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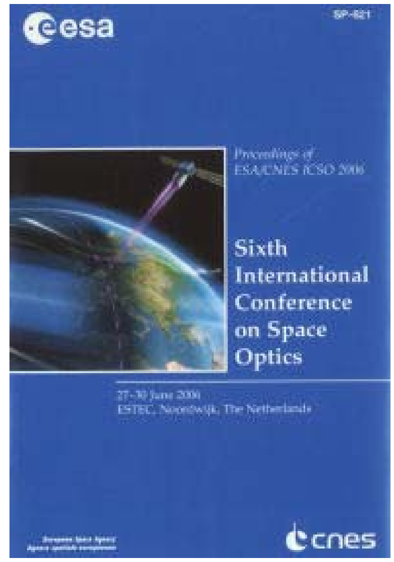

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DIODE-PUMPED Nd:MIXED-GARNET LASER WITH EMISSION AT 943 nm FOR WATER VAPOR DIAL

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ABSTRACT
In the frame of a technological development for ESA space water vapor DIAL application, we show that, by the compositional tuning technique, wavelength tuning of laser materials to match the water vapor absorption lines in the wavelength region 942-943 nm (and at about 935 nm) can be achieved. From preliminary investigations, two mixed-garnet crystal families have been identified as favorable ones, Nd:$YAG_{1-x}YSGG_x$ and Nd:$YSAG_{1-x}GGG_x$. In this work, two compositionally tuned Nd:mixed-garnet laser systems have been developed and tested. The first one (Nd(1%):$YSAG_{0.91}$ / $GGG_{0.09}$) exhibits an output wavelength peak at about 942.8-943.0 nm, the latter (Nd(0.83%):$YAG_{0.43}$ / $YSGG_{0.57}$) at 943.2 nm. Laser action of the two compositions has been obtained both in long pulse and in Q-switching mode.

1. INTRODUCTION

The 943 nm wavelength region is of particular interest because of the presence of strong atmospheric water-vapor absorption lines, very useful for remote sensing applications. Several works [1], [2], [3] have been made about the performances of the Nd:YAG $R_1 \rightarrow Z_5$ line of the quasi-three-level $^4F_{3/2} \rightarrow ^4I_{9/2}$ transition, which exhibits an emission peak wavelength at about 946 nm.
In order to match the absorption bands around 943 nm, well suited for differential absorption LIDAR, the compositional tuning technique [4] has been successfully applied: in the frame of this work, two different mixed-garnet compositions have been grown and developed, Nd:$YSAG_{0.91}GGG_{0.09}$ (from now on Nd:YSAG/GGG) and Nd:$YAG_{0.43}YSGG_{0.57}$ (from now on Nd:YAG/YSGG), at a Nd concentration of 1 at% and 0.83 at% respectively.
The laser behaviour of these mixed-garnet materials has been tested with diode-pumping in a plano/concave laser resonator as described in Section 3. The laser has been tested both in long pulse and in Q-switching mode. Laser action has been demonstrated in both regimes (Section 4 and 5) with low efficiencies, probably due to the effect of poor optical quality of the first available samples combined with the intrinsic quasi-three-level laser characteristics. The first composition (YSAG/GGG) showed an output wavelength peak at 943.0 ±0.1nm, the second one (YAG/YSGG) at 943.2 ±0.1nm (in-air wavelength values).

2. SPECTROSCOPIC CHARACTERISTICS

The spectroscopy of both the mixed-garnet compositions have been characterized. In Fig. 1 we see the fluorescence spectrum of Nd:YSAG/GGG, with the Nd:YAG spectrum superposed for comparison. The difference of the emission peaks center (934.64 nm and 943.04 nm in-air wavelength values) with respect to the corresponding Nd:YAG transitions (938.45 nm and 945.96 nm) is evident.
The FWHM spectral width at 943nm results 2.2nm.
In Fig. 2 it is reported the absorption spectrum in the pump spectral region: the strongest but narrowest absorption line falls at 808.5 nm, the secondary peak at 804.8 nm.

