rod cause poor beam quality and sometimes reduce the power output of a laser gain component. Key indicators of laser gain component optical quality are wavefront distortion, birefringence variation, and extinction ratio.

### Wavefront Distortion

Wavefront distortion of a laser rod is expressed in terms of the distortion of a plane wave that is propagated through the rod. The distortion of the wavefront is a consequence of any variation in the optical path length through the component, caused by inhomogeneities and strain in the crystal or geometric imperfections.

Wavefront deviation is customarily evaluated using a Fizeau double-pass interferometer. Distortions are readily measured by evaluating the curvature of interferogram fringes using computer generated phase analysis. Single-pass wavefront distortion is calculated and expressed in terms of phase variation across the aperture. Wavefront distortion can vary as a function of rod diameter and length, and is normally specified in terms of wavelength deviation at 632.8 nm per unit of rod length. Refer to the Wavefront Deviation graphics on the facing page.

### Birefringence

Strain and other imperfections in the laser gain component result in variation of the crystal lattice parameter, causing an isotropic gain material to be locally birefringent. This means that the index of refraction of the material (and propagation rate) depends upon the polarization of the beam propagating through the lattice. For a polarized beam transmitted through the material, the component of polarization parallel to the strain axis will propagate at a different rate than the perpendicular component. This difference in propagation rate results in a relative phase shift (retardance, expressed in nm) between the polarization components. This can also introduce some degree of circular polarization.

Greater strain or inhomogeneity in the propagation path will result in greater retardance. When a laser rod is viewed between crossed polarizers, variation in retardance across the aperture will provide a useful map of the material strain or inhomogeneity.

### Extinction Ratio

Extinction ratio is a simple and useful method of quantifying the residual strain in a laser rod. If a laser rod is perfect, then a linearly polarized beam transmitted through it will be unperturbed and it will be possible to completely extinguish the beam by placing a crossed polarizer in the beam path after it has transmitted through the rod. However, any birefringence in the rod will make it impossible to completely extinguish the beam.

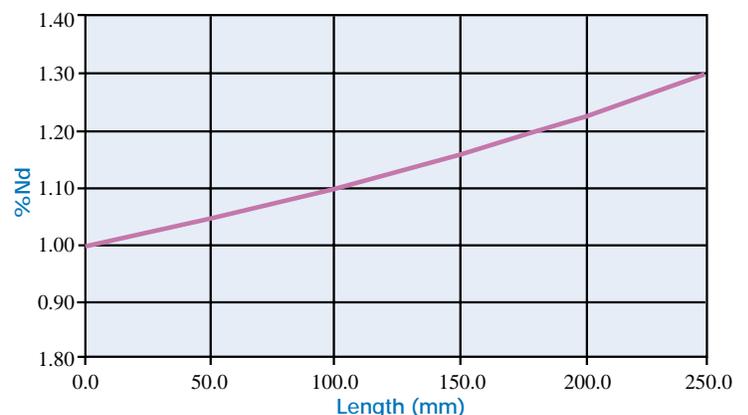
The extinction ratio is measured using a HeNe laser source with the component filling the beam aperture, and is defined as  $10 \cdot \log(T_1/T_2)$ , where  $T_1$  is the maximum transmitted beam intensity with the polarizers uncrossed, and  $T_2$  is the beam intensity with the polarizers crossed so as to minimize the transmitted intensity. YAG laser rods from VLOC typically show extinction ratios exceeding 25 dB.



## Manufacturing Growth

In the VLOC YAG Crystal Growth department, the Czochralski (Cz) growing process is used to produce YAG single crystals. In this process, the YAG material and dopant are melted in an Iridium crucible that is heated by induction and the crystal is grown under computer control. Depending on crystal size, from four to eight weeks are required to complete the growth cycle. VLOC continues to develop the growth process to produce larger YAG crystals with lower as-grown stress and higher optical uniformity.

### Nd:YAG Dopant Variation



Because the concentration of the Neodymium increases with the length of the crystal, only about 25% of the melt can be used. The figure above illustrates how Nd dopant concentration varies with crystal length.

Once the growth process is completed, the YAG crystal is slowly cooled to reduce the possibility of damage from high thermal stresses. The Cz growth process produces crystals with a highly-strained core region on the crystal axis and other symmetrical inhomogeneities that result in birefringence and wavefront distortion. The dopant contributes additional compressive stress to the lattice.

## Fabrication and Coating

After removal from the furnace, the crystal is cut, the ends are polished, and the defect-free regions of low stress are carefully mapped using a Fizeau interferometer. Laser gain and optical components are then cut from the defect free portion of the crystal and precisely shaped and polished according to customer specifications.

