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LNA: A New CW Nd Laser Tunable Around 1.05 and 1.08 μm

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***Abstract*—We have investigated the CW laser properties of the lanthamide hexa-aluminate $La_{0.9}Nd_{0.1}MgAl_{11}O_{19}$ at room temperature. When a 1 cm long crystal is pumped by an Ar^+ laser (514 nm) or a Kr^+ laser (752 nm), CW emission is obtained with slope efficiencies of 10 and 26 percent, respectively. A four-plate Lyot filter in the cavity forces the LNA crystal to oscillate in either of the two major bands centered at 10 820 Å (tuning range 80 Å) and 10 545 Å (tuning range 35 Å).**

INTRODUCTION

NEODYMIUM-doped, rare earth aluminates such as yttrium aluminum garnet (YAG) and yttrium aluminum perovskite (YAP) are of considerable interest as single-crystal, solid-state laser [1]. At present, only the Nd:YAG laser has achieved commercial importance. There are continuing efforts to find other neodymium-doped crystalline hosts which would retain the advantages of YAG as to performance without showing some of its disadvantages such as neodymium segregation during crystal growth, low solubility of Nd^{3+} in the YAG lattice, and limited tuning capability in an important region of the spectrum.

Since the discovery of hexagonal lanthanum neodymium hexa-aluminate [2] $La_{1-x}Nd_xMg\ Al_{11}O_{19}$, hereafter referred to as LNA, considerable effort has been devoted to improve its crystal growth [3] and characterize its properties. The best crystals of LNA (up to 70 mm length, 25 mm diameter) have been obtained by Aubert and his group at the LETI-CENG, France, using the Czochralski method [4]. LNA crystallizes with an hexagonal magnetoplumbite-like structure [2], [5]. The lanthanide ion environment consists of a 12-corner polyhedron. Further information has been obtained from the 4.2 K absorption spectra of LNA [6]. It indicates unambiguously that, in fact, lanthanide ions occupy three closely related sites instead of only one in the ideal magnetoplumbite structure.

The laser emission of LNA, both in CW and pulsed operation, has been observed independently by ourselves [4] and two Russian groups [7], [8]. These investigations have confirmed interest in LNA as a new, high-power, solid-state neodymium laser. Among the advantages of LNA is the ability to achieve a high neodymium content, more than six times greater than Nd in YAG (7×10^{20} ions cm^{-3}) without severe concentration quenching of the fluorescence or strong segregation of the doping ion along the laser rod.

The earlier laser work demonstrated that an LNA laser has an efficiency and threshold comparable to Nd:YAG. Our interest in this material was further stimulated by the broad fluorescence spectrum from the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions of the Nd in LNA which suggested the possibility of obtaining efficient, CW, tunable emission over a substantial wavelength range in a region of the spectrum that is generally devoid of tunable sources. An additional motivation which triggered this work at the Ecole Normale Superieure was the spectral shift produced by the crystalline field in LNA which fluoresces around 1083 nm. This wavelength is at the resonance transition in the triplet spectrum of helium. A practical efficient laser emitting at 1083 nm would permit further laser spectroscopic studies of the helium resonance levels [9] and provide a useful laser source for optical pumping in ^{3}He and ^{4}He. Optical pumping at 1083 nm allows us to obtain significant polarizations of the electronic and nuclear spins in these atoms. There are an astonishing number of applications that rely on the optical pumping process in helium [10], [11], many of which require the optical processing of large numbers of spins and which would benefit from an efficient laser source.

We report here the characteristics of the LNA laser and its tuning capabilities when pumped by either the green output of an argon ion laser or the infrared output of a krypton ion laser. In the sections following, we describe the laser characteristics of these crystals, e.g., threshold, gain, and tuning curves and mode structure. The results are compared to the performance of YAG under similar conditions.