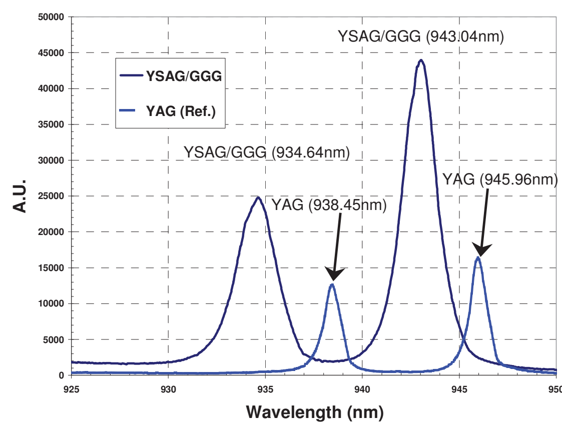

Fig. 1. Fluorescence analysis of the Nd:YSAG-GGG composition. As comparison, the fluorescence of a Nd:YAG sample is reported.

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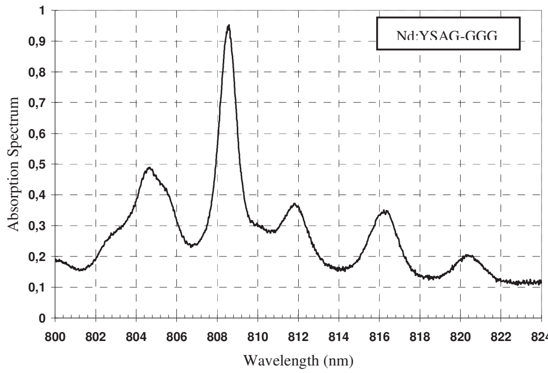

Fig. 2. Absorption spectrum in the pump spectral region of Nd:YSAG-GGG (spectroscopic thin sample).

The Nd:YAG/YSGG compositional tuning behavior and absorption spectrum in the pump spectral region are shown in Figs. 3 and 4. The shift of the emission peak at 943 nm (strongest transition) vs. the YSGG concentration coefficient (x) is reported in Fig. 3: in correspondence to a concentration coefficient value 0.57, the emission peak position is centered at 943.2 nm.

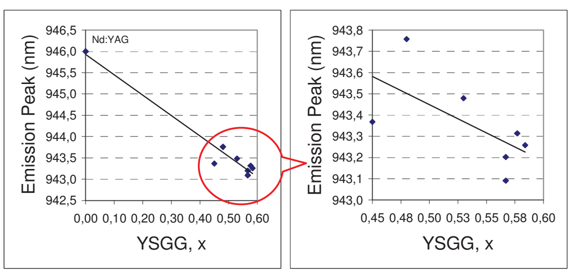

Fig. 3. Shift of the Nd:YAG/YSGG strongest emission peak at about 943 nm vs. YSGG concentration (x).

The Nd:YAG/YSGG absorption spectrum at the pump wavelength (Fig. 4) is very similar to the Nd:YSAG/GGG composition spectrum, with the two main absorption peaks located at 808.5 nm and 804.8 nm.

3. EXPERIMENTAL SETUP

The experiments here described have been performed with Mixed-Garnet rods of different diameters (3 and 5 mm) and lengths (3, 5 and 10 mm) of the two compositions, all with high transmission coatings at 808 nm (pump wavelength) and 1064 nm (four level transition wavelength); some rods have one face HR coated at 943 nm and the other face AR at 943 nm (from now on HR/AR rods), the remaining rods have both sides AR coated at 943 nm (from now on AR/AR rods).

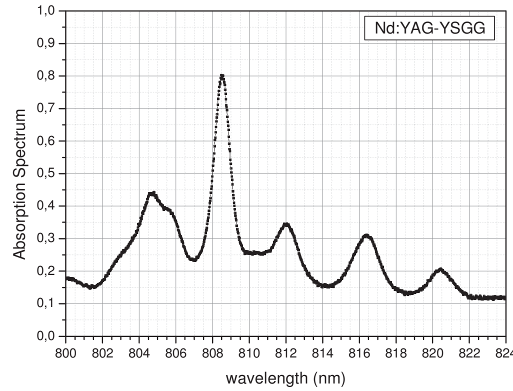

Fig. 4. Absorption spectrum in the pump spectral region of Nd:YAG-YSGG (spectroscopic thin sample).

