Blue microchip laser fabricated from Nd:YAG and $KNbO_3$

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Received August 4, 1995

A Nd:YAG/$KNbO_3$ composite-material microchip laser has generated blue radiation at 473 nm with output powers of 1 mW when diode laser pumped and 9 mW when Ti:sapphire laser pumped. The fundamental radiation generated by the quasi-three-level ${}^4F_{3/2}-{}^4I_{9/2}$ transition in Nd:YAG at 946 nm was frequency doubled in $KNbO_3$ angle cut to be type I critically phase matched at 45 °C. Despite the normally isotropic nature of Nd:YAG, the fundamental is emitted linearly polarized and orthogonal to the linearly polarized blue radiation.

Low-cost compact blue and green lasers are desired for applications such as reprographics, inspection, and optical data storage. Our group recently reported 130 mW of green power generated in a composite-material microchip device.[1,2] Although the blue diode laser is expected to become important, currently direct doubling of 860-nm laser diodes,[3] sum-frequency mixing of diode and 1064-nm radiation,[4] and doubling of the 946-nm Nd line[5] are more practical options. The microchip laser format is likely to be the most compact of the non-blue-diode options, and we report here on the successful operation of a diode-pumped cw blue (473-nm) microchip laser.

In its basic form a microchip laser consists of a short length of plane/plane-parallel gain material with dielectric coatings deposited on each surface.[6] End pumping of the crystal can lead to the formation of a stable cavity.[7,8] A high spatial and spectral quality laser output is generated from the highly divergent low-spectral-quality output of a standard laser diode array. Composite-material microchip lasers extend the design principle by placing two or more plane-parallel materials in close contact and dielectrically coating the outer surfaces of the crystal set.[1,9,10]

We report here on a blue microchip laser source consisting of a Nd:YAG/$KNbO_3$ composite-material microchip laser generating 946-nm fundamental radiation and second-harmonic radiation at 473 nm. Both Ti:sapphire and diode lasers have been used to pump the blue microchip laser, as shown in Fig. 1.

The 1-mm-thick 1.1-at.% Nd:YAG crystal was polished plane-parallel and positioned abutting a nominally 1.5-mm-thick plane-parallel $KNbO_3$ crystal angle cut for type I critical phase matching of 946-nm radiation at $T_{\mathrm{pm}} = 45\,°\mathrm{C}$. The surfaces of the composite material were coated to have high reflectance at 946 nm and high transmittance at 1064, 1320, and 473 nm. High transmittance was also specified at the 809-nm pump wavelength; however, subsequent measurements showed as much as 28% reflectance. The calculated 1% reflectivity of the YAG/$KNbO_3$ interface leads to only very weak étalon effects.

The quasi-three-level ${}^4F_{3/2}-{}^4I_{9/2}$ transition in Nd imposes limitations on the choice of host material. In Nd:YAG the Z_5 Stark level within the ${}^4I_{9/2}$ manifold is 848 cm^{-1} above the ground state. This was calculated to reduce the threshold by at least a factor of 4 in comparison with Nd:YVO_4 in which the Z_5 state occurs at 439 cm^{-1}. However, the low absorption coefficient of 1.1% Nd:YAG (0.85 cm^{-1}) at the pump wavelength compared with that of 3% Nd:YVO_4 (12 mm^{-1}) makes YAG less desirable as a microchip medium. More significantly, as Nd:YAG is isotropic it was expected that efficiently generating the 946-nm fundamental in the correct polarization for second-harmonic generation would require insertion of a polarizer. $KNbO_3$ was selected as the doubling material because of its high nonlinearity ($d_{\mathrm{eff}} = 13$ pm/V) and its ability to be birefringently phase matched for second-harmonic generation of the 946-nm fundamental. Disadvantages of this material are its narrow temperature acceptance bandwidth and that its domain structure

