Chameleon Vision-S – The Next Generation of One-Box Ti:Sapphire Lasers

The latest one-box ultrafast lasers offer superior performance (shorter pulses, higher average power, broader tuning range, and wider pulsewidth flexibility) for applications such as MPE microscopy, THz generation, and spectroscopy.

Overview

Following their introduction in 2002, widely tunable (i.e. > 200 nm) one-box ultrafast lasers such as the Chameleon family broadened the scope for femtosecond pulses by combining state-of-the-art performance with hands-free use and easy operation. Successive generations of these lasers offered improved performance by delivering increasingly higher power, wider wavelength ranges, automated and more flexible GVD precompensation, or shorter pulsewidths. Coherent combined all these advances in a single product – the Chameleon Vision-S, the first one-box ultrafast laser. This whitepaper provides a detailed review of the performance and ease-of-use of this unique laser source. In addition, this paper also discusses several application areas and examines how the Chameleon Vision-S' advanced features translate into application-based benefits.

Figure 1. *Chameleon Vision-S.*

One-Box Chameleon Ultrafast Oscillators

Throughout the 1990's (the first decade of commercial Ti:S lasers), time-resolved spectroscopy experiments and then-recently developed Multiphoton Excitation (MPE) Microscopy were carried out using open-architecture femtosecond lasers requiring some level of user intervention. An example of these open-architecture systems is the Coherent Mira 900. These lasers provided numerous options, accessories and very flexible (femtosecond/picosecond) performance. From the mid-90's, the progressive replacement of Ion pump lasers with CW DPSS green lasers improved reliability, noise, stability, space and energy/environmental footprint. Even after the introduction of DPSS green lasers, pump and Ti:S lasers remained two separate boxes requiring periodic re-alignment and optimization. The flexibility of these lasers satisfied the need of most existing users willing to adjust the laser for optimum performance and those who weren't too concerned about changing its configuration according to the experiment. But these lasers did not take into consideration the less experienced and growing category of users in life sciences or industrial applications. Within a few years, the first one-box ultrafast lasers were developed. These lasers operated either at a fixed wavelength or were tunable over a relatively narrow range (~100 nm), not sufficiently broad enough to enable key applications in microscopy or spectroscopy.

In response to the concerns of the industry, Coherent developed the Chameleon family of turnkey and broadly tunable ultrafast lasers, specifically designed to address MPE microscopy applications. These clean-room built systems, in which the solid-state pump and the Ti:S lasers were integrated in a compact and fully sealed laser head, were fully controlled by a single computer interface or push-button menu. With no need to physically align, clean, or manually adjust the laser optics, even a laser novice could confidently use these black-box systems. Moreover, their small footprint enabled simple integration with the scanning microscopes designed to support MPE imaging.

The advent of these ultrafast lasers providing an unprecedented ease of use and reliability, truly enabled the growth of MPE microscopy and other applications, resulting in the shipment of over 1,000 Chameleon lasers within the first 8 years of its introduction. The success of MPE microscopy relied on enhanced application-specific performances such as broader tuning ranges (particularly longer wavelengths) and higher powers in order to support deep tissue imaging. The development of faster wavelength tuning reduced the time required to excite different dyes in the same sample. Other models were optimized to produce shorter pulses, and therefore higher peak power in order to maximize the non linear excitation of some samples. Finally, novel integrated accessories were developed to compensate for varying amounts of group velocity dispersion (GVD) in the microscope optics. These accessories enabled the delivery of the shortest possible pulse widths at the sample, not just out of the laser. Finally in 2010, all these state-of-the-art performance benefits were integrated in a single, one-box laser, the Chameleon Vision-S, which thus became the first product to deliver superior performance in all key parameters, including push-button simplicity and hands-free reliability.