The active material, conductively cooled through a copper holder mounted on a cold plate, is optically pumped with a 1200 W QCW laser diodes (LD) stack with emission at about 808 nm, with pump pulse duration 150 µs and pulse repetition frequency 100 Hz. Also the LD stack is conductive-cooled in similar way. The pump radiation, fast-axis-collimated with a set of cylindrical microlenses, is focused onto the active material by mean of cylindrical and aspherical optics.
The temperature of the LD stack and active material cold plates is controlled by two refrigerators, operating in the temperature range 10-27 °C. The pump peak emission wavelength is temperature tuned to match the mixed-garnet absorption peaks at 805 nm and 808 nm via the LD thermal tuning characteristics (0.27 nm/°C).

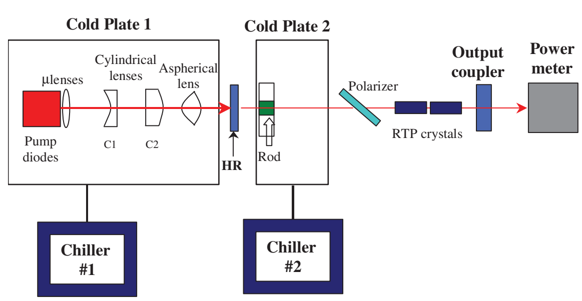

Fig. 5. Scheme of the set-up for the experiments with plano/spherical laser cavity.

The active material cold-plate temperature is set to 12°C in view of the quasi-three-level laser better performance at relatively low temperature.

The laser resonator (schematically shown in Fig. 5) is 12.5 cm-long for long pulse mode tests and 30 cm long for Q-switching. Only with AR/AR rods, a HR rear mirror at 943 nm is used, with high transmission at 808 and 1064 nm. The output coupler (OC) reflectivity at 943 nm varies from R=89.7% to 96.9%.
For the Q-switching tests, a thin film polarizer and a double crystal RTP Pockel's cell at 943 nm have been inserted in the cavity.

4. LONG PULSE LASER PERFORMANCE

This Section reports the test results in long pulse mode for the mixed-garnet compositions and for Nd:YAG (1.1 at% Nd^{3+} content) at 946 nm used for comparison and validation of both pump section and laser resonator.

4.1 HR/AR rods

Firstly, the output performances of the HR/AR rods are presented.

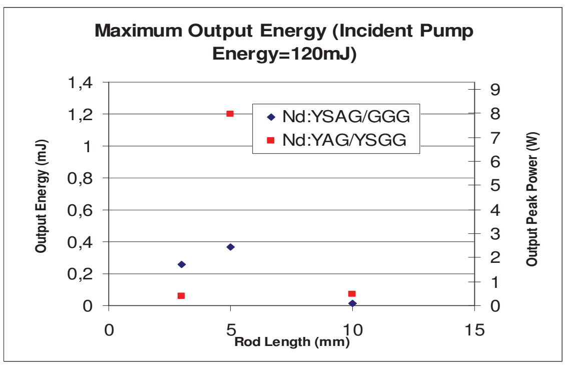

Fig. 6. Nd:mixed-garnet HR/AR rods of different lengths output energy in long pulse mode.

In Fig. 6 we see the maximum output energy/power obtained with the mixed-garnet compositions vs. different rod lengths (3, 5 and 10 mm). The incident pump energy from the LD stack, measured after the pump lenses, is 120 mJ. The output coupler reflectivity is R = 96.9%. In Fig. 7 for comparison are reported the input-output characteristics of a 3x5 mm Nd:YAG rod put in the same resonator, with output reflectivity respectively of 89.7%, 94.6% and 96.9%.
From Fig. 6 we notice that, although the optical quality of the laser material is strongly variable from one to the other sample, the highest output energies for both compositions have been obtained with the 5 mm-long rods.

