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Widely tunable yellow-green lasers based on the self-frequency-doubling material Yb:YAB

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We report widely tunable infrared and self-frequency-doubled operation in ytterbium-doped yttrium aluminum borate (Yb:YAB). In the infrared, tuning has been obtained between 1016 and 1090 nm and also near 1125 nm. A tuning range at the 1-W level of 55 nm has been obtained. As a self-frequency-doubled laser, green output powers of 65 mW at 510 nm and over 450 mW at 530 nm have been demonstrated with a maximum diode-to-green conversion efficiency of 5%. Yb:YAB has been shown to cover the wavelengths of the copper-vapor (510 nm), argon-ion (514 nm), doubled Nd:YAG (532 nm), green HeNe (543 nm), and the doubled $Yb:Sr_5(VO_4)_3F$ laser in the visible (~565 nm). © 2003 Optical Society of America

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1. INTRODUCTION

Self-frequency-doubled (SFD) crystalline laser materials can be used for simple, compact, all-solid-state visible sources. SFD lasers have been demonstrated in a variety of Nd^{3+}-doped and, more recently, Yb^{3+}-doped nonlinear crystal hosts, most notably yttrium aluminum borate (YAB),[1–4] $YCa_4O(BO_3)_3$–$GdCa_4O(BO_3)_3$,[5–8] and MgO, $LiNbO_3$.[9] The use of Yb^{3+} as an alternate dopant offers several advantages including high quantum efficiency, small quantum defect, and hence reduced thermal effects. Moreover, Yb^{3+} offers the prospect of broad tunability in the infrared and visible (when doubled). Previously, the best approach used to obtain diode-pumped, cw, tunable visible laser output has been the combination of ytterbium-doped yttrium aluminum garnet (Yb:YAG) and a separate non-linear crystal LiB_3O_5,[10] resulting in maximum visible power and a tuning range of 520 mW and 22.4 nm, respectively. Other materials that offer broad tunability in the infrared include Cr:forsterite[11] and $LiF:F_2^-$,[12] which when doubled result in tunable visible outputs at 587–654 nm and 550–610 nm, respectively, albeit in both cases in the pulsed regime. Both systems are also three-step processes requiring a relatively high-peak-power 1064-nm laser as a pump source and a separate nonlinear crystal to obtain visible output. Another approach that is used to obtain direct, tunable, visible laser operation involves upconversion in rare-earth-doped fibers, for example, holmium (540–553 nm)[13] and erbium (540–545 nm),[14] and, more recently, crystalline-upconversion lasers such as $Er:LiLuF_4$ (552 nm).[15] In upconversion systems, visible output powers have been limited to typically ~200 mW. For example, Heumann recently obtained 213 mW of output power from $Er:LiLuF_4$ with a slope efficiency of 35% using a Ti:sapphire pump source in a four-fold pumping arrangement. Power scaling is not trivial because of the low effective gain, which in turn requires high-brightness pump sources such as single-mode diode lasers or Ti:sapphire lasers. The laser output power in fibers is also affected by photo-induced degradation resulting from a multiphoton upconversion process creating color centers, leading to optical attenuation and hence increased thresholds.[16] As an alternative, self-doubled crystalline lasers offer simple cw or pulsed laser operation using relatively low-brightness laser diodes as pump sources that are scalable in output power using well-known techniques.

We have recently reported power scaling of a miniature SFD Yb:YAB laser[2] giving 1.1-W cw green output and over 4.3 W of infrared output. We now report cw, high-beam-quality, widely tunable, infrared (134 nm noncontinuous) and SFD operation in Yb:YAB. Yellow-green emission covering the wavelengths of the copper-vapor (510 nm), argon-ion (514 nm), doubled Nd:YAG (532 nm), green HeNe (543 nm), and doubled $Yb:Sr_5(VO_4)_3F$ (Yb:SVAP) (~565 nm) lasers have been obtained with output powers ranging from 12 mW to over 450 mW.

2. EXPERIMENT

A 10-cm hemispherical resonator was used for infrared tuning, and for green tuning an L-shaped cavity comprising a flat input mirror [coated high-reflectance (HR) at 1040 nm, high-transmittance (HT) at 977 nm], a flat dichroic turning mirror–output coupler (coated HR at 1040 nm, HT at 530 nm), and a 10-cm-radius-of-curvature reflector [coated HR at 1040 nm and 532 nm]. Lasing farther into the infrared (past 1090 nm) was accomplished by including an additional flat mirror [12% transmittance (T) at 1060 nm] in the L-shaped cavity, initially as an alignment tool but also to form a coupled cavity. The L-shaped resonator is shown in Fig. 1. The pump

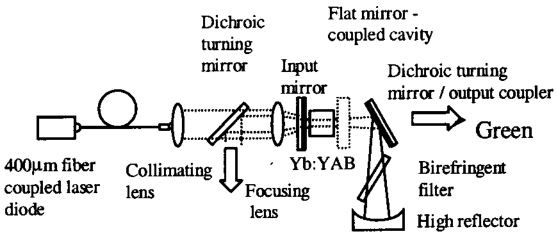

Fig. 1. Schematic of laser cavity used to obtain tunable green emission.

