A Coherent White Paper

Ytterbium Amplifiers Bring Simplicity, Power and Speed to Femtosecond Applications

Abstract

Monaco is a next generation ytterbium fiber ultrafast laser amplifier that provides easy access to tens of watts of average power with widely adjustable pulse rates, up to 50 MHz. This white paper examines how Monaco's performance enables new experiments in fields as diverse as THz microscopy and metal texturing, as well as extending the capabilities of applications such as multiphoton imaging.

Compact Femtosecond Amplifier

For many years, virtually all femtosecond laser amplifiers were based on titanium:sapphire (Ti:S) crystal technology. While this material remains unmatched for short pulse widths and high pulse energies, a growing range of existing and potential applications require performance beyond the typical operating range of Ti:S-based kilohertz lasers: specifically, higher average power and/or higher repetition rates. The requirements driving higher repetition rates are faster processing speed in industrial applications, or faster data acquisition and better averaging for scientific applications. If a threshold energy is required, for example to drill a hole, or to excite a sizable population of molecules, then the higher repetition rate implies a higher average output power from the laser. To meet these needs, scientists and engineers successfully developed a new and complementary family of gain materials – ytterbium-doped fibers or crystals – with the fiber format being especially useful in enabling amplified pulse repetition rates as high as 10s of MHz and output powers of many 10s of watts.

An example is the Monaco family of ytterbium fiber amplifiers from Coherent – see figure 1. The Monaco is a closed, compact, one-box system that combines a mode locked, 1035 nm fiber oscillator seeding fiber amplification stages to yield up to 60 W of average power with pulse energies as high as 80 μJ and repetition rates up to 50 MHz. Pulse widths are <300 fs and in order to match its output to the precise requirements of the application, Monaco can easily be operated from single shot to its full repetition rate, or in short, full-energy bursts at 50 MHz, and even adjusted to produce variable pulse widths up to 10 ps, all under software control with no manual intervention.

Figure 1. Monaco is a compact (180 x 360 x 670 mm) closed box femtosecond amplifier that delivers a unique combination of high average power and high pulse repetition rates.

The design, materials and manufacturing methods employed for Monaco have all been optimized to deliver consistently high performance in 24/7 usage. For example, all pump and amplifier optical components are contained in a single, sealed laser head which utilizes active cleaning to maintain output power and lifetime, as well as eliminate the need for routine maintenance. As part of Coherent's *Industrial Revolution in Ultrafast Science* initiative, the laser design has been iteratively optimized by Highly Accelerated Life Test (HALT) protocols, and each unit is subjected to Highly Accelerated Stress Screening (HASS) to ensure the highest possible reliability.

By extending the range of femtosecond amplifiers in terms of power and pulse rate, the Monaco family is dramatically expanding the range and capabilities of both scientific research and industrial tasks. In this whitepaper, we describe three very different applications that exemplify this trend.

High Quality THz Pulses

THz radiation is the portion of the electromagnetic spectrum sandwiched between the infrared and microwave regions. Because THz radiation with useful intensity is notoriously difficult to generate by conventional (e.g., blackbody) methods, it's only with the recent development of laser-based methods that this radiation window has transitioned from a curiosity to an important tool in various scientific and commercial applications. For example, it can be a powerful tool to interrogate dynamic electronic processes in solid-state materials and devices.

Pulsed THz radiation can be generated using ultrafast lasers and amplifiers to drive non-linear photonic processes and is proving particularly useful since it enables time-resolved experiments.

A common method is to utilize difference frequency generation (DFG) in a crystal such as lithium niobate ($LiNbO_3$). Because this process is highly non-linear, researchers often rely on amplified femtosecond pulses. For example, a team led by Professor Rupert Huber at the University of Regensburg (Germany) uses a Coherent titanium sapphire amplifier (Legend Elite Duo) to drive two tunable optical parametric amplifiers (OPAs) to create a source of frequency tunable THz [1]. Now a group of scientists from various institutes in Japan, led by Professor Hidemi Shigekawa (University of Tsukuba) are exploiting the bandwidth and turnkey simplicity of the Coherent Monaco to create THz pulses by relying on DFG between longer and shorter wavelength parts of the same pulse stream, resulting in THz frequencies up to about 1 THz [2]. They are then using the pulses in a THz scanning tunneling microscope (THz-STM). In both instances, the stability of the amplifier output pulses means that the THz pulses are essentially single cycle and are naturally CEP stable.

