Efficient continuous-wave self-frequency-doubling green diode-pumped $Yb{:}YAl_3(BO_3)_4$ lasers

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Efficient cw self-frequency-doubled green laser output of 160 mW has been obtained from $Yb{:}YAl_3(BO_3)_4$ crystal pumped by 1.4-W incident power from a fiber-coupled 976-nm laser diode. The incident-pump-power–green-output-power conversion efficiency is greater than 11.3%, and the electrical-input–green conversion efficiency is 3.9%. Tunable green output from 513.0 to 545.8 nm is also demonstrated with a quartz birefringent filter.

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Nd^{3+}-doped self-frequency-doubling (SFD) crystalline solid-state lasers based on $Nd^{3+}{:}LiNbO_3$ and $Nd^{3+}{:}YAl_3(BO_3)_4$ have been extensively studied since the first reports of their operation.[1,2] These lasers offer attractive simplicity for visible laser generation but suffer from a number of problems, such as low quantum efficiency, high quantum defects, reabsorption loss in the green, and, in particular, difficulties of growth of the nonlinear laser material, that are largely associated with the active Nd^{3+} ions. As a result, SFD solid-state lasers have not met with significant practical success.

More recently, Yb^{3+}-doped nonlinear crystalline materials have received attention as alternative SFD laser media. Yb^{3+} has no concentration quenching, no excited-state absorption, and no visible reabsorption loss,[3] and it offers high quantum efficiency, low quantum defects, and a potentially broad gain bandwidth. SFD green output of 60 mW at 532 nm was very recently reported by Montoya *et al.*[4] for $Yb^{3+}{:}LiNbO_3{:}MgO$ crystals pumped by a Ti:sapphire laser; SFD green output at low power (<1 mW) was also observed for the nonlinear laser crystals $Yb^{3+}{:}YCa_4B_3O_{10}$ (Ref. 5) and $Yb^{3+}{:}GdCa_4B_3O_{10}$.[6]

Wang and co-workers recently reported detailed studies of growth and spectral properties[7] and highly efficient diode-pumped infrared laser operation[8,9] of the new nonlinear laser crystal $Yb^{3+}{:}YAl_3(BO_3)_4$ (Yb:YAB). Yb:YAB has the advantages of easy growth [compared with $Nd^{3+}{:}YAl_3(BO_3)_4$], a large range of doping concentrations (at least up to 20 at. %) with good crystal optical quality, a large nonlinear optical coefficient ($d_{\mathrm{eff}} > 1.4$ pm/V), a long radiative lifetime (~680 μs), and good absorption and fluorescence spectral properties. Maximum output power of 654 mW at 1040 nm was obtained at an absorbed pump-power–output-power slope efficiency of 71% for pumping by a fiber-coupled 976-nm diode.[8,9] However, SFD green output was limited to only 1 mW, since the laser crystal was not appropriately cut for phase-matched second-harmonic generation. Further studies have shown that Yb:YAB has high gain and low threshold in *o*-polarized wave emission, which is favorable for type I phase matching of SFD green.

In this Letter we report, for what is believed to be the first time, efficient cw SFD green laser operation of a type I phase-matched 3-mm-thick Yb:YAB crystal pumped by a 976-nm fiber coupled diode. Tunable green output from 513 to 545.8 nm has also been demonstrated.

A 10-at. % Yb-doped Yb:YAB crystal was cut with roughly a type I phase-matching angle ($\theta \approx 31°$, $\varphi = 0°$) for 1 μm, obtained by calculation from the Sellmeier equations of the refractive indices of Yb:YAB.[10] We then carefully reoriented the crystal to give the strongest 532-nm green output power with input from a pulsed 1064-nm Nd:YAG laser and polished it to give optimum type I phase matching for normal incidence. The crystal, with dimensions of 3 mm × 3 mm × 3 mm, was uncoated for our later laser experiment. The polarized absorption coefficients at 976 nm were 15 cm^{-1} for the *o* ray and 12 cm^{-1} for the *e* ray, with an absorption bandwidth of 22 nm (FWHM).

The pump and laser cavity configuration is shown in Fig. 1. We imaged the 976-nm pump light from a 50-μm core-fiber-coupled 1.6-W laser diode through a flat-cavity end mirror onto the crystal to obtain a pump-mode diameter of approximately 73 μm. The Yb:YAB crystal was held in a temperature-controlled copper mount. The characteristics of the pump

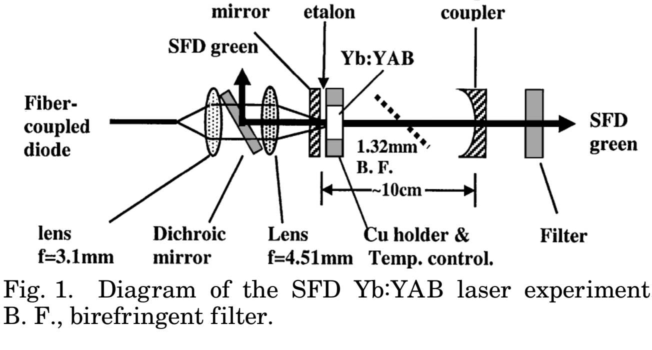

Fig. 1. Diagram of the SFD Yb:YAB laser experiment. B. F., birefringent filter.