source was a 15-W fiber-coupled InGaAs diode laser ($\phi = 400\ \mu$m, N.A.=0.16) operating at 977 nm. The fiber-coupled pump was imaged onto the Yb:YAB using a pair of aspheric lenses with an effective magnification of 0.74 resulting in a pump radius of 149 μm. The confocal length of the pump beam was in this case close to the crystal length of 3 mm. An antireflection-coated, 10-at.% Yb:YAB crystal ($3\times3\times3$ mm) cut at normal incidence for type I, phase-matched operation at 1064 nm was used for these experiments with the crystal held in a copper block that was maintained at room temperature. The laser-mode-beam diameter was adjusted for a best fit to the pump beam by varying the cavity length close to the stability limit for the 10-cm cavity. Tuning was accomplished using a single-plate quartz birefringent filter (2 mm thick) oriented at Brewster's angle. The Yb:YAB crystal was oriented with respect to the Brewster-angled birefringent filter such that the σ polarization only was allowed to lase. To protect the laser diode from backward-propagating second-harmonic radiation, a second dichroic turning mirror was placed between the collimating lens and focusing lens. The amount of green power coupled out of the laser cavity through the second dichroic turning mirror was typically 10–20% of the measured power. Green light was also coupled out of the cavity through the curved HR and off the birefringent filter. The total green emission coupled out of the cavity other than through the dichroic output coupler was typically 20–30% of the measured power. The powers reported here are measured directly from the dichroic output coupler only.

3. INFRARED TUNING

Wide tuning ranges are possible in a variety of Yb-doped crystalline materials, most notably YAG,[10,17] YAB,[1] $YCa_4O(BO_3)_3$–$GdCa_4O(BO_3)_3$,[5–7] and most recently $Sr_3Y(BO_3)_3$ (BOYS)[18] and SVAP.[19,20] In Yb:YAG the tuning range and maximum achievable output power are strongly dependent on the level of output coupling. Low-transmission output couplers result in large tuning ranges at the cost of maximum output power. For example, Saikawa[10] used an output coupler of 99.9% reflectance to achieve tuning between 1024 and 1109 nm with a power of ~150 mW. In comparison, the same system with an output coupler of 97% reflectance resulted in tuning between 1029 and 1080 nm and a maximum power of ~700 mW. In Yb:GdCOB, Chenais[5] obtained tuning between 1018 and 1086 nm with a tuning range at the 1-W level of 30 nm using a 4.2%-T output coupler with 5.2 W of absorbed power. Most recently Chenais[18] obtained tunable operation of Yb:BOYS between 1017 and 1086 nm with a tuning range at the 1-W level of ~48 nm, albeit in a quasi-cw mode.

In the experiments detailed here with Yb:YAB using an R=99.9% output coupler and a 2-mm birefringent filter, infrared tuning between 1016 and 1090 nm and near 1125 nm was achieved with a maximum infrared output power of ~300 mW at 1060 nm; the pump power was limited to 8.7 W incident. The emission linewidth in the high-Q cavity with a birefringent tuner varied between 0.3 and 1.5 nm, compared with 4–10 nm without any wavelength control. To obtain output powers greater than 1 W, higher-transmission output couplers were used. Laser tuning results are shown in Fig. 2 for 0.5%-T and 2.5%-T output couplers with the calculated gain spectrum included for comparison. Using a 0.5%-T output coupler and 10.3 W of incident pump power, a maximum tuning range at the 1-W power level of 55 nm (1020–1075 nm) was possible. The maximum power, center wavelength and average emission linewidth of the tuned output were 2.05 W, 1045 nm and <0.2 nm, respectively. The maximum tuning range was found to be limited by the free spectral range of the birefringent filter and the short-wavelength transmission of the dielectric coatings. When tuning the laser near 1080 or 1020 nm the emission would jump between these two wavelengths. In comparison, the laser without a birefringent filter delivered 2.37 W with a linewidth of 3.0 nm centered at 1044 nm. Higher maximum output powers were possible using a 2.5%-T output coupler (3.57 W), although this reduced the tuning range at the 1-W level to 38 nm (1020–1058 nm). The emission linewidth remained unchanged at less than 0.2 nm and the laser operated in the TEM_{00} mode at all times.

Another approach to obtain limited tuning is by adding an intracavity etalon. With an uncoated 50-μm etalon we obtained tuning, shown in Fig. 3 (with all tuned spectra overlaid), over a range of approximately 6 nm around 1038 nm. Output powers varied less than 10% (3.65–3.92 W) over this range with the tuned output within 10% of the free-running output (4.03 W). The laser linewidth was in this case reduced from ~0.5–1.0 nm to less than 0.12 nm, limited by detector resolution.

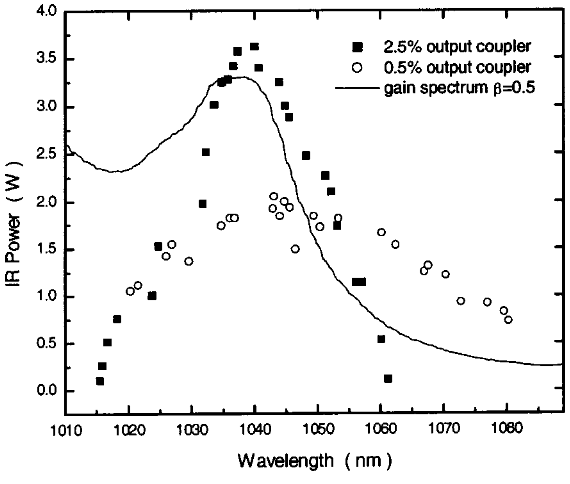

Fig. 2. Infrared output power as a function of tuned wavelength for 0.5%-T and 2.5%-T output coupling.

