Multiline generation capabilities of diode-pumped Nd:YAP and Nd:YAG lasers

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Abstract. Multiline generation capabilities of diode pumped Nd:YAP and Nd:YAG lasers within 1.3 – 1.5 µm wavelength range at room temperature are reported. Two optical resonators designed for 1.3 µm and 1.4 µm laser operation have been realized. Using a single quartz plate as a tuning element, six single emission lines within the 1.3 – 1.5 µm spectral range for both Nd:YAG and Nd:YAP lasers have been reached. Moreover, as also demonstrated, it was possible to obtain Nd:YAG/Nd:YAP dual frequency regime operation for some line combinations.

1. Introduction
So far, the neodymium ion Nd3+ has been one of the most frequently used laser ions. The success of this ion is due to its favorable energetic level structure and spectroscopic properties suitable for laser generation. Since 1961, when this ion was lasing first time using a CaWO4 crystal [1], the Nd3+ ion has been successfully tested with more than 180 crystalline laser hosts [2]. Nevertheless, by far the most important solid-state laser for scientific, medical, industrial and military applications based on Nd3+ ion is Nd:YAG, because it has a high gain and good thermal and mechanical properties. Thanks to this, relatively cheap high-quality Nd:YAG rods and appropriate reliable highly-efficient high-power pumping laser diodes are affordable. Another attractive laser host for neodymium is the yttrium aluminium oxide YAlO3 (YAP,YIO), due to its natural birefringence combined with good thermal and mechanical properties similar to those of YAG [3]. Owing to the birefringent character of the YAP matrix, the thermally-induced birefringence does not degrade the laser performance [4].

Even though the available laser emissions of Nd:YAG and Nd:YAP cover tens of lines between 0.94 µm and 1.84 µm, the most frequently used lines are 1064 nm and 1070 nm for Nd:YAG and Nd:YAP, respectively, which corresponds to transition 4F3/2 → 4I11/2 of the Nd3+ ion [4, 5]. In the work presented, we focused on laser lines corresponding to transition 4F3/2 → 4I13/2 which covers laser emission from 1.32 to 1.44 µm. Although the stimulated emission cross-sections at this transition are more than ten times lower [6] in comparison with emission at 1064 nm, and the quantum defect is higher than 35 %, this wavelength can be obtained relatively easily with reasonable efficiency by using a low-loss resonator (multi-Watt output was demonstrated previously using diode pumped Nd:YAG laser operating even at 1444 nm [7]). Unlike 1064 nm
Figure 1: Liquid water absorption [9] versus wavelengths within 1000 – 1650 nm. Main Nd:YAG laser emission lines in this range as well as emission of Er:glass laser at 1.54 µm are marked.

wavelength, radiation in the 1.3 - 1.4 µm spectral range is much more absorbed by water – see Fig. 1. The highest absorption coefficient (∼ 31 cm⁻¹) of liquid water in this region corresponds to 1.44 µm, which is even higher in comparison with the “eye-save” 1.54 µm radiation. For 1.44 µm radiation, the soft tissue penetration depth is 320 µm. Going to shorter wavelengths down to 1.32 µm, the penetration depth into the soft tissue can change about one order. From our investigation [8] of radiation transmission through the eye structures, a difference has been observed in radiation attenuation for a particular eye tissues and for the measured wavelengths. The knowledge of energy loss distribution, e.g., inside the eye, is very important from the point of internal tissue injury.

The aim of this study was to investigate the diode-pumped Nd:YAG and Nd:YAP laser tuning capabilities in the spectral range of general interest 1.3 – 1.5 µm. The laser emission within this band is very much required for many applications in medicine, atmospheric physics, and spectroscopy due to high absorption of this radiation in liquid water and water vapor. In our experiment, six single emission lines within the desired spectral region have been observed for both Nd:YAG and Nd:YAP active media. Moreover, it was possible to operate both lasers in the dual frequency regime for some line combinations, which makes these lasers interesting for sum and different frequency generation.

2. Materials and methods
2.1. Active medium and pumping source
In our experiment, 1.3 at. % and 1.0 at. % doped Nd:YAG and Nd:YAP active media, respectively, grown by the Czochralski method, were used. The Nd:YAG and Nd:YAP samples φ5×5 mm and φ5×8 mm in dimensions, respectively, were of high quality and free of crack or twins.

As a pumping source, a fibre-coupled (core diameter 400 µm, numerical aperture 0.22) 808 nm laser-diode (HLU20F400, LIMO Laser Systems) was employed. The laser diode was operated in pulsed regime with low duty cycle (pulse length 10 ms, repetition rate 10 Hz, maximum pulse power amplitude 15 W), so it was not necessary to actively cool the laser crystals mounted in a copper heat sink. The diode radiation was focused into the active medium by two achromatic doublets with a focal length of 75 mm, resulting in the spot size of about 360 µm.

2.2. Spectroscopic characteristics
Emission spectra of Nd:YAG and Nd:YAP samples were measured by fiber coupled-spectrometer Ocean-Optics NIR 512 (0.9 – 1.7 nm wavelength range) along the crystal longitudinal axis together with a cut-off filter used for laser-diode excitation radiation at 808 nm. In the case of
anisotropic Nd:YAP crystal, the polarization-resolved emission spectra were evaluated. To do this, an oriented film polarizer was placed in front of the spectrometer entrance. The Nd:YAG and Nd:YAP emission spectra within the range of our interest (1300 – 1450 nm) are shown in Fig. 2a) and Fig. 2b), respectively.

