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# 1.9 W yellow, CW, high-brightness light from a high efficiency semiconductor laser-based system

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## ABSTRACT

Semiconductor lasers are ideal sources for efficient electrical-to-optical power conversion and for many applications where their small size and potential for low cost are required to meet market demands. Yellow lasers find use in a variety of bio-related applications, such as photocoagulation, imaging, flow cytometry, and cancer treatment. However, direct generation of yellow light from semiconductors with sufficient beam quality and power has so far eluded researchers. Meanwhile, tapered semiconductor lasers at near-infrared wavelengths have recently become able to provide near-diffraction-limited, single frequency operation with output powers up to 8 W near 1120 nm.

We present a 1.9 W single frequency laser system at 562 nm, based on single pass cascaded frequency doubling of such a tapered laser diode. The laser diode is a monolithic device consisting of two sections: a ridge waveguide with a distributed Bragg reflector, and a tapered amplifier. Using single-pass cascaded frequency doubling in two periodically poled lithium niobate crystals, 1.93 W of diffraction-limited light at 562 nm is generated from 5.8 W continuous-wave infrared light. When turned on from cold, the laser system reaches full power in just 60 seconds. An advantage of using a single pass configuration, rather than an external cavity configuration, is increased stability towards external perturbations. For example, stability to fluctuating case temperature over a 30 K temperature span has been demonstrated. The combination of high stability, compactness and watt-level power range means this technology is of great interest for a wide range of biological and biomedical applications.

**Keywords:** Nonlinear Optics, Second Harmonic Generation, Diffraction-Limited Light, Semiconductor Lasers, Tapered Diode Lasers, Yellow Lasers

## 1. INTRODUCTION

For applications such as flow cytometry<sup>1</sup>, photocoagulation<sup>2</sup>, imaging<sup>3,4</sup> and cancer treatment<sup>5</sup>, yellow lasers have started to attract a lot of attention in recent years. Indeed, higher signal-to-noise ratios can be achieved for some important fluorophores when excited with light at 562 nm compared to the more commonly available green lasers at 532 nm<sup>6</sup>. Significant effort has been going into developing high power lasers at wavelengths in the yellow and orange spectral region, but this remains technically challenging.

Yellow emitting lasers can be produced using a range of technologies. Diode-pumped solid-state (DPSS) lasers with nonlinear frequency conversion have produced >1 W at several wavelengths in the yellow-orange spectral range<sup>7-9</sup>. The relatively low optical conversion efficiency means that these systems usually cannot run without water cooling. DPSS lasers emitting directly in the visible spectral range are possible using different Pr<sup>3+</sup>-, Sm<sup>3+</sup>-, Dy<sup>3+</sup>-, and Tb<sup>3+</sup>-doped crystal host materials<sup>10</sup>. In Tb<sup>3+</sup>-doped fluorides, up to approximately 100mW has been demonstrated at around 585 nm<sup>11</sup>. Direct diode pumping has, however, resulted in significantly lower efficiency<sup>10</sup>. 20 W has been demonstrated using VECSEL OPS lasers [14]. However, these lasers suffer from the same drawbacks as DPSS lasers. Yellow light can also be produced with fiber lasers, but these tend to be either low power<sup>12</sup>, pulsed<sup>13,14</sup>, or very complex<sup>15</sup> systems.

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Laser diode-based systems offer relief from many of these drawbacks. They lend themselves well to integration into compact, cheap and highly efficient systems. However, laser diodes emitting directly in the yellow-orange spectral region are so far limited to powers on the scale of a few mW, demonstrated in BeZnCdSe and InAlGaP devices<sup>16,17</sup>. In the near infrared (NIR), on the other hand, tapered laser diodes now exist that combine single-frequency operation with output powers up to 8 W at 1120 nm<sup>18</sup>, with longer wavelengths under development<sup>19</sup>. Prior to this work, up to 550 mW at 561 nm has been generated by frequency doubling such a laser at 1122 nm<sup>20</sup>.

In this proceeding, we present the generation of 1.9 W single-frequency light at 562 nm by single-pass cascaded frequency doubling of the emission of a tapered laser diode of the type described in<sup>18</sup>. Cascaded frequency doubling involves the use of several subsequent nonlinear crystals and is highly efficient, with second harmonic (SH) output powers even exceeding the sum of the SH powers achievable from each crystal individually<sup>21,22</sup>. Furthermore, we show that the simplicity of our system leads to a high thermal stability, thereby removing the need for water cooling. With a small footprint of just 183 mm × 114 mm × 50 mm, this makes the laser system ideal for integration in larger systems.

