Yttrium Aluminum Garnet

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Abstract

Yttrium Aluminum garnet (YAG) is commonly employed as a laser host for a variety of rare earth elements, especially neodymium. This paper examines the crystal structure of Nd:YAG and the physical and thermal properties which make it such an excellent laser host. Finally, some of the features of the Nd:YAG luminescence and emission spectra are considered.

1 Introduction

YAG was first synthesized in 1951 and was first employed as a laser host for a research group at Bell Laboratories in 1964[1]. Today Nd:YAG is the most widely used solid state laser medium, with a wide variety of applications in medicine, materials processing, and the military. It is a clear, hard, optically isotropic crystalline substance, possessing essentially all of the characteristics materials used in solid state lasers should exhibit, including good mechanical strength, a high degree of transparency in the portion of the spectrum where the laser operates, good thermal properties, and the ability to sustain a precise optical polish[2].

2 The Nd:YAG Crystal

Chemically, YAG is $Y_3Al_5O_{12}$. Like other garnet systems, it crystallizes in the cubic group, space group $O_h(10)$ Ia3d.The unit cell of a compound with the garnet structure $A_3B_5O_{12}$ is shown in Figure 1. The unit cell of such a compound contains eight formula units. The B atoms occupy two types of sites with different oxygen coordination: 16 octahedral a positions and 24 tetrahedral d positions. The a sites form a body centered cubic lattice while the 24 A ions lie in dodecaheral c positions. These ions are surrounded by eight oxygen ions which form the corners of a distorted cube. The replacement ions which are responsible for the laser properties of the crystal mainly occupy the c positions. The site symmetry at the place of the yttrium ions is orthorhombic and the substituted neodymium ions experience a low symmetry crystal field in the YAG host lattice[3].

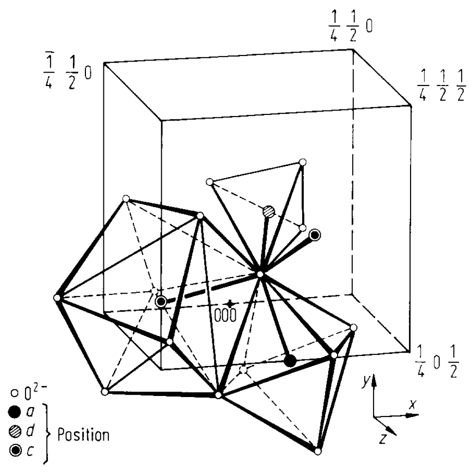

Figure 1: *Motif of Garnet Crystal Structure[3]*

In Nd:YAG about 1 percent of the Y^{3+} ions are substituted by Nd^{3+} ions. The atomic radii of the two ions differ by about 3 percent, so as more Nd ions are added the crystal becomes strained and YAG lattice can become distorted. Consequently, the concentration of Nd ions in Nd:YAG can have a considerable effect on the quality of the crystal's laser properties[4]. Specifically, the cubic structure of YAG favors a narrow fluorescent linewidth, which results in high gain and low threshold for laser operation, so deviations from the YAG crystal structure can impair the quality of the laser[4]. When the

Melting point	1970 C
Mohs Hardness	8.5
Young's Modulus	$3*10^3$ kg-cm^{-2}
dislocation denities	approx.$10^{-2}cm^{-2}$
Thermal Expansion coefficient	
[100]orientation	$8.2*10^-6$ C^{-1}, 0-250 C
[110]orientation	$7.7*10^-6$ C^{-1}, 0-250 C
[111]orientation	$7.8*10^-6$ C^{-1}, 0-250 C
Index of refraction	1.82 (at 1.0μm)
Scatter Losses	α_{sc}=1.82
Thermal Conductivity	0.13 W-cm^{-1}-K^{-1} (at 300K)
Thermal Expansion	7.5 K^{-1} (at 300K)
Specific Heat	0.59 W-s$(g-K)^-1$ (at 300K)

Table 1: *Some Physical, Optical, and Thermal Prpoerties of Nd:YAG]*

concentration of Nd ions becomes too great, the laser begins to suffer from flourescent line broadening and reduction in fluorescent lifetimes[5].

3 Physical and Thermal Properties

The YAG structure is highly stable from the lowest temperatures up to its melting point. No transformations have ever been reported in its solid phase. The complex cubic lattice does not have any apparent easy slip directions. It has low dislocation densities and very small strain and inhomogeneity as long as the crystals are grown sufficiently slowly. Nd:YAG also has a high resistance to thermal induced stress fracture[3]. A table of physical, thermal, and and optical properties of Nd:YAG are givien in Table 1[4].

One of the more significant thermal properties of Nd:YAG is its high thermal conductivity relative to other neodymium hosts. This allows for the rapid removal of wasted heat due to inefficient excitation in the medium and enables to Nd:YAG laser to produce a continuous beam of high quality[6]. Such continous operation is virtually impossible to achieve with other solid state lasers, whose lower thermal conductivity restricts them to operating for only short pulses.

