AppNote2: What Pulse Repetition Rate do you REALLY need?

(or, "Why should I settle for 1kHz or 250kHz?")

One of the most common situations that KMLabs encounters when engaging with new customers is a conversation somewhat like this:

***Customer**:* "What do you have for ultrafast lasers running at 1 kHz?"
***KMLabs**:* "What is your pulse energy requirement?"
***Customer**:* "1 mJ is plenty."
…<pause>…
***Customer**:* "Actually, my experiment needs pulses with only about 50μJ energy, but this is more energy than the 250 kHz laser from *<competitor>* provides. So I guess I need a 1 kHz system."
***KMLabs**:* "I think we can offer you a better solution."

Customers are constantly coming to us believing that there are only two choices for Ti:sapphire laser amplifiers: mJ-level at low (1 kHz) repetition rate, and few μJ at higher (100-250 kHz) rep rates.

This *perceived* rep rate limitation arises from the technology used in other companies' offerings. But this is ***not*** the case for KMLabs, which supplies the highest performance, broadest line of ultrafast Ti:sapphire laser amplifier systems available today. We have supplied lasers that generate nearly 20W average power in a single stage of amplification (up to 50W in 2 stages), and systems that ***can run at virtually any repetition rate from 1 kHz up to >1 MHz***. We believe the determining factor for repetition rate should be the pulse energy required for your experimental application – not technical limitations in the laser. In the above conversation, for example, with a pulse energy requirement of 50 μJ, we recommended a Wyvern-500 laser with a configuration that can provide 50 μJ at repetition rates up to 150 kHz, and furthermore that can operate over a wide parameter range (90 μJ at 100 kHz to 18 μJ @ 200 kHz), providing unmatched experimental flexibility. KMLabs can also offer our Wyvern-1000 that is capable of operating from 10-50kHz, providing 180uJ @ 50kHz to 1mJ @ 10kHz with a simple single stage amplifier using easy to use computer control across this entire range of repetition rates.

Why is KMLabs unique in this capability? There are two reasons:

1. KMLabs patented cryogenic cooling technology virtually eliminates the effect of thermal lens loading that has limited competitors' offerings to 1 kHz repetition rate at higher pulse energies. By appropriately choosing the cavity configuration and incorporating cryogenic cooling, Ti:sapphire regenerative amplifiers can be configured for any repetition rate/pulse energy.

2. KMLabs long ago made a strategic decision not to restrict ourselves technically by requiring our own pump lasers (which provide the energy source for the Ti:sapphire). As a consequence, we can make use of virtually *any* laser on the market that generates the proper amount of green light. So we can offer a broad range of operating parameters in our ultrafast lasers and quickly take advantage of new products and lasers that come on the market. Furthermore, this flexibility allows us to take advantage of lasers that far exceed competitors' offerings in terms of $$/photon.

Of course, the wide variety of systems that KMLabs can provide creates a wider choice for the customer. In this AppNote, we provide an overview for the classes of pump lasers, where they ideally operate, and what this means in terms of operation for KMLabs lasers.

Pulsed and CW green lasers used by KMLabs Ultrafast ti:sapphire lasers require pumping by coherent light within the absorption band of the material (see inset). The absorption spectrum of ti:sapphire peaks in the blue-green at 490 nm; however, most ultrafast ti:sapphire lasers today are pumped with green light at 527-532 nm, corresponding to the frequency-doubled wavelength of Nd-doped solid state laser materials. Virtually all of these frequency-doubled Nd

Ti:sapphire lasers, and ultrafast lasers in general, require very high-brightness excitation, generally provided by another laser, to operate. This requirement is related to the fundamentals of ultrafast pulses, and laser gain. Ultrafast laser pulses require a broad spectral bandwidth—a relationship given by the *time-bandwidth product*—one manifestation of the Heisenberg uncertainty principle. On the other hand, *lasers* are much easier to make operate over a narrow bandwidth, because they rely on population inversion and optical gain. Optical gain "cross section" – which is what determines how much excitation density is needed to make a laser operate-- is inversely related to the linewidth of the gain transition. Thus, materials suited for ultrashort pulse generation make use of laser materials that have a relatively low gain cross section (in particular in relation to the energy storage lifetime). The result is that the very high excitation density required to make a laser work is best supplied by another laser.