## 2. CONFIGURATION AND CHARACTERIZATION

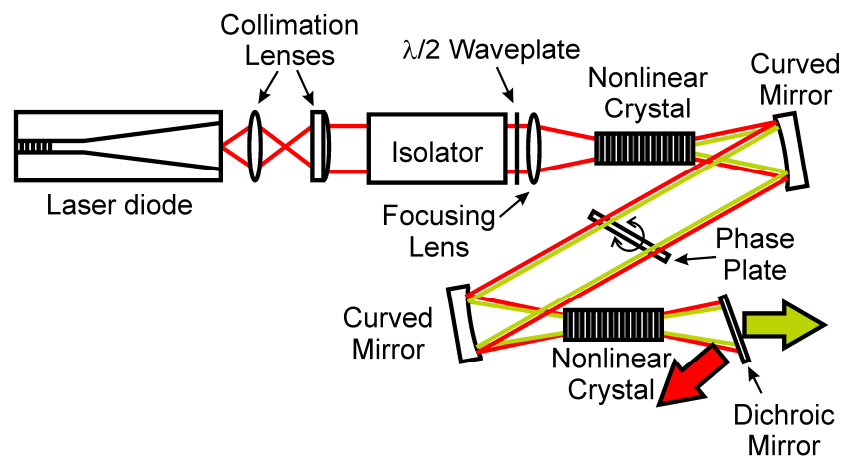


Figure 1. A sketch of the optical configuration frequency doubling light from 1125 nm to 562 nm. The infrared-emitting diode laser is collimated with a pair of anti-reflection coated lenses and sent through an optical isolator. A half-wave plate after the isolator rotates the polarization to vertical. A lens focuses the light into the first crystal. Two curved mirrors re-focus the beam at low angles of incidence into the second crystal, with a transparent phase plate placed between the curved mirrors for dispersion compensation. A dichroic mirror filters away the infrared light after the second crystal, allowing the SHG light to be measured with a power meter after the dichroic mirror.

The setup for obtaining efficient frequency doubling of the NIR light is sketched in figure 1. The laser diode is described in<sup>18</sup>. It is mounted p-side up and has two contacts for controlling injection current: One for the ridge waveguide section and one for the tapered amplifier section. A distributed Bragg reflector (DBR) section at the end of the ridge waveguide section ensures single frequency operation. The emission from the laser diode is collimated in the fast axis with an aspheric lens, refocusing the slow axis. The slow axis is then subsequently collimated using a cylindrical lens. To protect the laser from backreflections, the beam is then passed through an optical isolator (isolation > 30 dB, transmission ~95%). The polarization of the light is rotated to vertical using a half-wave plate and the beam is focused into the first nonlinear crystal using a plano-convex lens. A 40 mm long, periodically poled (period 8.17 μm) lithium niobate was chosen because of its high conversion efficiency. The crystal is doped with magnesium oxide to avoid photorefractive effects. To enhance the nonlinear efficiency, the so-called cascade concept is used, employing yet another nonlinear crystal of the same type, into which the light is refocused using a pair of curved mirrors. During assembly, a phase plate oriented near Brewster's angle was inserted between the curved mirrors and adjusted to ensure the proper phase relation in crystal 2 between the SH beam generated in crystal 1 and the residual fundamental beam. The two crystals were of the same type and dimensions and exhibited the same nonlinear conversion efficiency. After the second crystal, the residual NIR light is filtered away by use of a dichroic mirror and the yellow output beam is expanded and collimated to a

diameter of 2 mm. A photodiode monitors the power level of the output light. The components are mounted on a baseplate and enclosed with a lid, giving the laser system a total size of 183 mm × 114 mm × 50 mm.

The laser diode is operated at a current of 350 mA to its ridge waveguide section and a current of 10.5 A to its tapered section. With these currents the laser power after the isolator is 5.8 W, resulting in 1.93 W of second harmonic light after the second crystal. This is a conversion efficiency of 33% of the full NIR power or 45% of the NIR power in the central lobe of the beam profile, in which 74% of the NIR power resides. The total power consumption of the laser head, including heating of the crystals and cooling of the laser diode, is 30 W, yielding an electro-optical conversion efficiency of 6.4%. The spectrum of the second harmonic emission is shown in figure 2. The  $M^2$  of the 562 nm light is <1.4 in both axes, and the beam profile in focus is shown in figure 3.

