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White Paper

Advances in Laser Diode and OPSL Technologies Render Ion and Metal Vapor Lasers Obsolete

There are now many applications for visible and UV continuous wave lasers in the tens to hundreds of milliwatts power range, covering e.g. life sciences, metrology and inspection. Originally these were dominated by ion and HeCd metal vapor lasers due to their early availability. However, these sources are characterized by numerous well-known practical deficiencies (e.g., large size, electrical inefficiency, limited reliability and lifetime, high cost of ownership) which made them quite vulnerable to next generation technology. As a result, solid-state lasers (laser diode modules and crystal based lasers e.g. of Nd:YAG type) captured a significant market share upon their introduction. Still, these solid-state lasers were not a panacea, having several drawbacks of their own. This enabled ion and HeCd lasers to persist in the marketplace for far longer than many industry experts predicted. But, now the development of high performance laser diode modules and next-generation optically pumped semiconductor lasers (OPSLs) has completely overcome the drawbacks of earlier solid-state lasers. Specifically, these new lasers offer advantages over virtually every aspect of legacy ion/metal vapor technologies, including performance, size, power consumption and heat dissipation, reliability and lifetime, and cost of ownership. This whitepaper compares these technologies and shows why the end of these venerable gas lasers is finally at hand.

The Pros and Cons of Gas Lasers

Ion (argon, krypton) and HeCd lasers generally produce a high quality beam, with TEM_{00} output and a M^2 approaching the best value of 1.0. For applications which are not cost sensitive, they can also be configured with long coherence lengths, thus enabling interferometry based uses. Moreover, ion lasers can deliver output at wavelengths from the near UV (e.g. 334 nm) to 799 nm in the near-IR (see Table 1). Furthermore, for many years, they were simply the only industrially suited sources of CW blue, green, yellow and red light capable of producing tens of milliwatts or more. As a result, a host of applications in life sciences have been tailored to use 488 nm and/or 514 nm, which are strong blue and green output wavelengths of the argon ion laser. And HeCd lasers for many years were used in CW UV light applications such as stereolithography.

Conversely, these lasers have many cons which are well-documented. They have a large size to power

Table 1. *Most commonly applied wavelengths (in nm) of ion, HeCd, diode lasers and OPSLs.*

	UV	Violet	Blue	Green	Yellow	Orange	Red	IR
Argon	351 364		457 477 488	514				
HeNe				543[a]	594[b]	612[c]	633[d]	
HeCd	322 354	442						
Laser Diode	375	405 445	488				635 640 660 685	730 785
OPSL	355		458 460 480 488	514 532	552 561 568 577		639	1064

[a] green, [b] yellow, [c] orange, [d] red HeNe version

ratio, especially in terms of the dimensions of the laser head. Their electrical to optical conversion efficiencies are less than 0.1%. This means a high performance power supply is required as well as active dissipation of the heat which is the end product of over 99% of the input electrical power. In addition, ion lasers typically require frequent optical tweaking, unless equipped with expensive automated cavity alignment systems, and HeCd lasers are even less stable! Plus their single most expensive component, the plasma tube, has a finite lifetime, which together with their electricity consumption accounts for the high cost of ownership of these lasers. As a result, gas lasers represent a mature technology with technical/physical limitations and high cost of ownership.

The first viable alternatives to gas lasers were sources based on Nd doped laser crystals initially pumped with lamps and later with diodes, making them completely solid-state. These diode pumped solid-state (DPSS) lasers produce a strong output line at 1064 nm which can be intracavity doubled to give green output at 532 nm. Frequency tripling delivers UV output at 355 nm. In addition, these lasers also produce a couple of weaker output wavelengths, which can be frequency doubled to 473 nm and 561 nm.

DPSS lasers offer many advantages over ion and HeCd lasers. They are much smaller and an order of magnitude more efficient. They have no short-lived, high-cost consumable, unlike the plasma tube in gas lasers. Plus these lasers offer solid-state reliability and longevity. However, they cannot produce the range of wavelengths of gas lasers and most importantly, cannot generate the 488 nm wavelength that has become ubiquitous in the life sciences marketplace. So applications that can use their 532 nm output have migrated to Nd-based lasers but those needing other wavelengths have stayed with ion lasers in spite of their practical inferiority.

Laser Diodes

Laser diodes are the most common laser type in use today, found in far more consumer products (e.g., DVD players) than all other laser types combined. And higher power units act as pumps in many other laser types, including DPSS lasers and OPSLs. Moreover, when it comes to electrical efficiency and compact packaging, laser diodes are unmatched by any other laser type.

