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Efficient yellow beam generation by intracavity sum frequency mixing in DPSS Nd:YVO_4 laser

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

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Abstract. We present our studies on dual wavelength operation using a single Nd:YVO_4 crystal and its intracavity sum frequency generation by considering the influence of the thermal lensing effect on the performance of the laser. A KTP crystal cut for type-II phase matching was used for intracavity sum frequency generation in the cavity at an appropriate location for efficient and stable yellow output power. More than 550 mW of stable CW yellow-orange beam at 593.5 nm with beam quality parameter (M^2) $\sim$ 4.3 was obtained. The total pump to yellow beam conversion efficiency was estimated to be 3.83%.

Keywords. Diode-pumped solid-state lasers; dual wavelength operation; sum frequency generation; yellow laser.

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1. Introduction

Laser sources in the visible spectra have many applications in medicine, biology, and display technology [1]. Diode-pumped solid-state lasers are efficient and compact light sources for generating laser radiation in blue, green, and red spectral regions by intracavity frequency doubling. However, the region from 550 to 650 nm cannot be obtained by frequency doubling because of the absence of fundamental lasers that operate efficiently in the corresponding spectral region. One efficient approach to generate laser light in this spectral region is based on sum frequency generation (SFG), in which coherent frequencies of ν_1 and ν_2 are mixed using a nonlinear crystal, such as KTP, LBO, BIBO etc. and radiation of frequency $\nu_3 = \nu_1 + \nu_2$ is generated. The yellow-orange light at 593.5 nm can be generated by sum frequency mixing of 1064 nm and 1342 nm using Nd^{3+}-doped vanadate laser crystals (Nd:YVO_4 or Nd:$GdVO_4$). The simple way for dual wavelength operation is to use dual gain dual cavity configurations for lasing at 1064 nm and 1342 nm independently which are then coupled at the frequency mixing crystal through sum frequency generation. More than 750 mW of yellow-orange beam at 593.5 nm has been reported by this technique [2]. However, such cavity configurations are complex, requiring two pump sources and two gain media. In addition, one has to take care to avoid feedback to one laser from the other. Further, the pump to yellow beam conversion efficiency from such systems is quite low (∼1%) [3]. On the contrary, use of single crystal for dual wavelength operation for the purpose of SFG is highly efficient and less complex. More than 2 W of yellow beam has been generated from a single Nd:YVO_4 crystal [4]. However, use of single crystal for dual wavelength operation suffers from mode competition leading to instability in the output sum frequency power and it is difficult to maintain optimum ratio of intracavity circulating power at these two wavelengths for efficient SFG. In addition, pump power-induced thermal effects in the gain medium further aggravates these problems. Hence, to generate efficient yellow beam by sum frequency mixing using a single gain medium, it is important to understand the influence of various parameters, particularly the pump power-induced thermal effects on the dynamics of the laser. However, no such work is available in the literature. In this paper, we present our studies on dual wavelength operation using a single Nd:YVO_4 crystal and its intracavity sum frequency generation by considering the influence of the thermal lensing effect on the performance of the laser. Our studies show that the optimum position of the nonlinear crystal for maximum SFG shifts with the pump power and hence necessary readjustment of the resonator is required. Based on our studies, we report more than 550 mW of stable CW yellow-orange beam at 593.5 nm with 3.83% optical-to-optical conversion efficiency.

