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Simultaneous cw dual-wavelength laser action and tunability performance of diode-pumped Yb^{3+}:$Sr_5(VO_4)_3F$

A.N.P. Bustamante [a,b,*], D.A. Hammons [b], R.E. Peale [a], B.H.T. Chai [a,b], M. Richardson [a], A. Chin [c]

[a] Center for Research and Education in Optics and Lasers, University of Central Florida, 4000 Central Florida Boulevard, Orlando, FL 32816-2700, USA

[b] Crystal Photonics, Inc., 2729 N. Financial Court, Sanford, FL 32773, USA

[c] Polaroid Corporation, 1 Upland Road, Norwood, MA 01062, USA

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Abstract

Simultaneous cw laser operation at 1044 and 1120 nm in Yb^{3+}:$Sr_5(VO_4)_3F$ (SVAP) under diode pumping has been achieved for the first time. Output powers of 29.9 mW at 1044 nm and 26.5 mW at 1120 nm were obtained under simultaneous operation. A maximum output for each transition operating separately was 103 mW at 1044 nm and 157 mW at 1120 nm. In addition, we demonstrate over 27 nm of wavelength tunability of the 1120 nm band. © 2001 Published by Elsevier Science B.V.

1. Introduction

Rare earth doped laser materials possessing split Stark sub-levels with multiple allowed transitions provide the possibility of realizing oscillation at more than one wavelength. Pulsed simultaneous multiple wavelength operation has been reported in a number of neodymium host crystals such as Nd:$Y_3Al_5O_{12}$ [1], Nd:$LiYF_4$ [2], Nd:$Sr_5(PO_4)_3F$ [3] and multiple ion doped $Y_3Al_5O_{12}$ [4,5]. These laser crystals have only been operated in a pulsed state with dual polarization. Continuous wave (cw) laser operation has also been demonstrated with a high dopant concentration in $LiNdP_4O_{12}$ [6] and in Nd:$YAlO_3$ [7] and Nd:YVO_4 [8], where a high stimulated emission cross-section and high population inversion is required to eliminate effects of cross-saturation of adjacent modes of the same transition. Here, we demonstrate for the first time, diode-pumped tunable laser operation with over 27 nm of wavelength tunability and the capability of simultaneous cw laser action at 1044 and 1120 nm with the same polarization in Yb^{3+}:$Sr_5(VO_4)_3$ (SVAP). Moreover, we show that with properly designed tuning elements one can change the wavelength of the 1120 nm band while simultaneously lasing the 1044 nm line.

Ytterbium doped apatite host structures are particularly well suited for simultaneous cw multi-wavelength laser operation. The favorable laser properties of Yb^{3+}:SVAP, high slope efficiencies,

* Corresponding author. Address: Center for Research and Education in Optics and Lasers, University of Central Florida, 4000 Central Florida Boulevard, Orlando, FL 32816-2700, USA. Fax: +1-407-328-9799.

E-mail address: andrea@gdi.net (A.N.P. Bustamante).

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high emission cross-section and low threshold [9–11], can lead to compact high average power diode-pumped laser systems, emitting either in a narrow emission line at 1044 nm, or tunable emission centered at 1120 nm, or both simultaneously. By combining the high emission cross-section and high ion doping concentration, one can create significant population inversions on the split electronic and vibrational excited state sublevels. Since the oscillation of modes are occurring in different transitions from the excited state, less mode competition is expected through cross-saturation of modal population inversions [6]. Moreover, the two transitions are characterized as a quasi-four-level and a true four-level laser system for the 1044 and 1120 nm transitions, respectively. Thus, deleterious effects of ground state reabsorption are seen for 1044 nm emission, since the terminal laser level lies inside the ground state manifold and contains a thermalized fraction of population. Despite the lower emission cross-section at 1120 nm, the four-level system can be made to operate efficiently and is advantageous since the gain media can be made arbitrarily thick to absorb all the pump energy and have efficient energy extraction.

The combination of a quasi-four-level and a true four-level system within the same laser media gives advantages to diode-pumped operation for efficient and high average power systems. Multi-wavelengths from a single laser source have the unique ability to perform differential wavelength operations and pump/probe measurements. Simultaneous dual wavelength cw lasing of Yb^{3+} doped $Ca_5(PO_4)_3F$ was previously demonstrated at 981 and 1042 nm [12]. However, the emission from one line was orthogonally polarized to the emission of the other line.

2. Crystal growth and spectroscopic properties

We have grown crystalline SVAP boules with up to 6% Yb (by weight in the starting melt). Crystal growth was carried out using the Czochralski technique. Contrary to common practice in growing oxyfluoride crystals, we have found that high oxidation in the growth atmosphere produces better quality SVAP single crystals, without the tendency toward grain boundaries, cracks, inclusions or spiraling.