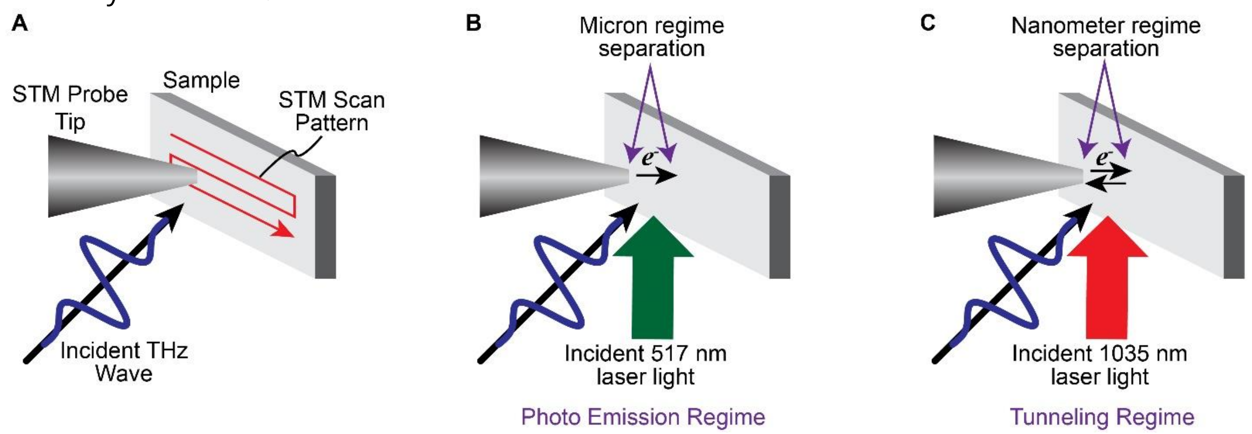

Figure 2. (A) The THz-STM technique enables photonic measurements of surfaces far beyond the optical diffraction limit. Researchers are using pump-probe techniques with THz pulses and optical pulses under different conditions, (B) large (micron) probe distance and (C) under nanometer tunneling conditions.

In a conventional STM, a nanoscale tip is brought so close to the surface under examination that a bias voltage causes a tunneling current to pass between the tip and the surface. In THz-STM, a transient voltage bias is applied by irradiating the tip region with THz pulses and the recorded signal is the resulting tunneling current. The THz-STM thereby enables photonic probing of the ultrafast dynamics of interesting solid-state materials including semiconductors. Specifically, it provides the very high spatial resolution of STM technology with the very high speed of ultrafast science.

However, the transient electric field is both amplified and modulated, and to better understand the method, researchers need a way to measure this field in real time. Developing a technique for this purpose was one of the main goals of experiments in the lab at University of Tsukuba. They have recently published their successful technique [2] based on a type of pump-probe with a single source where part of the Monaco is used to create the THz pulses and part is used as a probe pulse. Specifically, the near-IR (1035 nm) probe light is used to measure the hot electron tunneling current and at slight larger probe-surface distances, the frequency-doubled (517 nm) amplifier pulses are used to create a photoelectron signal.

There are several advantages to using Monaco in this type of THz-STM study. First it is a closed-box, hands-free source that allows the scientists to focus on their complex experiments rather than on laser operation. Second, it provides the stable well-behaved pulses needed to generate single cycle (CEP stable) THz pulses. Third it provides a much higher pulse repetition rate compared to Ti:Sapphire systems enabling faster data acquisition. And last, its stability is maintained over a wide range of user-controlled pulsing rates, enabling optimized studies of processes over a wide range of timescales: in this work, from the picosecond to microsecond regimes.

Materials Processing – Texturing Metal Surfaces

Lasers have been used to perform a wide range of surface treatments on metals. Examples include case hardening, where the surface layer properties are modified to be different than the bulk material, as well as novel polishing and texturing methods for cast iron diesel engine components. The limitations of nanosecond lasers for surface treatment meant that these older applications were mainly stochastic in nature, essentially creating an average effect over an extended area. Specifically, the long pulse width together with the thermal conductivity of metals limited the ability to create localized deterministic features on the micron scale. This situation improved with the advent of picosecond lasers at industrial power levels. And now, the power and high repetition rate of the Monaco femtosecond laser enables straightforward micron-scale texture patterns on nearly any metal surface with virtually no sub-surface thermal effects, and importantly, at applications-enabling throughput speeds.