For a long time, though, their potential in CW visible applications remained untapped. In part, this was because of their undesirable beam properties; the raw output beam is highly divergent, elliptical and astigmatic. Plus their spectral characteristics (mode spectrum, wavelength) are very temperature sensitive. In addition, for many years GaAs based laser diodes only offered output in the near-IR output. However, over the past decade, the development of new material systems has resulted in laser diodes with output throughout the visible spectrum. This has led companies such as Coherent to develop high-performance packaged modules with long lifetimes based on these visible laser diodes.

The Coherent OBIS family (see Figure 1) uses laser diode and OPSL technologies. Independent of technology, wavelength and power class, every model offers identical form, fit and function; mechanical, optical and electrical. OBIS lasers are fully packaged devices in which all potential limitations of laser diodes have been addressed. In OBIS, the raw diode laser light source with its inherent limitations (risk of damage by electrostatic discharge, temperature and current/voltage effects), beam parameter and wavelength deficiencies is completely transformed into a viable, rugged, functional laser with high beam quality and wavelength accuracy. These systems are equipped with integrated beam shaping and full temperature stabilization. An integrated controller also provides high-speed (up to 150 MHz) output modulation and a USB user-interface. Moreover, OBIS lasers are available at numerous wavelengths spanning the range from 375 nm to 785 nm. And depending on the application, different beam shapes (e.g. elliptical, circular, line, cross hair, top hat) can be provided.

Key features of OBIS lasers
- Compact solid-state package
- Integrated control electronics
- Superior beam quality
- Minimal rms noise
- CW and pulsed up to 150 MHz
- Analog and digital modulation
- USB, RS485 and Analog interface
- OEM and end user versions

Figure 1. *OBIS: offering plug-and-play simplicity allowing for faster integration thereby reducing the cost of integration and time to market.*

Optically Pumped Semiconductor Lasers (OPSLs)

The OPSL is a diode-pumped laser, but unlike other diode-pumped lasers, the laser medium is a thin semiconductor disk rather than a crystal (see Figure 2). The upper layers of this large area chip are designed to efficiently absorb near-IR pump light (from laser diodes) and to emit laser light at a wavelength determined by the size and stoichiometry of the quantum wells contained in these layers.

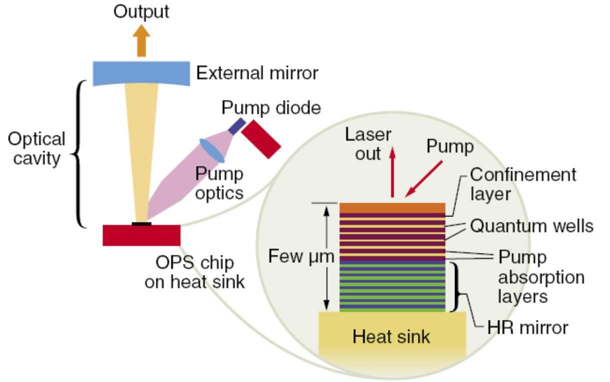

Figure 2: *Schematic of an OPSL.*

In contrast to the more common edge emitting diode laser, the resonator output mirror is not the exit face of the chip but an external mirror. This external cavity structure allows for laser beam shaping, including mode control and insertion of optical components, e.g. for frequency doubling. With this approach, an OPSL can generate a high-quality, diffraction-limited, single-transverse mode (TEM_{00}) visible wavelength beam at high output powers. For example, the large pump area and thin gain chip drastically reduces the demands on the pump geometry, one of the attributes allowing the power of OPSL technology to be scaled from the milliwatt to multi-watt range. Efficient rear-surface cooling of the chip also means that there is no thermal lensing in the gain medium. So the power of a given laser can be smoothly adjusted from 10% to100% of nominal power with no impact on beam quality or pointing, unlike crystal based lasers where thermal lensing is a major performance-limiting design consideration. Due to the short upper state lifetime of the gain medium, “green noise”, an effect occurring in standard frequency doubled crystal lasers such as Nd:YAG causing mode and hence power fluctuations, cannot occur. This is one of the major reasons for the excellent noise characteristics of OPSLs.