EXPERIMENTAL RESULTS

A. *The Laser Cavity*

The laser cavity used in this investigation was constructed in the laboratory and is shown schematically in

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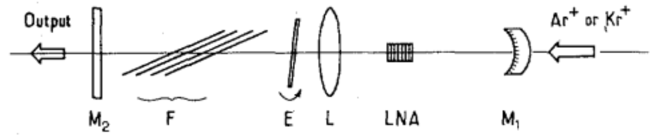


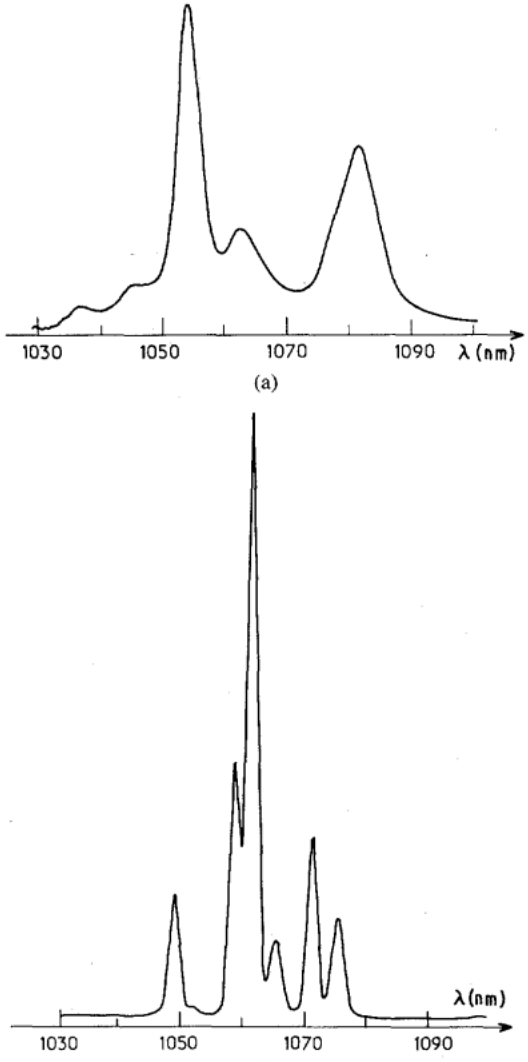
Fig. 1. The cavity used for the LNA laser pumped by an Ar$^+$ or a Kr$^+$ gas laser. M_1 is a dichoric meniscus which focused the pump at the center of its internal surface. L is a lens. M_2 is a plane output mirror of transmission T. For tuning the wavelength, selective elements are added: a four-plate birefringent Lyot filter F and a thin solid etalon E.

Fig. 1. Element M_1 is a meniscus which acts as both a lens for the pump radiation and as a curved mirror forming one end of the laser cavity. The radii of the two faces of the meniscus are calculated so that the focal length of the equivalent lens and the radius of curvature of the end mirror are about the same, 4.2 cm. The pump radiation is thus focused on the crystal with a beam waist on the order of 10 μm in diameter. The other cavity elements are set so that the cavity beam waist coincides with the pump beam waist. The meniscus is transparent at the pump wavelengths, but is totally reflecting in the 1050–1090 nm range. The crystal is mounted so that its front surface is close to the focus of the pump radiation. An antireflection-coated lens L of focal length 2.75 cm is located behind the crystal. It is mounted on a traveling stage so that the crystal fluorescence emission could be focused at points between the plane output mirror M_2 and infinity, these two points representing the range of stability of the cavity. With the lens focusing the emission on the output mirror, we obtain the familiar concentric cavity. The total length of the cavity is approximately 25 cm. The beam waist within the laser cavity is on the order of 30 μm. The plane output mirror has a transmission of 35, 16, 10, or 1 percent in the 1054–1082 nm wavelength region. This configuration was used for fluorescence, gain, and threshold measurements.

B. Fluorescence

The fluorescence spectrum of Nd in LNA is shown in Fig. 2(a). The spectrum was obtained by replacing the output mirror with an optical fiber. The fluorescence emission was then examined with a $\frac{1}{2}$ m grating spectrometer and detected with a germanium detector. The data are uncorrected for the spectral response of the apparatus. The fluorescence shows two broad, principal peaks centered at 1054 and 1082 nm. The full widths at half height of the two peaks are 44 and 74 Å, respectively. For the purposes of comparison, the fluorescence spectrum obtained under identical conditions from Nd in YAG is shown in Fig. 2(b). Fluorescence widths in YAG are typically 6 Å. The excitation source in both cases is the IR output from a Kr$^+$ laser at 752 nm.