2. Experimental set-up

The schematic of experimental set-up for dual wavelength operation at 1064 nm and 1342 nm is shown in figure 1a. In end pump configuration, the pump source used was a fibre-coupled laser diode that delivered a maximum 30 W of output power with an emission wavelength of 808 nm at 25°C. The fibre had a core diameter of 400 μm and a numerical aperture of 0.22. The output at the fibre tip was collimated and focussed using two plano-convex lenses of focal length 25 mm (L1) and 50 mm (L2) with a magnification of two. Both the lenses were coated for antireflection at 808 nm for the transmission of pump power more than 95%. In diode end-pumped laser, the choice of the gain medium is very important for simultaneous generation of dual wavelength laser radiation. The Nd:YVO_4 crystal has been identified as one of the promising laser materials for diode pumping because of its high absorption over a wide pumping wavelength bandwidth and its large stimulated emission cross-section at both 1064 nm ($\sigma_{1064} = 25 \times 10^{-19}$ cm^2) and 1342 nm ($\sigma_{1342} = 7.6 \times 10^{-19}$ cm^2). More importantly, the moderate ratio of the stimulated emission cross-sections between the two wavelengths is favourable for dual wavelength operation. In our experiment, we have used a-cut Nd:YVO_4 crystal with a doping concentration of 0.3 at% Nd^{3+} with dimensions of $4 \times 4 \times 10$ mm^3 for dual wavelength lasing operation at 1064 nm and 1342 nm. The laser crystal was wrapped in indium foil and mounted in water-cooled copper mount which was cooled at 20 ± 0.1°C by using a chiller unit. One end surface of the crystal was coated for high reflection ($R >$ 99.5%) at 1342 nm, antireflection coated ($R < 2\%$) at 1064 nm and 808 nm which acts like a rear mirror M1 for 1342 nm lasing wavelength. Another end surface was antireflection coated for 808 nm and 1342 nm to reduce the insertion losses at low gain lasing wavelength of 1342 nm. In a V-cavity configuration mirrors M1, M2 and M3 formed the laser resonator for 1342 nm laser radiation whereas 1064 nm laser radiation was generated in the resonator formed by mirrors M1′, M2 and M4. Plane mirror M1′ was the rear mirror for 1064 nm which was highly transmitting ($T > 98\%$) at the pumping wavelength 808 nm and highly reflecting ($R > 99.8\%$) at 1064 nm. Plano-concave mirror M2 of 50 mm radius of curvature was the folding mirror and coated for high reflection ($R > 99.5\%$) at 1342 nm, 1064 nm and highly transmitting ($T > 95\%$) at 593.5 nm. Plane mirrors M3 and M4 were coated for partial transmission at 1342 nm and 1064 nm respectively with 95% and 89% reflectivity to take out the laser output from the cavity. The cavity lengths for both wavelengths were optimized for simultaneous dual wavelength operation. The geometrical cavity length was ∼10.5 cm for 1342 nm laser radiation whereas for 1064 nm cavity length was ∼12 cm. The output power was separated out by using a plane mirror which was coated for high reflection at 1064 nm and high transmission at 1342 nm at an angle of 45° and the individual power for both the wavelengths was measured with the help of power meter.

For the intracavity frequency mixing, plane mirrors M3 and M4 were replaced by a plano-concave mirror M3′ with 200 mm radius of curvature of having high reflecting coating ($R > 99.5\%$) at 1342 nm, 1064 nm and 593.5 nm. A 10 mm long KTP crystal cut for type II phase matching was used for sum frequency generation and placed in the folded arm of the laser resonator between mirrors M2 and M3′ as shown in figure 1b. For efficient intracavity sum frequency mixing, the position of the nonlinear crystal is very important to achieve small laser mode size as well as proper mode matching for both the fundamental wavelengths 1342 nm and 1064 nm in the nonlinear crystal. The proper position of the nonlinear crystal can be determined by ABCD matrix analysis of the resonator if the thermal focal length is known. In fibre-coupled laser diode pumped solid-state laser thermal focal length f_{th} can be determined by the expression [5]:

$$f_{\mathrm{th}} = \frac{4\pi K \varpi_{\mathrm{p}}^2}{\eta_h P_{\mathrm{ab}}} \left[\frac{\mathrm{d}n}{\mathrm{d}T} + (n_{\mathrm{l}} - 1)(1 + \nu)\alpha_{\mathrm{T}} \right]^{-1}, \quad (1)$$

where K is the thermal conductivity, ϖ_{p} is the average pump size in the active medium, η_h is the average fractional thermal loading for simultaneous lasing at 1064 nm and 1342 nm, P_{ab} is the absorbed pump power, $\mathrm{d}n/\mathrm{d}T$ is the thermo-optic coefficient, n_{l} is the refractive index of the laser crystal at lasing wavelengths, ν is the Poisson ratio and α_{T}