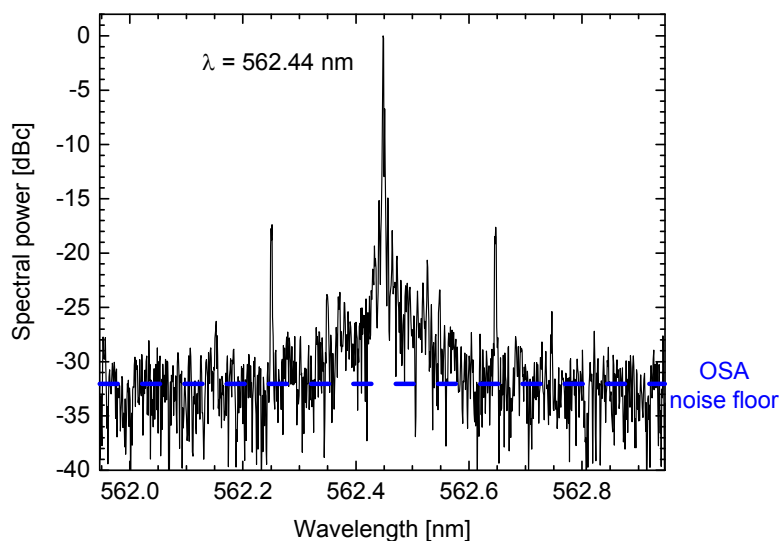


Figure 2. The spectrum of the laser output. The peak wavelength is 562.44 nm and the 3 dB width is less than 3 pm, limited by the resolution of the optical spectrum analyzer.

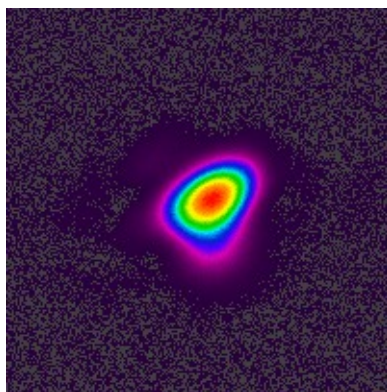


Figure 3. The beam profile of the emitted 562 nm light in a focus.  $M^2 < 1.4$  in both horizontal and vertical axes.

For various applications, a rapid turn-on time from room temperature can be very important. The system was designed to allow rapid (within 60 seconds) heating and stabilization of the nonlinear crystals and the laser diode. The power during a typical turn-on is shown in figure 4. In that measurement, the starting temperature for the laser diode and the nonlinear crystals was about 25°C, and the final temperatures were 20°C for the laser diode and 77.8°C and 79.4°C for crystals 1 and 2, respectively. Within one minute, the stability on all three temperatures was better than 0.02 K.

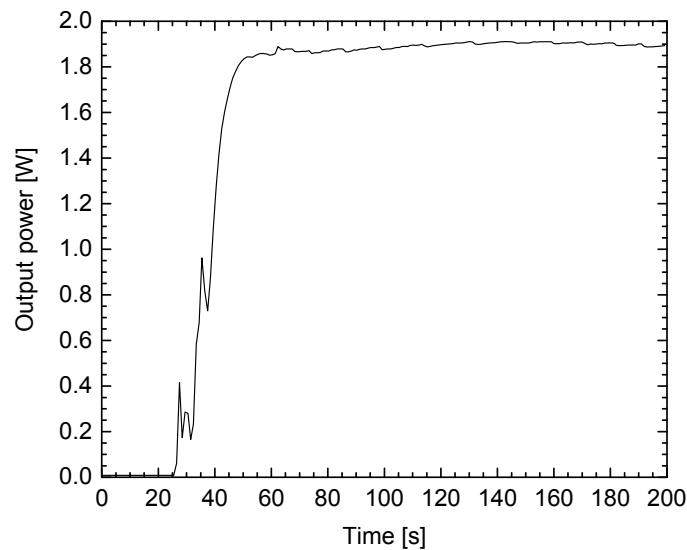


Figure 4. The power of the laser system stabilizes within one minute after turning it on from room temperature at time 0. During this time, the nonlinear crystals are heated to about 79°C with stability better than 0.02 K.