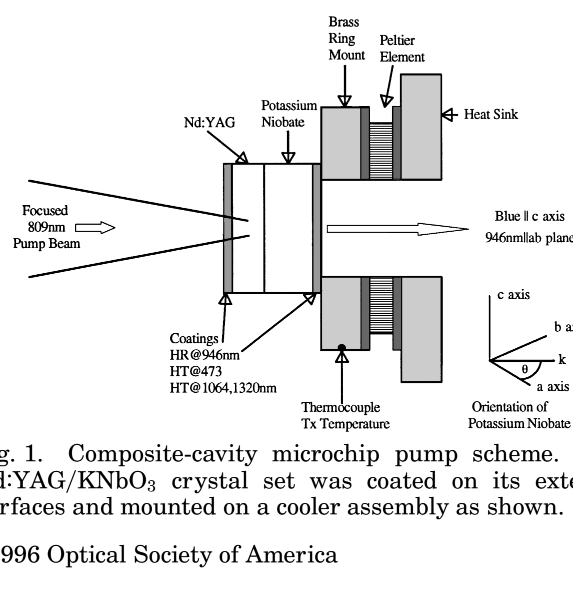

Fig. 1. Composite-cavity microchip pump scheme. The Nd:YAG/$KNbO_3$ crystal set was coated on its external surfaces and mounted on a cooler assembly as shown.

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is easily disturbed. Our prototype samples had only small clear apertures because of domain-reversal problems.

In initial experiments an 850-mW cw Ti:sapphire laser tuned to $\lambda_p = 808.5$ nm was focused by an $f = 25$ mm lens to a spot size of 17 ± 5 μm within the crystal set. The 28% reflectance of the input coating and the 49.2% absorption within the Nd:YAG crystal led to a maximum absorbed pump power P_{abs} of 279 mW.

The crystal heat-sink temperature T_x, which maximized the blue output power at full pump power ($P_{abs} =$ 279 mW), was measured to be 36.6 °C with a full-width 40% maximum bandwidth of 2.8 °C, as shown in Fig. 2. At this peak 3.6 mW of blue light was generated and approximately 43 mW of 946-nm radiation escaped the cavity in this direction, as shown in the inset of Fig. 2. The 20% change in 946-nm power over this measurement range may be due to the temperature dependence of threshold and/or mirror reflectivities. The second-harmonic generation is a relativity small cavity loss mechanism, so no significant reduction in the 946-nm power was observed at phase matching. The short nonlinear crystal length resulted in an acceptably broad temperature bandwidth. This was not necessarily at the expense of greatly reduced efficiency, as the second-harmonic power may not be strongly dependent on the nonlinear crystal length, depending on the major cavity loss mechanisms.[9] The low thermal acceptance bandwidth of the $KNbO_3$ and the thermal transfer between the nonlinear crystal and the hot gain material are expected to result in a degradation of the phase matching both along and across the beam. However, the close agreement between the observed (2.8 °C) and calculated (2.9 °C) temperature bandwidths suggests that reasonable phase matching was achieved.

The 946-nm and blue output beams were TEM_{00} with a blue mode size of $\omega_0 \approx 45$ μm and with <1:1.1 ellipticity. At full pump power and at optimum temperature ($T_x = 36.6$ °C) an étalon examination indicated the presence of three blue frequencies, while an optical spectrum analysis detected three axial modes centered at 946.2 nm with a mode spacing of 0.25 nm. Just above threshold two modes were still present. The calculated longitudinal mode spacing for this cavity was 0.1 nm, suggesting that spatial hole burning prevents adjacent modes from oscillating. No parasitic laser oscillation was detected at either 1064 or 1320 nm.

The blue and 946-nm output powers as a function of the absorbed pump power were measured and are shown in Fig. 3. At maximum pump power $P_{abs} = 279$ mW the crystal temperature T_x at which the blue power was optimized was 36.6 °C. As the pump power was reduced additional heat was required to ensure that the $KNbO_3$ crystal remained phase matched. Therefore in these experiments the thermoelectric controller temperature setting T_x was readjusted for each pump power so that the blue output power could be maximized.