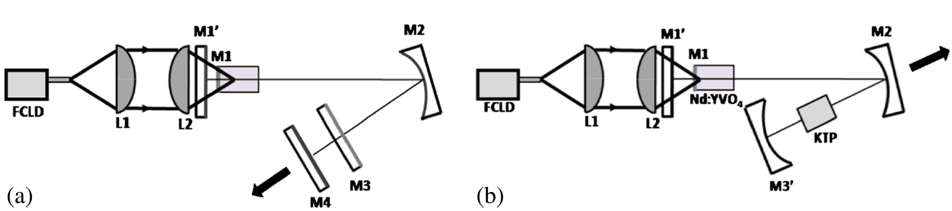

Figure 1. (**a**) Schematic of experimental set-up for dual wavelength operation at 1342 nm and 1064 nm and (**b**) experimental set-up for sum frequency mixing of 1342 nm and 1064 nm.

is the thermal expansion coefficient. The focal length of the thermal lens in Nd:YVO_4 is estimated by using the following parameters: $K = 5.1$ W/m-K, $\varpi_p = 445 \mu$m, $n_{1064} = 2.165$, $n_{1342} = 2.154$, $dn/dT = 2.9 \times 10^{-6}$/K, $\nu = 0.3$, $\alpha_T = 4.43 \times 10^{-6}$/K, and $\eta_h = 0.31$. The focal lengths of the thermal lens were estimated to be 13 cm and 21 cm for 1342 nm and 1064 nm respectively at 20 W of absorbed pump power. In our experiment, the length of the cavity was adjusted to maintain a proper spot size at the KTP crystal and optimum power ratio for fundamental beams by translating the end mirror M3′. The stability curves for 1064 nm and 1342 nm lasing wavelengths as a function of distance d_3 (distance between mirror M2 and M3′) are shown in figure 2a for the absorbed pump power of 11.5 W. It is clear from the plotted curve that cavity is stable for a distance (d_3) between 25 mm to 32 mm for both the wavelengths simultaneously. Thus, the optimum cavity lengths for 1342 nm and 1064 nm were kept to be ∼105 mm and 115 mm respectively. In figure 2b we have plotted the variation of the spot size for 1064 nm and 1342 nm wavelengths at different positions between mirrors M2 and M3 with $d_3 = 30$ mm at 11.5 W of absorbed pump power. It is observed that at a distance between 12 mm and 15 mm from the mirror M2, the spot sizes for both the fundamental wavelengths are nearly matched. We further observed from figure 2c that as the absorbed pump power increases the position of the nearly matched spot sizes between mirrors M2