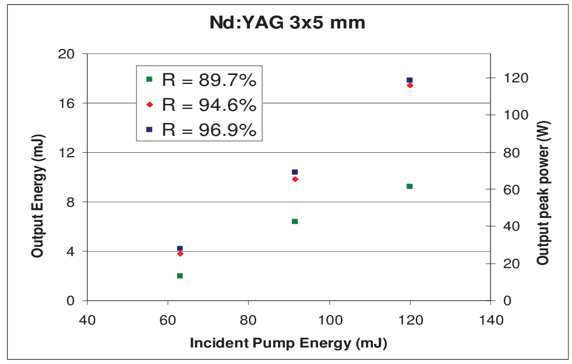

Fig. 7. HR/AR 3x5 mm Nd:YAG rod, input-output characteristics in long pulse mode at different OC reflectivity.

The laser output wavelength spectra, measured with an optical spectrum analyzer, show for the Nd:YSAG/GGG composition a center peak emission at 943.0 ±0.1nm (in-air value, see Fig. 8). The corresponding center laser emission of Nd:YAG/YSGG is at 943.2 ±0.1nm (in-air value, see Fig. 9). We can notice that the laser emission of Nd:YSAG/GGG composition is close to two of requested target values: 943.248nm and 943.083nm (in-vacuum wavelength values of water vapor absorption lines), the correspondent in-air values being (considering n=1,000274 at 950nm and T=15°C) 942.990nm and 942.825nm. The Nd:YAG maximum output energy in long pulse at 946 nm (about 17 mJ), obtained with 96.9% OC reflectivity, was 15 times higher than the best mixed-garnet performance. The main reason probably stands in the poor optical quality of the first growth samples.

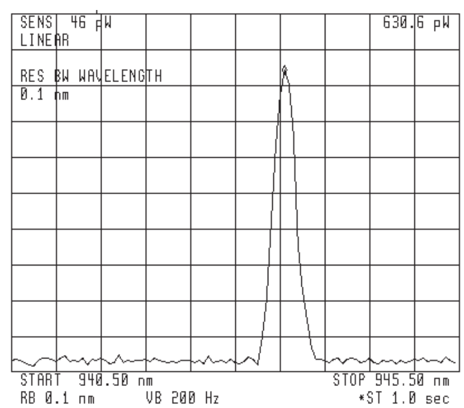

Fig. 8. Nd:YSAG/GGG laser spectrum. Measured center wavelength: 943.0±0.1 nm.

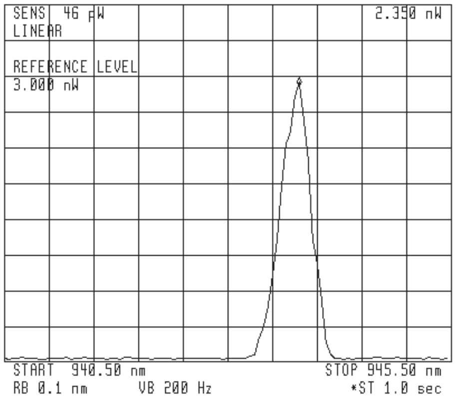

Fig. 9. Nd:YAG/YSGG laser spectrum.
Measured peak center wavelength: 943.2±0.1 nm.

4.2 AR/AR rods

Secondly we report the results obtained from the AR/AR rods. Figs. 10 and 11 show the maximum energy/power output obtained with the two mixed-garnet compositions vs. different rod lengths (3, 5 and 10 mm) and diameters (3 and 5 mm). The incident pump energy from the LD stack is 90 mJ measured after the HR rear mirror (30 mJ of the total 120 mJ pump radiation is lost due to the limited HR transmission at the pump wavelength). Different OC reflectivity values (89.7%, 94.6% and 96.9%) are used. Fig. 12 reports the input-output characteristics of Nd:YAG rods at 946 nm with the same resonator and input energy, for comparison.

