

## **Miniature Solid-State Lasers for Pointing, Illumination, and Warning Devices**

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### **Abstract**

In this paper we review the current status of and progress towards higher power and more wavelength diverse diode-pumped solid-state miniature lasers. Snake Creek Lasers now offers unprecedented continuous wave (CW) output power from 9.0 mm and 5.6 mm TO type packages, including the smallest green laser in the world, the MicroGreen™ laser, and the highest density green laser in the world, the MiniGreen™ laser. In addition we offer an infrared laser, the MiniIR™, operating at 1064 nm, and have just introduced a blue Mini laser operating at 473 nm in a 9.0 mm package. Recently we demonstrated over 1 W of output power at 1064 nm from a 12 mm TO type package, and green output power from 300-500 mW from the same 12 mm package. In addition, the company is developing a number of other innovative new miniature CW solid-state lasers operating at 750 nm, 820 nm, 458 nm, and an eye-safe Q-switched laser operating at 1550 nm. We also review recently demonstrated combining volume Bragg grating (VBG) technology has been combined with automatic power control (APC) to produce high power MiniGreen™ lasers whose output is constant to  $\pm 10\%$  over a wide temperature range, without the use of a thermoelectric cooler (TEC). This technology is expected to find widespread application in military and commercial applications where wide temperature operation is particularly important. It has immediate applications in laser pointers, illuminators, and laser flashlights, and displays.

### **Introduction**

Miniature solid-state lasers that achieve a large power density (output power/cm<sup>3</sup>) have become very desirable from a number of vantage points. For most applications, real estate (i.e. the laser footprint in two dimensions) is expensive. These applications include military, homeland security, consumer, instrumentation, materials processing, space, and remote sensing. In addition, the recent proliferation of battery powered applications including laser flashlights, Dazzlers, and other electro-optic modules that utilize modern high density lithium battery technology, require miniature high density laser sources that minimize volume and power consumption. Compact high-density lasers maximize laser efficiency while minimizing package size; efficient lasers also minimize the volume and weight of the control unit used to provide electrical power and cooling functions to the laser head.

In this paper we first review the status of miniature diode-pumped solid-state lasers (DPSSL's) developed and currently offered by Snake Creek Lasers (SCL). This is followed by reviewing new miniature lasers that have been demonstrated and are nearing production. We then discuss a particularly important aspect of miniature DPSSL's; their temperature sensitivity and the recent development by SCL [2] of a revolutionary new technology, extended temperature range (ETR) operation, that allows high power MiniGreen™ and other solid-state lasers to operate over a wide temperature range and thus operate with near constant power output in desert or arctic ambient conditions. ETR eliminates the need for a TEC which significantly increases battery lifetime for portable and hand-held applications. Finally, we discuss applications of miniature DPSSL's with particular emphasis on usage in the military and for homeland security.

### **Review of Miniature Solid-State Laser Technology**

Most modern warfighting electro-optic modules utilize semiconductor diode laser sources emitting at visible, infrared, and eye-safe wavelengths around 635 nm, 700-900 nm, and 1500-1600 nm. Such diode laser sources are readily available and in many cases relatively inexpensive. Diode lasers also have relatively high electrical-optical conversion efficiencies, but suffer however from poor beam-quality and a gap in the visible electromagnetic spectrum near 532 nm. While the astigmatic output of diode lasers can be managed by appropriate optics that collimate the output beam over a short distance, typically less than 30 m, for applications with greater ranges the resulting beam profile and divergence characteristics are unacceptable. By contrast, DPSSL's produce circularly symmetric output beams in a single or low-order mode that have excellent far-field beam profiles that propagate in a predictable manner and can be collimated with off-the-shelf beam expander lenses. In addition, DPSSL's have output wavelengths in the green 532 nm region, near the peak response for the human eye and near the optimum wavelength for underwater propagation that cannot at present be addressed by diode lasers. Efforts to achieve green diode lasers are underway in a number of laboratories around the world, but the development time of such new semiconductor laser technologies is long. Other efforts at Corning and other institutions have concentrated on frequency doubling diode lasers, a technology that has been under development for over two decades. This approach has achieved some success, but most doubled diode architectures rely on the development of nonlinear crystals such as PPLN or PPKTP with high nonlinear coefficients, but which are very temperature sensitive and require a TEC for stabilization.