The majority of laser texturing applications are focused on transforming the tribological (frictional) properties of a moving surface, and/or hardening the surface, or enabling bone/implant binding in dental devices and orthopedic implants. In a quite different vein, a recent study by Professor Caleb S. Brooks and co-workers at the University of Illinois (USA) have used the Monaco laser to change the liquid “wettability” of copper heating surfaces – hydrophilic vs. hydrophobic characteristics – in order to study its impact on boiling liquids in thermal systems that rely on two-phase boiling [3]. (The test liquid was distilled water.) An improved understanding could potentially benefit the performance of some types of refrigeration, air conditioning and heating technologies.

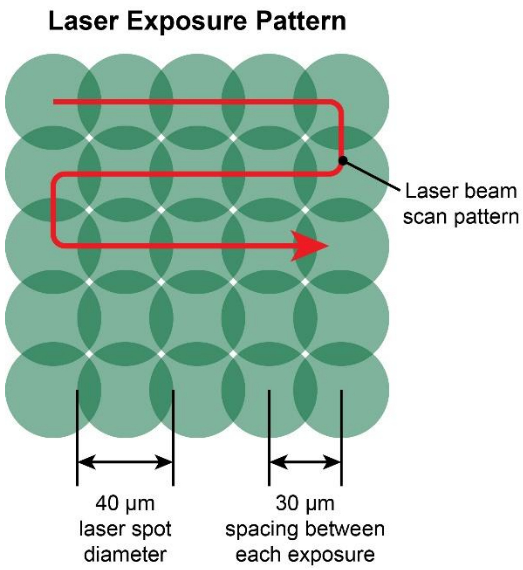

Figure 3. Step wise scanning of the focused spot from a femtosecond amplifier is used by researchers at the University of Illinois to texture copper heating surfaces.

Here they stepwise scanned a focused spot from a laser beam across the surface of a copper heating unit – the step size and spot diameter are both a few tens of micrometers. This yielded a self-organized periodic nanostructure with a marked increase in hydrophobic character. (The wettability was measured by the Sessile drop method which reveals the contact angle – how severely water beads on the surface.)

They then operated a test cooling platform loaded with distilled water under a range of different operational (e.g., pressure) conditions, to compare thermodynamic parameters such as onset of nucleated boiling (ONB) for a polished and laser-textured surface. Among other conclusions, their study showed that increasing the wettability via laser texturing measurably delays the ONB under all their different test conditions.

Three-Photon Imaging – Deep Tissue Microscopy

Multiphoton excitation (MPE) microscopy is a major research area for ultrafast laser pulses and the Monaco amplifier has already been used for this purpose. The largest share of these applications involve neuroscience, typically studying the cerebral cortex of small mammalian subjects. For most *in vivo* studies, the mouse brain is the standard mammalian model, with the organ made accessible by a small glass window incorporated in the cranium. The inherent z-axis depth discrimination in MPE imaging enables scientists to study both the form and real-time function of small groups of interconnected neurons in the mouse cortex at individual neuron resolution. Here a key trend is to study larger groups of neurons and extend the depth of these observations into the subcortical tissue (i.e., an imaging depth of >1.5 mm).

