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Dual wavelength operation in diode-end-pumped hybrid vanadate laser

A J SINGH, S K SHARMA, P K MUKHOPADHYAY* and S M OAK
Solid State Laser Division, Raja Ramanna Centre for Advanced Technology, Indore 452 013, India
*Corresponding author. E-mail: pkm@rrcat.gov.in

Abstract. Dual wavelength operation at 1062.8 nm and 1064.1 nm in a diode-pumped hybrid laser comprising of Nd^{3+}-doped birefringent YVO_4 and $GdVO_4$ crystals is demonstrated. A detailed characterization of the laser is performed under CW and pulsed operation. Under Q-switching, 4 W of average power at 5 kHz repetition rate is obtained with 32 ns FWHM pulse duration corresponding to 25 kW of the peak power. The intensity and the polarization of the individual spectral components can be easily controlled by changing the relative gain and the relative orientation of the two crystals. The resulting pulsed dual-wavelength laser has the potential to be used as a source for generating terahertz radiation.

Keywords. Diode-pumped solid-state lasers; hybrid laser; dual wavelength operation.

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1. Introduction

Terahertz radiation in the spectral range of 0.1–3 THz has many applications in biological imaging, spectroscopy, chemical identification and heterodyne radiometry for astrophysics [1,2]. Difference frequency mixing (DFG) of the two closely spaced wavelengths in a nonlinear crystal is an effective method for generating coherent THz beam [3]. With a view to generate THz radiation, in recent years, much work has been done on the dual wavelength operation in diode-pumped solid-state lasers, particularly in the NIR spectral range by exploiting the transitions in the nearby sub-energy levels in the gain medium [4–6]. But, in these systems power at the respective wavelength cannot be controlled independently because of the homogeneous nature of the transitions and also the output is affected by strong gain competitions. Further it is very difficult to control the state of polarization of the individual wavelength which is particularly important for DFG in GaSe crystal which supports type-II phase matching for THz generation [7].

In this paper, to the best of our knowledge, we report for the first time the demonstration of high-power pulsed dual wavelength operation in a diode-pumped hybrid laser made of Nd^{3+}-doped yttrium vanadate (YVO_4) and gadolinium

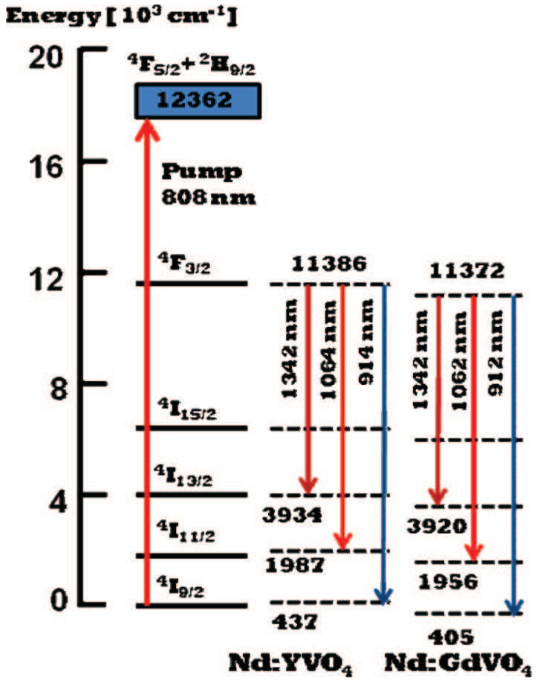

Figure 1. Energy level diagram of Nd^{3+}-doped vanadate crystals. The downward arrows represent the major transitions at 1.06, 1.3 and 0.9 μm. The upward arrow represents the pump transition under diode pumping.

vanadate ($GdVO_4$) crystals. The individual power at the two wavelengths and their state of polarization can be easily controlled independently by changing the gain and the relative orientation of the two crystals.

2. Spectroscopic properties of Nd^{3+}-doped vanadate crystals

The energy level diagrams for Nd:YVO_4 and Nd:$GdVO_4$ crystals are shown in figure 1. The Nd^{3+} ion has multiple allowed transitions departing from the metastable level $^4F_{3/2}$ to the lower-lying-energy Stark sublevels $^4I_{13/2}$, $^4I_{11/2}$ and $^4I_{9/2}$, leading to potential laser radiations at ~1.3, 1.06 and 0.9 μm, respectively. Above the upper laser level are located pump bands starting with the manifold $^4F_{5/2}$, which is responsible for absorption around 800 nm. In Nd^{3+}-doped laser material, $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions producing radiation at ~1.06 μm have the highest emission cross-sections. On the other hand, the emission cross-sections for transitions at 0.9 μm and at 1.3 μm are ~ order of magnitude lower than that for 1.06 μm.

It can be seen from figure 1 that the energy levels of Nd^{3+} ion are modified slightly due to the crystal fields of yttrium and gadolinium vanadate crystals leading to slightly different emission wavelengths for the respective transitions. In this

Table 1. Lasing properties for $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition.

