Moving solid-state cyan lasers beyond 20 mW

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ABSTRACT

We report on cavity-enhanced second-harmonic generation of 488 nm radiation in a 5 mm long periodically poled KTiOPO4 (PPKTP) crystal pumped by the output of a single-mode 976 nm semiconductor external cavity laser. At a pump laser output power of 660 mW, a mode-matching efficiency into an enhancement cavity of 65 % was observed. A maximum power of 156 mW at 488 nm was generated in the enhancement cavity of which 130 mW was coupled out. Under these pump laser conditions an overall optical conversion efficiency of 20 % and an overall electrical to optical efficiency of 9 % was measured. Both the spatial and spectral properties of the 488 nm beam are of very high quality. Typically, a near-diffraction-limited beam with $M^2<1.1$ is produced with low astigmatism and little ellipticity.

Keywords: cavity enhancement, 488 nm, blue laser, external cavity laser, frequency conversion, SHG, PPKTP, thermal-induced bistability

1. INTRODUCTION

The market opportunity for air-cooled argon-ion lasers has been remarkably stable for many years. Argon-ion lasers command a large share of the blue-green laser market, with diverse applications including: flow cytometry and DNA sequencing; semiconductor wafer inspection and alignment systems; digital imaging and reprographics; high power laser projectors; and laser light shows. That this 39-year-old technology has had such staying power in a highly competitive marketplace is a testament to the extraordinary performance capabilities and elegant simplicity of the design. The Argon-ion laser's long history also has made them very cost-effective. Yet many of the traditional applications of the argon-ion laser are slowly disappearing. Digital photo-finishing has started to use DPSS lasers at 473 nm and 532 nm, whereas semiconductor wafer inspection is expected to employ 355-nm or even 266-nm DPSS lasers in the future. Analytical instrumentation for biological applications remains the stronghold of the argon-ion laser. Low-power (10 to 30 mW), single-line 488-nm (cyan) argon-ion lasers are almost ubiquitous in this field because popular fluorescent reagents have their peak absorption efficiency at or near 488 nm. Many other fluorophores, such as those used in DNA sequencing, are traditionally excited by multi-line argon-ion lasers which primarily exploit the 488-nm and 514.5 nm lines. Although much work has been done to develop new fluorophores that take advantage of DPSS lasers at 532 nm and 473 nm, the bulk of the fluorophore legacy remains at 488 nm.

Bio-analytical instrumentation is a demanding application that requires a high-performance solution. The excellent optical performance characteristics of argon-ion lasers have been pivotal to their widespread adoption and have led to their use in thousands of commercial instruments. But argon-ion technology is not without limitations: size (5"x6"x12" for head and 5"x6"x11" for power supply), power consumption (~2.5 kW) and limited operational life (~5000 hours). Because these characteristics are increasingly important, there is a growing need for a solid-state alternative to the cyan argon-ion laser that does not entail compromises in optical performance. Furthermore, there is a strong demand for more than 20-30 mW out of a solid-state design. In particular, in semiconductor wafer inspection, 100-150 mW is required. The limited life time of an air-cooled argon-ion laser tube at these power levels has very much limited their applicability. To address this market opportunity a scalable platform is required that maintains the excellent optical beam quality that cyan solid-state lasers have demonstrated [1], and at the same time achieves a lifetime on the order of ten to twenty thousand hours at a competitive price. In this article the potential of a cavity-enhanced frequency-doubling approach is investigated.

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2. THE OPTICAL ENHANCEMENT CAVITY

The enhancement cavity is based on a symmetric bow-tie ring-cavity configuration. Fig. 1 is a schematic layout of the optics. Unwanted back reflections to the 976-nm pump laser are greatly reduced with this ring cavity design. The reduction of back reflections is especially important because no small-sized low-cost 976 nm optical isolators are commercially available. The cavity finesse is approximately 37, which is relatively low for a typical enhancement configuration. The reason for this is to relax the requirements for the control-loop system that will keep the blue output power constant over the life of the laser, given the range of environmental conditions the laser has to endure.

The crystal used in the enhancement cavity is a periodically-poled KTP crystal. The single-pass conversion efficiency was measured to be 0.68%/W in a separate experiment when optimal focusing was used. On resonance of the enhancement cavity, the circulating pump power increased to 4.8 W, producing 130 mW in a 488-nm beam. Accounting for the 83% blue transmission of the blue out-coupler this observed blue power agrees reasonably well with the power predicted by the single-pass efficiency. These output power results are quite encouraging for a 100-mW type product and the conversion efficiency could be further improved by raising the finesse of the enhancement cavity at the cost of narrower cavity resonances.