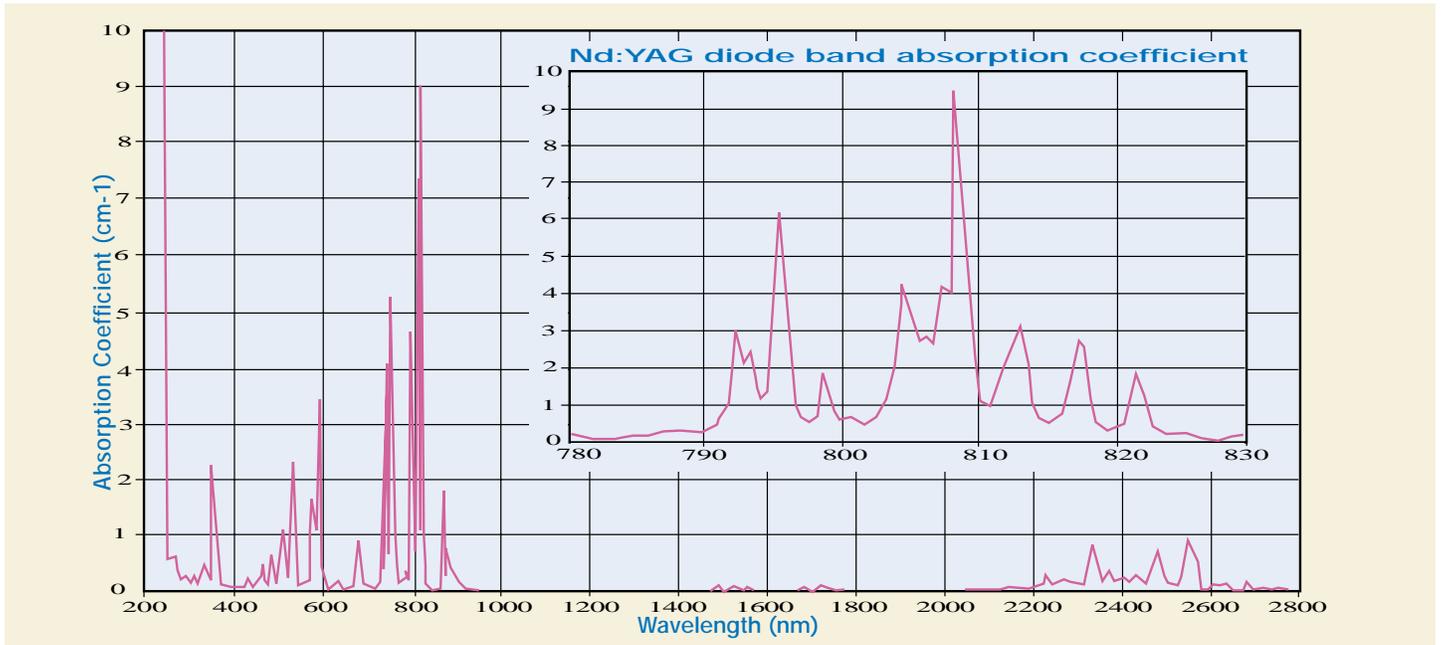
For standard applications, rod end surfaces are polished flat to within 1/10 of a wave (632.8 nm) and parallel to within 10 arc seconds. After fabrication and inspection, thin film anti-reflection coating of a material such as  $MgF_2$  is applied to each transmission surface, reducing the reflectance at the specified wavelength to less than 0.15%.



## Nd:YAG Absorption Coefficient

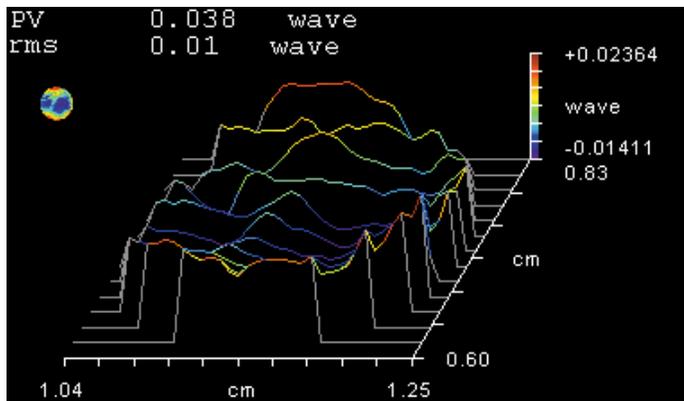
The figure below shows the absorption coefficient for the Nd-ion in YAG between the UV cutoff and the water absorption bands in the mid-infrared.

The inset highlights the  $4F_{5/2}$  absorption coefficient for the Nd-ion in the highly efficient diode-pumping region. The peak Nd absorption line for this region is 808.6 nm.

