Diode-pumped Q-switched Nd:YVO$_4$ yellow laser with intracavity sum-frequency mixing

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A compact high-power yellow pulsed laser has been demonstrated by use of intracavity sum-frequency mixing in a diode-end-pumped Q-switched Nd:YVO$_4$ dual-wavelength laser. A three-mirror configuration forming two separate laser cavities is used to optimize the gain match for simultaneous dual-wavelength emission in Q-switched operation. Under the optimum cavity-length condition, the highest yellow average power is 340 mW and the peak power is 2 kW, obtained at 12.5 W of pump power. © 2002 Optical Society of America
OCIS codes: 140.3480, 140.3540, 140.3550, 140.3580.

Recently, diode-pumped Nd-doped lasers were developed as compact all-solid-state sources in the blue, green, and red spectral regions by use of intracavity frequency doubling. However, the region from 550 to 650 nm is seldom covered by these sources. Laser sources in the yellow-orange spectrum are required for medical applications in particular.[1] A high-repetition-rate pulsed source has the practical benefit of reducing thermal damage to the surrounding tissue. Since the systems available at present consist mainly of pulse dye lasers, copper-vapor lasers, and krypton-ion lasers, an all-solid-state laser would certainly be an attractive alternative source. The approaches based on solid-state laser techniques for generating yellow lasers include sum-frequency mixing (SFM) of a flash-pumped Q-switched Nd:YAG dual-wavelength laser[2,3] and frequency doubling of an intracavity Raman-shifted Nd:YAG laser.[4-6]

The Nd:YVO$_4$ crystal has been identified as a promising material for diode-pumped lasers with dual-wavelength emission because of its high absorption over a wide pump-wavelength bandwidth and its large stimulated-emission cross section at both the $^4F_{3/2}-^4I_{11/2}$ and the $^4F_{3/2}-^4I_{13/2}$ transitions. For Nd:YAG crystal, the ratio of the stimulated-emission cross section between the $^4F_{3/2}-^4I_{11/2}$ and the $^4F_{3/2}-^4I_{13/2}$ transitions is approximately 5/5.1,[7] whereas this ratio is approximately 2/2.1 for Nd:YVO$_4$ crystal.[8] In this Letter we report a compact, efficient scheme for generating a 593-nm laser based on intracavity SFM of a diode-pumped Q-switched Nd:YVO$_4$ dual-wavelength laser.

Good spatial and temporal overlap of the two different wavelengths is essential for SFM. In the present cavity we use overlapping collinear cavities for simultaneous 1064- and 1342-nm emission from a Q-switched Nd:YVO$_4$ laser and employ an intracavity β-barium borate crystal to obtain SFM 593-nm output. Previously, Henderson[9] proposed a Y cavity for Q-switched dual-wavelength Nd:YAG lasing and offset of the open times of the Q switches for the different

wavelength emissions so that the lasers would have relatively good temporal and spatial overlap between the two wavelengths. However, a reliable, easily aligned, transportable laser system is desired to facilitate practical applications. The cavity configuration is shown in Fig. 1. The Nd^{3+} concentration of the laser crystal was 0.5 at. %, and its length was 6 mm. The pump source was a 15-W fiber-coupled laser diode with a core diameter of 0.8 mm and a numerical aperture of 0.18. The fiber output was focused into the crystal, and the pump spot size was ~0.35 mm. The input mirror, M1, was a 1-m radius-of-curvature concave mirror with antireflection coating at the pump wavelength on the entrance face ($R < 0.2\%$), high-reflection coating at both lasing wavelengths ($R > 99.8\%$), and high-transmission coating at the pump wavelength on the other surface ($T > 90\%$). Note that mirror M1 was not optimum because of limited mirror availability. The optimum mirror M1 would have a high-reflection coating at 593 nm. One side of flat mirror M2 was coated to be highly reflecting at 1342 nm ($R > 99.8\%$) and highly transmitting at 1064 nm ($T > 95\%$). The other side of mirror M2 was antireflective at 1064 nm ($R < 0.2\%$). For flat mirror M3, one side was coated to be highly reflecting at 1064 nm and highly transmitting at 593 nm ($T > 90\%$). The other side of mirror M3
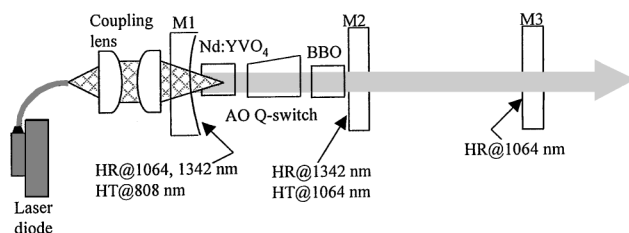