The polarized spectroscopic properties of Yb^{3+} doped SVAP were measured using a Bomem DA8 Fourier-transform spectrometer. As with other Yb^{3+} doped gain media, laser action is based on the one excited 4f manifold, approximately 10,000 cm^{-1} above the ground state [10]. For Yb^{3+} systems, there are 12 weighted transitions in the absorption $^2F_{7/2}$–$^2F_{5/2}$ configuration. However, many transitions overlap and some Stark levels are not thermally populated at 300 K thus we see only a few transitions at room temperature. The absorption spectrum of Yb^{3+}:SVAP shows a sharp line at 986 nm corresponding to the zero phonon line. The Stokes sideband transitions, which occur at higher energies, were observed as a broad band centered at 905 nm and a shoulder at 915 nm. In addition, we observe the anti-Stokes sideband at 1044 nm with an absorption coefficient of 0.18 cm^{-1}. In Fig. 1, the polarized Stokes shifted photoluminescence spectrum of Yb^{3+}:SVAP, shows the sharp line electronic transition of the 1044 nm line and a vibrational transition seen as a broad band centered at 1120 nm. The measured lifetime of the Yb^{3+}:SVAP is 544 μs, which occurred, in a single exponential decay. An emission band at 1163 nm is also evident in Fig. 1, which had not been previously reported. Its emission cross-section is calculated assuming its origin is from undoped SVAP with a measured lifetime of 320 μs.

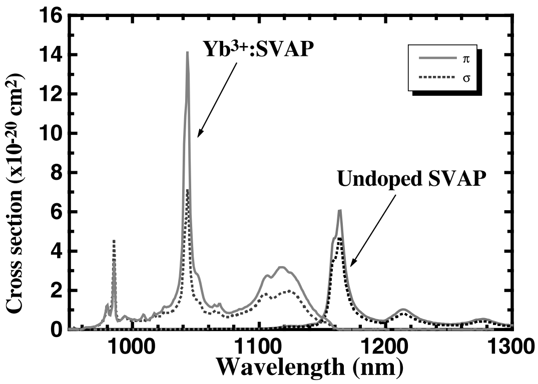

Fig. 1. Polarized emission spectrum of SVAP.

Additional experiments are being performed to understand the origin of this emission.

3. Diode-pumped laser operation

Diode-pumped operation of Yb^{3+}:SVAP was achieved for the first time by generating emission at 907 nm from a new high brightness, InGaAs/AlGaAs laser diode which overlapped well with the broad absorption at 905 nm. The diode had a maximum output of 1.74 W at 907 nm from a 200 μm stripe. A 125 μm diameter microlens (anti-reflection coated aspheric lens) was utilized to collect the emission from the laser diode's fast axis and help equalize the divergence from the fast and slow axes. After the microlens, a 60-mm focal length achromatic doublet lens was used to collect the diverging pump beam. Since the laser diode beam is essentially monochromatic, the achromatic doublet lens was utilized because of its ability to compensate for spherical aberrations. After collimation, the pump beam is refocused with a 50-mm focal length, plano/convex lens. None of the lens anti-reflection coatings were optimized for the 907 nm pump light. The overall transmission of the pump optics was 96%.

Diode-pumped laser experiments were performed to demonstrate and characterize laser operation at both 1044 and 1120 nm. CW laser operation was achieved using an end-pumped hemispherical linear cavity consisting of a flat high reflector and a 10-cm radius of curvature (ROC) output coupler. The Yb^{3+}:SVAP laser rod ($5 \times 5 \times 9$ mm^3) was placed close to the high reflector and a nominal output coupling of 1% was used for both experiments. The crystal, which absorbed approximately 60% of the pump light, was maintained at room temperature using a thermoelectric cooler. The absorption coefficient of Yb^{3+}:SVAP at 907 nm is 0.97 cm^{-1}.

Operation of the 1044 nm transition, 1120 nm transition, or both simultaneously was performed using three sets of mirrors with an equal ROC but different spectral characteristics. To sustain operation at either of the individual lasing transitions, the spectral response of the mirror was made to create a large loss for the non-lasing management of the loss components for the two lines to create a flat gain band for the two transitions. Further optimization of this system would require a detail loss budget for the two transitions including items such as absorption coefficient at the lasing wavelength (function of temperature) anti-reflection coating, mirrors spectral response and alignment.

Laser operation of the 1044 and 1120 nm transitions were characterized while they were individually lasing. Output powers exceeding 103 mW with a slope efficiency of 36% and a threshold of 90 mW of absorbed pumped were obtain at 1044 nm. Operation of the 1120 nm band occurred across a broad laser emission centered at 1117 nm. A slope efficiency of 31% was achieved as shown in Fig. 2, with a threshold of 100 mW of absorbed pump power. Anti-reflection coatings on the crystal were optimized for 1120 nm, which resulted in a higher transmission, and subsequently gave a higher output power than that of the 1044 nm emission.

