

Single- and dual-wavelength laser operation of a diode-pumped Nd:LaF₃ single crystal around 1.05 μm and 1.32 μm



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ABSTRACT

Calibrated room temperature polarized emission spectra recorded between 850 and 1400 nm and nearly free from any reabsorption effect are presented for the first time. A laser output power of 2.35 W is obtained at 1063.45 nm with a laser slope efficiency of about 56% by pumping an uncoated Nd:LaF₃ single crystal with a fiber-coupled laser diode at 790 nm inside a standard two-mirror linear laser cavity. True dual-wavelength laser operation on two orthogonally polarized laser lines around 1040 and 1065 nm as well as continuous laser wavelength tuning around 1040 nm, 1048 nm and 1064 nm are also achieved for the first time by using either an intracavity etalon or a birefringent filter. Laser operation is finally obtained around 1330.73 nm with a maximum output power of 0.18 W and a laser slope efficiency of about 4% and simultaneous dual-wavelength laser operation at 1329.04 and 1359.67 nm is demonstrated by using a glass etalon.

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1. Introduction

In spite of the present supremacy and the growing interest of Yb-doped crystals like Yb:KGW, Yb:YAG, Yb:SFAP or Yb:CaF₂ for the development of ultra-short pulse laser oscillators and/or ultra-high peak power laser chains around 1 μm , there is a renewed interest for a series of broad-band Nd-doped crystals which could offer nearly the same possibilities in terms of ultra-short pulse production and amplification along with a number of advantages such as lower laser thresholds and other possibilities such as laser operation at several laser wavelengths with the same or different polarization states for different applications. This is the case for instance of the recently re-investigated multisite (Nd,Y)- and (Nd,Lu)-doped CaF₂ laser crystals with strongly overlapping emission bands peaking around 1.053 μm and 1.062 μm , emission bandwidths of about 30 nm at half maximum and emission lifetimes of the order of 325 μs [1,2]. This is also the case of other well-known [3–7] but not completely explored crystals such as the

structurally disordered oxide Nd:LMA (LaMgAl₁₁O₁₉), with overlapping emission bands peaking around 1.056 μm and 1.065 μm and an emission lifetime of about 300 μs [3,4], and the single-site fluoride Nd:LaF₃ with overlapping emission bands peaking around 1.047 and 1.062 μm and a radiative emission lifetime of the order of 735 μs [4,5].

In the present communication we concentrate more particularly on the case of Nd:LaF₃ for several reasons. We realized that the available spectroscopic data [3,4,7] were either incomplete or misleading because of reabsorption effects and that it would be worth to investigate the laser behavior and the laser characteristics of this crystal around 1.06 μm at multi-watt pump power levels and to examine the offered laser performance around 1.3 μm , what had never been reported before. The highest output power ever reported with Nd:LaF₃ [8] did not exceed about 300 mW and it was measured for a combination of laser wavelengths around 1.04 and 1.06 μm , not for single- or true dual-wavelength laser operations.

2. Emission properties

Fig. 1 shows the emission spectra of Nd:LaF₃ registered at room temperature in π (for E//c) and σ (E $\perp$ c) polarization from 830 to 1380 nm. These spectra were obtained by exciting the crystal with a CW Ti:sapphire laser set at 808 nm and by using an OSA (Optical

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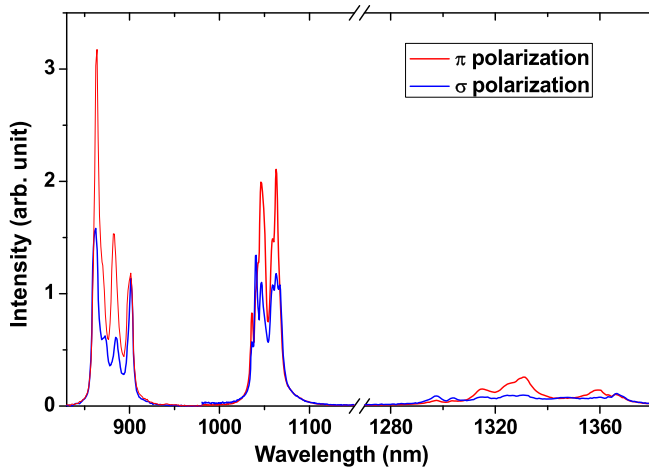


Fig. 1. Room temperature polarized emission spectra of Nd:LaF₃ under 808 nm excitation.

Spectrum Analyser). They were both calibrated between each other and corrected from the spectral response of the apparatuses. As usual, these spectra consist of three sets of bands located around 900 nm, 1050 nm and 1330 nm and assigned to the three respective $^4F_{3/2} \rightarrow ^4I_{9/2}$, $^4F_{3/2} \rightarrow ^4I_{11/2}$ and $^4F_{3/2} \rightarrow ^4I_{13/2}$ Nd³⁺ emission transitions.

Compared to the spectra which were reported by Fan et al. [4], who only displayed the emission band around 1050 nm, the spectral resolution of our spectra appears a little better, as good in fact as that indicated by the spectra reported later by Butha et al. for Nd:LaF₃ thin films [5]. Nevertheless, the latter were not quite correctly registered since the band recorded around 900 nm - the “zero-line” peaking around 863 nm more specifically - appeared with a smaller intensity than the one occurring around 1050 nm, which is the reverse of what we found. Such a discrepancy often appears when reabsorption effects are not addressed carefully enough, something which is known since a long time and was already discussed in such a pioneer review article as [6]. Indeed, depending on the experimental excitation and emission conditions and on the sample temperature, strong self-absorption may occur around 900 nm, where absorption and emission lines corresponding to $^4F_{3/2} \leftrightarrow ^4I_{9/2}$ optical transitions coincide, and artificially distorts and decreases the corresponding emission peaks. Such distorted emission spectra then lead to wrong estimations of branching ratios and stimulated emission cross sections.