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end-mirror coating are critical because a sharp edge between transmission at the pump wavelength and reflection at the laser wavelength (1010–1100 nm) is required. The Lambda Research Optics coating used for the experiment had 93% transmission at 976 nm, >99.8% reflection from 1010 to 1100 nm, and 80% transmission in the green. A 10-cm radius-of-curvature output coupler (~94% transmission in the green and >99.8% reflection at 1010–1100 nm) was used to complete the Yb:YAB laser cavity, which had an overall length of approximately 10 cm. A 1.32-mm-thick single-plate quartz birefringent filter was inserted into the cavity for experiments in tunability. The SFD green output power was measured at both ends of the cavity, at one end directly from the output coupler and at other end by a 45° dichroic mirror (highly reflective at green and highly transmissive at 976 nm) placed between the collimating and the focusing lenses. The green output powers quoted in this Letter refer to the sum of SFD green obtained from both ends of the laser cavity (typically, the output power from the coupler was 80% of the total power, although this was quite dependent on cavity adjustment). To extract all green power from the output coupler one must coat the input mirror with highly reflective coating in the green, and we plan to address this in later experiments.

Because Yb^{3+}:YAB is a quasi-four-level system, it is expected that laser emission at the fundamental (infrared) will be shifted to longer wavelengths for low-loss cavities, owing to the reduced reabsorption losses at longer wavelengths.[11] For example, the absorption coefficient at 1061 nm is less than 0.07 cm^{-1}, whereas the absorption coefficient at 1040 nm is approximately 0.28 cm^{-1}, for the Yb:YAB crystal used here. For SFD operation, in which the output coupler had a broadband highly reflective coating from 1010 to 1100 nm, the fundamental output wavelength was shifted to 1061 nm [note that, for a 4% output coupler, the free-running wavelength of the fundamental was 1040 nm (Ref. 9)]. When the maximum output power was obtained, the fundamental laser output bandwidth was as much as 12 nm.

To explore the limits of the bandwidth of fundamental laser emission we adjusted the distance and the parallelism between the flat-input mirror and the uncoated input face of the Yb:YAG crystal to form a thin-air-space etalon, as shown in Fig. 1. The resulting infrared and green laser emission spectra, respectively, measured by an optical spectrum analyzer (Anritsu Model MS9030A) are shown in Figs. 2(a) and 2(b). Infrared emission peaks were observed at 1061.3, 1060.2, and 1059.0 nm, with a bandwidth of 0.4 nm and wavelength separation corresponding to a free spectral range of the etalon with spacing of 510 μm. The main emission peak in the green was at 530.6 nm, with a bandwidth of 0.2 nm at a total output green power of 143 mW. We anticipate that single-frequency operation can be achieved readily with appropriately designed intracavity etalons.

Figure 3 shows the measured SFD green and residual infrared output powers as a function of incident pump power. The crystal-mount temperature was set at 20 °C by a Peltier temperature controller. The maximum incident pump power (unpolarized) onto the crystal was 1400 mW, and more than 90% of the pump power was absorbed by the crystal. The pump power at threshold for both the infrared and the green was 150 mW. A maximum of 80 mW residual *o*-polarized infrared output was obtained after the output coupler. The maximum *e*-polarized SFD green output power was 143 mW, corresponding to an incident-pump-power–green-output-power (pump–green) conversion efficiency of 10.2%. The green output power increases quadratically with the incident pump power, indicating that the pump–green conversion efficiency can be increased further with increasing pump power.