Diode-pumped laser tuning experiments were accomplished using a linear hemispherical laser resonator similar to that described above. The output coupler was changed to a 20-cm ROC ($T = 0.5\%$) and the cavity length was extended to 19.5 cm. The mirrors had a broad band reflectivity covering completely the region of interest. Tuning was accomplished by inserting a single plate

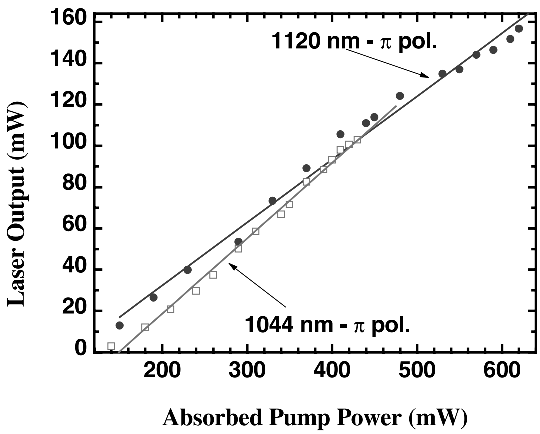

Fig. 2. Laser output power at 1044 and 1120 nm as a function of absorbed 907 nm pump power in Yb^{3+}:SVAP.

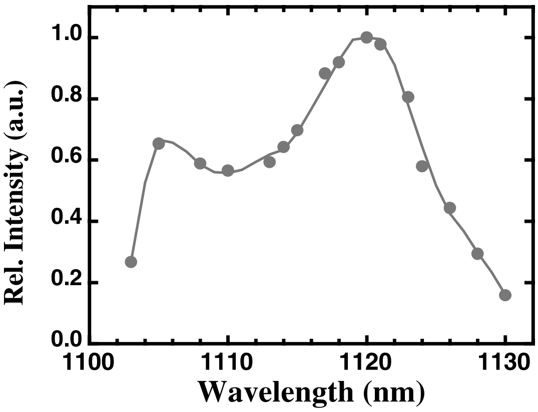

Fig. 3. Tunable laser range of Yb^{3+}:SVAP.

birefringent filter into the cavity. Over 27 nm of tuning was measured, from 1103 to 1130 nm, as shown in Fig. 3. Although the data in Fig. 3 is corrected for the response of the silicon detector being used, the poor sensitivity of the detector on the long wavelength side limits the measurement. Broader tunability should be possible.

Simultaneous laser operation was also achieved at both 1044 and 1120 nm. As shown in Fig. 4, multiple wavelength operation is possible for high gain media, such as Yb^{3+}:SVAP, for cw or long pulse operation without significant gain depletion. Using the diode-pumped linear hemispherical laser cavity discussed above, simultaneous lasing was obtained. The pump mirror was a broad band HR covering the 1044 and 1120 nm regions. The output coupler (nominal 1%) had a 10-cm ROC. Using a filter with a high reflection at 1120 nm and high transmission at 1044 nm, we were able to measure the power of the individual laser emission lines. The power of the 1044 nm laser line was 29.9 mW and that of the 1120 nm emission was 26.5 mW with an unoptimized cavity. Both the 1044 nm emission and the 1120 nm emission were measured to have the same polarization, which corresponded to the polarization of the pump source. Additional losses were resulting from the coatings and mirrors reflectivity causing the lower laser output. Further study of the interaction between the two laser lines is required to develop a dual-wavelength laser system.

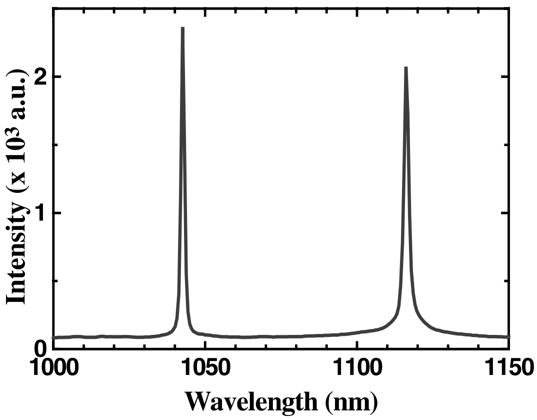

Fig. 4. Simultaneous diode-pumped Yb^{3+}:SVAP laser emissions at 1044 and 1120 nm.

In addition, tuning of the 1120 nm emission was accomplished with the 1044 nm lasing simultaneously. Tuning from 1113 to 1120 nm was obtained with the insertion of a single plate birefringent tuner. Although the cavity losses were not optimized for maximum simultaneous lasing and tuning, the system shows the ability to have tunable emission and a reference emission line from the same source.

4. Conclusions

Diode-pumped simultaneous dual wavelength operation has been achieved at 1044 and 1120 nm. We have shown over 27 nm of tunability at the 1120 nm emission band. With a optimization of the cavity loss parameters for the two wavelengths, we expect much broader tunability with simultaneous lasing of the 1044 nm line. In addition, the broad tunability and high gain of Yb^{3+}:SVAP provide favorable conditions for ultra-short pulses.

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