The key features of OPSL

- Power scaling
- Wavelength flexibility
- Highly efficient nonlinear harmonic generation
- Excellent beam and mode quality
- High power stability & low noise
- No “green problem”
- No thermal lensing
- Fiber coupling with high efficiency
- High reliability & lifetime due to semiconductor design
- Modulation capability: directly up to 100 kHz

In addition to power scaling and power adjustment, OPSL technology enables wavelength scaling. By changing the composition and size of the quantum wells in the gain chip, OPSL output can be designed to be anywhere from 700 nm to 1200 nm. Efficient intracavity frequency doubling adds the wavelength range 350 nm to 600 nm (see Figure 3).

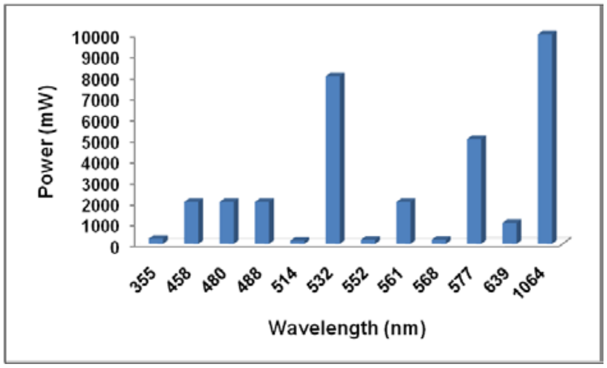

Figure 3. *Wavelengths and maximum output powers of currently available OPSLs.*

To summarize, OPSL technology provides power scalability, wavelength flexibility and excellent laser parameters (beam quality, power stability, noise).

Coherent pioneered the commercial use of OPSL technology starting in 2001 with 20 mW power 488 nm lasers under the brand name Sapphire™ (see Figure 4). The Sapphire brand quickly expanded to include other wavelengths and higher powers. In 2007, Coherent launched a new OPSL product line, the Genesis™ family, covering the range from medium to high (multiwatt) powers. Then in 2009, a multiwatt, single-longitudinal mode OPSL (up to 7 Watts at 532 nm) was released by Coherent under the brand name Verdi™ G-series. At Photonics West 2011, Coherent introduced the OBIS family (see Figure 1) in which both laser diode and OPSL technologies are applied. Right from the beginning, the OPSL technology has been quickly and widely adopted by OEMs and end users alike, so that there are now over 25,000 OPSLs in the field, with over 2000 at the multi-watt level.

Figure. 4: *Sapphire LP: Coherent's series of OPSLs*

Comparison: Laser Diodes, OPSLs, Ion and HeCd Lasers

Table 2 highlights the main points of comparison between the four different laser types – laser diode, OPSL, ion and HeCd. It highlights that, in just about every category that impacts performance and/or cost, laser diodes and OPSLs are superior to ion and metal vapor lasers.

For instance, in terms of size, semiconductor lasers of the diode and OPSL type are typically ten to 150 times smaller than legacy gas lasers, depending on their wavelength and power class. This means that these modern lasers occupy less valuable lab space, and enable the construction of smaller, lighter instruments. Plus a smaller laser can often be located much closer to the interaction zone in an instrument, eliminating the cost and space of complex beam delivery optics.

The efficiency of laser diodes and OPSLs are drastically higher than that of gas lasers: typically 10 up to 40 times better. This lowers power consumption, reducing operating costs and making these lasers much more environmentally friendly than older technologies. Depending on their power level, gas lasers often require a special three-phase electrical power source, whereas solid-state lasers operate at normal line voltage and current levels even at output powers in the multiwatt range. Higher efficiency also means less unwanted heat – heat that has to be actively dissipated, putting further demands and power costs into a system. And of course, this lower thermal demand simplifies integration into systems, particularly closed instruments where the laser is internally buried.

Table 2: *Schematic comparison of key features of Argon/ Krypton, HeCd, diode lasers and OPSLs*

	Argon/ Krypton	HeCd	Laser Diode	OPSL
Laser size	- -	- -	++	+
Power consumption/efficiency/ heat load	- -	- -	++	+
Power scalability	- size/ costs	-	- needs bars/ stacks	++
Power stability	0	-	+	++
Noise	0	-	0	++
Beam quality	++	-	0	++
Multi-wavelength capability	++	-	-	-
Wavelength range	0	-	+	++
Wavelength precision	++	++	-	+
Mode spectrum/ stability	0	-	-	++
Background discharge light	-	-	++	++
Warm-up time	0	-	++	++
Lifetime of laser	-	-	++	++
Economy/Cost-of-Ownership	-	-	++	+(+)

OPSLs even exceed gas lasers in what was traditionally their strongest feature, namely high beam quality. Plus, these modern solid-state lasers are highly stable, eliminating the need for manual or automatic tweaking of cavity optics. Power stability and noise characteristics are also superior for both laser diodes and OPSLs. Plus neither solid-state laser type emits residual non-coherent light, which has been a severe handicap in many "low-signal" applications for gas lasers. In addition to optical noise, air-cooled gas lasers also suffer from disturbing fan vibrations and air flow/turbulences, required by their high cooling demand. These consequences/after-effects of the high (air-) cooling demand simply do not exist with laser diodes and OPSLs.