Fig. 1. Schematic of intracavity SFM in the diode-end-pumped Q-switched Nd:YVO$_4$ dual-wavelength laser at 1064 and 1342 nm. AO, acousto-optic; HR, highly reflective; HT, highly transmitting; BBO, β-barium borate.

was antireflective at 593 nm. The 20-mm-long Q switcher (Gooch and Housego) had antireflection coatings at 1064 and 1342 nm on both faces and was driven at a 41-MHz center frequency with 3.0 W of rf power. The cavity length between M1 and M2 was 7 cm for 1342-nm oscillation. However, the cavity length between M1 and M3 was 15 cm for 1064-nm emission.

Henderson developed a computational model of the dynamic behavior of a dual-wavelength Q-swtiched laser.[9] This model can be extended to the present case:

$$\frac{dN}{dt} = R_p - cN(\sigma_1\phi_1 + \sigma_2\phi_2) - \frac{N}{\tau_f}, \tag{1}$$

$$\frac{d\phi_1}{dt} = \frac{l_{cr}}{l_1}c\sigma_1 N - \frac{\phi_1}{\tau_{c1}} - \eta_{\text{SFM}}\phi_1\phi_2, \tag{2}$$

$$\frac{d\phi_2}{dt} = \frac{l_{cr}}{l_2}c\sigma_2\phi_2 N - \frac{\phi_2}{\tau_{c2}} - \eta_{\text{SFM}}\phi_1\phi_2, \tag{3}$$

where the subscripts 1 and 2 denote ϕ, σ, l, and τ_c at $\lambda_1 = 1342$ nm and $\lambda_2 = 1064$ nm, respectively, N is the population inversion density, R_p is the average pump intensity, τ_f is the emission lifetime, ϕ is the photon density, σ is the stimulated-emission cross section, l_{cr} is the crystal length, c is the speed of light, l is the cavity length, τ_c is the effective photon decay time as a result of all the linear losses, and η_{SFM} is the effective conversion rate as a result of the intracavity SFM.

The condition $d\phi_1/dt \equiv d\phi_2/dt$ is need for optimum temporal overlap between the two wavelengths. From Eqs. (2) and (3), it can be found that the condition $d\phi_1/dt \equiv d\phi_2/dt$ can be satisfied if $\sigma_1/l_1 = \sigma_2/l_2$ and $\tau_{c1} = \tau_{c2}$. In fact, τ_c can be varied by fine adjustment of the cavity alignment. Therefore, the cavity lengths here are chosen to satisfy the relationship $\sigma_1{:}\sigma_2 = l_1{:}l_2$ for optimum temporal overlap. The physical principle of the relationship $\sigma_1{:}\sigma_2 = l_1{:}l_2$ is based on that fact that increasing the cavity length can lower the average photon density, so the competing ability of the transition with the larger emission cross section can be reduced.

The operation of the intracavity SFM at pulse repetition rates of 10, 20, and 30 kHz is shown in Fig. 2. The threshold for 593-nm operation of the laser was ~3.5 W. At the maximum pump power of 12.5 W, 340 mW of average yellow output power was obtained at a repetition rate of 10 kHz. Yellow pulses were recorded by a LeCroy 9354C digital oscilloscope (500-MHz bandwidth) and a fast Si p−i−n photodiode with a rise time of ~0.35 ns. The pulse width at 593 nm increased slightly from 16 to 20 ns when the repetition rate varied from 10 to 30 kHz. A typical oscilloscope trace is presented in Fig. 3, showing that over the time duration of ten consecutive pulses the peak-to-peak intensity fluctuation was less than 10%. The conversion efficiency of the pump power into yellow output power was ~2.7%. If mirror M1 had

had a high-reflection coating at 593 nm, the conversion might have had little or no increase, because the Nd:YVO$_4$ crystal has strong absorption at 593 nm. Nevertheless, the peak power at a repetition rate of 10 kHz can reach 2 kW at the maximum pump power of 12.5 W. The beam quality factor at the maximum output power was measured to be less than 1.3.