The maximum blue power P_{blue} of 4.3 mW was generated at $P_{abs} = 279$ mW. The 946-nm output reached threshold at $P_{abs} = 40$ mW with a slope efficiency with respect to absorbed power of approximately $\eta = 18.7\%$ and a maximum output of $P_{946} = 45$ mW. As the crystal coating specifications on both sides were identical, we can expect similar outputs from both coated surfaces. The 1.02° walk-off between the fundamental and the second harmonic introduced by the 1.5-mm-long $KNbO_3$ crystal was calculated to have reduced the conversion efficiency by only 23%.

Experiments with a higher-quality crystal set with the $KNbO_3$ angle cut to phase match at the lower $T_{pm} = 40$ °C produced a single-direction blue output power of 9.2 mW when pumped with Ti:sapphire. Unfortunately this set was damaged before full characterization.

Intensity fluctuations that are due to mode coupling in green microchip lasers, green noise, have been reported.[9,11] In our blue microchip laser blue noise was present, producing intensity fluctuations the depth and spectral content of which varied with crystal temperature. An rf spectrum analysis indicated that both distinct frequency and random noise are present, depending on the operating conditions. This was of

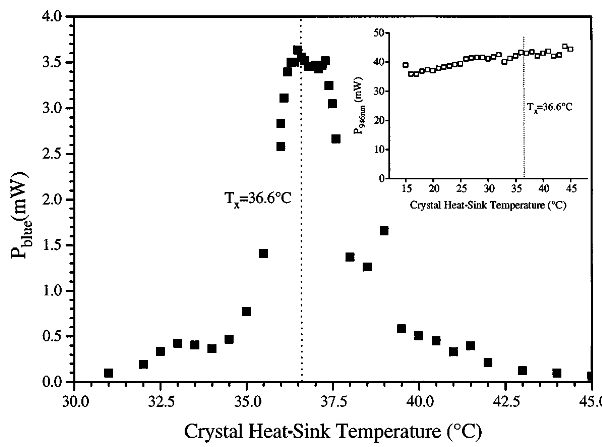

Fig. 2. Blue laser output power as a function of the crystal heat-sink temperature at maximum absorbed Ti:sapphire pump power $P_{abs} = 279$ mW. The inset shows 946-nm output power under the same operating conditions.

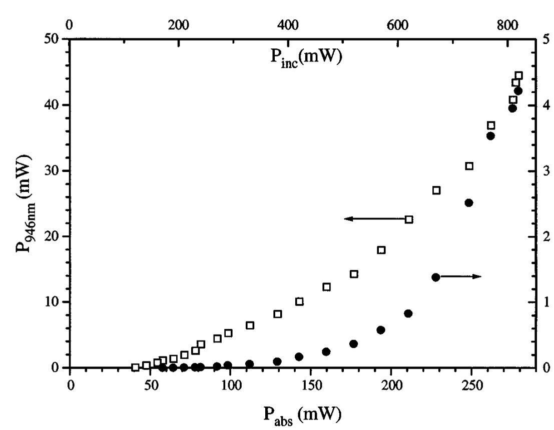

Fig. 3. Ti:sapphire-pumped blue (filled circles, right y axis) and 946-nm (open squares, left y axis) laser output power as a function of pump power (P_{inc}, incident; P_{abs}, absorbed) at the crystal heat-sink temperature T_x that optimize the blue output at each pump power.

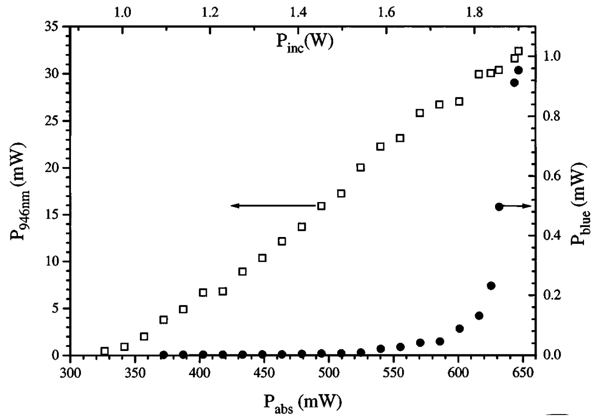

Fig. 4. Diode-pumped blue (filled circles, right y axis) and 946-nm (open squares, left y axis) laser output power as a function of pump power (P_{inc}, incident; P_{abs}, absorbed) at the crystal setpoint temperature $T_x = 26.9\,°C$ that optimized the blue output at the maximum absorbed pump power $P_{abs} = 647$ mW.

higher frequency than the relaxation oscillations of the cavity (<1 MHz).