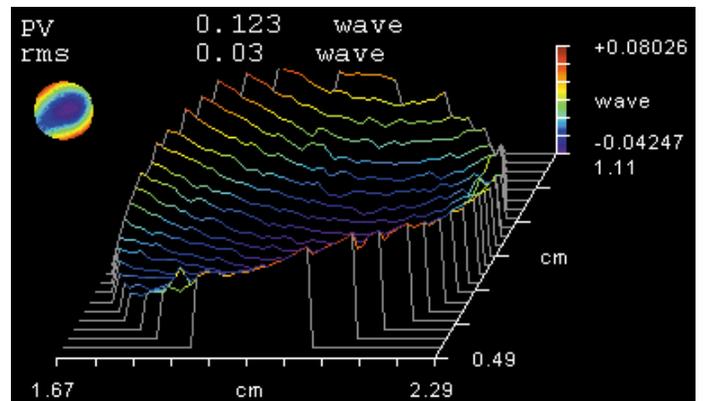


The figures below show typical single-pass transmitted wavefront maps for VLOC 3 mm  $\varnothing$  x105 mm L and 8 mm  $\varnothing$  x203 mm L rods. As might be expected, wavefront variation increases with rod diameter and length.

Wavefront Deviation (3x105mm)



Wavefront Deviation (8x203mm)

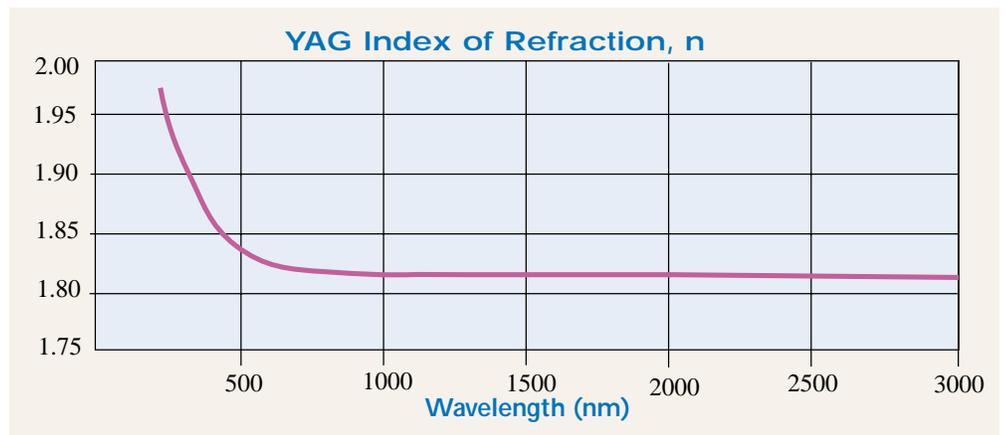


## Sellmeier Equation:

$$n^2 = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E}$$

where

$$\begin{aligned} A &= 1 \\ B &= 2.2779 \\ C &= 0.01142 \\ D &= 0 \\ E &= 0 \end{aligned}$$



From: E.D. Filer, C.A. Morrison, G.A. Turner, and N.P. Barnes, OSA Proceedings on Advanced Solid-State Lasers, H.P. Jenssen and G. Dube, eds. (Optical Society of America, Washington, D.C. 1990), Vol. 6, pp. 354-362.

## YAG index of refraction and reflectance

Wavelength (nm)	n	R
266	1.9278	0.1004
354	1.8725	0.0923
532	1.8368	0.0870
808	1.8217	0.0848
946	1.8186	0.0843
1030	1.8173	0.0842
1064	1.8169	0.0841
1333	1.8146	0.0838
1444	1.8140	0.0837
1500	1.8137	0.0836
1640	1.8132	0.0836
2014	1.8123	0.0834
2097	1.8121	0.0834
2123	1.8121	0.0834
2940	1.8113	0.0833

## Nd:YAG Crystal Device Specifications

Nd Concentrations Available 0.2 to 1.4%

### Standard Rod Dimensions

- Diameter 0.5 mm to 15.0 mm
- Length 1.0 mm to 220.0 mm
- Slabs Miniature to large configurations

### Laser Rod Specifications

Transmitted Wavefront (per inch of rod length)	Standard Grade $\lambda/8$	Premium Grade $\lambda/20$
• Extinction Ratio	Greater than 25 db	
• Surface Quality	10/5	
• Clear Aperture	95%	
• Parallelism	<10 arc seconds	
• Perpendicularity	<5 minutes	
• Surface Flatness	$\lambda/10$ @ 632.8 nm	
• Barrel Finish	Ground or Polished	
• Chamfer	0.13 +/- 0.08 mm @ 45°	
• Diameter Tolerance	+0.0, -0.025 mm	
• Length Tolerance	+/- 0.5 mm	

### Configurations

- Flat/Parallel
- Tilt Ends
- Radius Ends
- Brewster/Brewster Ends
- Slab Designs
- Polished and Grooved Barrels
- Diode Pumped Mini-rods
- Custom Geometries