Different cavity-length ratios were employed to investigate the influence of the competitive interaction between two wavelengths. When $(l_1/l_2) < 0.7(\sigma_1/\sigma_2)$ or $(l_1/l_2) > 1.2(\sigma_1/\sigma_2)$, the average yellow output
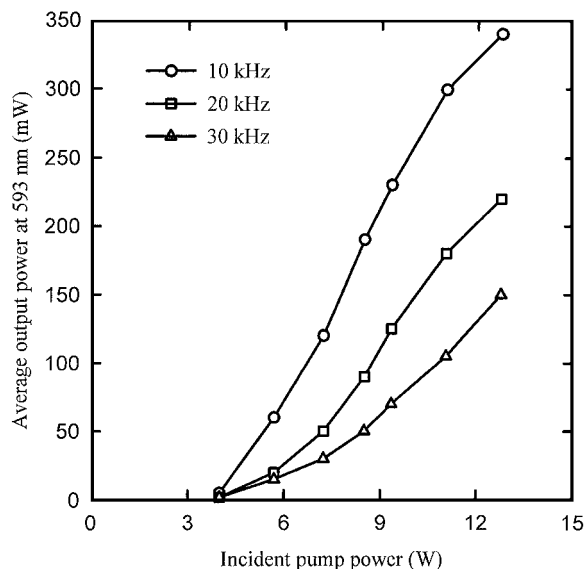

Fig. 2. Dependence of the relative output powers at intracavity SFM on the incident pump power at pulse repetition rates of 10, 20, and 30 kHz.
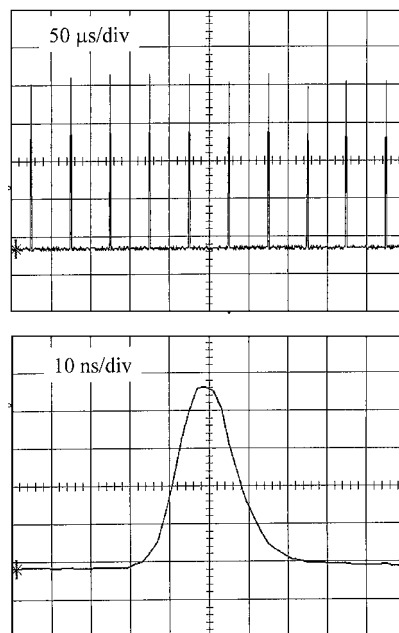

Fig. 3. Top, oscilloscope trace of a train of 593-nm pulses from the intracavity SFM in the diode-end-pumped Q-switched Nd:YVO$_4$ dual-wavelength laser at a pulse repetition rate of 20 kHz. Bottom trace, expanded shape of a single pulse, showing 18-ns width (FWHM).

power decreased noticeably. The reduction of the yellow power is due mainly to the substantial gain difference between two wavelengths.

Finally, it is worthwhile to mention that the thermal lens in the Nd:YVO$_4$ crystal always affects the stability of the present resonator. For a laser pumped by a fiber-coupled diode the focal length of the thermal lens, f_{th}, can be approximately given by[10]

$$\frac{1}{f_{th}} = \frac{\xi P_{abs}}{4\pi K_c \omega_p{}^2} [dn_0/dT + (n_0 - 1)\alpha_T], \quad (4)$$

where ξ is the fractional thermal loading, P_{abs} is the absorbed pump power, K_c is the thermal conductivity, n_0 is the refractive index of the laser crystal, dn_0/dT is the thermo-optic coefficient of n_0, α_T is the thermal-expansion coefficient, and ω_p is the averaged pump size in the active medium. The focal length of the thermal lens is estimated by use of the following parameters: $\xi \approx 0.4$, $K_c = 0.0523$ W/K cm, $dn/dT = 3.0 \times 10^{-6}$/K, $\omega_p = 0.35$ mm, $n = 2.165$, $l = 6$ mm, and $\alpha_T = 4.43 \times 10^{-6}$/K. The focal length of the thermal lens is found to be ~19 cm at 12.5 W of absorbed pump power. This focal length is very close to the length of the present 1064-nm cavity. Therefore, the cavity configuration needs to be redesigned for further scaling up of the output power.

We have proposed and demonstrated, for what is to our knowledge the first time, the use of intracavity SFM in a diode-end-pumped Q-switched Nd:YVO$_4$ dual-wavelength laser to generate high-power yellow light. A three-mirror configuration forming two separate laser cavities is used to achieve simultaneous emission of two wavelengths in Q-switched operation. Experimental results show that adjusting the cavity-length ratio to $(l_1/l_2) \approx (\sigma_1/\sigma_2)$ can result in the optimum temporal overlap between two wavelengths for SFM. Under the optimum cavity-length condition, the highest yellow average power is 340 mW and the peak power was ~2 kW, obtained at 12.5 W of pump power.

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