Introducing the Verdi G10
Technology proven in the most noise sensitive applications

High power, low noise (0.02%) and output power agility make this 10 Watt laser the ideal pump source for Ti:Sapphire oscillators and high repetition rate amplifiers.

Introduction and Overview

Multi-watt green (532 nm) lasers are key building blocks in scientific laser systems, particularly as Continuous Wave (CW) pump sources for ultrafast systems based on Ti:Sapphire technology. Current economic conditions are making research funds harder to find than ever, so it’s vital that these lasers provide a high performance/cost ratio as well as superior reliability and lifetime. Based on optically pumped semiconductor laser (OPSL) technology, the new 10 Watt Verdi G from Coherent meets all these requirements while providing unprecedented flexibility, including variable output power with no effect on beam quality or beam pointing. Just as important, the Verdi G10 exhibits much lower noise (< 0.02%) than competitive multi-mode diode-pumped solid-state (DPSS) lasers and consequently has proved to be an ideal source for even the most noise sensitive applications, most notably those requiring CEP-stabilization of the ultrafast output.

OPSL Basics

The Verdi G10 is the newest and most powerful of Coherent extensive OPSL-based products, which currently service applications from biotech and OEM instrumentation, to medical therapeutics and high power light shows. OPSL technology has established itself as the most reliable technology ever commercialized by Coherent and has a proven track record with over 25,000 units in the field. Verdi G lasers are multi-watt OPSLs designed specifically for the low noise and high performance requirements of scientific applications.

Figure 1 schematically illustrates the main components of an OPSL laser. The monolithic III-V semiconductor chip contains quantum wells layers alternated between absorption layers while one of the end mirrors of the cavity is actually a large area within the gain chip that is pumped by one or more laser diodes.

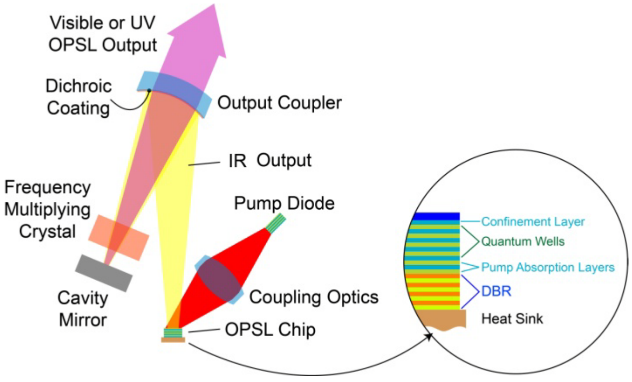


Figure 1. Verdi G series lasers utilize optically pumped semiconductor technology to produce near infrared laser light that is converted to visible output by intracavity frequency doubling.

The absorption layers are optimized to efficiently absorb pump radiation, resulting in a high population of charge carriers. This leads to population inversion and recombination in the quantum wells, which emit near infrared laser light. Behind these absorption/emission layers are several alternating high index and low index layers that act as a low-loss DBR (Distributed Bragg Reflector) mirror optimized for the chosen OPSL fundamental wavelength.

The output wavelength is determined by the thickness and stoichiometry of the quantum well structure and can be optimized to produce output anywhere from 900 nm to 1200 nm. Intracavity frequency doubling efficiently converts this near-IR fundamental to a wavelength in the visible and beyond, providing a choice of potential output wavelengths between 450 nm and 600 nm. In Verdi G lasers, the lasing wavelength is finely tuned and then narrowed to a handful of longitudinal modes centered on 532 nm by means of an intracavity birefringent filter (BRF).

Relaxed Pumping Geometry – Simpler and More Reliable Laser

Compared to DPSS lasers, OPSLs, such as the Verdi G10, have substantially relaxed pumping requirements in terms of geometry and pump wavelength control. This simplifies the OPSL design and construction, thus lowering its capital costs and providing a straightforward path to higher output power. As a result, the compact Verdi G10 is the first CW green OPSL with sufficient power to pump ultrafast Ti:Sapphire oscillators as well as high-repetition rate regenerative ultrafast amplifiers, such as the Coherent RegA.