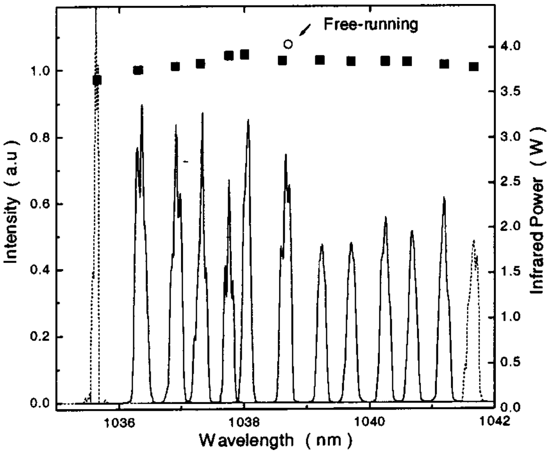

Fig. 3. Etalon tuning of infrared emission using a 2.5%-T output coupler, average linewidth ~0.12 nm.

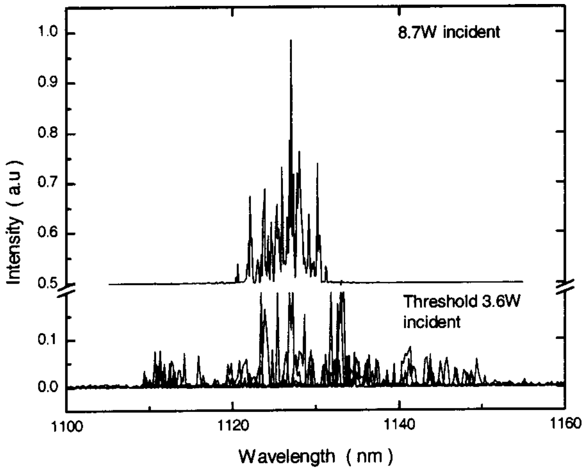

Fig. 4. Coupled-cavity infrared emission past 1100 nm with lasing below 1100 nm suppressed.

Lasing farther into the infrared was possible when mirrors highly transmitting between 1020 and 1090 nm and highly reflective between 1100 and 1200 nm were used. Lasing occurred in this case, as shown in Fig. 4, primarily between 1120–1135 nm with spiked output near threshold ranging between 1110 and 1150 nm. Threshold pump powers as low as 2.9 W incident were possible in a coupled-cavity configuration [the configuration described in Section 2 and shown in Fig. 1 with an additional (12% T at 1060 nm) flat mirror placed less than 5 mm from the laser crystal]. The flat mirror also aided the alignment of the L-shaped cavity. Output powers were limited to the milliwatt range primarily because of the high-Q cavity. Lasing appeared to be dominated by chaotic spiked relaxation oscillations. The temporal output was 100% modulated with pulsewidths of the order of 1–5 μs and repetition rates in the tens of kilohertz. Lasing was also obtained at these extended wavelengths using a simple hemispherical cavity. In this case, when a 10-cm radius-of-curvature output coupler (HR at 1150 nm and 70% T at 1060 nm) was used, a threshold pump power of 6.1 W incident was obtained. With a maximum pump power of 8.7 W, over 20 mW of output between 1128 and 1136 nm was possible, again limited by the low-output coupling. The laser operated cw with a typical variation in output power of ~24% (2σ/average) over a 10-min period. At higher pump powers damage was sustained on the input mirror, limiting further power scaling. Limited tuning between 1127 and 1136 nm was obtained using an uncoated 50-μm quartz etalon. Output powers were in the milliwatt range. Tuning with a birefringent filter was not possible as the Brewster-angled plate introduced too much loss. In comparison, tuning in Yb:YAB near 1130 nm was obtained by Burns *et al.*[3] in a 1.3-mm coupled-cavity, microchip configuration with a maximum pump power of 1.4 W. In this case tuning between 1120 and 1140 nm was obtained by controlling the crystal temperature and thus the mirror–etalon spacing of the laser cavity. A maximum output power of 23 mW near 1130 nm was reported.

Lasing in the 1110–1150-nm range was quite unexpected, and was possible only by suppressing stronger emissions between 1030 and 1090 nm. From the spectra, shown in Fig. 5, it is clear that any lasing past 1070 nm can be considered four-level as the absorption is near zero. The calculated room-temperature gain cross section at 1125 nm [assuming only a small number of excited ions are required to overcome losses in a high-Q cavity, for example, 1–2 times $\beta_{\min}$ (=0.043), where $\beta_{\min}$ is the minimum fraction of excited ions required to balance the ground-state absorption] is estimated as $0.6 \times 10^{-22}\,\mathrm{cm}^2$, which is 1/20 of that at the gain peak at 1040 nm and less than 1/3 of that at 1090 nm. Predictions of the threshold pump power at these key wave-