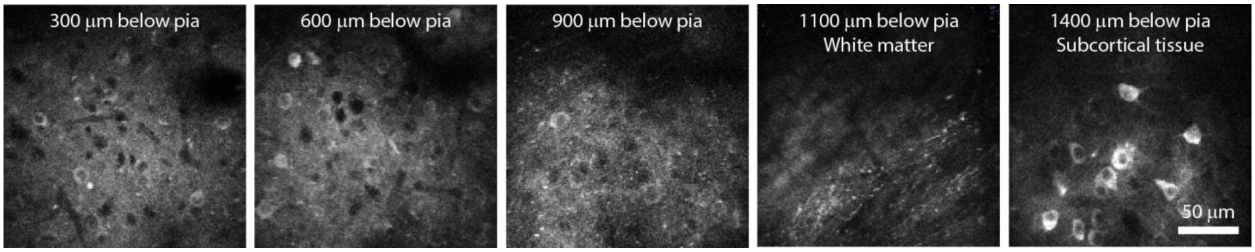

Figure 4. Allen Institute 3P images from the visual cortex in a densely labeled GCaMP6s mouse. Experimental details: 1300 nm excitation through a cranial window (400 µm of glass). Emx1-IRES-Cre;CaMk2a-tTA;Ai94 mouse, with GCaMP6s in most excitatory neurons. Olympus x25/1.05 WI objective. No aberration correction other than the objective collar. Max illumination intensity 100 mW at the pial surface.

The two principal factors that determine the maximum viewing depth with MPE are scatter and absorption of the incident laser radiation. As a result, there are two windows in the near-IR where the penetration depth is maximized: at 1300 nm, and in the 1700-1800 nm region. Fortuitously, the 1300 nm region is ideal for three-photon (3P) excitation of probes based on green fluorescent protein (GFPe), and the longer wavelengths align with 3P excitation of red-shifted probes such as the mFruit series. However, 3P imaging requires both higher pulse energy than can be generated by 80 MHz mode-locked oscillators, and lower repetition rates to minimize the chances of thermal damage. On the other hand, Ti:S amplified systems work well at kHz repetition rates which are too slow for real time imaging. Fortunately, Monaco plus a tunable OPA (see side-bar) provides the requisite combination of high pulse energy across both the 1300 and 1700 nm windows and high repetition rates – up to 4 MHz.

A team of researchers led by Jack Waters, Ph.D. at the Allen Institute are using Monaco and a tunable OPA (Opera F) at 1300 nm to perform three-photon observations of how mouse cortex processes neuromodulatory signals triggered by visual stimuli. He explains that the use of 3P excitation is particularly useful in obtaining high-quality deep images from densely labeled tissue – see figure 4. He adds that the 1300 nm wavelength provides another critical advantage – the ability to penetrate the mouse cranium, eliminating the need for a small glass window and enabling a wider field of view.

Side-Bar

Pumping Tunable OPA

Yb-based amplifiers like Monaco provide straightforward access to high average power at MHz repetition rates, at a fixed wavelength and with a pulse width of <300 fs. Many applications in microscopy and spectroscopy require tunable output and/or shorter pulse widths. Both of these needs can be met by using the Opera F, an OPA specifically optimized for pumping by Monaco. With conventional femtosecond OPA architectures, designers often have to trade-off the tuning range and pulse width. Instead, the Opera F uses a hybrid design that integrates a non-collinear stage to generate pulses with a broad bandwidth (readily compressible to 50-70 fs), together with a collinear stage which delivers a broad wavelength tuning range. As a result, the idler output is tunable from 1200 nm to 2500 nm, and the signal output from 65 nm to ~920 nm. The pulse repetition rate can be as high as 4 MHz, making this ideal for three-photon imaging and other applications where maximum data acquisition speeds are paramount. In addition, a specialized type of OPA – the White Dwarf OPCPA by CLASS 5 based in Hamburg – can be pumped by Monaco at speeds up to 10 MHz and is used for advanced fast imaging of neuronal activity. This setup has demonstrated pulse widths <9 fs.

Future Trends

Looking to the future, the broad and unique operating regime of ytterbium-based ultrafast amplifiers can be expected to support an increasingly diverse range of industrial and scientific applications. At the same time, this relatively new laser technology is not yet close to approaching performance maturity, so users can expect a steady stream of new products with performance milestones that further expand the applications potential of the ytterbium gain material.

References

1. *Sub-cycle control of terahertz high-harmonic generation by dynamical Bloch oscillations,* O. Schubert et al, **Nature Photonics**, 2014, 8, 119-123.
2. *Subcycle Transient Scanning Tunneling Spectroscopy with Visualization of Enhance Terahertz Near Field,* S. Yoshida et al, **ACS Photonics,** 2019, 6, 6, 1356-1364.
3. *Influence of wettability due to laser-texturing on critical heat flux in vertical flow boiling,* J.L. Bottini et al, **International Journal of Heat and Mass Transfer**, 2018, 127, 806-817.