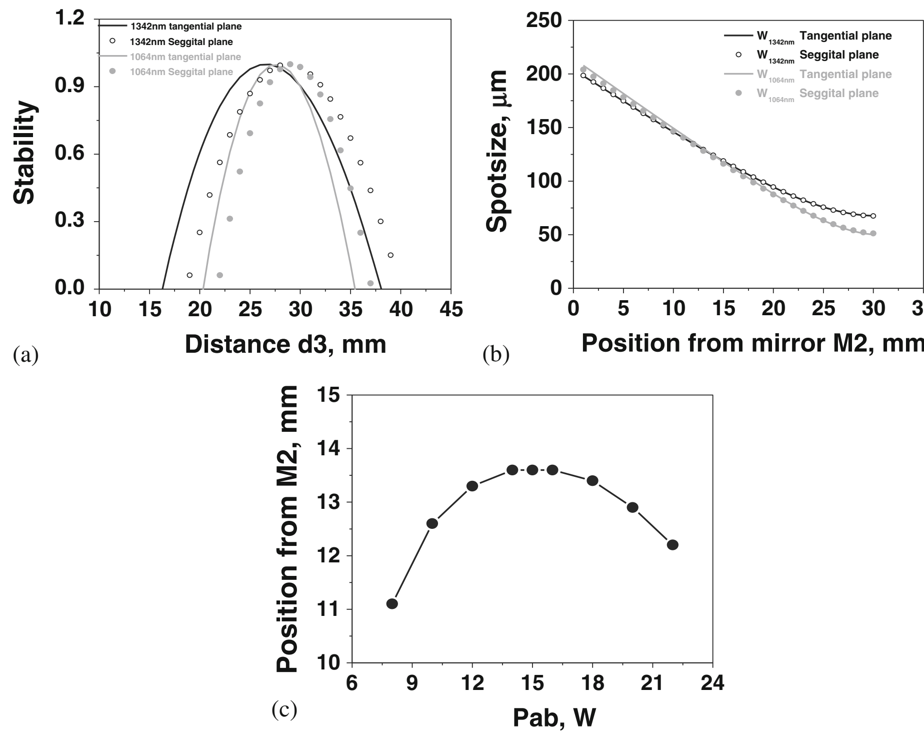

Figure 2. (**a**) Stability curve as a function of distance d_3, (**b**) variation of TEM_{00} spot size between mirror M2 and M3′ for $d_3 = 30$ mm and (**c**) change in the position of nearly matched spot sizes with absorbed pump power.

and M3 also shift for both fundamental wavelengths. Therefore, for efficient sum frequency mixing, nonlinear crystal should be placed at an optimum position and cavity configuration need fine adjustment for simultaneous dual lasing operation for efficient generation of yellow output power.

3. Results and discussion

The performance of simultaneous dual wavelength lasing in V-cavity is shown in figure 3a. In this cavity configuration, the values of threshold pump power for 1064 nm and 1342 nm were measured to be 2.1 W and 3 W respectively. As the pump power increases the output power for both wavelengths varies in the same manner and at 13.6 W of absorbed pump power we obtained ∼2.2 W of output power at 1064 nm and ∼1.9 W