The broad width of the LNA curve, as compared to the YAG one, results from the fact that there are three different fluorescing sites in the LNA lattice [6]; each of them is submitted to a slightly different crystallographic field due to the different ion environment. The relative widths of the two sets of fluorescence data illustrate the wider tuning range one might expect from the Nd in LNA as compared to YAG [12].



(a)

(b)

Fig. 2. Fluorescence spectra of Nd in LNA (a) and in YAG (b) excited by the infrared line of a Kr$^+$ laser at 752 nm. Solid lines above the curves in Fig. 2(a) show the tuning range of the LNA laser emission.

C. Laser Performance

We studied the laser performance of two different LNA crystals of 0.5 cm diameter and antireflection coated on their two parallel, polished faces. The first crystal, labeled 1 in Table I, was 1 cm long with the crystal c axis parallel to the rod length. The second crystal, labeled 2, was 2.4 cm long with its a axis parallel to the rod length.

The crystal characteristics and symmetry are described in detail in [2]. The use of a, b, and c to describe the hexagonal crystal follows the usual notation. Nd concentrations in both crystals were on the order of 10 at.percent ($x = 0.1$). The crystals were operated at room temperature with no forced cooling.

Laser emission from the two crytals was studied under two different pumping conditions:

1) with the 514 nm line of an Ar$^+$ laser, pumping the Nd ions into the $^4G_{7/2}$, $^2G_{9/2}$, and $^2K_{13/2}$ bands

2) with the 752 nm line of a Kr$^+$ laser, pumping the Nd ions into the $^4F_{7/2}$ and $^4S_{3/2}$ bands.

Table I shows the absorption of the two LNA crystals for the different pump sources. For crystal 1 (with crystal

TABLE I
RESULTS OBTAINED FOR THE LNA LASER WHEN PUMPING EITHER WITH AN Ar^+ LASER (AT λ = 514 nm) OR A Kr^+ LASER (AT λ = 752 nm). IN ALL CASES, THE TRANSMISSION OF THE OUTPUT MIRROR IS 10 PERCENT.

	Ar^+ Pumping (514 nm)			Kr^+ Pumping (752 nm)		
	Absorption (Percent)	Threshold (mW)	Efficiency (Percent)	Absorption (Percent)	Threshold (mW)	Efficiency (Percent)
LNA 1	60	160	10	76	90	26
LNA 2	92	300	4.5	90	~200	~10

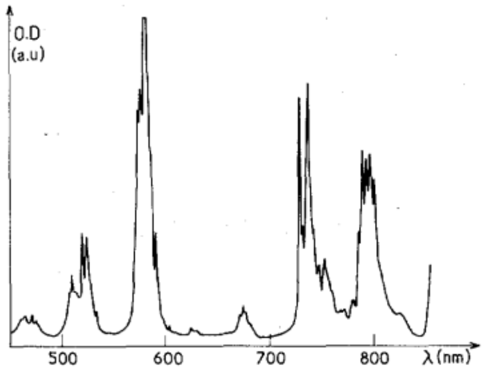


Fig. 3. Unpolarized absorption spectrum of LNA. The light is propagating along the crystallographic *c* axis.

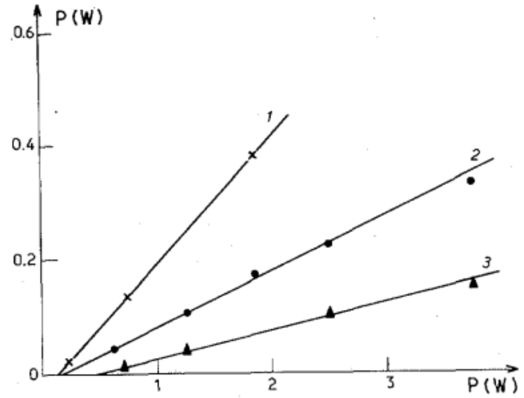


Fig. 4. Output power of the LNA laser as a function of the pump power. Transmission of the output mirror: T = 10 percent. Curve 1 refers to the LNA crystal 1 (1 cm, along *c* axis) pumped by a Kr^+ laser (at λ = 752 nm). Curves 2 and 3 refer to LNA 1 and LNA 2 (2.4 cm, along *a* axis) pumped by an Ar^+ laser (at λ = 514 nm).