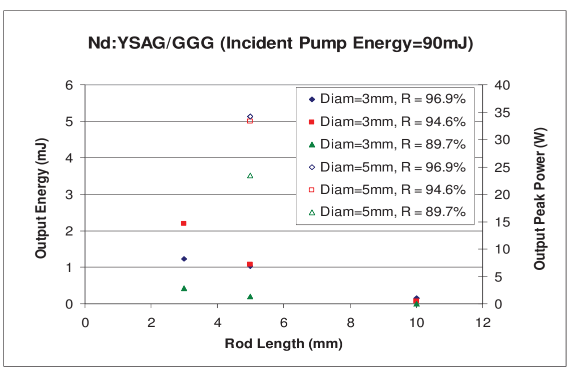

Fig. 10. Nd:YSAG/GGG output energy in long pulse mode vs. different AR/AR rod diameter and length, for different OC reflectivity.

The Nd:YSAG/GGG composition shows again its best performance (≈5 mJ output energy) with the 5 mm-long rod, specifically the 5 mm diameter one, for R = 96.9%.

The Nd:YAG/YSGG exhibits its highest output (≈3 mJ) with the 3 mm-long rod.

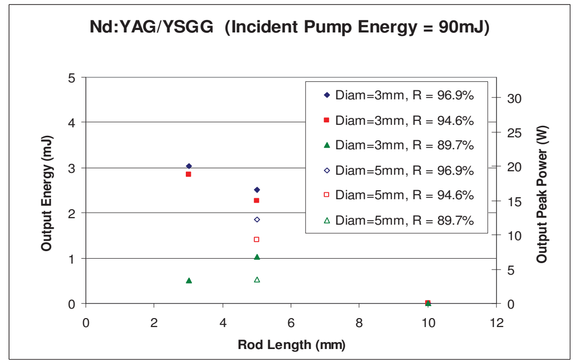

Fig. 11. Nd:YAG/YSGG output energy in long pulse mode vs. different AR/AR rod diameter and length, for different OC reflectivity.

In general the AR/AR rods exhibit higher output energy/power than the HR/AR rods, probably due to the higher coating transmission at the pump wavelength and because the thermal distortions of the active material are not directly coupled with the cavity alignment.
Nd:YAG rods of different lengths (3, 5 and 10 mm) with different output reflectivity (89.7%, 94.6% and 96.9%) have been tested in the same resonator at 946 nm. The 3x5 mm rod exhibits the best performance, ≈29 mJ with OC R= 94.6%. All the Nd:YAG AR/AR rods produce > 20 mJ output energy per pulse.

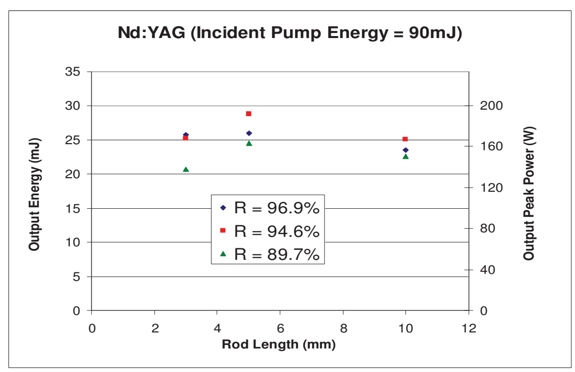

Fig. 12. Nd:YAG output energy in long pulse mode vs. different AR/AR rod length, for different OC reflectivity.

5. Q-SWITCHING

The Q-switching tests have been carried out employing only the mixed-garnet rods with the best output performances in long pulse, i.e. the Nd:YSAG/GGG

5x5 mm rod and the Nd:YAG/YSGG 3x3 mm one. The thin film polarizer and the Pockel's cell (double RTP crystal) were placed between active material and output coupler, as shown in Fig. 5. The OC reflectivity was R=89.7% for Nd:YSAG/GGG and R=94.6% for Nd:YAG/YSGG. In Fig. 13 the Q-switching results of the two mixed-garnet compositions are shown. In Fig. 14 the output characteristics of two different length YAG rods (respectively 3 and 10 mm) with OC R=89.7% are reported for comparison.