How is all this achieved? Because of the design and geometry of the OPSL cavity, output power can be raised by increasing the power of the pump diode, increasing the area of the OPSL gain chip, and for future higher power, even increasing the number of pump diodes. Moreover, none of these necessitate complex or sensitive alignment because the OPSL chip is so thin (< 10 microns), thus matching the pump light to the laser's mode volume collapses to a two dimensional problem (a mode area rather than a volume), so all that is required is to reimage the circular conditioned output of the pump diode(s) onto the chip's surface. This simplifies the assembly process of the Verdi G10 and reduces manufacturing costs while delivering consistent performance.

In contrast, a DPSS laser's pump beam, focus, collimation and its pointing all have to be carefully matched to the mode volume throughout the entire length of the laser crystal rod.

In the early days of OPSL technology, Coherent engineers recognized that thermal loading of the gain chip could be a practical hurdle to power scaling of Verdi G lasers. But this has been completely addressed in two ways. First, Verdi G lasers utilize an expanded mode volume and a novel folded cavity design. Since it is the power density that determines the temperature increase, an obvious solution is to spread the power over a wider area of the chip. But, simply increasing the mode volume without increasing cavity focal length would push the laser into an unstable operating regime comprising of multiple transverse modes. On the other hand, dramatically increasing the cavity focal length would make the laser unnecessarily large and reduce opto-mechanical stability. Instead, Verdi G lasers use a compact cavity incorporating optics that act as a magnifying telescope and uncouple mode diameter and cavity length. This arrangement enables power scaling because it simultaneously supports a large beam diameter in the OPSL chip but with a narrow, well-behaved waist near the SHG crystal.

The thin gain chip also eliminates thermal lensing enabling extreme output power flexibility with no beam quality penalties. This is explored in detail later in this article.

No Need to Control Pump Wavelength

In the case of a DPSS laser, the laser diode output wavelength has to be carefully matched to the narrow Nd absorption line which has a full width half maximum (FWHM) value of 4 nm. This necessitates selecting diodes and then actively and precisely controlling their operating temperature and hence output wavelength.

This is an issue because current diode laser fabrication technology always yields some diode array variation in output wavelength. Thus, bars intended for pumping DPSS lasers must be measured and selected for output wavelength. A vertically integrated manufacturer like Coherent can utilize some of the Nd-rejected bars in non-wavelength sensitive applications.

Wavelength matching also adds an additional level of complexity and cost to the DPSS laser itself. That's because the output wavelength of any laser diode depends on its operating temperature. In the case of a bar at 808 nm, the output wavelength shifts by about 0.3 nm per °C. Over the life of the diode, the operating current will increase and will also affect the pump wavelength by about 0.15 nm per amp.

In contrast, the broad absorption spectrum of the OPSL eliminates the need for tight control of pump diode wavelength and the costs associated with wavelength selection and yields. The pump diodes only need to be designed to provide an output wavelength shorter than the value corresponding to the band-gap. Plus there is also no need to tightly control the operating temperature of the diode array in the OPSL, thus eliminating the cost and complexity of closed-loop temperature servos. Instead it is sufficient merely to rely on the active baseplate cooling used in solid-state lasers to regulate overall laser head temperature. This simpler design lowers costs and inherently increases laser reliability.

The high absorption efficiency of the semiconductor gain chip also means that only a single diode array – in the form of a fiber array package (FAP) – is required in the Verdi G10, whereas first generation DPSS lasers pumped at 808 nm required at least two diode arrays to reach even 8 Watts. And since the FAP is the only potential consumable in either a DPSS or OPSL, the long term operating costs are greatly reduced by this factor alone. Plus the typical mean time to failure (MTTF) of the Coherent FAPs used in our Verdi lasers is now over 50,000 hours, due in large part to our use of our unique AAA technology, making for very low cost of ownership.