Ti:sapphire is the most-exceptional laser medium yet discovered for ultrafast pulse applications. Its exceedingly wide gain bandwidth means that the excitation density required to make the laser work is quite high. Furthermore, the very broad spectrum means that the quantum defect for ti:sapphire is relatively large—a 532 nm photon absorbed results in a photon emitted at an average ~800 nm wavelength. The energy difference—about 1/3 of the total light energy absorbed—is the "quantum defect" which is dissipated as heat.

Ultrashort pulses→ Broad spectral bandwidth → large quantum defect, low gain → large volume heat dissipation

Fortunately, the titanium ions used to make the laser transition reside in a sapphire host— Al_2O_3, a transparent crystal with both toughness and thermal conductivity second only to diamond in nature. The broad spectral bandwidth, if it existed only in any other host material other than diamond, would likely never work as a laser.

KMLabs has taken this capability two steps further with cryogenic cooling, which effectively counters the use of such extraordinary power densities in the laser material .

lasers are now diode-pumped laser, where the Nd laser material is energized by diode bars. However, different host materials for Nd result in very different operating parameters, particular in terms of the excited-state lifetime of the material which determines the optimum repetition rate for a given material. Many of the lasers used for ultrafast laser amplifier systems are operated in pulsed, q-switched mode, which stores energy in the Nd laser material, then dumps it quickly in a high peak-power pulse that can be efficiently frequency-doubled, and where the output pulse has a duration substantially shorter than the ~4 microsecond excited state lifetime of the ti:sapphire itself.

Fortunately for the ultrafast laser market, progress in diode-pumped green lasers is driven by a number of large markets, including medical and industrial. Most of these applications require nanosecond pulses from a q-switched laser, and thus are very appropriate for ultrafast pumping applications. In particular, recent advances in very high-power 532 nm laser have been driven by manufacturing needs in photovoltaics. KMLabs has been the ultrafast laser manufacturer positioned to make use of these developments.

More broadly, three Nd-doped frequency-doubled lasers dominate the market today: Nd:YLF, Nd:YAG, and Nd:YVO4 (Vanadate). A few of the materials properties are tabulated below:

Material	Excited state lifetime	Gain cross section	Optimum operating repetition rate	Thermal conductivity	~Max Average power @ 532 nm
Nd:YAG	230 µs		5-20 kHz	14 W/(m·K)	300W
Nd:YLF	550 µs		1-3 kHz		50W
Nd:YVO4	50-100 µs	38×10^{-19} cm²	50 kHz→CW	5.2 W/(m·K)	30W

In surveying the above table, the optimum operating repetition rate for a particular laser material is a function of the excited-state lifetime of the material and its gain cross section. For low repetition rate operation, a long lifetime is desirable: the gain medium is pumped continuously, and will accumulate energy in the excited state of the laser for a time corresponding to this lifetime. Thus, Nd:YLF is the “king” for low-repetition rate, 1 kHz operation, and can provide pulse energies of 50-60 mJ in a ~200 ns pulse. This is well-matched to Ti:sapphire lasers utilizing near-room temperature crystals, since these lasers experience significant thermal lens limitations even at 1 kHz operation, which becomes increasingly severe and eventually unworkable at higher repetition rates. Furthermore, at higher repetition rates, Nd:YLF laser performance becomes limited by the very low gain in the material, which causes a loss of overall efficiency.

On the other hand, the development of doubled Nd:YLF lasers is largely driven by its use in pumping Ti:Sapphire lasers. Nd:YLF is a birefringent laser material that has poor thermal shock resistance, and is slightly soluble in water. Furthermore, replacement crystals are quite expensive. This contributes to a generally higher operating cost for Nd:YLF lasers compared with Nd:YAG, even though the average power capabilities of these lasers is only a fraction of what is possible with Nd:YAG. Thus, the *cost per photon* for Nd:YLF is about an order of magnitude higher than for Nd:YAG.