Table 1 shows the effects of the Yb:YAB crystal-mount temperature on threshold pump power, maximum green output power, and pump–green conversion efficiency. The maximum green output

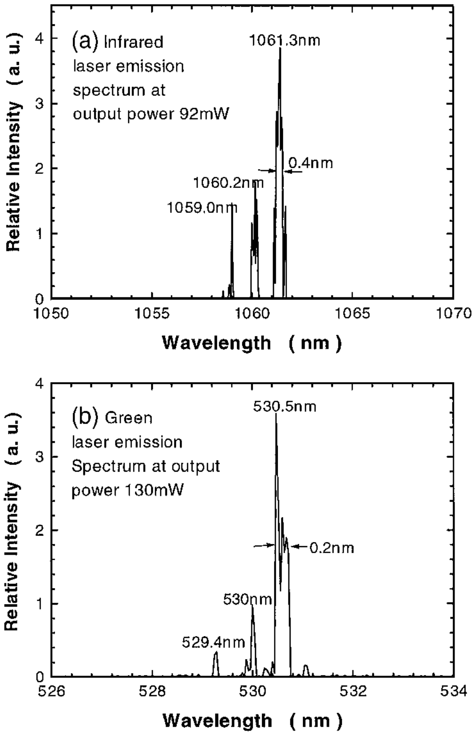

Fig. 2. (a) Infrared and (b) green laser emission spectra of the Yb:YAB SFD lasers.

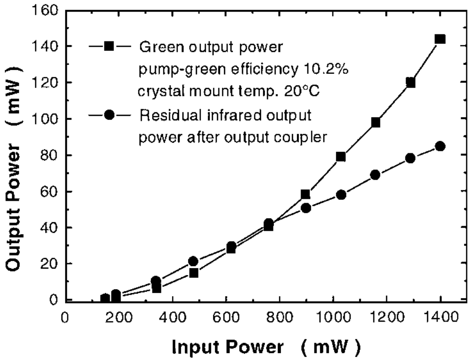

Fig. 3. Infrared and green output power as a function of incident pump power.

Table 1. Effect of the Temperature Crystal on Threshold Pump Power, Maximum Green Output Power, and Pump–Green Conversion Efficiency at Incident Pump Power of 1400 mW

Crystal-Mount Temperature (°C)	Threshold Pump Power (mW)	Max Green Output Power (mW)	Pump–Green Efficiency (%)
4	219	143	10.2
6	190	146	10.4
8	150	160	11.3
10	150	155	11.1
12	141	152	10.8
14	141	150	10.7
16	141	149	10.6
18	141	146	10.4
20	150	143	10.2
22	150	141	10.0
24	150	139	9.9

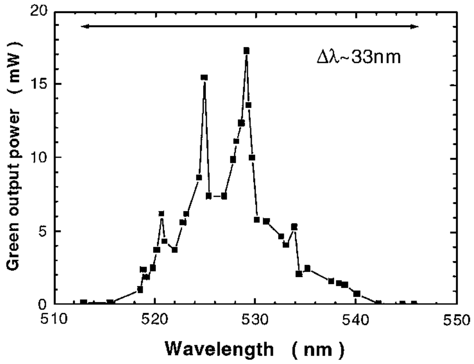

Fig. 4. Green output power as a function of wavelength tuned by a 1.32-mm-thick quartz birefringent filter.

power of 160 mW was obtained for a crystal-mount temperature of 8 °C, giving a pump–green conversion efficiency of 11.3% and electrical-input–green power conversion efficiency of 3.9%. The threshold pump power increased quite rapidly, and green output power decreased for crystal-mount temperatures below 8 °C; the reason for this is not clear at present.

The TEM_{00} mode for the green output at full power was obtained by adjustment of the laser cavity alignment to minimize the effects of beam walk-off. The output power stability was ±2.0% for 30 min. Up to the limit of the available pump power, we saw no evidence of effects of thermally induced distortion, including thermal lensing and optical damage of the Yb:YAB crystal.

For investigation of wavelength-tunable operation, a 1.32-mm-thick quartz single-plate birefringent filter was inserted into the cavity, as indicated in Fig. 1. Green output power as a function of laser wavelength is shown in Fig. 4. The total tunable range was ~33 nm, from 513.0 to 545.8 nm, with a typical bandwidth of 0.4 nm, and the maximum output power was 17.3 mW at 529.1 nm. Because the crystal was not antireflection coated, it was not adjusted for optimum phase-matching angle during the tuning process. Higher output power should be obtained with an antireflection-coated crystal and adjustment of the phase-matching angle for different wavelengths.

The cw green output powers achieved in the present experiments are believed to be the highest reported for any Yb^{3+} SFD materials by a considerable margin, and they compare favorably with the highest power reported for a diode-pumped Yb:YAG laser incorporating KTP as the intracavity frequency-doubling medium.[12] The visible tuning range of 33 nm achieved for Yb:YAB also exceeds that reported for the KTP–Yb:YAG configuration.[13]

In conclusion, we have demonstrated, for what is believed to be the first time, efficient cw self-frequency-doubling green laser output and wavelength tunability over 33 nm in the visible from diode-pumped Yb:YAB lasers. Relative ease of growth and favorable optical and thermal properties suggest that Yb:YAB has considerable potential as a practical laser material.

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