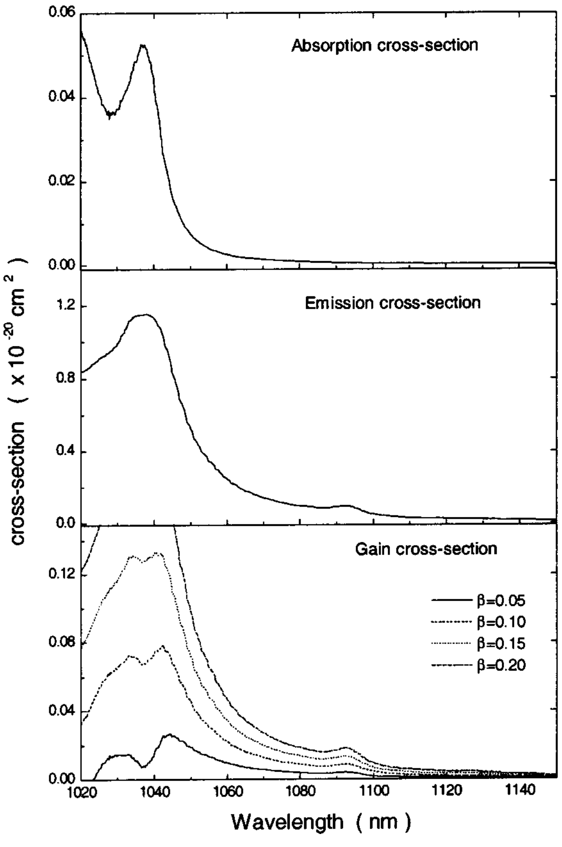

Fig. 5. Absorption, emission and gain cross section of Yb:YAB for σ polarization.

lengths were made using the approach of Taira *et al.*[21] Calculations were made assuming a pump wavelength of 976 nm, lifetime of 680 μs, fractional population of upper laser level of 0.57, cavity waist (ω_0)=pump waist (ω_p) = 150 μm, round-trip loss of 1%, pump absorption coefficient of 8 cm^{-1}, crystal length 3 mm, Yb concentration of $3.12 \times 10^{20}\,\mathrm{cm}^{-3}$, and a pump quantum efficiency of 1. The results are summarized in Table 1. Clearly the predicted threshold pump power at 1125 nm is close to triple that at 1090 nm. This was not observed in the coupled-cavity laser where the threshold pump power was similar at 1125 nm (~2.9 W) to that at 1090 nm (2.7 W). The low threshold is attributed to small cavity-length changes in the coupled cavity producing large variations in the cavity Q at the lasing frequency, effectively driving the laser into a spiked regime.[22] In the case of lasing near 1125 nm with a simple hemispherical cavity, the threshold pump power was considerably higher (~6.1 W), as predicted by the laser threshold calculations.

Table 1. Comparison of Threshold Pump Powers for Yb:YAB at 1040, 1090, and 1125 nm

Property	Wavelength, nm		
	1040	1090	1125
Emission cross section ($\times 10^{-20}\,\mathrm{cm}^2$)	1.41	0.088	0.023
Fractional population of lower laser level ($\times 10^{-3}$)	28	3.5	0.9
Predicted threshold, W	1.2	2.5	8.9
Measured threshold, W	~1.5	~2.7	~2.9 coupled cavity ~6.1 hemispherical cavity

4. DISCUSSION OF INFRARED TUNING

Of all the Yb-doped crystals, Yb:YAB has been demonstrated to tune noncontinuously over the largest bandwidth (134 nm). The maximum tuning range appears to be limited by the transmission losses of the dielectric coatings as well as by reabsorption of the laser emission at the short-wavelength end of the spectrum and by the low available gain at the long-wavelength end. Increased output powers are expected with improved coating and resonator design. The only other self-frequency-doubling material that has shown a tuning range comparable with that of Yb:YAB is Yb:GdCOB.[5] In this material, lasing between 1013 and 1115 nm in a high-Q cavity[6] and with a 10-W pump (5.2 W absorbed), a tuning range at the 1-W level[5] of 30 nm was obtained. Both Yb:GdCOB and Yb:YAB would be expected to exhibit similar tuning ranges considering the balance between emission bandwidth (44 nm versus 20 nm) and gains ($\sigma_e = 0.33$ versus $0.8 \times 10^{-20}\,\mathrm{cm}^2$) of the two materials.

A comparison of output powers and infrared tuning ranges of various Yb-doped crystalline materials is shown in Table 2. Of all the materials listed, Yb:YAB shows the widest range of operation although higher efficiencies are possible by other materials over shorter ranges, for example, Yb:SVAP[20] (1102–1131 nm) and Yb:YAG[17] (1016–1060 nm). It is expected that materials with large tuning ranges can, when mode locked, deliver the shortest ultrashort pulses. While Yb:YAB can be mode locked[23] (~200 fs pulse width), other materials such as Yb:GdCOB[24] and Yb:BOYS[25] have delivered shorter pulses to date, (90 fs and 69 fs, respectively) by virtue of flatter emission bandwidth. The real advantage of materials such as Yb:YAB lies in their ability to produce tunable visible output over a large wavelength range and with relatively high output power.

Table 2. Comparison of Output Powers, Infrared Tuning Ranges and Material Properties of Various Ytterbium Crystalline Materials

Property	Material				
	Yb:YAB	Yb:YAG[10,17]^a	Yb:GdCOB[5]	Yb:BOYS[18]	Yb:SVAP[19,20]
Emission bandwidth,^{b} nm	20–30^b	9–18	44–50^b	60^b	39@1117
Peak emission λ, nm	1038	1030	1032	1066	1044
Emission cross section, ($\times 10^{-20}\,\mathrm{cm}^2$)	0.8	2–3	0.46	0.2	1.3
Min–max emission, nm	1016–1090 1110–1150	1006–1087[17] 1024–1109[10]	1013–1115[6]	1017–1086	1044 1102–1132
Maximum tuned power, W;	2.1	14	2.1	1.9	0.3
Range, nm	1022–1080	1018–1054	1018–1086	1017–1086	1102–1132
Tuning range, 1-W level, nm	1020–1075	1016–1060[17]	1028–1058[5]	1028–1076^c	—
Efficiency, % at λ, nm:					
maximum	33% 1040				31% 1044
pump-to-laser	1–5% 1125	40% 1032	36% 1043	30% 1060^c	17% 1120
Mode-locked pulsewidth, fs	197[23]	340[26]	90[24]	69[25]	—

[a] Numbers in square braces are reference numbers.
[b] Emission bandwidth is determined FWHM for a fractional upper-level population of 0.5, otherwise from fluorescence spectrum.
[c] Chopped 1/17 duty cycle.