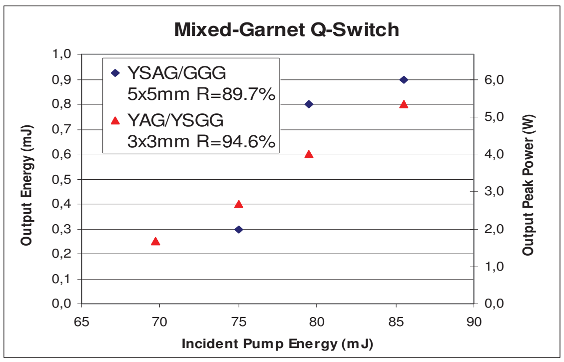

Fig. 13. Input-output energy for Nd:mixed-garnet AR/AR rods of different length in Q-switch mode.

The best performance in Q-switching, like in long pulse mode, has been obtained with the 5x5 mm Nd:YSAG/GGG rod (0.9 mJ); a flattening behavior is evident in the input-output curve at incident input energy above 80 mJ. The Nd:YAG/YSGG rod exhibits a maximum output energy of 0.8 mJ without any definite flattening effect.

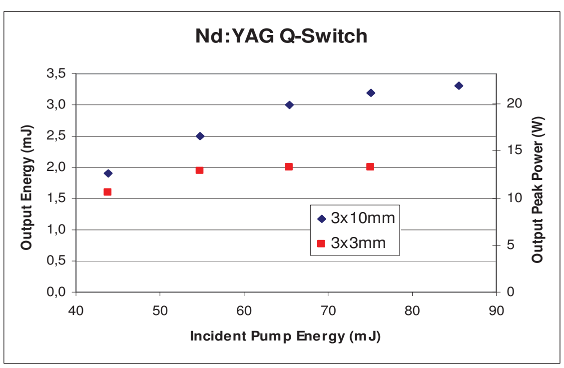

Fig. 14. Nd:mixed-garnet AR/AR rods of different length output energy in Q-switch mode.

The best performance of Nd:YAG at 946nm (3.2 mJ) has been obtained with a 3x10 mm rod and OC R=89.7%; a 3x3 mm rod exhibited in the same condition up to 2 mJ output energy, with R=94.6%. In both cases, flattening of the output vs. input cure is evident at incident pump energy above 60 mJ.

6. CONCLUSIONS

By means of the compositional tuning technique, two different wavelength-tuned mixed-garnet materials (Nd:YSAG/GGG and Nd:YAG/YSGG) show laser emission in the predicted wavelength region at 943 nm, well suited for remote sensing water vapor for space DIAL applications.
Laser emission has been obtained both in long pulse and Q-switching regimes.
The tests indicate a lower laser efficiency than that of Nd:YAG at 946 nm, probably also due to the optical quality of the first available mixed-garnet samples.

ACKNOWLEDGMENTS

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REFERENCES

1. Th. Axenson et al., High-energy Q-switched 0.946-µm solid-state diode pumped laser, *J. Opt. Soc. Am. B*, Vol. 19, No. 7, 1535-1538, July 2002.

2. F. Hanson, Efficient operation of a room-temperature Nd:YAG 946-nm laser pumped with multiple diode arrays, *Opt. Lett.*, Vol. 20, No. 2, 148-150, January 1995.

3. T. Y. Fan and R. L. Byer, Modeling and CW Operation of a Quasi-Three-Level 946 nm Nd:YAG Laser, *IEEE J. of Quantum Electron.*, Vol. QE-23, No. 5, 605-612, May 1987.

4. B. M. Walsh et al., Compositionally Tuned 0.94-µm Lasers: A Comparative Laser Material Study and Demonstration of 100-mJ Q-Switched Lasing at 0.946 and 0.9441 µm, *IEEE J. of Quantum Electron.*, Vol. 37, No. 9, 1203-1209, September 2001.