c axis parallel to the resonator axis), it does not depend on the crystal orientation compared to the pump laser polarization. For crystal 2 (with crystal *a* axis parallel to the resonator axis), the absorption is strongly modulated when the rod is rotated around the cavity axis (for instance, with Kr^+ pumping, it varies between 60 and 90 percent). The absorption of LNA is larger for the 752 nm line of the Kr^+ laser than for the 514 nm line of the Ar^+ laser. This result is understood from the absorption spectrum of the material which is shown in Fig. 3.

The laser output was not polarized with crystal 1 and linearly polarized with crystal 2. With no frequency-selective elements in the cavity, the laser oscillated at the peak of the fluorescence at 1054 nm. Thresholds and efficiencies were measured for the two LNA crystals with mirror transmission of 10 percent under different pump conditions. The results are summarized in Table I. In Fig. 4, we plot the gain curves obtained when pumping with the 752 nm emission from a Kr^+ laser and with the 514 nm emission from an Ar^+ laser. Thresholds of less than 50 mW were observed with weak output coupling ($T \leq$ 0.5 percent). Thresholds increased with increasing mirror transmission, reaching 600 mW of Ar^+ (514 nm) at T = 35 percent.

The laser efficiency of LNA is significantly larger when pumping with the 752 nm output of the Kr^+ laser than with the 514 nm line of the Ar^+ laser. One reason for this difference is that the absorption of the crystal is larger for the infrared than for the green (see Table I, Fig. 3, and [8]). Another reason is that the more excited are the upper Nd states, the more probable are the nonradiative processes of energy transfer [13]; consequently, an excitation in the visible should lead to a poorer laser efficiency than in the infrared. The best laser action of LNA was observed with crystal 1 in Kr^+ pumping. Fig. 4 reports an output power of 400 mW for approximately 1.9 W of pump power. For a very careful alignment of the cavity, up to 500 mW was observed for the pumping conditions. This value corresponds to a conversion efficiency of 26 percent for the power or to a quantum efficiency of 36 percent.

Fig. 4 and Table I show that crystal 1 has a better laser action than crystal 2. This fact is related to the induced emission cross sections which are different for the two crystallographic orientations [7], [8].

For comparison between LNA and YAG laser properties, we replaced the LNA by an uncoated YAG : Nd (1 at.percent) rod of 1 cm length; pumping with the 752 nm line from the Kr^+ laser, we obtained basically identical results as with the LNA crystal 1. Our results show that an LNA crystal, cut along the *c* axis, has approximately the same laser properties as a YAG crystal of the same length. This implies that passive losses in the LNA are comparable in magnitude to Nd:YAG. This is consistent with the observations of Bagdasorov *et al.* [8]. An LNA crystal with the laser axis along the *a* direction, however, yields poorer performance.

D. Tuning Characteristics

With a four-plate Lyot filter F (shown in Fig. 1) in the cavity, the LNA laser output could be tuned to either the

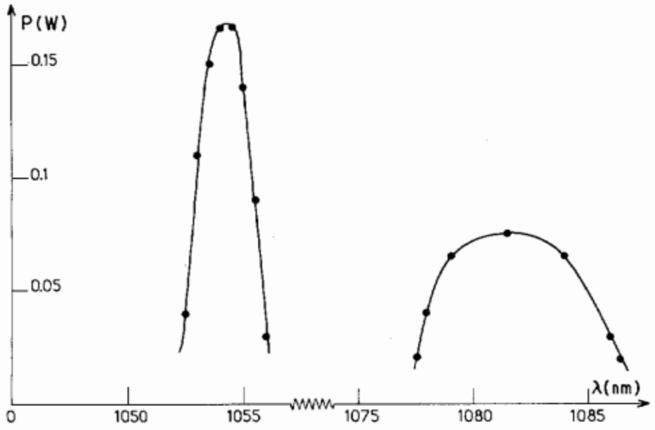


Fig. 5. Tuning curves of the LNA laser (crystal 1) obtained with a four-plate Lyot filter and a solid etalon in the cavity. The pumping source is an Ar$^+$ laser emitting 4 W at 514 nm.