![Nd:YAG emission spectra](image1)

![Polarization-resolved Nd:YAP emission spectra](image2)

Figure 2: Nd:YAG emission spectra (a) and polarization-resolved Nd:YAP emission spectra (b) within the 1.30 – 1.45 µm spectral range

2.3. Measuring instruments
Laser output characteristics in terms of mean power, emission spectra, and spatial beam profile were measured by Molectron energy/power meter EMP2000 in connection with PowerMax probe PM3, fiber-coupled Spectrometer Ocean-Optics NIR 512 sensitive in the 0.9 – 1.7 µm spectral range, and Spiricon camera Pyrocam III, respectively.

3. Experimental arrangement and results
The laser experiment set-up is schematically illustrated in Fig. 3. Two semi-hemispherical laser resonators 110 mm long formed by a flat pump mirror and a curved output coupler (curvature radius 150 mm) were realized — the first one for 1.3 µm spectral region ($R_{oc} = 91 \% @ 1.3 \mu m$) and the second one for 1.4 µm ($R_{oc} = 98 \% @ 1.4 \mu m$). The Nd:YAG and Nd:YAP active media mounted on a copper heat sink were situated closest to the pump mirror, i.e., the location of the cavity beam waist. For laser line selection, a single quartz plate 1.5 mm thick was placed inside the optical resonator at Brewster’s angle between the output coupler and laser active medium.

![Experimental set-up](image3)

Figure 3: Layout of experimental set-up for switchable Nd-doped-crystal laser-operation within the 1.3 or 1.4 µm spectral bands
In the case of laser systems without a tuning element inside the resonator, the spectral line shapes for Nd:YAG and Nd:YAP active media together with beam profiles are displayed in Fig. 4a) and Fig. 4b), respectively. It is worth mentioning that for the Nd:YAG crystal designed for emission at 1.3 \( \mu \text{m} \) wavelength, the laser inherently operated in the dual frequency regime (see Fig. 4a). The corresponding maximal mean powers \( P_{\text{mean}} \), oscillation thresholds \( P_{\text{thr}} \), and slope efficiencies \( \eta_{\text{diff}} \) for the Nd:YAG and Nd:YAP lasers are summarized in Table 1.

![Figure 4: Spectral lines of Nd:YAG (a) and Nd:YAP (b) lasers designed for operation at 1.3 \( \mu \text{m} \) and 1.4 \( \mu \text{m} \) spectral regions without tuning element inside the resonator. Inset: spatial beam profiles at max. pumping](image)

| Laser   | \( \lambda \) [\( \mu \text{m} \)] | \( P_{\text{mean}} \) [mW] | \( P_{\text{thr}} \) [mW] | \( \eta_{\text{diff}} \) |
|---------|-----------------------------------|----------------------------|--------------------------|-------------------|
| Nd:YAG  | 1.3                               | 374                        | 160                      | 0.33              |
|         | 1.4                               | 167                        | 230                      | 0.22              |
| Nd:YAP  | 1.3                               | 420                        | 167                      | 0.33              |
|         | 1.4                               | 121                        | 560                      | 0.14              |

If the birefringent quartz plate serving as a tuning element was inserted inside the laser resonator, six single emission lines within the spectral range 1.3 – 1.5 \( \mu \text{m} \) were reached for both Nd:YAG and Nd:YAP lasers. In addition, for some spectral line combinations, it was possible to operate the lasers in the dual frequency regime. The individual spectral lines obtained for Nd:YAG and Nd:YAP materials are shown in Fig. 5a) and Fig. 5b), respectively.
Figure 5: Spectral lines of Nd:YAG (a) and Nd:YAP (b) lasers designed for operation at 1.3 µm and 1.4 µm spectral regions reached by birefringent quartz plate tuning

4. Conclusion
To conclude, multiline generation capabilities of diode-pumped Nd:YAP and Nd:YAG lasers within the range of general interest 1.3 – 1.5 µm have been investigated. Using pulsed 808 nm laser-diode pumping (10Hz, 10 ms, $P_{\text{mean}} = 1.5$ W) together with a single 1.5 mm thick quartz plate placed in the resonator at Brewster’s angle, six single emission lines (max. mean power in parentheses) within the desired spectral range were obtained for each laser; specifically – 1321.0 nm (188 mW), 1340.5 nm (156 mW), 1357.5 nm (131 mW), 1413.3 nm (43 mW), 1432.0 nm (40 mW), 1445.0 nm (70 mW) for the Nd:YAG laser, and 1340.8 nm (114 mW), 1341.5 nm (78 mW), 1342.8 nm (157 mW), 1402.8 nm (15 mW), 1407.8 nm (28 mW), 1432.8 nm (100 mW) for the Nd:YAP laser in the same resonator configuration. Moreover, for some spectral line combinations, it was possible to operate both lasers in the dual frequency regime, which makes these lasers interesting for sum and different frequency generation. Further improvement in terms of generation of other laser lines is expected by using a tuning element with a smaller transmission bandwidth. For example, a sequence of birefringent quartz plates and polarizers forming so called Lyot filter, exhibiting a sharper filter function, could be a proper solution.

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