To avoid reabsorption effects, our spectra were registered by using a simple technique which we already experienced for many other Nd-doped systems [9] and which is close to that used for instance in Ref. [10]. The sample was glued behind a small pinhole of about 500 μm and laser excitation (pump spot of about 50 μm diameter) was produced at one edge of the pinhole in order to mask the fluorescence inside the crystal and to collect only that coming from the pump spot. Then, the fluorescence spot was imaged on the entrance of the fiber which is coupled to the OSA. Doing so, the emission intensity which is observed around the zero-line at 863 nm was optimized with respect to the other lines observed around 1 μm by slightly adjusting the position of the pump spot and its image at the entrance of the fiber. The relative intensities of the $^4F_{3/2} \rightarrow ^4I_{9/2}$ emission lines thus obtained between 850 nm and 950 nm were further checked by using the reciprocity method [9] which consists in converting the associated $^4I_{9/2} \rightarrow ^4F_{3/2}$ absorption spectra knowing the positions of the corresponding energy levels. Using the energy levels reported in Ref. [11] and polarized absorption spectra (already reported in Ref. [5]) recorded at room

temperature, the resulting emission spectra exhibited three emission lines around 863 nm, 883 nm and 900 nm with relative intensity ratios, as measured for instance in π polarization, of 1, 0.44 and 0.33, in close agreement with the relative intensity ratios 1, 0.47 and 0.36 displayed in Fig. 1.

Additionally, we noticed that the ratio between the emission cross sections derived around 1060 nm and 1330 nm by Butha et al. [5] were not consistent with their own intensity data. Thus, by using our own corrected emission spectra and the well-known Fuchtbauer-Ladenburg expression [4], with $\tau_R = 735 \mu s$ (according to [4]), for the radiative emission lifetime, $n = 1.6$ for the average refraction index around 1 μm, it is derived the following emission cross sections (with an experimental precision of about 10%): $\sigma_{em}^\pi(1063 \text{ nm}) = 2.1 \times 10^{-20} \text{ cm}^2$ and $\sigma_{em}^\sigma(1040.5 \text{ nm}) = 1.2 \times 10^{-20} \text{ cm}^2$, in good agreement with [4], $\sigma_{em}^\pi(1331 \text{ nm}) = 0.8 \times 10^{-20} \text{ cm}^2$, instead of about $0.3 \times 10^{-20} \text{ cm}^2$, as given in Ref. [5], and $\sigma_{em}^\pi(882 \text{ nm}) = 1.3 \times 10^{-20} \text{ cm}^2$. These measurements were further checked by using our emission spectra to derive the branching ratios: $\beta_1 = \beta(^4F_{3/2} \rightarrow ^4I_{9/2}) = 40.7\%$, $\beta_2 = \beta(^4F_{3/2} \rightarrow ^4I_{11/2}) = 48.5\%$ and $\beta_3 = \beta(^4F_{3/2} \rightarrow ^4I_{13/2}) = 10.8\%$. Compared to Butha's results [5], which was expected due the reabsorption distortion effects mentioned above, our β_1 value is slightly larger than theirs, thus our β_2 value is slightly smaller. Using the ratio of the β_2 and β_3 values, as used in the past literature [6], it is found $R = \beta_2/\beta_3 \approx 4.5$, something which is quite close to the theoretical value reported in Ref. [6].

Returning now to the description of the spectra reported in Fig. 1, it is worth noting first that higher emission intensities and probably better laser performance will be obtained in π-polarization, except for the σ-polarized emission line located around 1040 nm. It is also worth noting that each band is quite broad which means that some continuous wavelength tuning should be possible, which will be more specifically addressed in the following section, and that some short-pulse laser operation or short-pulse amplification could be achieved in the future, like in glasses, which is quite interesting. As in glasses, however, the emission cross sections are rather low, one order of magnitude lower than in the case of Nd:YAG [12], for instance, which means probably higher laser thresholds. This drawback is a bit compensated by a long radiative lifetime (three times longer than in the case of Nd:YAG) thus a large $\sigma \cdot \tau$ product and a large energy storage capability, and by the fact that simultaneous laser operation on different emission lines with specific polarizations could be interesting for some particular applications.

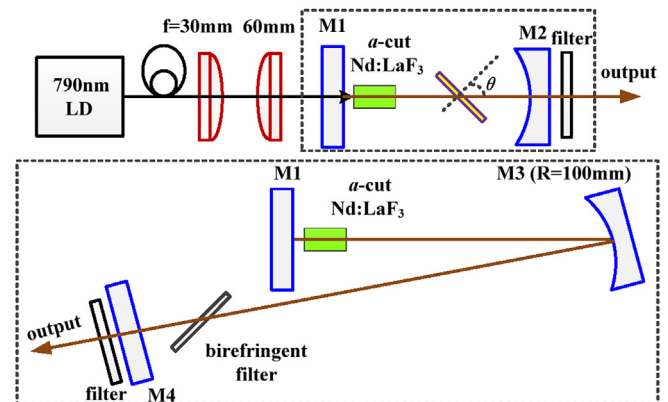


Fig. 2. Schematic of diode-pumped Nd:LaF₃ laser cavities.

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