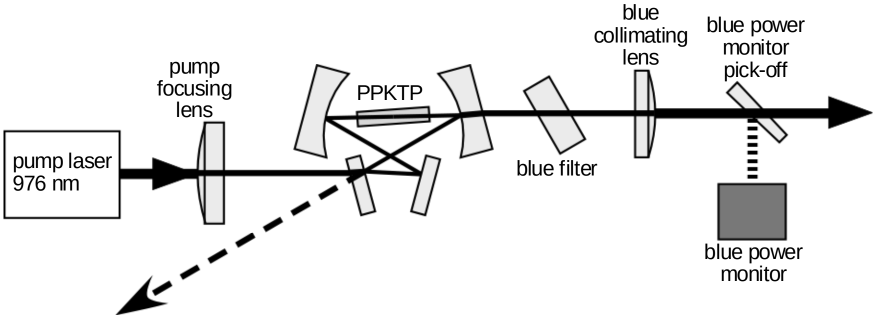

Figure 1. Optical layout of 488 nm laser.

3. SECOND-HARMONIC OUTPUT POWER

The enhancement cavity provides an elegant method of increasing the doubling efficiency of a given crystal by boosting the circulating pump power. The amount of 488 nm power generated from the enhancement cavity strongly depends on the optical pump power and how accurately the pump laser wavelength is tuned on the resonance of the enhancement cavity. At the time of this writing, a full control system for locking to a resonance of the enhancement cavity is not yet in place. Therefore, accurate noise and power stability measurements are not presented. However, we implemented a simple proportional loop that allowed us to lock the laser to a fixed position relative to the cavity resonance, in order to measure some properties of the beam.

The frequency-doubled power was measured as a function of the drive current through the pump laser and the results are presented in Figure 2. The spikes in the measured blue power are a result of the pump laser wavelength cycling in and out of resonance with the modes of the enhancement cavity. A maximum of approximately 130 mW was measured at a drive current of 940 mA. Given the fact that the curved mirror has a transmission of only 83% for 488 nm, over 150 mW was generated in the PPKTP crystal.

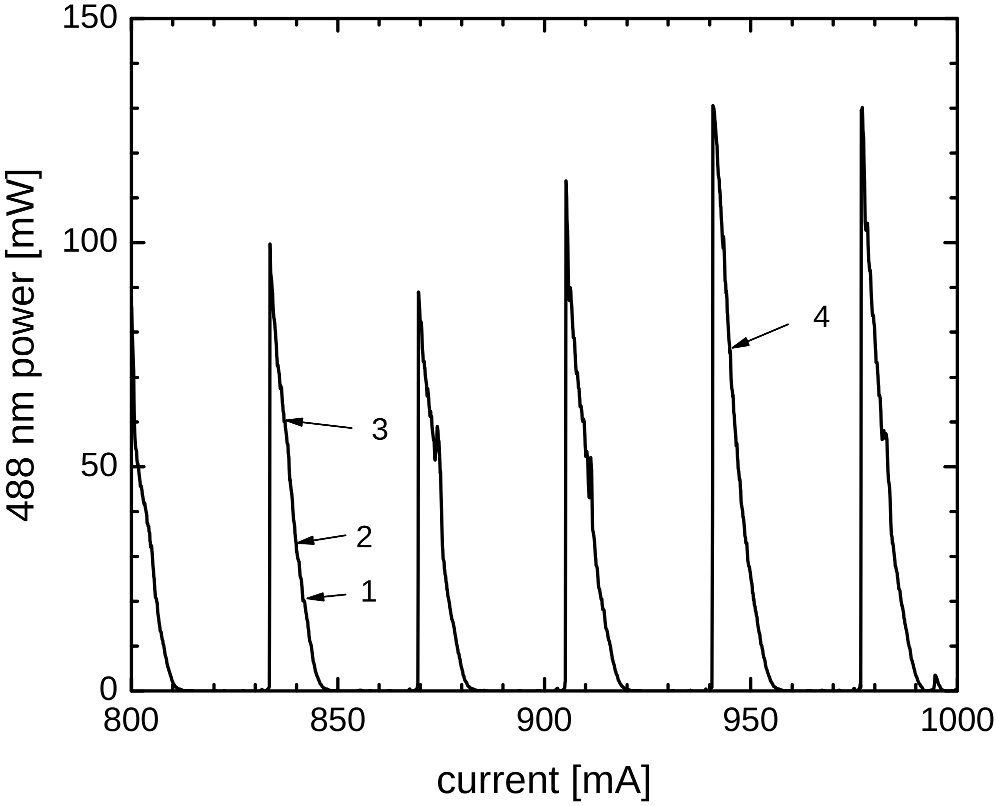

Figure 2. Measured 488 nm power generated from the enhancement cavity when the current of the 976 nm pump laser is scanned from high-to-low values. A different response is observed depending on whether the current is scanned from high-to-low values or from low-to-high values due to the thermal response of the PPKTP crystal in the cavity. The positions 1-4 correspond to beam quality measurements presented in Table 1.