At SCL we have chosen to develop miniature DPSSL's that achieve high conversion efficiencies in small packages, and that use nonlinear optical crystals such as KTP that have very wide temperature acceptance bandwidths. As we will show in the following discussion, although DPSSL's are themselves temperature sensitive, by combining the attributes of VBG's with those of APC, one can produce extended temperature range DPSSL's that operate over the full range of commercial and most of the range of military temperature environments.

What are the desirable attributes of miniaturized military DPSSL's? In Table 1 below we list those features most often asked for by SCL customers. Of the eight attributes listed,

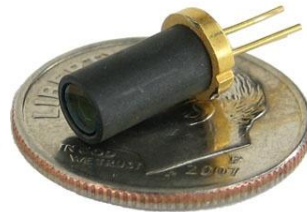
the last, operation over a wide temperature range, is the most important one, because modern electro-optic modules simply cannot afford the power drain of a TEC. In-field usage of battery powered laser-based modules for pointing, illumination, and other applications requires that the maximum operational lifetime be achieved, conserving power for only those features that make the module functional.

**Table 1: Miniature Solid-State Laser Attributes For Military Applications**

- **Maximize Output Power /Volume (Power Density) Ratio**
- **Robustness to Shock and Vibration**
- **Maximize Efficiency, Minimize Power Consumption: Long Operating Lifetime**
- **Maximum Device Lifetime**
- **Operate With Standard Batteries**
- **Beam-Quality Single-Mode or Low-Order Mode**
- **Monochromatic Output With No Other Wavelengths Present**
- **Operate Over Wide Temperature Range Without a Thermoelectric Cooler**

At SCL, we have developed and continually improve miniature DPSSL lasers that have found widespread use in military and commercial applications. The lasers we describe have been successfully integrated into dozens of applications worldwide, including military applications. In addition to outstanding performance, SCL lasers have been found to be rugged and reliable. These lasers are also finding widespread application in the display industry and the company is now capable of manufacturing them in large quantities. We now describe some of these outstanding products.

**Figure 1: MicroGreen™ 532 nm Lasers**



The MicroGreen™ laser shown in Figure 1 was the first device introduced by SCL almost three years ago, with a power output of 5 mW. Based on a 5.6 mm diameter TO diode package, this laser emits a near-perfect single-transverse-mode beam with an  $M^2 < 1.2$ , and is now available with power outputs of 5, 10, 15, and 30 mW. Significantly higher output powers have also been demonstrated, and will be introduced in the future. When combined with a beam expander or collimating lens, this laser produces a bright circular beam with excellent beam-propagation characteristics at a green wavelength, 532 nm. An output window eliminates the leakage of residual 1064 nm and 808 nm light.

This is presently the smallest green laser in the world, and at SCL we are continually striving to increase the power output and efficiency.

**Figure 2: MiniGreen™ 532 nm Lasers**



MiniGreen™ Lasers were also introduced three years ago, with a green 532 nm output power of 50-100 mW. A photograph of the device is shown in Figure 2. Since that time continual improvements have resulted in three models we presently offer, with powers of 100, 150, and 200 mW. This device is built around a 9.0 mm diameter TO diode package, and includes a window to eliminate the leakage of 1064 nm and 808 nm light, resulting in pure green power output. This laser produces more green output power per unit volume than any other green laser and is presently the highest density green laser in the world. The output beam-quality is typically single-mode with an  $M^2$  of  $< 1.2$  for 100 mW lasers, and transitions to a lower order mode with  $M^2 < 2.0$  at 200 mW. As with the MicroGreen™ laser, we have demonstrated output power significantly higher than 200 mW and diode to green output efficiencies near 40% that will be introduced in the future.