Ultra-Low Output Noise – No “Green Noise”

OPSLs such as Verdi G are not the first solid-state lasers to produce CW visible output through the use of intracavity frequency doubling. However, many of the earlier DPSS lasers suffer from output noise due to a phenomenon called “green noise,” or the “green problem.”

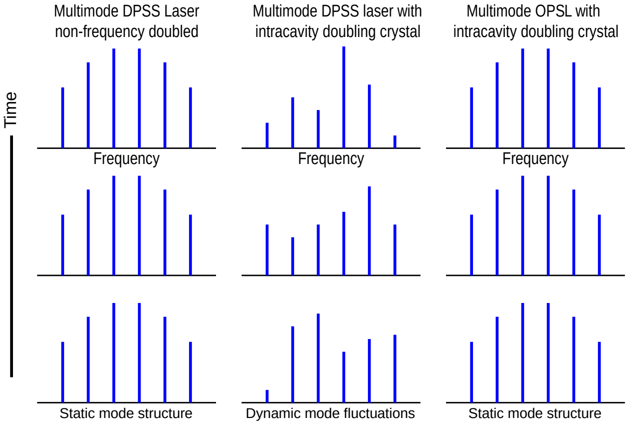


Figure 2. With DPSS lasers operating on multiple longitudinal modes, intracavity doubling causes chaotic mode behavior. This does not occur in OPSLs because of the short upper state lifetime.

With cavity lengths measured in centimeters or even tens of centimeters, CW near-IR lasers can support many longitudinal modes. Usually in such lasers, the intra-cavity beam intensity is divided between multiple longitudinal modes, each with a slightly different frequency (see Figure 2). When a doubling crystal is inserted into a fundamental intra-cavity beam with multiple longitudinal modes, it creates chaotic behavior of these modes resulting in intensity noise in both the fundamental and doubled output.

The reason for this noise is that when a doubling crystal is inserted inside the cavity, both second-harmonic generation (doubling the frequency of one longitudinal mode) and sum-frequency generation (adding the frequencies of two different longitudinal modes) are possible. Sum-frequency generation directly couples different longitudinal modes and thereby enables dynamic interactions between longitudinal modes which compete chaotically for the same finite available gain. Because the upper state lifetime of the gain medium (the laser crystal) is many orders of magnitude longer than the cavity round trip time, these effects build up over several cavity roundtrips. The final result is a chaotic situation, where different modes alternate between high and low power. This long-recognized instability phenomenon is called the “green problem,” [ref 1] since the first commercial CW lasers using intra-cavity doubling were green 532 nm DPSS laser. This can be eliminated in high performance scientific multiwatt DPSS lasers (e.g., the Coherent Verdi V series) by forcing the laser to operate on a single stable cavity mode (See Figure 3).

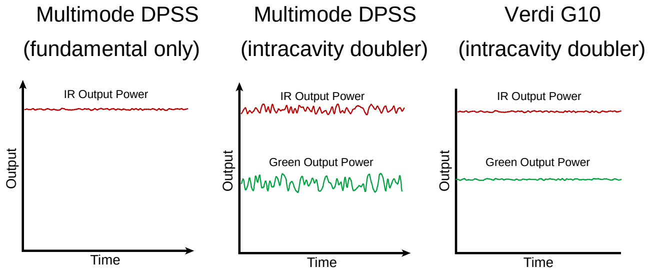


Figure 3. Intracavity doubling causes chaotic green noise in DPSS lasers operating on multiple longitudinal modes. It cannot cause this chaos in OPSLs like Verdi G because of these lasers’ very short upper state lifetime.