Crystal	$Nd:YVO_4$	$Nd:GdVO_4$
λ_{em} (nm)	1064	1062.8 nm
Doping	0.3 at.%	0.5 at.%
$\Delta\lambda_{em}$ (nm)	0.96	1.0
$\sigma_{em} \times 10^{-19}$ cm^2	15.6	7.8
Emission polarization	Parallel to C-axis	Parallel to C-axis
λ_{abs} (nm)	808	809
$\Delta\lambda_{abs}$ (nm)	2.6	1.8
τ_f	90 μs	90 μs
K (W m^{-1} K^{-1})	5.1	11.7

paper we focus on the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition and the main lasing properties like the peak emission and absorption wavelengths (λ_{em}, λ_{abs}), respective bandwidths ($\Delta\lambda_{em}$, $\Delta\lambda_{abs}$), fluorescence lifetime (τ_f) and thermal conductivity (K) are listed in table 1. It can be seen from table 1 that $Nd:YVO_4$ and $Nd:GdVO_4$ have very similar lasing properties suitable for diode pumping with a polarized emission at 1064 and 1062.8 nm. This enables efficient and controllable dual wavelength operation by combining both the crystals in a single cavity.

3. Experimental set-up and results

The hybrid laser arrangement for dual wavelength operation at 1.06 μm is shown schematically in figure 2. The laser resonator is a compact two-mirror linear cavity. The back mirror M1 is a concave mirror of 1 m radius of curvature with highly reflection (HR) coating ($R > 99.8\%$) at 1064 nm and high transmission (HT) coating ($R < 5\%$) at the pump diode emission wavelength of 808 nm. The output mirror M2 is a plane mirror with 8% transmission at 1064 nm. Though the mirror coatings are specified at 1064 nm, their spectral bandwidth is large enough for negligible difference in the performance at 1062.8 nm. We have used 0.3 at.%-doped 12 mm long $Nd:YVO_4$ crystal and 0.5 at.%-doped 7 mm long $Nd:GdVO_4$ crystal as the gain media. We have choosen longer $Nd:YVO_4$ crystal with lower doping concentration to reduce the pump power-induced heating effect in the crystal as it has lower thermal conductivity than $Nd:GdVO_4$. Both the crystals are wrapped with indium foil and press-fitted in separate water-cooled copper mount for effectively removing the generated heat. The crystals are pumped separately by two fibre-coupled laser diodes (FCLD1 and FCLD2) so that the gain in each crystal can be varied independently. The $Nd:GdVO_4$ crystal is placed near M1 and the fibre tip of the FCLD1 is reimaged on it with a spot diameter of 200 μm using a couple of plano-convex lenses (L1 and L2). The output from FCLD2 is collimated by the lens L3 and folded by a beam steering mirror M3 (HR at 808 nm and HT at 1064 nm) and focussed on the $Nd:YVO_4$ crystal placed near the plane coupler mirror M2. The mirror curvatures, their separation and the pumping spot size are chosen by ABCD matrix analysis of the cavity including the thermal lens

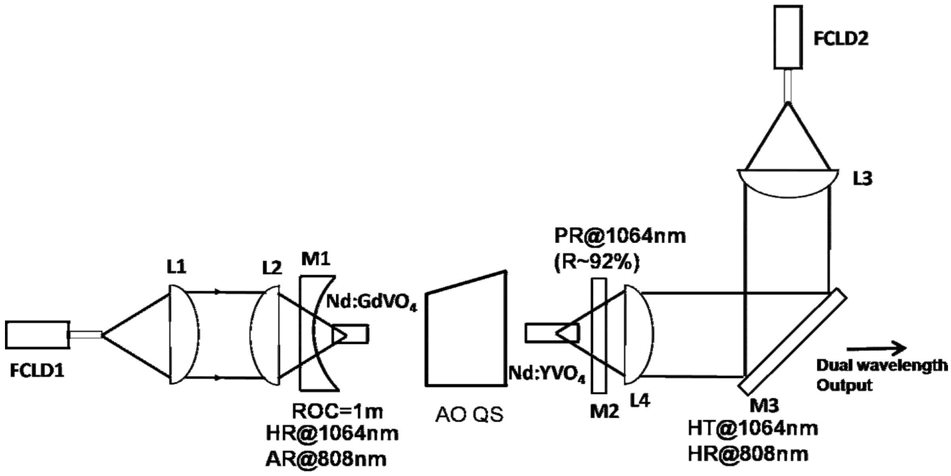

Figure 2. Schematic of the dual wavelength laser set-up.