4. TRANSVERSE OPTICAL BEAM QUALITY

The requirements on the optical beam quality for a 488 nm commercial product are strict. Typically, a beam with $M^2<1.2$ is required, the ellipticity should be less than 10%, and the astigmatism should be essentially zero. This is difficult to achieve from semiconductor laser systems that usually emit non-ideal optical beams with significant astigmatism, ellipticity, and poor M-squared. We shaped the 976-nm pump and observed a mode-matching efficiency of around 65% into the enhancement cavity. The transverse optical beam quality of the frequency-doubled 488 nm laser beam was measured by focusing the beam with a 50-mm lens and analyzing the spot sizes in the vicinity of the focus with a beam profiler (Thorlabs WM-1000). Fits to the measured results as plotted in figure 2 indicate a good beam quality with $M^2<1.15$. As can be seen in Table 1, M^2 increases from 1.05 at low power to 1.15 at the highest power.

Table 1 shows the dependence of the 488-nm beam quality as a function of output power at different cavity resonances and as a function of power on the slope of one resonance. The beam quality remains very good provided the pump laser is locked to the peak of a cavity resonance, and shows a slow degradation if the power is reduced by locking the pump laser on the side of a resonance. This is expected since the transverse filtering by the cavity is reduced if it is not fully on resonance.

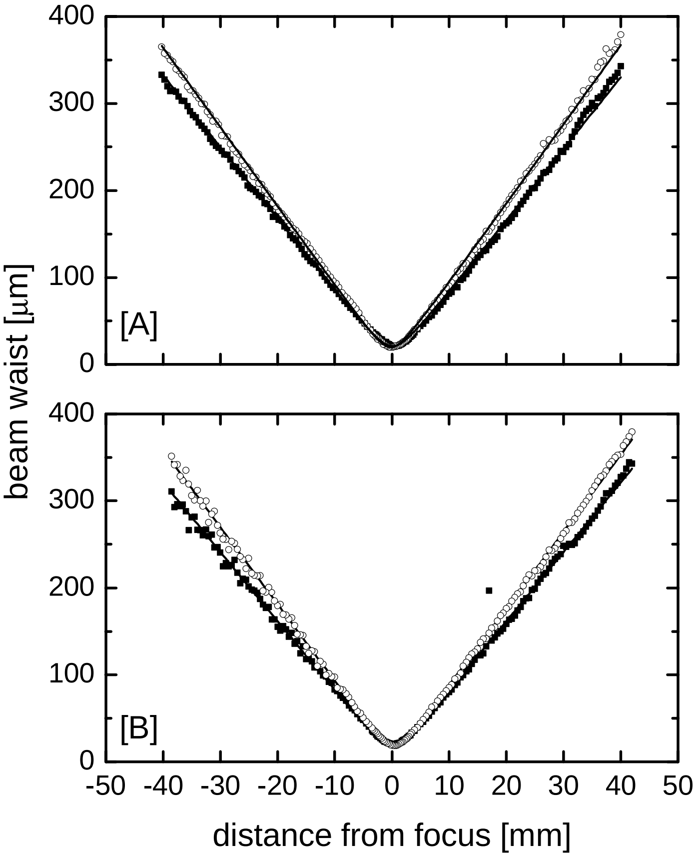

Figure 3. 488-nm optical beam quality measurements at high power (A) and low power (B). Open circles represent measurements in the vertical plane while solid squares are measured in the horizontal plane In (A) the 488 nm power was 71 mW at a pump laser current of 972 mA. The measurements indicate M^2_x=1.12 and M^2_y=1.15. The ellipticity $w0_x/w0_y$ = 0.93. In (B) the pump laser current was 454 mA and the measured blue power 19 mW. casein (B), the beam parameters are: M^2_x=1.03, M^2_y=1.06, ellipticity wo_x/wo_y=0.97.

Position on resonance	1	2	3	4	5
P_{488}	19 mW	32 mW	60 mW	71 mW	19 mW
I_{pump}	854 mA	854 mA	854 mA	972 mA	454 mA
M^2_x	1.14	1.08	1.12	1.12	1.03
M^2_y	1.13	1.09	1.08	1.15	1.06
w_x/w_y	0.88	0.89	0.87	0.93	0.97

Table 1. Beam quality measurements at different 488-nm power levels near the peak of the resonance and on the slope of the resonance. The combination of P_{488} and I_{pump} as indicated in the table can be used to identify the position on the slope of the resonance from Figure 2.

5. CONCLUSIONS

The feasibility of a high power semiconductor-pumped 488 nm laser was studied. The design is based on frequency doubling 976-nm radiation in a PPKTP crystal that was placed in an enhancement cavity of relatively low finesse. Encouraging results with a maximum of 130 mW power and good optical beam quality were obtained. The use of a low-finesse enhancement cavity forms a solid basis for relatively simple control loops. This material is based upon work supported by the National Science Foundation under Grant No. DMI-0320215.

REFERENCES:

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[1] E.H. Wahl, B.A. Richman, C.W. Rella, G.M.H. Knippels, and B.A. Paldus, "Optical performance comparison of argon-ion and solid-state cyan lasers", *Optics & Photonics News* **14**, 36-42, November 2003.