Vision S: Higher Average Power, up to 2.3 Watts

In many applications, having extra power is a valuable benefit. Ti:S lasers for MPE microscopy typically produce 2 to 3 Watts of average power around the center of the tuning range. While this power may appear much higher than what a biological sample will tolerate, it turns out that transmission losses in the microscope system (as high as 90%) and scattering/absorption losses in tissues especially for deep imaging, make it desirable to have as much power as possible at the laser output. In addition, towards the extreme ends of this range (<720 nm and > 1,000 nm) the available power may be marginal for adequate excitation of many important markers like the short-wavelength dyes used for uncaging experiments or the long-wavelength excitation red-fluorescent proteins. For this reason, increasing the output power of the laser over its entire tuning range benefits MPE, as well as many other applications

Ti:S has long been known to be the best gain material for ultrafast lasers since it supports very broad bandwidth operation and hence very short pulses and wide tuning. The output power of a Ti:S laser of course depends on the available pump power. As the available pump power scales up from 5 Watts to close to 20 Watts, the design challenges for the Ti:S laser engineers shift from minimizing intra-cavity losses to managing the increased thermal load in the active medium and other cavity elements. In parallel, expanding the available tuning range requires a more complex mirror coating design, using many tens of layers to provide adequate reflectivity. This often leads to higher optical absorption with consequent distortion of the spatial mode and output power rollover, unless coatings and substrates are carefully designed and optimized.

These design challenges were met when Coherent started integrating its unique 18 Watt Verdi pump lasers in most Chameleon laser models. Delivering 20% more power than any other CW green pump laser, Verdi-18 represents the single most important reason why Chameleon lasers can deliver the highest commercially available output power from a tunable, 100 fs class oscillator - more than 3.5 Watts at 800 nm (Chameleon Ultra II). Among shorter pulsed and GVD-precompensated lasers, Chameleon Vision-S is unique in its capability to deliver over 2.3 Watts of power at the laser output port and directly available to the microscope system. This extra pump power translates into brighter and deeper images at the ends of the laser tuning range, with both multi-beam systems and with high-loss microscopes.

Finally, the use of an 18 Watt pump laser provides Chameleon lasers with substantial design headroom. This means that the higher output power of the Chameleon lasers is achieved with a conservative use of diode and green pump power, resulting in intrinsically higher reliability and longer lifetimes.

Vision S: Shorter (73 fs) Pulsewidth – Higher Peak Power

In most non-linear optics experiments, the signal strength has a quadratic or even higher order dependence on the peak power of the excitation pulses. This means that increases in the available peak power achieved by decreasing the pulse duration at constant average power can improve the signal level.

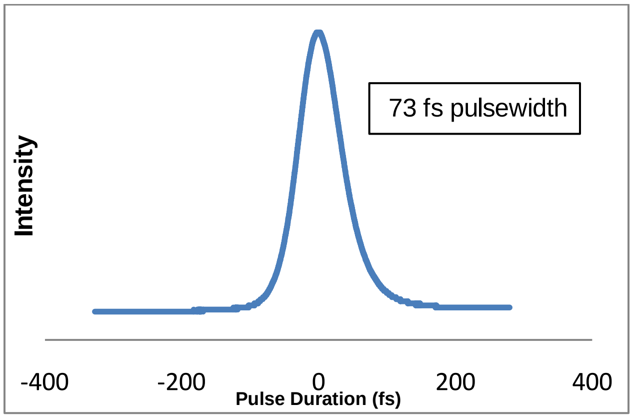

Figure 2, *Autocorrelator trace showing 73 fs pulsewidth*

This is also the case with MPE and other non-linear microscopy modalities, although it should be noted that an excessive increase in peak power may also damage the biological sample. With its 2.6 Watts of typical average power and 75 fs pulses (see figure 2), Chameleon Vision-S offers higher peak power than any competitive product. Due to the Fourier transform relationship between laser pulsewidth and spectral bandwidth, shorter pulse generation require larger oscillating bandwidths. The laser cavity must be optimized to support this bandwidth and manage the GVD (Group Velocity Dispersion) of the intra-cavity laser pulses as they propagate inside the laser. GVD compensation is necessary because the various laser intra-cavity components are wavelength-dispersive. This means that longer wavelengths travel faster than shorter wavelengths within the cavity, resulting in a so-called chirped pulse with non transform-limited time duration: a red-shifted leading edge and a blue-shifted trailing edge. This propagation effect is not overly important with 150 fs to 200 fs pulses, but it becomes very noticeable with pulse durations of just 75 fs. If left unchecked, GVD will compromise or prevent stable mode-locked operation of the laser.