**Figure 3: MiniIR™ 1064 nm Lasers**



Recently, SCL introduced a 1064 nm infrared laser, the MiniIR™, shown in Figure 3, in response to requests for miniature lasers for higher power illumination applications and other specialized applications such as measuring the small-signal gain in laser amplifiers. The beam-quality was of importance, and this device produces 350 mW output power with an  $M^2$  of  $< 1.1$ . An output window eliminates the leakage of 808 nm light.

#### **MiniBlue 473nm Laser**

SCL has just introduced its first miniature blue laser, operating at 473 nm. With a near diffraction-limited output beam, and a power of 5 mW, these devices are expected to find

widespread application as pointers, in biological applications, and in laser flashlights. The laser is built in a standard diode 9.0 mm diameter TO package. We have already observed over 30 mW of output power from these devices in the laboratory and expect to offer higher power commercial versions in the near future.

### **New Miniature Solid-State Lasers**

SCL has recently developed a number of new miniature laser devices and continues to develop others. Our concentration has been on increasing the available output power at 1064 nm and 532 nm, as well as developing blue lasers at 473 nm and 458 nm. Our most aggressive program in the past year has been in finding a solution to the problem of stabilizing the output power of DPSSL's with temperature, and we have succeeded in this effort.

**Figure 4: Infrared MiniPlusIR 1064 nm Laser**

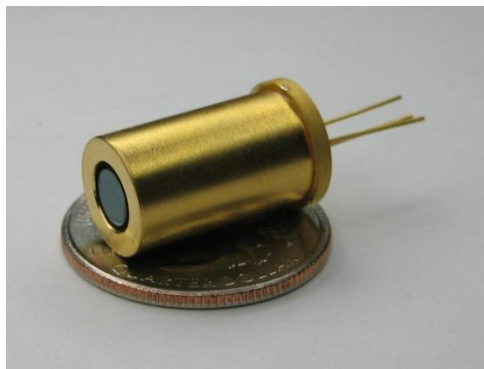
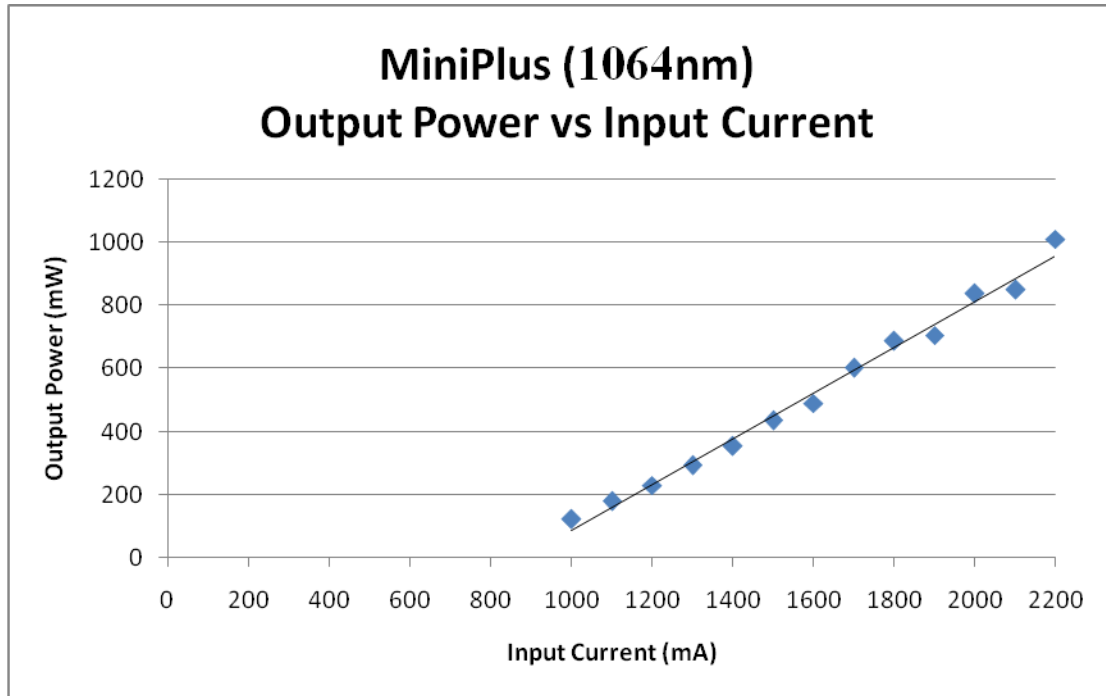