However, Verdi G lasers, like all other OPSLs, are inherently free of green noise, because this noise source is a fundamental consequence of the upper state lifetime of the gain material. Specifically, in a DPSS the upper state lifetime is in the microsecond regime. But with OPSL technology, the gain medium is a semiconductor material where radiative and non-radiative recombination of charge carriers are both very fast processes. As a result, the effective upper state lifetime is a few nanoseconds or less (i.e. on the timescale of the cavity round trip time). Thus, on the laser mode timescale there is no stored gain, only instantaneous gain. The behavior of the individual cavity modes therefore is determined solely by the cavity where the gain just follows along.

If the cavity is properly aligned and stable, as in the case of Verdi G lasers, then even if the OPSL is operating on multiple longitudinal modes, there is no green noise whatsoever from the frequency doubling process (see Figure 3). As a result, Verdi G lasers offer excellent noise characteristics in an economical format: <0.02 % rms noise over the range 10 Hz to 100 MHz. This makes these lasers an optimum choice for even the most noise-sensitive applications.

Low Noise for CEP

Pumping ultrafast laser systems is the single largest application for scientific-grade CW green lasers like the Verdi G 10. The most demanding ultrafast configuration is carrier envelope phase (CEP) stabilization – stabilizing and manipulating in the frequency domain the often-forgotten underlying CW mode structure whose interference produces the mode-locked pulse. This involves preventing drifts and jitter in the carrier envelope offset frequency (see Figure 4).

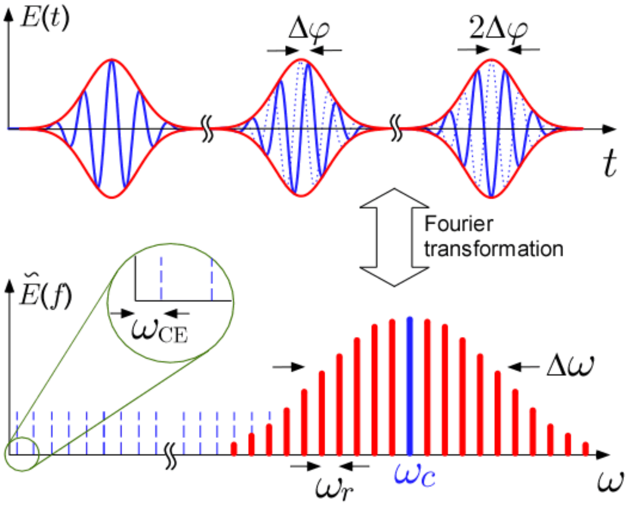


Figure 4.Typical laser cavity

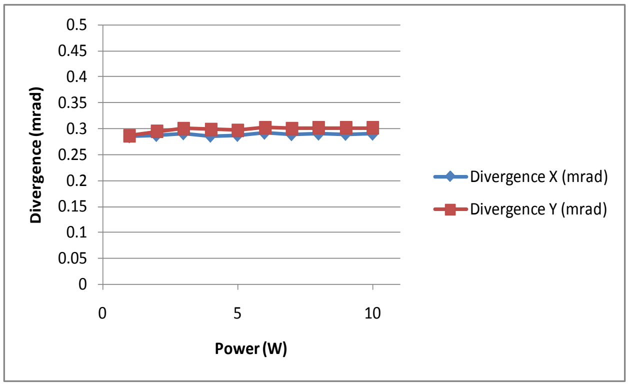
As shown schematically in Figure 4, in a typical laser cavity, there are many modes grouped around the center frequency ω_c, with a mode spacing determined by the inverse of the round trip time ω_r. Ideally, these modes would be completely stable in the frequency domain. In real lasers, even minute opto-mechanical instabilities cause the absolute frequency of each mode to jitter and drift in time. This is addressed by locking the output to deliver a zero phase offset or a fixed phase offset. As far back as 2004, independent research [2] showed that successful CEP locking critically requires pumping the ultrafast oscillator with a green laser with ultra-low output noise. In particular they found that multimode DPSS lasers were not optimum for this task because of their high noise. They found that a successful solution was to use a single-mode DPSS laser, specifically a Coherent Verdi V series laser.