All Chameleon lasers use a simple and robust, prism-based approach for tuning and GVD compensation. With this scheme, the beam path length through two glass prisms and the free space is a function of the wavelength (because of linear dispersion) and can be manipulated to create a negative GVD, and will effectively cancel the positive GVD from the other transmissive and reflective optics. By moving the relative positions of the prisms, the laser's on-board processor is able to precisely adjust the amount of negative GVD as the laser's center wavelength is tuned, without affecting the output beam location or its pointing stability.

The overall wavelength-dependent management of the negative GVD of the prism-pair offsetting the positive GVD of the rest of the cavity is the key in providing short pulse duration throughout the tuning range of the laser.

Vision S: Integrated GVD Precompensation

Most Ti:S lasers producing 100 fs to 200 fs pulses are designed to provide transform-limited pulses at the laser output location. This is a desirable situation because the bandwidth of these pulses is relatively small (4 nm to 8 nm), thus easy to handle, and works well when the number of dispersive elements placed by the user between the laser output and the experiment is relatively small. This is not the case when a 75 fs laser is used in conjunction with some type of Multiphoton microscopes. In fact, microscopes including acousto-optic modulators (AOMs) and objective lenses composed of as many as 15 individual lenses, often exhibit a total GVD exceeding 15,000 fs^2. Such a GVD can easily stretch a 75 fs transform-limited pulse to become 500 fs long or more by the time it reaches the biological sample.