Figure 4 shows a new device, the MiniPlusIR Laser, which is built into a custom 12 mm TO diode package. This package features all copper construction for good thermal conductivity, and can handle diode powers of greater than 5 W. Using a 2 W 808 nm diode, the data shown in Figure 5 was obtained. The laser produces over 1 W of 1064 nm output power using a Nd:YVO<sub>4</sub> crystal, and a near diffraction-limited single-mode beam. By using higher power diode lasers we expect to increase the output power of MiniIRPlus lasers to greater than 2 W in the near future.

Using the same package shown in Figure 4, we have recently embarked on a project to demonstrate high power watt level green (532 nm) output, having already reached a significant fraction of that goal.

**Figure 5: New MiniPlusIR Laser**

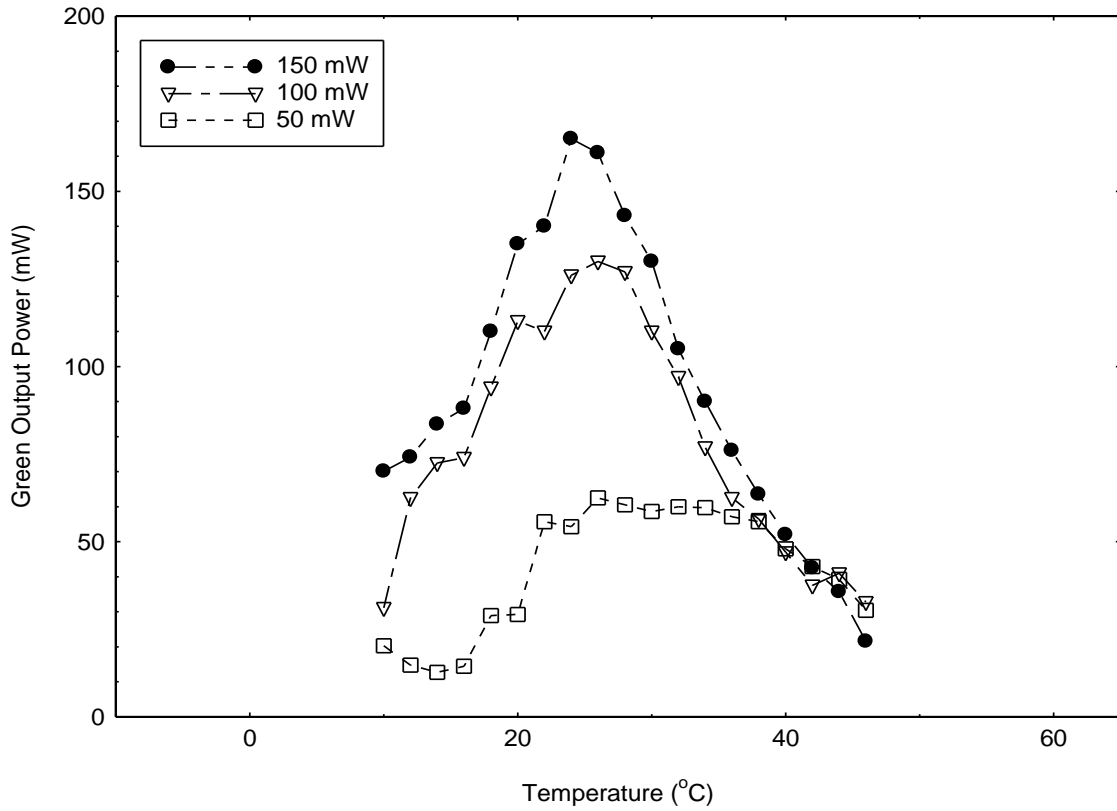


### **MiniGreen ETR Lasers**

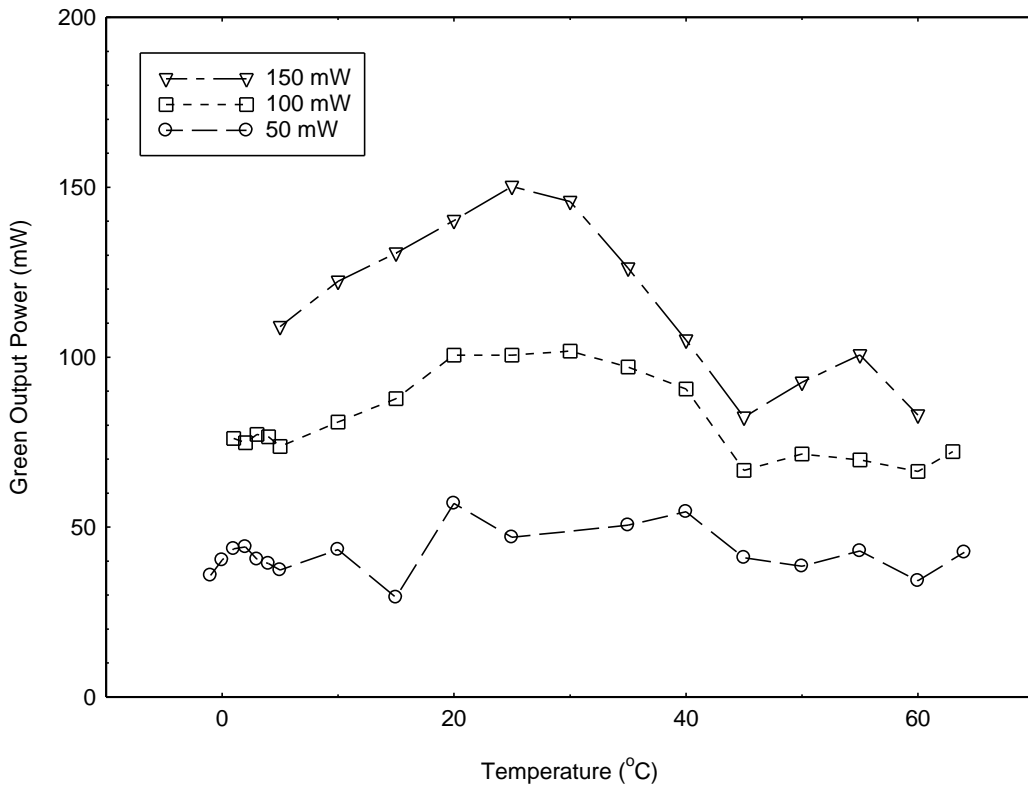
#### **Temperature Independent Solid-State Lasers**

The performance (output power, mode quality, power stability) of DPSSL's are inherently sensitive to changes in ambient temperature conditions, most importantly due to strong temperature dependence of the output wavelength of the pump diode laser, about 0.3 nm per degree C slewing towards the red. Other sensitivity factors include the change in diode laser efficiency with temperature decreasing as temperature increases, and phase-mismatching of the doubling crystal used to produce green light as temperature varies. Figure 6 illustrates the strong temperature dependence for the output power of MiniGreen™ DPSSL's for 50, 100, and 150 mW output lasers that have been aligned near room temperature, about 22 °C. While a 50 mW laser may demonstrate relative stability over about an 18 °C temperature range, the range narrows as power is increased, primarily due to the larger heat load associated with the pump diode laser. Therefore, DPSSL's are normally actively temperature-controlled either by TEC's or by inclusion into an oven. Both techniques require relatively high power consumption and are therefore unacceptable in any portable or battery-powered application.