5. VISIBLE TUNING

Tunable visible laser radiation is required in many applications including optical data storage, medical diagnostics, biomedicine, biochemistry, chemical analysis, and flow cytometry. Compact, tunable laser sources are sought to replace larger laser systems and to tailor sensing and sorting of specific bio-organisms. Self-frequency-doubled ytterbium lasers are extremely compact and offer wide tunability across the visible spectrum.

In Yb:YAB, widely tunable green–yellow emission was obtained using the cavity shown in Fig. 1 with mirrors highly reflecting at the fundamental and a dichroic turning mirror to couple out the green. With a maximum pump power of 8.7 W, limited by damage sustained to the mirrors while tuning, green–yellow laser operation was obtained between 510 and 545 nm as shown in Fig. 6. (To overcome the transmission loss of the dichroic turning mirror at short wavelengths, the included angle between the crystal and output coupler was increased to 100° when lasing below 1040–520 nm). Output powers ranged between 25 mW at 510 nm to $\sim$450 mW at the peak near 530 nm. The Yb:YAB crystal was maintained at room temperature, although for short-wavelength output ($\sim$510 nm), increases in green output power of 50% were possible by decreasing the crystal temperature from 22 to 5 °C. This large increase in output power results from the reduction of the high reabsorption losses of the thermally populated terminal laser level at the fundamental wavelength (1020 nm). The visible output power at 510 nm increased quadratically with pump power (up to 65 mW with a maximum incident-pump power of 11.1 W), indicating that there is further scope for power scaling.

The infrared and green emission spectra consisted of several bands recorded using an Anritsu MS9030A optical spectrum analyzer as depicted in Figs. 7(a) and 7(b). The laser operated for more than one hour with no change or shift in wavelength. At this wavelength (510 nm) the amplitude noise varied, depending heavily on the bandwidth of the emission. With a narrow IR bandwidth ($\sim$0.6 nm), green amplitude noise (2σ/average) of 25% was obtained, compared with 5% for the infrared. This reduced to 10% green and 2% IR (amplitude noise) when the laser operated with the same green power but with an IR bandwidth of 1.2 nm. The relatively high level of green amplitude noise, considering an extremely stable wavelength spectrum, was not unexpected as the laser operated on between four and ten longitudinal modes. Operation with a larger emission bandwidth, and hence more longitudinal modes, resulted in more stable output. Green powers remained unchanged as the infrared bandwidth was within the wavelength-acceptance bandwidth of Yb:YAB (1.2 nm cm). It is interesting to note that the stability of the output spectra in the infrared, and hence green, was determined by weak-coupled etalons between the antireflection-coated crystal faces ($<1\%$ reflectivity at 1020 nm) and the highly reflective input mirror. Small changes in the input-mirror-to-crystal separation would force the IR mode spacing to jump from 0.2 to 0.1 nm. The laser operated indefinitely in either regime. Near the gain peak at 1060 nm the IR—shown in Fig. 7(c)—and green spectra were dominated by more chaotic output, although still with an IR bandwidth of less than 1 nm. The increase in spectral noise near 1060 nm is because the stronger gain at this wavelength reduces the influence of any of the weak etalons.

The beam quality of the visible output near 510 nm was determined by measuring the laser beam spot size at vari-

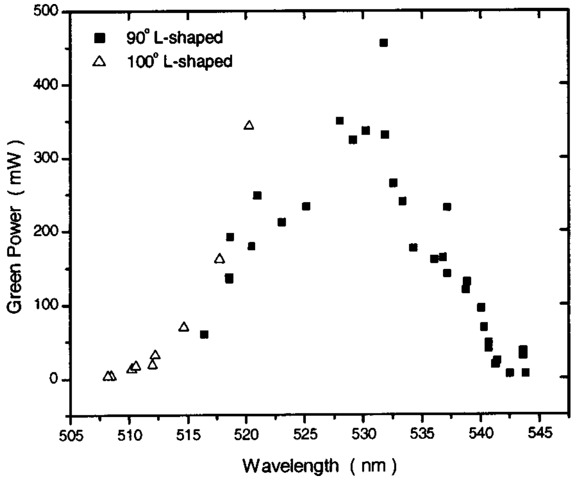

Fig. 6. Visible tuning range in Yb:YAB, pump power = 8.7 W.