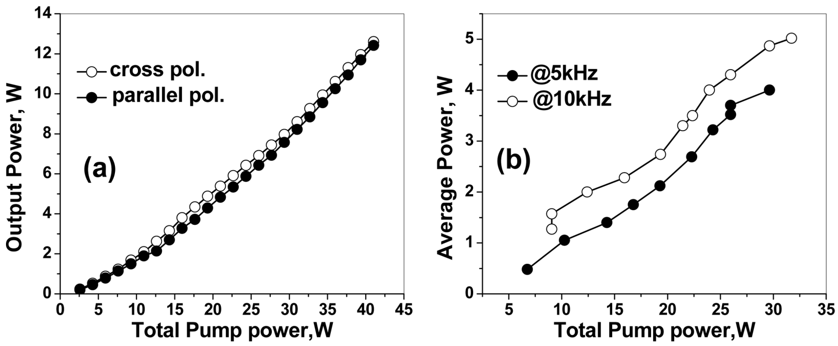

Figure 3. Slope efficiency curves of the hybrid laser. (**a**) CW operation and (**b**) pulsed operation.

focal length, to achieve optimum overlap between the pump beam and the TEM_{00} cavity mode. The laser is repetitively Q-switched by an acousto-optic modulator at a repetition rate variable in the range of 5–10 kHz. The dual wavelength output through the mirror M3 is finally characterized with the help of a power meter (OPHIR 30A-SH-V1), a spectrum analyzer (Agilent 86146B) and a fast photodiode (UPP-40-UVIR-P).

First we operated the laser by pumping individual crystal and checked the emission wavelength. At an incident pump power of 20 W, 7 W of CW power at 1062.8 nm is obtained from the Nd:$GdVO_4$ crystal whereas the Nd:YVO_4 crystal delivers 5.5 W of CW power at 1064.1 nm. The output from each crystal is linearly polarized in a direction parallel to the C-axis of the crystal. In figure 3a we plot the CW output power from combined laser when both the crystals are pumped simultaneously. The solid points represent the laser output power as a function of pump power when the C-axes of the crystals are oriented parallel to each other and the open points represent the same when the C-axes are oriented orthogonally. It

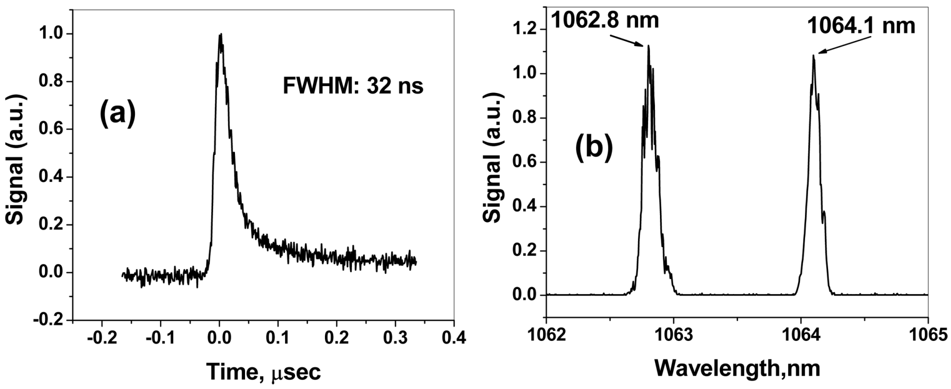

Figure 4. (**a**) Q-switched pulse shape and (**b**) spectral profile from the hybrid laser.

can be seen from figure 3a that the input–output relation is the same for both the configurations and a maximum of 12.5 W of CW power is obtained which is exactly equal to the sum of the power from the individual crystals. Figure 3b shows the variation of the average power as a function of the pump power when the combined laser is repetitively Q-switched by the acousto-optic modulator. A maximum average power of 4 W and 5 W is obtained at the repetition rate of 5 and 10 kHz respectively. Further power scaling at the lower repetition rate is limited by the formation of secondary pulses. A typical pulse shape from the hybrid laser is shown in figure 4a. The minimum FWHM pulse width is measured to be 32 ns and found to be nearly independent of the repetition rate below 10 kHz. The maximum total peak powers are estimated to be 25 kW and 15.6 kW at 5 and 10 kHz repetition rates respectively which are sufficient for efficient THz frequency generation in GaSe crystal assuming the power is equally distributed at the two operating wavelengths [4]. The recorded spectral profile from the hybrid laser is shown in figure 4b at the maximum operating pump power. It can be seen from figure 4b that the output spectra consist of two wavelengths centred at 1062.8 nm and at 1064.1 nm with nearly equal intensities. The difference frequency corresponds to 0.35 THz which is of particular importance as the nonlinear crystals have minimum absorption at this frequency [7]. The intensity and the polarization of the individual spectral components can be easily controlled by changing the relative gain and the relative orientation of the two crystals.

4. Conclusion

In conclusion we have for the first time demonstrated dual wavelength operation at 1062.8 and 1064.1 nm in a diode-pumped hybrid laser comprising of Nd^{3+}-doped birefringent YVO_4 and $GdVO_4$ crystals. Under Q-switching operation, 4 W of average power at 5 kZ repetition rate is obtained with 32 ns FWHM pulse duration corresponding to 25 kW of peak power. The intensity and the polarization of the individual spectral components can be easily controlled by changing the relative gain and the relative orientation of the two crystals. The laser is suitable for 0.35 THz frequency generation by the process of optical rectification in a nonlinear crystal.

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