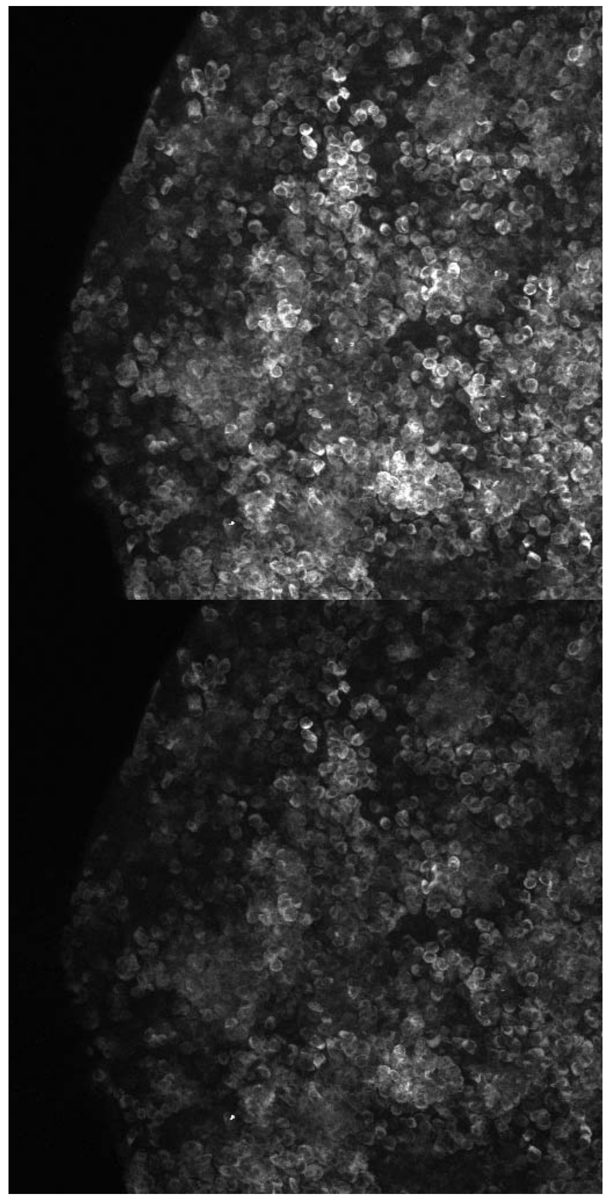

Figure 3, *Two images of a pituitary gland sample labeled with GfP show the effects of optimized GVD precompensation (left) versus no precompensation. Images recorded with a Zeiss LSM 7 MP microscope and a Coherent Chameleon Vision laser. Images courtesy of Jean-Michel Lago, Carl Zeiss sas.*

The solution to eliminate this pulse broadening is to impart a negative GVD to the pulse leaving the laser, to counter the positive GVD of the downstream optics. In the Chameleon Vision-S this function is integrated within the laser to optimize beam pointing stability, automation and system cleanliness. Also, for maximum flexibility, the GVD precompensator is designed with a wide dynamic range that can be smoothly adjusted from zero to a maximum value of 22,000 fs^2 at a wavelength of 800 nm and up to 43,000 fs^2 at 690 nm. As a result, the GVD precompensator in the Vision-S offers enough correction to compensate every commercial microscope incorporating an AOM and also specialized home-built microscopes with very high dispersion.

So far we've described the use of precompensation to minimize the pulse duration at the sample. In reality, minimizing the pulse may optimize the signal level but not necessarily optimize other experiment parameters, like sample viability or photobleaching. For this reason, the large GVD compensation range can be used to smoothly vary the pulse duration from fully compensated (75 fs) to fully dispersed value (hundreds of femtoseconds). To address precisely this point, Chameleon Vision-S has been designed to offer the broadest available range of on-sample pulse durations, making it a useful tool not only for optimizing image brightness but also for studies on photobleaching, dye and fluorescent protein development.

Vision S: Broader and Faster Wavelength Tuning

Another unique benefit provided by Chameleon Vision-S is its 360 nm tuning range, extending its tuning range from 690 nm to 1,050 nm – see figure 4.

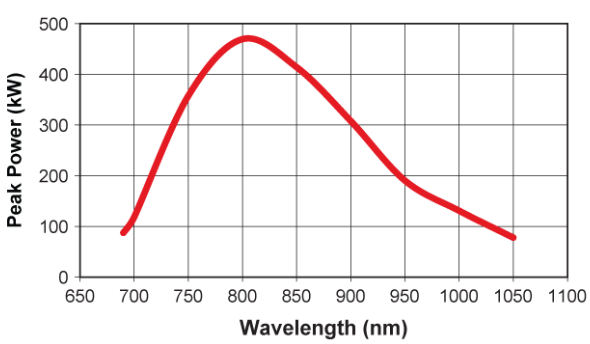

Figure 4, *tuning curve of Chameleon Vision-S*

This is the largest tuning range provided by a sub -100 fs, GVD pre-compensated tunable laser. The advantages of a broad tuning range in MPE and SHG microscopy are becoming increasingly compelling as red fluorescent proteins become more popular and longer wavelengths are more widely recognized as leading to lower photodamage and deeper imaging.

This broad tuning range is enabled by the high available pump power and by the use of extremely low loss intra-cavity mirrors. While most MPE users will not take advantage of the full power available at 800 nm, as they move to the ends of the tuning range, they will approach a region where the optical gain of Ti:S is much lower than at 800 nm. This means that the laser output will be much more sensitive to optical losses like scattering and absorption of mirrors and other surfaces. Chameleon Vision-S mitigates this limitation of Ti:S in two ways. First, by taking advantage of the higher pump power from the integrated Verdi-18 pump laser. And second, by using extremely low loss and large bandwidth mirrors that have been developed to specifically support a large oscillating bandwidth with broad tunability. In addition, the simple Chameleon Vision-S cavity, with only two intra-cavity prisms moving during the tuning, enables scanning of the entire tuning range of 360 nm in less than 15 seconds, faster than any other Ti:S laser.