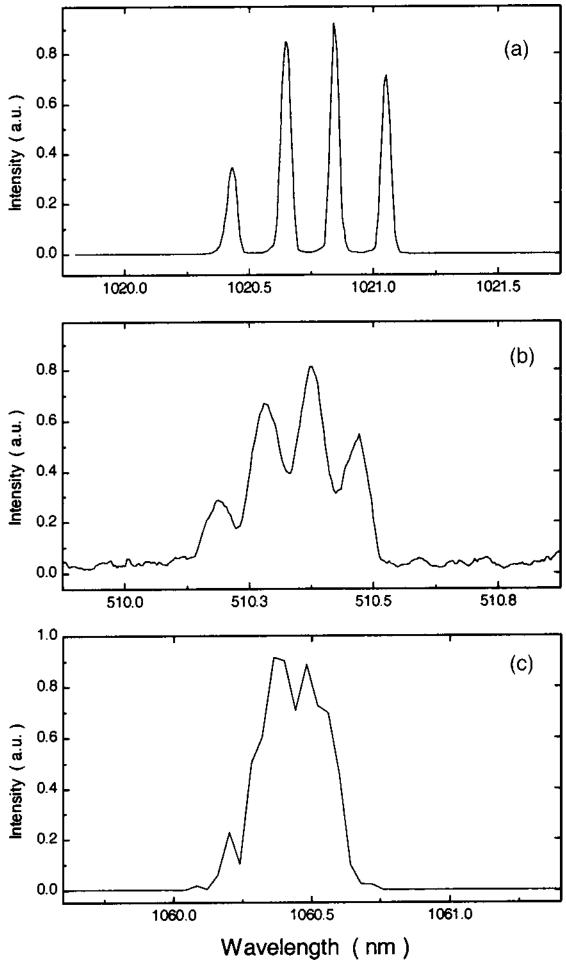

Fig. 7. (a) Infrared-tuned emission spectrum near 1020 nm; (b) self-doubled green near 510 nm, and (c) infrared emission at the gain peak near 1060 nm. Resolution bandwidth at 1020 and 510 nm of 0.1 nm and at 1060.4 nm of 0.2 nm.

ous distances through the focus of a plano–convex lens. With this technique, an M^2 value of 1.1 was determined, indicating near-diffraction-limited output.

Operation at longer wavelengths was also possible by modifying the resonator to suppress lasing between 1020 and 1090 nm. In a coupled cavity without a birefringent filter, IR and self-doubled laser operation was obtained across the wavelength ranges of 1110–1150 nm and 555–575 nm, respectively. Near threshold (2.9 W), the self-doubled laser operated at 564 nm with a linewidth of ~0.1 nm. At maximum pump power (8.3 W incident), the laser operated across a broader range between 558 and 566 nm and with a maximum visible output power of 12 mW. As shown in Fig. 8, the visible output power in this wavelength range increased linearly with pump power, which is consistent with operation in a pulsed–gain-switched or saturated regime. The pulsed behavior is attributed to cavity length fluctuations in the coupled cavity as discussed in Section 3.

By using a simple linear, hemispherical cavity with high transmittance at 1020–1090 nm and high reflectivity at 1150 nm we obtained approximately 2 mW of laser emission between 565 and 568 nm. The threshold in this case (6.1 W) was much higher than for the coupled cavity and the output power increased quadratically with pump power. In the hemispherical cavity the yellow amplitude noise (77% 2σ/average) was less than in the coupled cavity (100% modulation), although still high compared with tuned operation between 510 and 545 nm (10–25% depending on emission linewidth). The high level of noise is attributed to a lack of frequency control, allowing the laser to skip across a relatively large wavelength range (1120–1135 nm) with different levels of gain and effective nonlinearities.

To maintain optimum phase matching the Yb:YAB laser crystal was rotated from its normal position at 1064 nm. The crystal was rotated by 0.063°/nm. Taking into account the angular acceptance of 1.35 mrad cm, a value for the wavelength acceptance of 1.23 nm cm, or 3.7 nm for the Yb:YAB crystal used here, was obtained. In practice both the birefringent filter and laser crystal were rotated to obtain optimum phase matching. Optimization of the crystal angle above 1100 nm was not possible; the reason for this is probably high threshold and large shifts in wavelength, and this may have limited the yellow output power when operating in the linear hemispherical cavity (in the coupled cavity the laser effectively operated pulsed–gain-switched, and the doubling efficiency was high). It is interesting to note that at high pump powers with low effective output coupling, noncollinear sum-frequency generation of the pump and laser output was possible. This resulted in low-power (~100 μW) visible emission between 500 and 520 nm.

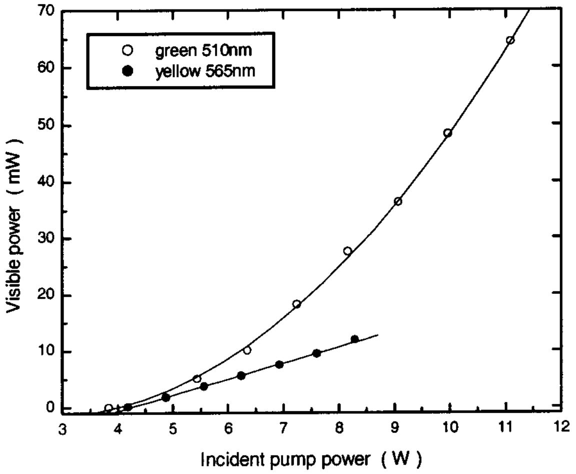

Fig. 8. Laser power slope efficiency for visible emission at 510 nm in a hemispherical cavity with a birefringent tuner and at 565 nm in a coupled cavity.