Applications such as laser materials processing benefit most from high average power, robustness, and low operating cost. These applications have primarily made use of pulsed Nd:YAG lasers. YAG is one of the earliest solid-state laser hosts demonstrated, and still one of the best (the YAG laser crystal is closely related to sapphire, with comparable—though not quite as good—thermal conductivity and toughness). The 230 µsec lifetime means that average power in these lasers only approaches its maximum at several kHz, and peaks at ~10 kHz repetition rate. Furthermore, the higher gain of Nd:YAG compared with YLF means that the YAG lasers can operate quite well to repetition rates of several 10's of kHz (though cavity reconfiguration may be necessary for these very high rep rates).

In terms of "bang for the buck" doubled Nd:YAG lasers are the champion for ti:sapphire laser pumping—by a large margin. A 150W 532 nm Nd:YAG laser (10 kHz) costs about the same as a 25W, 1 kHz Nd:YLF laser. Furthermore, the long-term operating cost for these two lasers also gives the YAG laser a slight edge. Recently, the latest offerings in this area specify average power as high as 400W.

Why haven't these Nd:YAG lasers been widely used for Ti:sapphire? Because of thermal lensing issues. This is the problem that KMLabs solves using patented cryogenic cooling. The KMLabs Dragon and Wyvern-1000 ultrafast laser amplifiers have no problem operating at the 10 kHz repetition rate where a 532 nm Nd:YAG laser works best, with performance that is now limited not by thermal lensing, but by cryogenic cooling capacity. Using a single off-the-shelf low-vibration cryocooler to cool a ti:sapphire crystal, it is possible to effectively utilize well over 100W of 532 nm light from such pump lasers. Ongoing KMLabs work is steadily increasing the effectiveness of cryocooling to make use of higher average powers.

Nd:YVO_4 lasers also provide unique capabilities when coupled with the KMLabs Wyvern regenerative amplifier. Continuous Wave (CW) frequency-doubled green lasers have long been a mainstay for pumping mode-locked ti:sapphire oscillators that are the starting point for all ultrafast ti:sapphire amplifier systems (as well as for other applications). The KMLabs Wyvern-X amplifier makes use of these CW green lasers for regenerative amplifier applications operating at pulse repetition rates at unprecedented MHz and higher repetition rates, and with pulse energies of 12 µJ and greater at several hundred kHz repetition rates. The average power capability of the Wyvern-X laser is several times that of competing CW-pumped ultrafast laser amplifier systems. Furthermore, the up-to-date optical design provides for the shortest pulse duration practical in this architecture.

However, even more exciting for Nd:YVO4 lasers is their use as pulsed, q-switched pump sources at high repetition rate. These lasers are widely used for industrial micromachining applications, and although their average power capability is not in the same category as Nd:YAG, Cryocooling makes it possible to use Vanadate to address a parameter range for ultrafast laser amplifiers that has not been previously accessible—the moderate pulse energy, high repetition rate "sweet spot" that is ideal for many scientific and spectroscopy applications: pulse energies in the range of 100 µJ (sufficient for efficient frequency conversion and pumping of several OPA's), with repetition rate up to 100 kHz.

A summary of KMLabs products, with pump laser details, pulse energies, and repetition rates, is shown below:

KMLabs Product	Pump Laser Gain Medium	Pulse Energy (approx.)	Repetition Rate
Griffin, Swift	Nd:YVO4, CW	15nJ	75 – 100MHz
Cascade	Nd:YVO4, CW	30nJ	1kHz – 4 MHz
Swift Cascade	Nd:YVO4, CW	400nJ	1kHz – 4 MHz
Wyvern-X	Nd:YVO4, CW	10uJ	100kHz – 1MHz
Wyvern-500	Nd:YVO4, q-switched	300uJ	20kHz – 200kHz
Wyvern-1000	Nd:YAG q-switched	4mJ	1kHz – 50kHz
Wyvern-HE	Nd:YLF	9mJ	1kHz – 3kHz
RedWyvern	Nd:YAG q-switched	12mJ	1kHz – 20kHz
RedWyvern-30mJ	Nd:YLF	30mJ	1kHz – 3kHz