### Thin Film Coatings

- AR/AR at 1064 nm, R < 0.15%  
Damage Threshold >20 J/cm<sup>2</sup>, 10 ns pulse
- Dichroics, HR 1064 nm >99.8%R, HT 808 nm >95.0%T  
Damage Threshold > 15 J/cm<sup>2</sup>, 10 ns pulse
- Partially Reflecting Designs
- Custom Designs Available

## Laser/Spectroscopic

$4F_{3/2}$ to $4I_{11/2}$	Stark level transitions
Transition wavelength (nm)	Normalized output intensity
1052.1	0.300
1054.9	0.018
1061.5	0.627
1064.1	1.000
1064.6	0.418
1068.2	0.267
1073.7	0.515
1077.9	0.363
1105.5	0.114
1111.9	0.233
1115.8	0.279
$4F_{3/2}$ to $4I_{13/2}$	Stark level transitions
1318.7	0.144
1320.3	0.048
1333.5	0.057
1335.1	0.078
1338.1	0.191
1341.9	0.094
1353.3	0.049
1357.2	0.168
1415.0	0.078
1427.1	0.022
1432.0	0.052
1444.4	0.100

From: "Spectroscopic Properties of Nd<sup>3+</sup> in YAG" by R.C. Powell in "Nd:YAG Lasers" By L.G. DeShazer, ed. (New York: Springer-Verlag, 1984).

## Material Properties <sup>13,14,15</sup>

### Optical Properties

Refractive Index	1.8169 at 1064 nm
Primary Diode Pump Band	808.6 nm
Fluorescence Lifetime	230 $\mu$ s @ 1.0% Nd

### Thermal Properties

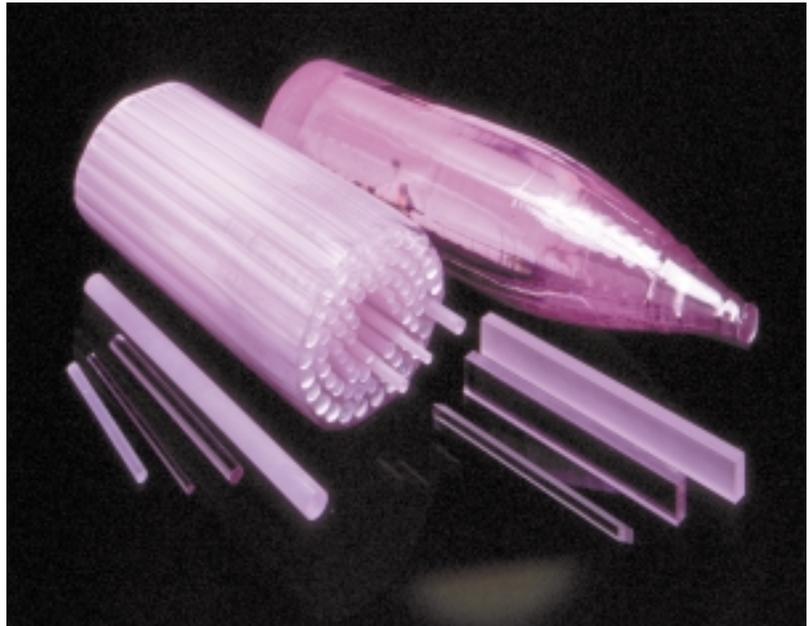
Thermal Conductivity (20 C)	0.129 W/cm $\cdot$ K
Specific Heat	0.59 J/g $\cdot$ K
Linear Expansion Coefficient	8.2 x 10 <sup>-6</sup> /K <100> 7.7 x 10 <sup>-6</sup> /K <110> 7.8 x 10 <sup>-6</sup> /K <111>
Nonlinear Index	3 X 10 <sup>-13</sup> esu
Dissipative Fracture Limit	175–200 W/cm
dn/dt	+8.9 X 10 <sup>-6</sup> K <sup>-1</sup>

### Physical Properties

Nd Doping Level	0.2 to 1.4% atomic
Chemical Formula	Y <sub>3-x</sub> Nd <sub>x</sub> Al <sub>5</sub> O <sub>12</sub>
Molecular Weight	595.3 g/mole
Crystal Structure	Cubic / garnet
Lattice Constant	12.01 Å
Melting Point	1970 C
Density	4.55 gm/cm <sup>3</sup>
Knoop Hardness	1350 +/- 35 kg/mm <sup>2</sup>

### Mechanical Properties

Young's Modulus	282 GPa (45x10 <sup>6</sup> psi)
Tensile Strength	280 MPa
Poisson's Ratio	0.28



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VLOC Subsidiary of II-VI Incorporated manufactures synthetic crystals, optics and thin films. VLOC is recognized as a world leader in the production of YAG products for industrial, scientific, medical, defense and research applications.

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