6. DISCUSSION OF VISIBLE OPERATION

Yb:YAB has been shown to lase over a large wavelength range in the infrared and visible (510–545, ~565 nm). Previously we have obtained free-running visible output powers of 1.1 W, and now at slightly lower pump powers, tuning between 510 and 565 nm with output powers from 12 mW at 565 nm to over 450 mW at 530 nm. In comparison, Montoya *et al.*[9] obtained 58 mW of green laser emission in Yb^{3+}:MgO,$LiNbO_3$ under "critical alignment conditions" with a Ti:sapphire laser pump source (absorbed pump power of 800 mW). Maximum visible output powers were limited by thermal detuning of the phase matching because of the low thermal acceptance of Yb^{3+}:MgO,$LiNbO_3$ (~0.7 °C cm). Tunable visible emission was reported but no powers given. On the other hand self-doubled output in Yb:GdCOB[7] has been reported to be limited because of the broadband laser emission. Mougel *et al.*[7] reported that "the fundamental laser emission shifted to nullify the phase-matching condition for which losses increase in the cavity." It was noted that to obtain SFD operation, a frequency-selective device such as a birefringent filter could be used, although no reports of tunable visible operation have been made. Only small differences exist between the two borates and so these materials would be expected to behave similarly as nonlinear materials. The GdCOB host has indeed been demonstrated to double efficiently when used in an intracavity-doubled Nd:$GdVO_4$ laser.[27] The outstanding performance of Yb:YAB as a tunable SFD laser is reasoned to be attributable to a somewhat sharper gain curve over Yb:GdCOB, which prevents large excursions of the fundamental emission. Efficient doubling is thus possible in Yb:YAB despite the relatively narrow spectral acceptance. The problems are further exacerbated in Yb:GdCOB because of the extraordinarily long lifetime–storage time (3 ms compared with 0.66 ms in YAB). This results in a long relaxation-oscillation-damping time constant and hence would allow, with small perturbations of the cavity loss, large inversion densities resulting in spiked output with fewer round trips for mode selection. Coupled with a broad emission bandwidth and narrow spectral acceptance, these effects probably limit the self-doubled output of this material when using ytterbium as the active ion.

The large thermal acceptance of YAB (~28 °C cm) and reduced thermal loading when using ytterbium over neodymium as the active ion allow substantial SFD powers to be generated which at this stage appear to be limited only by the fundamental intracavity intensity and coating–resonator designs.

7. CONCLUSIONS

High-beam-quality, stable, tunable, green–yellow operation of Yb:YAB has been obtained with a maximum visible continuous tuning range of 35 nm (>55 nm noncontinuous) and output powers ranging from 12 to 450 mW. The Yb:YAB laser can be tuned over a wide range covering the spectrum of several available lasers including the copper-vapor (510 nm), argon-ion (514 nm), doubled Nd:YAG (532 nm), green HeNe (543 nm) lasers, and the doubled Yb:SVAP laser in the visible (~565 nm). In the infrared, a tuning range (at the 1-W level) of 55 nm was obtained with a maximum power of 2.05 W at ~1060 nm with resolution-limited linewidth of 0.12 nm. Both the green and infrared laser powers are limited by the available pump power and—at short wavelengths—crystal temperatures. It is expected substantial increases in visible output power are possible with higher-power diodes and improved coating designs.