Benefits for Different Applications

The main applications for the Chameleon Vision-S are MPE and other non-linear in-vivo imaging techniques, THz generation, and pump and probe experiments.

Chameleon Vision-S has been developed as an ideal tool for MPE imaging because it offers access to longer wavelengths, high average power and widely adjustable on-sample pulsewidth. There is agreement in the research community that long excitation wavelengths enable deeper imaging in most live specimens. In contrast, the trade-offs of average power and pulsewidth (i.e. peak power) are still the subject of debate, and widely dependent on fluorophores, sample preparation and sample specificity. While the use of non-linear optics dictate that decreasing the pulse duration at constant average power leads to an increase in image brightness in many specimens, the same result can be identically achieved by increasing the average power. These increases in power lead to the question of what is the limiting damage mechanism: thermal (average power) or non-linear (peak power). The answer depends on the sample type and preparation, and on the type of non-linear imaging employed: MPE, SHG, THG or CARS. In standard two-photon excitation, the fluorescence signal depends on the square of the excitation power, while some damage mechanisms are the result of three-photon absorption, possibly through an intermediate metastable step.

Signal intensity $\alpha\ (P_{peak})^2 \times$ pulsewidth $= P_{ave} \times P_{peak}$

whereas

Damage probability α (Ppeak)$^3 \times$ pulsewidth $= P_{ave} \times (P_{peak})^2$

In THz generation, an ultrafast laser pulse is focused on a voltage biased semiconductor antenna. This causes rapid cycling of the potential across the antenna causing it to emit radiation with waveforms on the order of 100 fs, i.e. in the THz regime. Figure 5 schematically illustrates the basics of this THz generation setup, including the high NA (hemispherical) lens used to collimate the THz output into a useful beam.

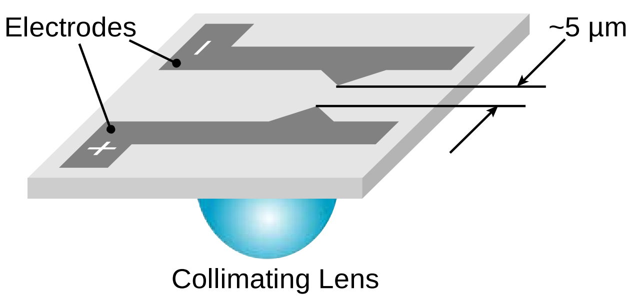

Figure 5, *A typical terahertz switch*

Chameleon Vision S offers two clear advantages for THz spectroscopy and imaging applications. First the short 75 fs pulsewidth translates directly into a higher total THz bandwidth. And second, Chameleon Vision S delivers much higher peak power than any other 75 fs oscillator, resulting in higher THz intensity when used with large-area photoconductive antennas or optical rectification crystals. This translates into higher signal-to-noise data and/or shorter data acquisition times.

For pump and probe applications involving electronic transitions in solid or liquid phase samples, the high average and peak power of Chameleon Vision-S can be used to generate a supercontinuum spectrum from a Photonic Crystal Fiber (PCF) and – in parallel – to pump the sample using the SHG of Chameleon (345 nm to 525 nm)

The combination of hands-free operation and short pulsewidths also makes the Chameleon Vision-S an excellent option for seeding regenerative and regenerative/multipass amplifier systems in multi-user facilities such as Coherent Legend Elite, where ease-of-use and flexibility are both important. For these applications, Chameleon Vision-S provides both hands-free operations (important at the back-end of a complex UF amplifier system) and broad flexibility as a stand-alone oscillator. This is particularly true where the amplifier system is used as a shared resource by multiple users with varying degrees of laser expertise.

Conclusion

Until recently, users of one-box ultrafast lasers could choose from products that deliver state-of-the-art performance in selected areas such as high peak power, shorter pulses, wider tuning and so on. With Chameleon Vision-S, researchers can now get state-of-the-art performance in all these areas from a single product.