1054 or the 1082 nm bands. The bandwidth of the laser output in this case was approximately 0.6 Å. With the Lyot filter, it was possible to suppress the tendency of the system to oscillate at 10 545 Å and force the system to oscillate in the 10 820 Å band. The Lyot filter permitted limited tuning over a portion of the fluorescence in each band. A thin, uncoated etalon E inserted into the cavity provided a much improved tuning range and reduced the bandwidth of the laser output significantly.

The tuning curve obtained with a four-plate Lyot filter and a 0.2 mm thick, uncoated etalon in the cavity is shown in Fig. 5. The pump source for the results shown here was 4 W from an Ar$^+$ laser at 514 nm. A similar tuning curve results when the IR output of the Kr$^+$ laser is used to pump the LNA crystal. The tuning range in the 1082 nm band extends from 1078.0 to 1086.0 nm (20 percent power points), while the tuning range in the 1054 nm band extends from 1053.0 to 1056.5 nm (20 percent power points). In general, increasing the pump power extended the tuning range. The fluorescence curve of Fig. 2(a) suggests that with sufficiently large pump powers, most of the wavelength region between 1051 and 1086 nm should be accessible.

In order to restrict the LNA laser emission to only a few longitudinal modes, different solid etalons were inserted into the cavity. A 2 mm thick, uncoated etalon yielded a laser output at 1083 nm with two longitudinal modes separated by 1.9 GHz. This difference corresponds to the spatial hole burning interval for this particular cavity. The power output of the laser in this case was 210 mW at 1083 nm. A 1 mm thick etalon with a 50 percent transmission coating yielded single-mode operation. The power output under single-mode conditions at 1083 nm was 150 mW. In each case, the LNA laser was pumped by 1.9 W of 752 nm power from a Kr$^+$ laser. When the LNA laser is tuned to the 1054 nm peak, the power output increases by approximately 30 percent.

E. CW Pumping with Lamps

We have replaced the YAG rod in a Microcontrole CW laser cavity (YAG 904) with the LNA crystal 2 and obtained CW laser emission at 1054 nm. The laser head employs 2 Kr arc lamps of 3 kW each for pumping. The lamp threshold current is about three times greater with the LNA crystal (32 mm in length, oriented along the *a* axis) than with the YAG rod (92 mm in length) normally employed in this cavity which includes two highly reflecting mirrors. The LNA power output at 1054 nm is 66 mW. The emission is linearly polarized. We expect very significant improvement when longer optical quality crystals of LNA with the proper crystal orientation become available.

CONCLUSIONS

LNA appears to be an excellent CW laser crystal with an efficiency comparable to that of YAG when pumped by another laser. Since the Nd concentration quenching is not very effective in LNA [2], [7], [8], we can expect even better results by increasing the Nd content in the LNA crystal. The large conversion efficiency (26 percent) with IR pumping in conjunction with its rather broad tuning range in the 1 μm region makes it an attractive material for several applications.

LNA may be useful substitute for YAG in applications where the greater Nd concentration may make it possible to decrease the size of the active element [14]. In particular, pumping LNA with CW laser diode arrays should be attractive. Laser diode pumping of YAG with a high efficiency has already been demonstrated [15], and its extension to LNA should follow directly with similar performance in perhaps a smaller package. The present results with IR pumping from a Kr$^+$ laser are encouraged in that respect.

It is also of interest to note that the main laser line of LNA at $\lambda = 1054$ nm corresponds exactly to the maximum of fluorescence of Nd in phosphate and fluorophosphate glasses, which are used as amplifiers in laser fusion devices. LNA could thus be an advantageous alternative to Li YF$_4$:Nd as an oscillator for this application [16].

Considerable improvement should be possible in the growth of LNA crystals of better optical quality. The LETI group is actively pursuing the optimization of LNA crystal growth [17]. In this sense, the results reported here should be regarded as minimum performance levels with improvement to follow.

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