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REFERENCES

1. P. Wang, P. Dekker, J. M. Dawes, J. A. Piper, Y. Liu, and J. Wang, “Efficient continuous-wave self-frequency-doubling green diode-pumped Yb:YAl$_3$(BO$_3$)$_4$ lasers,” Opt. Lett. **25**, 731–733 (2000).
2. P. Dekker, J. M. Dawes, J. A. Piper, Y. Liu, and J. Wang, “1.1W CW self-frequency-doubled diode-pumped Yb:YAl$_3$(BO$_3$)$_4$ laser,” Opt. Commun. **195**, 431–436 (2001).
3. P. Burns, J. M. Dawes, P. Dekker, J. A. Piper, J. Li, and J. Wang, “Coupled-cavity, single-frequency, tunable cw Yb:YAB yellow microchip laser,” Opt. Commun. **207**, 315–320 (2002).
4. P. Dekker, J. Blows, P. Wang, J. Dawes, J. Piper, T. Omatsu, Y. Liu, and J. Wang, “Yb:YAl$_3$(BO$_3$)$_4$: an efficient green self-frequency-doubled laser source,” in *Advanced Solid State Lasers*, C. Marshall, ed., Vol. 50 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2001), pp. 476–483.
5. S. Chenais, F. Druon, F. Balembois, G. Lucas-Leclin, P. Georges, A. Brun, M. Zavelani-Rossi, F. Augé, J. P. Chambaret, G. Aka, and D. Vivien, “Multiwatt, tunable, diode-pumped CW Yb:GdCOB laser,” Appl. Phys. B: Lasers Opt. DOI 10.1007/s003400100477 (2001).
6. F. Augé, F. Balembois, P. Georges, A. Brun, F. Mougel, G. Aka, A. Kahn-Harari, and D. Vivien, “Efficient and tunable continuous-wave diode-pumped Yb^{3+}:CaGdO(BO$_3$)$_3$ laser,” Appl. Opt. **38**, 976–979 (1999).
7. F. Mougel, K. Dardenne, G. Aka, A. Kahn-Harari, and D. Vivien, “Ytterbium-doped Ca$_4$GdO(BO$_3$)$_3$: an efficient infrared laser and self-frequency doubling crystal,” J. Opt. Soc. Am. B **16**, 164–172 (1999).
8. D. A. Hammons, M. Richardson, B. H. T. Chai, A. K. Chin, and R. Jollay, “Scaling of longitudinally diode-pumped self-frequency-doubling Nd:YCOB lasers,” IEEE J. Quantum Electron. **36**, 991–999 (2000).
9. E. Montoya, J. A. Sanz-Garcia, J. Capmany, L. E. Bausa, A. Diening, T. Kellner, and G. Huber, “Continuous wave infrared laser action, self-frequency doubling and tunability of Yb^{3+}:MgO:LiNbO$_3$,” J. Appl. Phys. **87**, 4056–4062 (2000).
10. J. Saikawa, S. Kurimura, N. Pavel, I. Shoji, and T. Taira, “Performance of widely tunable Yb:YAG microchip laser,” in *Advanced Solid State Lasers*, H. Injeyan, U. Keller, and C. Marshall, eds., Vol. 34 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2000), pp. 106–111.
11. S. M. Giffin and I. T. McKinnie, “Tunable visible solid-state lasers based on intracavity frequency doubling of Cr:forsterite in KTP,” Opt. Lett. **24**, 884–886 (1999).
12. S. M. Giffin, I. T. McKinnie, and V. V. Ter-Mikirtychev, “Tunable visible solid-state lasers based on second harmonic generation of LiF:F$_2^-$ in potassium titanyl phosphate,” Opt. Lett. **23**, 192–195 (1998).
13. J. Y. Allain, M. Monerie, and H. Poignant, “Room temperature CW tunable green upconversion holmium fibre laser,” Electron. Lett. **26**, 261–263 (1990).
14. J. Y. Allain, M. Monerie, and H. Poignant, “Tunable green upconversion erbium fibre laser,” Electron. Lett. **28**, 111–113 (1992).
15. E. Heumann, S. Bar, H. Kretschmann, and G. Huber, “Diode-pumped continuous-wave green upconversion lasing of Er^{3+}:LiLuF$_4$ using multipass pumping,” Opt. Lett. **27**, 1699–1701 (2002).
16. H. Zellmer, P. Riedel, and A. Tunnermann, “Visible upconversion lasers in praseodymium-ytterbium-doped fibers,” Appl. Phys. B: Lasers Opt. **69**, 417–421 (1999).
17. A. Giesen, U. Brauch, I. Johannsen, M. Karszewski, U. Schiegg, C. Stewen, and A. Voss, “Advanced tunability and high-power TEM$_{00}$ operation of the Yb:YAG thin disc laser,” in *Advanced Solid State Lasers*, C. Pollock and W. Bosenberg, eds., Vol. 10 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1997), pp. 280–284.
18. S. Chenais, F. Druon, F. Balembois, P. Georges, R. Gaume, P. H. Haumesser, B. Viana, G. P. Aka, and D. Vivien, “Spectroscopy and efficient laser action from diode pumping of a new broadly tunable crystal: Yb^{3+}:Sr$_3$Y(BO$_3$)$_3$,” J. Opt. Soc. Am. B **19**, 1083–1091 (2002).
19. A. N. P. Bustamante, D. A. Hammons, R. E. Peale, B. H. T. Chai, M. Richardson, and A. Chin, “Simultaneous cw dual wavelength laser action and tunability performance of diode-pumped Yb^{3+}:Sr$_5$(VO$_4$)$_3$F,” Opt. Commun. **19**, 309–313 (2001).
20. A. K. Hankla, G. J. Wagner, T. J. Carrig, N. A. Brilliant, and C. A. Denman, “Single-frequency operation of a diode-pumped Yb:SVAP laser tunable from 1104 nm to 1128 nm,” in *Advanced Solid State Lasers*, M. C. Fermann and L. R. Marshall, eds., Vol. 68 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2002), pp. 401–405.
21. T. Taira, W. M. Tulloch, and R. L. Byer, “Modelling and quasi-three-level lasers and operation of cw Yb:YAG lasers,” Appl. Opt. **36**, 1867–1874 (1997).
22. J. J. Zayhowski, “Q-switched operation of microchip lasers,” Opt. Lett. **16**, 575–577 (1991).
23. M. J. Lederer, M. Hilderbrandt, V. Z. Kolev, B. Luther-Davies, B. Taylor, J. M. Dawes, P. Dekker, J. A. Piper, H. H. Tan, and C. Jagadish, “Passive mode locking of a self-frequency-doubling Yb:YAl$_3$(BO$_3$)$_4$ laser,” Opt. Lett. **27**, 436–439 (2002).
24. F. Druon, F. Balembois, P. Georges, A. Brun, A. Courjaud, C. Honninger, F. Salin, A. Aron, F. Mougel, G. Aka, and D. Vivien, “Generation of 90-fs pulses from a mode-locked diode-pumped Yb^{3+}:Ca$_4$GdO(BO$_3$)$_3$ laser,” Opt. Lett. **25**, 423–425 (2000).
25. F. Druon, S. Chenais, P. Raybaut, F. Balembois, P. Georges, R. Gaume, G. Aka, B. Viana, D. Vivien, S. Mohr, and D. Kopf, “CW and femtosecond regime of a new very broadband Yb-doped BOYS crystal,” in *Advanced Solid State Lasers*, M. E. Fermann and L. R. Marshall, eds., Vol. 68 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2002), pp. 164–167.
26. C. Hönninger, R. Paschotta, M. Graf, F. Morier-Genoud, G. Zhang, M. Moser, S. Biswal, J. Nees, A. Braun, G. A. Mourou, I. Johannsen, A. Giessen, W. Seeber, and U. Keller, “Ultrafast ytterbium-doped bulk lasers and amplifiers,” Appl. Phys. B: Lasers Opt. **69**, 3–17 (1999).
27. J. Liu, X. Xu, C. Wang, S. Wang, J. Wang, H. Chen, Z. Shao, and M. Jiang, “Intracavity second-harmonic generation of 1.06 μm in GdCa$_4$O(BO$_3$)$_3$ crystals,” Appl. Phys. B: Lasers Opt. DOI 10.1007/s003400000432 (2000).