4 Luminescence and Spectral Emission Properties of Nd:YAG Crystals

A figure of the most significant energy levels associated with the Nd:YAG laser are shown in Figure 2. The most prominent of these transitions is the 1.064μm line from the R_2 component of the $^4F_{3/2}$ energy level to the Y_3 component of the $^4I_{11/2}$ level. The upper level is a metastble state with a lifetime of .203ms. The levels shown in this figure are all associated with the inner 4f shell of Nd which is partially screened from external fields by the 5d and 6s outer shells[7].

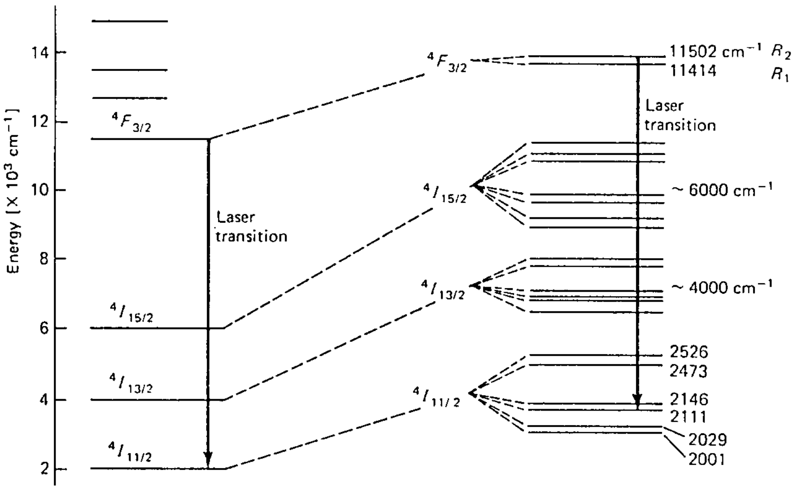

Figure 2: *Partial Energy Level Diagram of Nd:Yag[4]*

Although it is the Nd ions in Nd:Yag are responsible for the the laser transitions in the medium, the YAG host does have an effect on the Nd ion's energy levels since the Nd ions interact with the ctrystal field. These interactions with the crystal field are responsible for Stark splittings of the Nd energy levels with $J > 3/2$ [3]. The principle contributor to the crystal field is its strong cubic componenent while axial and orthorhombic components are responsible for the fine structure of the Nd ion's energy spectrum. The cubic component of the Crystal field arises from exchange and Coulomb interactions between the Nd^{3+} ion's 4f electrons and its eight nearest neighbor O^{2-} ions.

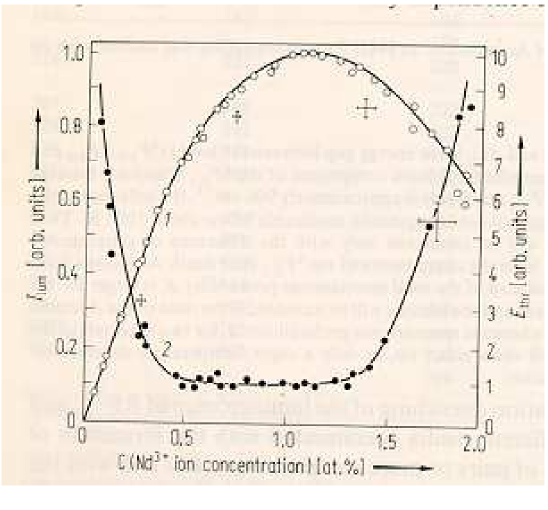

Figure 3: *Concentration dependence of luminescence of 1.06415 μm line intensity (1) and excitation threshold (2) of the A emission line for a Nd:YAG crystal $^4F_{3/2}$ to $^4I^{11/2}$ transition at 300K.[3]*

Not only are the energy level splittings produced by the crystal field significant in their own right, but they can be employed to answer some critical questions about the operation of the Nd:Yag laser. For example, the optimum concentration of Nd^{3+} ions in a Nd:YAG crystal can be determined by studying the luminescence intensity of the 9382 and

9458 Angstrom lines due to transitions to the highest stark component of the $^4I_{9/2}$ state. This component is spaced far from the ground state and is essentially unpopulated at room temperature. A plot of the luminescence intensity dependence for the most intense line of the $^4F_{3/2}$ to $^4I_{11/2}$ transition. As is evident from the graph, the maximum luminescence intensity is at a neodymium concentration of about 1.1 percent. Similarly, The laser threshold energy can be plotted in the same figure as a function neodymium concentration. As the figure indicates, the minimum excitation threshold is at nearly the same concentration as the maximum luminescence intensity, indicating that a crystal doped with about 1.1 percent neodymium is optimal laser medium[3].

5 Conclusions

While it is not the ideal laser medium, Nd:YAG has a number of desirable properties, particularly, thermal properties which which make it one of the best laser media used today. No other laser crystal has achieved the widespread commercial success of Nd:YAG, and over thiry years after it was first discovered to be a laser medium, it continues to find new applications in science and technology.

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