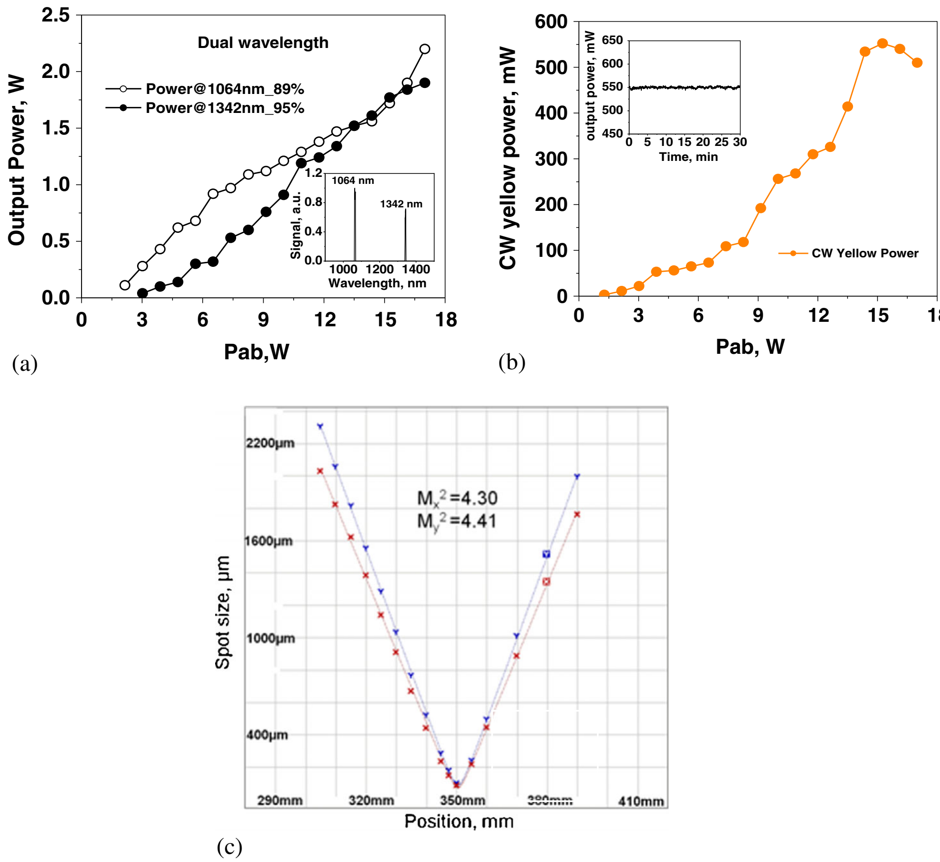

Figure 3. (**a**) Variation of simultaneously dual wavelength output power with absorbed pump power and spectrum of dual wavelength output (inset), (**b**) variation of CW yellow output with absorbed pump power and inset showing output yellow power trace for half an hour operation and (**c**) M^2 parameter curve at maximum yellow output power.

that of 1342 nm. The spectrum of dual wavelength output is shown in the inset of figure 3a.

For intracavity sum frequency generation, KTP crystal was placed at a proper position between mirrors M2 and M3′ as shown in figure 1b. The variation of output CW yellow power at 593.5 nm with the absorbed pump power is shown in figure 3b. As the absorbed pump power crosses the threshold level for both the fundamental wavelengths, yellow beam emerges from the cavity. Initially, the output yellow power increases slowly with the absorbed pump power but beyond 8 W of absorbed pump power, output power increases rapidly due to increase in power of fundamental wavelengths. At 11.5 W of absorbed pump power we obtained 552 mW of maximum CW yellow output power with a pump to yellow conversion efficiency of 3.83%. The output power was reasonably stable over the time as shown in the inset of figure 3b. It can be seen that CW yellow output power was stable within ±5%. The output beam was circular in shape with a nearly Gaussian intensity distribution. Figure 3c shows the beam quality parameter (M^2) measurement curve at 550 mW of yellow output power and M^2 was measured to be ∼4.3. On further increasing the pump power, output power starts to roll off due to mode mismatching between fundamental wavelengths.

In conclusion, by using a single Nd:YVO_4 crystal for simultaneous dual wavelength operation at 1064 nm and 1342 nm, stable and efficient yellow beam was generated using a type-II KTP crystal. More than 550 mW of stable CW yellow-orange beam at 593.5 nm was obtained with pump to yellow conversion efficiency of 3.83%. The experimental studies and analysis show that to generate stable and high power CW yellow light at 593.5 nm by intracavity sum frequency mixing using a single gain medium, precise optimization of the cavity and position of the nonlinear crystal are required.

References

[1] H M Kretschmann, F Heine, G Huber and T Halldorsson, *Opt. Lett.* **22**, 1461 (1971)

[2] J Janousek, S Johansson, P T Lichtenberg, S Wang, J L Mortensen, P Buchhave and F Laurell, *Opt. Exp.* **13(4)**, 1188 (2005)

[3] A J Singh, P K Gupta, S K Sharma, P K Mukhopadhyay, K S Bindra and S M Oak, *Proc. of NLS-21* (Anna University, Chennai, Jan. 2012).

[4] J H Liu, G C Sun and Y D Lee, *Laser Phys.* **22(7)**, 1199 (2012)

[5] M E Innocenzi, H T Jura, C L Fincher and R A Fields, *Appl. Phys. Lett.* **56**, 1831 (1990)