An examination of the polarization of the output beams showed that the 946-nm radiation was strongly linearly polarized (>1:10^3) and orthogonal to the linearly polarized blue output. That the blue radiation was strongly polarized is a condition of the phase-matching geometry of the $KNbO_3$ crystal.[12] However, as Nd:YAG is isotropic there is no intrinsic mechanism to ensure that the 946-nm output is optimally linearly polarized parallel to the $KNbO_3$ ab plane and is thus phase matched for optimum blue generation. In a laser resonator such as this, one expects two linearly polarized eigenmodes at 946 nm to exist with polarizations parallel and perpendicular to the $KNbO_3$ c axis. However, under all experimental conditions (varying T_x and P_{abs}) the laser oscillated polarized parallel to the ab plane. This may have been due to stress effects in the Nd:YAG crystal or the positioning of the fundamental modes across the gain profile. Even when the $KNbO_3$ temperature was optimized for phase matching the polarization remained the same, presumably because the nonlinear loss (4-mW blue compared with 50-mW output coupling of the fundamental) was still small compared with the difference in net gain for the two possible polarization eigenmodes.

The potential of this microchip device in a compact diode-pumped assembly was examined. A 2-W (200 μm × 1 μm emitter) diode laser and a 95% transmitting aspheric lens pair were used to focus the $\lambda_p =$ 808.5 nm pump beam to an approximately 220 μm × 20 μm full-width spot on the crystal surface. The substantial reflectivity of the crystal surface and the low absorption coefficient of the Nd:YAG led to a maximum absorbed power of $P_{abs} = 647$ mW. A maximum blue output power of $P_{blue} = 0.954$ mW at the maximum absorbed pump power of $P_{abs} = 647$ mW was observed. This was accompanied by $P_{946} = 32$ mW of fundamental radiation, as shown in Fig. 4. The 946-nm fundamental output threshold occurred at $P_{abs} = 326$ mW, resulting in an absorbed power slope efficiency of 9.9%. In each case the crystal heat-sink temperature was maintained at $T_x = 26.9\,°C$ and the laser diode temperature at $T_d = 36.1\,°C$. An attempt at optimizing the diode wavelength by its temperature T_d and the crystal heat-sink temperature T_x at each pump power proved difficult, producing bistability in the output power.

The polarizations of the fundamental and blue outputs were linear and orthogonal to each other and displayed the same insensitivity to pump power and crystal heat-sink temperature as observed with Ti:sapphire pumping. A spectral analysis of the fundamental output showed the presence of two modes at maximum pump power with one mode present just above threshold. The beam quality of the blue output showed a single spot of high ellipticity (1:1.7), whereas the fundamental beam showed three spots consistent with TEM_{00} (mode size $\omega_0 \approx 60\,\mu$m) and TEM_{10} transverse modes.

The use of crystal sets free of $KNbO_3$ damage, with improved 810-nm transmission coatings, and the use of higher-brightness diodes will increase 946-nm output powers. As the blue output increases at a greater rate than the associated 946-nm output, significant efficiency improvements are expected. Investigations are in progress to determine the optimum angle cut temperature and crystal lengths along with a clarification of the mechanisms leading to the polarization eigenmodes observed and means by which the blue noise can be eliminated.

We acknowledge the support of the United Kingdom Engineering and Physical Sciences Research Council (grant number GR/K14766). The subject matter and results reported here are subject to pending United Kingdom and international patent applications.

Note added in proof: More than 25 mW of 473-nm cw radiation has been generated with improved quality chipsets 1.2-W diode pumped.

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