The huge thermal load for gas lasers leads to another secondary issue, namely long warm-up times. Specifically, ion lasers typically need about 15 minutes to come to stable thermal equilibrium, i.e., to reach specified performance and stability. With HeCd lasers, the warm up time is even longer – 20 minutes or more. The instant warm up of laser diodes and OPSLs is a considerable practical advantage, especially for systems which are started every day or several times a day. In addition to the time and cost of this nonoperational warm up period, there is also the cost of ownership impact – the gas and metal vapor lasers are consuming electricity and valuable tube lifetime during warm up, even though they cannot be used during that time.

In normal and high-usage (e.g. 24/7) applications, the single biggest cost issue with gas lasers however is usually the finite lifetime of the plasma tube. Depending on laser type, power class and operating conditions, the lifetime of this component ranges from 3,000 to 10,000 hrs. The maintenance-free lifetime of the solid-state lasers discussed here are typically in the 20,000 hrs range.

Lower power consumption and no expensive consumables add up to much lower operating costs for solid-state lasers as can be seen in Table 3. In addition, the capital costs of violet and UV semiconductor solutions are considerably lower than those of corresponding ion and HeCd lasers, which further increases the overall cost gap. And, while visible low-power air-cooled ion lasers come with comparable or slightly lower capital costs than their semiconductor counterparts, this initial economy is quickly overridden by the higher operating costs.

In a few applications, a key advantage of argon and krypton ion lasers has been their multi-wavelength capability. But due to the small size, integration and installation advantages, and economy (power consumption, warm-up times, maintenance, lifetime), a multi-wavelength laser diode/OPSL package is now a technologically superior and economically competitive alternative.

What will the future bring? Coherent's OBIS family, introduced in 2011 at Photonics West, provides laser diode and OPSL technology in the same Form-Fit-Function package. This is opening a new chapter of user-friendliness. Independent of technology, wavelength and power class, every model offers identical mechanical, optical, electrical, interfacing design with an unprecedented plug-and-play simplicity. The wavelength scalability of laser diode and OPSL technology will be further exploited to add legacy and customized wavelengths to the current wavelength range of 355 nm to 1064 nm. In addition, expansion into the IR and UV will be accomplished by applying different wafer materials and wafer types. For OPSLs, UV wavelengths can also be generated very elegantly by nonlinear optical processes (e.g., frequency-doubling). The exploitation of the power scalability will lead to higher powers.

And finally, it is important to underline the true impact of the wavelength flexibility of laser diodes and OPSLs. In the past, applications parameters had to be tailored to best fit one or more of the limited wavelengths available from gas lasers. But with today's semiconductor lasers – both the laser diode and OPSL type – there has been a paradigm shift; finally lasers can be tailored to the application instead of vice versa.

Summary

All-solid-state technology, in the form of laser diodes and OPSLs, now offers an overwhelming list of technical, integration and economical advantages over ion and metal-vapor lasers. These advantages are reflected in sales figures, which show thousands of laser diodes and OPSLs are now sold every year into applications that were formerly dominated by gas lasers in life sciences (e.g. cytometry, microscopy, sequencing, medical diagnosis and therapy), semiconductor inspection and testing, graphic arts, homeland security, forensics, environmental monitoring, metrology and scientific research.

Table. 3: *Operating costs for various laser types for an operation time of 10,000 hours.*

	OPSL 488 nm	Argon Ion 488 nm	Laser Diode 445 nm	HeCd 442 nm	OPSL 355 nm	Argon Ion UV
Power class (mW)	50	50	50	50	100	100
Electricity costs (0.19C/kWh)	100	1,900	29	1,100	1,000	26,600
Water cooling (5EUR/1000l)	0	0	0	0	0	25,500
Total operating costs (EUR)	**100**	**1,900**	**29**	**1,100**	**1,000**	**52,100**