Now several independent groups have validated that the similarly low (0.02%) noise available from Verdi G lasers is also ideal for pumping CEP-stabilized systems. And where other green lasers specify their noise over a limited frequency range, the Verdi G10 noise specification covers the entire 10 Hz to 100 MHz range.

No Thermal Lensing – Completely Adjustable Power

The typical high performance DPSS laser is based on a rod-shaped laser crystal. End pumping sets up a radial thermal gradient along the length of the crystal, creating a strong positive thermal lens which adds focusing power to the resonator. So to achieve TEM_{00} output, the curvature of one or more of the cavity mirrors is designed to compensate for this. Adjusting the pump power changes the intensity of the thermal gradient and hence the power of the thermal lens. This will change the output beam diameter and divergence. (In Coherent’s AVIA™ family of industrial lasers for example, a feedback feature called ThermaTrak™ addresses this problem by moving a motorized intracavity lens as the power is smoothly adjusted.) Moreover, in some low-performance DPSS lasers the thermal lens can cause some high order beam distortions.

Since the Verdi G10 is an OPSL, the gain medium is a very thin (< 10 microns) semiconductor chip mounted on a rear surface block that is actively cooled. Although a radial thermal gradient still results from laser operation, the entire structure is so thin that thermal lensing is negligible. This was tested beyond normal operation by measuring the wavefront of a reference laser beam reflected off the OPSL chip (i.e. with there the chip acts as passive mirror). Even when pump power was focused to a small spot diameter on the OPSL chip, thus creating thermal and refractive index gradients, the total wavefront distortion was just barely observable at about λ/40. This immunity from thermal lensing is the reason that the power of the Verdi G 10 can be smoothly adjusted from hundreds of milliwatts up to 10 watts, with no measurable degradation in beam divergence or beam diameter (Figure 5). This output power flexibility greatly increases the versatility, utility and value of the Verdi G 10, particularly where it is used as a shared resource.



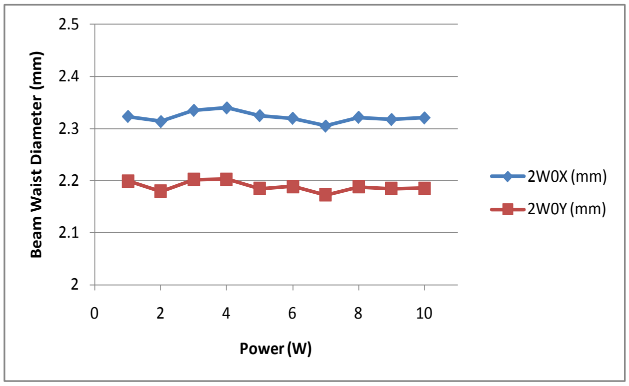


Figure 5. Beam Waist Diameter and Divergence

Conclusion

The green CW laser has been a keystone of scientific lasers applications dating back to the argon ion laser and its common use pumping tunable and then ultrafast dye lasers. DPSS lasers displaced the ion laser as the *de facto* pump standard because they offered clear advantages in terms of superior performance, reliability and costs. OPSLs, such as the Verdi G, have successfully emerged as next generation alternatives to DPSS because of their higher performance to cost ratio. Now they have reached the watershed 10 Watt power level and matched the best available DPSS noise performance, making OPSLs ready to dominate key applications which demand both power and performance.

References

1. T. Baer, *Large amplitude fluctuations due to longitudinal mode coupling in diode-pumped intracavity-doubled Nd:YAG lasers*, J. Opt. Soc. Am. B, vol 3, **9,** pp 1175-1180 (1986).

2. S. Witte, R.T. Zinkstok, W. Hogervorst, and K.S.E. Eikema, *Control and Precise Measurement of Carrier Envelope Phase Dynamics,* Appl. Phys B 78, 5-12 (2004).

3. Contact Coherent for a list of ultrafast laser users and equipment suppliers who have independently tested and validated the Verdi G Series for use as a pump source in CEP-stabilized setup.