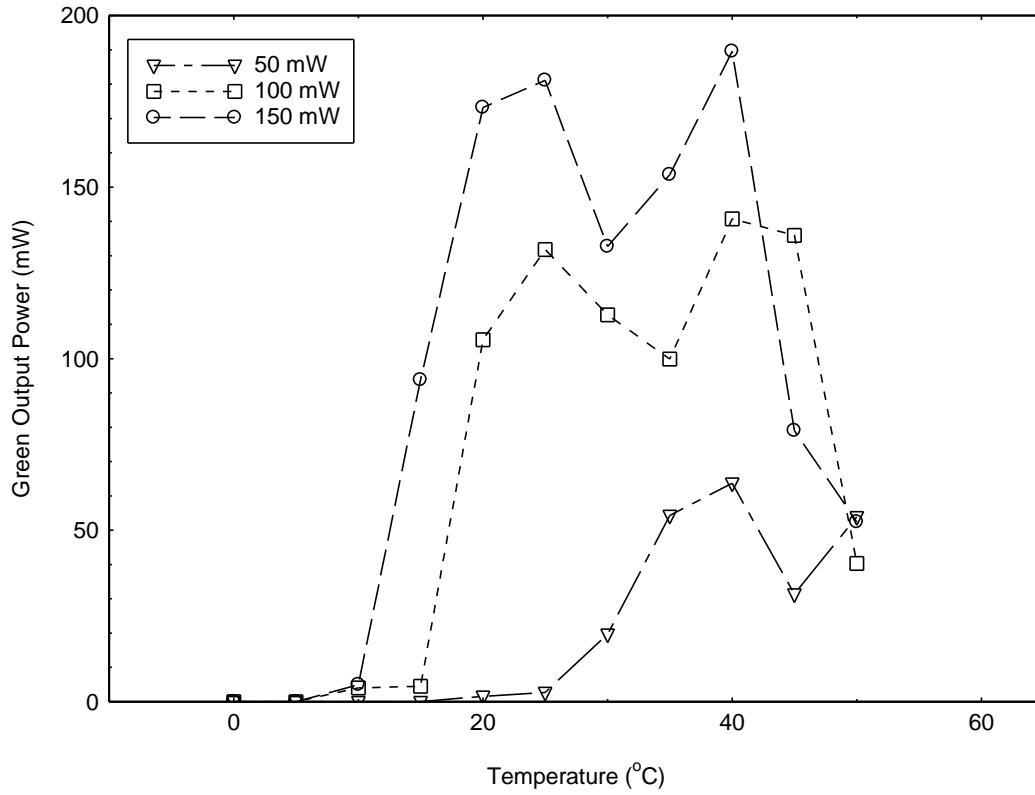
**Figure 6: Green Laser Output Variation With Temperature**



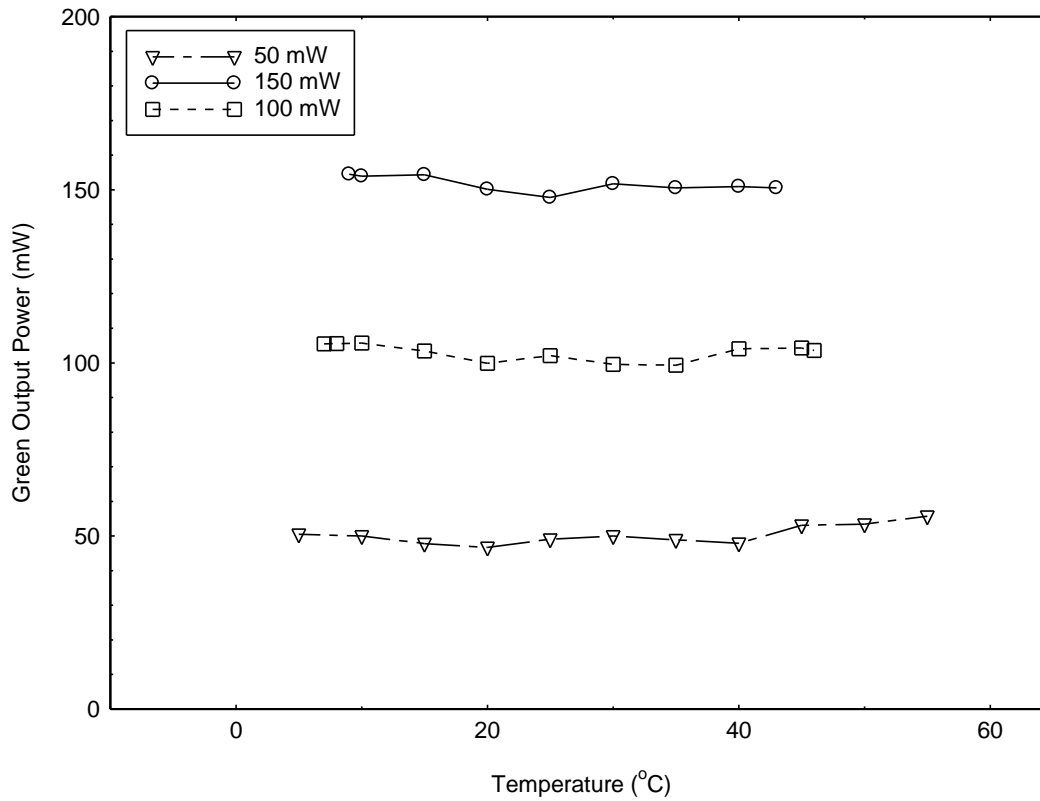
**Figure 7: Green Laser Output With APC Only**