Stability towards changes in ambient temperature is also important, especially for applications where operation without water cooling is desired. To test this, the case temperature of the laser system was varied with the use of an adjustable temperature water chiller. The resulting power dependence is shown in figure 5, which shows that the system remains thermally robust despite a temperature change of 30 K. No active stabilization of the output power was performed.

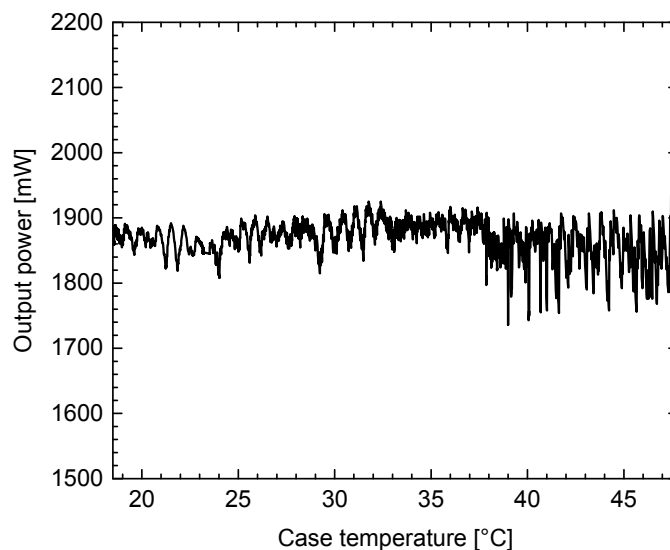


Figure 5. Without stabilization of the laser power, the temperature of the laser module case was varied from about 18°C to about 48°C. The laser power fluctuated within  $\pm 6\%$ , showing the thermal robustness of the system.

Next up in our series of tests was the long term stability. The laser was allowed to thermally stabilize and was set to maintain the output power at 1.5 W. The stability over 250 hours of operation was clearly evident and is shown in figure 6.

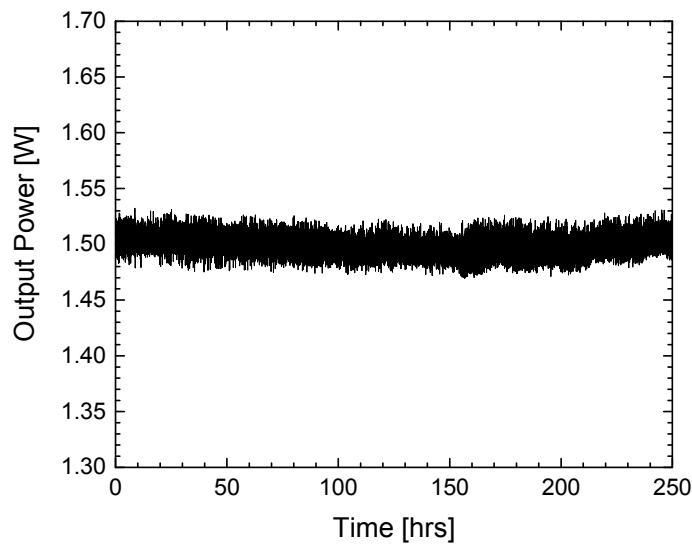


Figure 6. Long-term stability of the laser system over 250 hours of operation. The laser output power was stabilized to a set point of 1.5 W using feedback from the internal photodiode.

### 3. CONCLUSIONS AND OUTLOOK

The laser system described in this work generates up to 1.9 W of single-frequency, diffraction-limited laser light at 562 nm based on a laser diode. It has a high electro-optical efficiency of 6.4% and a high single-pass opto-optical nonlinear frequency conversion efficiency of 33%. The laser is stable when exposed to changes up to 30 K in its case temperature and when lasing for long time durations such as 250 hours or more.

Such a yellow-emitting source has applications within dermatology, ophthalmology, flow cytometry and other fields such as cancer treatment. Thus, the continued efforts to reach high powers and more wavelengths in the yellow spectral region are of great interest. Power scaling options such as beam combining of separate NIR beams and sum frequency generation<sup>23</sup> could enable powers well above 2 W.

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