**Figure 8: Green Laser Output With VBG Only**



**Figure 9: Stabilized Output With VBG + APC**



By using APC, where a portion of the laser output is fed back using a photodiode to a control circuit that adjusts the diode drive current to maintain constant output power, the somewhat better results shown in Figure 7 are obtained. In our experience, a 50 mW green laser can then be stabilized over a wider range, typically 20-30 °C, if a  $\pm 10\%$  power stability is desired. With higher powers of 100 mW and 150 mW, the temperature range again narrows. At higher temperatures, as the diode output wavelength slews through the narrow Nd:YVO<sub>4</sub> absorption band, the current to the diode increases monotonically until a safe pre-set current limit is reached. Beyond the temperature corresponding to this point, the laser loses control.

Recently, we have used VBG technology to injection lock the pump diode laser and stabilize the output wavelength. The temperature range over which this occurs is determined by the VBG characteristics, as well as the heat load of the diode laser. In general, higher heat loads corresponding to higher green output power lead to narrower temperature locking ranges. In Figure 8 we again show 50, 100, and 150 mW green lasers that were aligned near room temperature. The resulting output curves again have a narrow temperature range because while the diode wavelength has been locked, the diode efficiency and the harmonic crystal doubling efficiency vary with temperature. The ideal situation is obtained when both APC and VBG technology are combined, as shown in Figure 9 for 50, 100, and 150 mW green lasers aligned near room temperature. In this situation, the VBG locks the diode wavelength over a wide temperature range, insuring that the pumping efficiency is near constant, and the APC removes the remaining variations due to the diode efficiency and the variation in the doubling efficiency with temperature. Based on this new technology [2], SCL has introduced green DPSSL's with  $\pm 10\%$  power stability over a 50 °C temperature range without a TEC. The elimination of the TEC opens up green DPSSL's for demanding military and industrial applications.

### **Miniature Laser Applications**

SCL's continuing development of miniature DPSSL devices that are increasingly powerful, robust, and have a very small form factor, has led to the advancement of a number of important laser applications. Table 2 shows a list of applications for these devices, which run the gamut from military to law enforcement, forensics, displays, and many others.

**Table 2: Miniature Laser Applications**

- Laser Illumination: Visible, Infrared
- Low and High Power Laser Pointers
- Laser Signaling and Emergency Devices
- Replace Tactical Lights
- Laser Flashlights and Laser Dazzlers
- Multi-Colored Laser Flashlights and Dazzlers
- Laser Rangefinding
- Replace Low Beam-Quality Diode Lasers For Long Distance Operation

An example of such an application is the eye-safe laser flashlight shown in Figure 10 below. The device incorporates an SCL MicroGreen™ laser, an SCL power supply, and a proprietary beam expansion and zoom system [2]. The device is powered with a standard DL-123 lithium battery.

**Figure 10: Eye-Safe Green Laser Flashlight**



**References:**

- [1] [www.snakecreeklasers.com](http://www.snakecreeklasers.com)
- [2] U. S. and International Patents Pending