THE TI:SAPPHIRE LASER

# The flexible research tool

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When the Ti:Sapphire laser was first invented, it took the research community by storm. Today, it has an important role in imaging, spectroscopy and many other applications.

Ti:Sapphire (Ti:Sa) was initially proposed and demonstrated as a near-infrared gain medium in 1982, and was commercialized by Spectra-Physics in 1988 with the launch of a continuous-wave laser. This was followed in 1990 by a picosecond mode-locked oscillator, and in 1991 with a femtosecond version. Soon after this, the whole ultrafast research community, which until then had been using visible-wavelength dye lasers for the generation of ultrafast tunable pulses, adopted Ti:Sa technology in a matter of months — an instant shift rarely seen in research.

Table-top commercial amplified systems followed during the mid-1990s, leveraging chirped pulse amplification techniques. In 1996, the introduction of the first high-power diode-pumped solid-state 532 nm laser significantly reduced the complexity of pumping ultrafast Ti:Sa lasers (which until then had relied on argon-ion gas laser technology), and drastically reduced the amplitude noise — important for femtosecond spectroscopy experiments.

Another milestone in the development of Ti:Sa technology was the stabilization of the carrier–envelope phase of ultrafast pulses, paving the way for the generation of attosecond ($10^{-18}$ s) pulses in the X-ray spectrum using high-harmonic generation. Attosecond laser sources are now poised to become the next tool for probing dynamic chemical processes with unprecedented time resolution. An octave-spanning carrier–envelope phase-stabilized ultrafast oscillator can also be used as a frequency comb. Frequency combs are accurate 'optical clocks' that can be used to measure optical frequencies with extraordinary precision, a technique for which Theodore W. Hänsch and John L. Hall received the Nobel Prize for Physics in 2005. Furthermore, the Ti:Sa crystal has been at the heart of numerous large amplifier systems that deliver terawatt and petawatt peak powers.

Ti:Sa technology offers unique benefits and a tremendous flexibility in performance over competing gain media. No other material can offer: 1) spectral outputs that range from ultra-narrow single frequencies to wide bandwidths spanning several hundred nanometres, providing ultrafast pulses as short as a few oscillations of the electric field; 2) repetition rates that range from maximum-energy single shots to multi-gigahertz quasi-continuous-wave output; 3) a tunability of 400 nm; and 4) average powers of many watts.

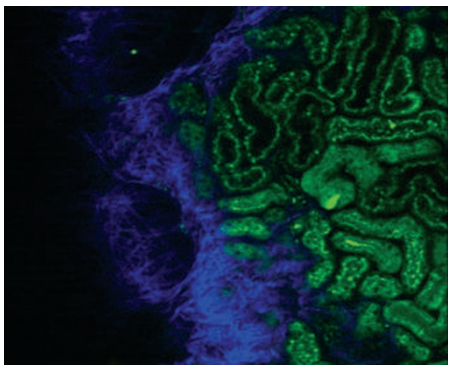

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Image of a mouse kidney, using second-harmonic generation imaging for collagen (blue) and multiphoton microscopy imaging for protein (green).

As the technology has matured over the past two decades, a complete set of accessories has been developed to support and complement Ti:Sa lasers. Optical parametric oscillators and amplifiers can extend wavelength tunability to the deep-ultraviolet (<200 nm) and mid-infrared regions (>20 μm).

Ti:Sa lasers and amplifiers have enabled countless applications for fundamental research in physics, biology and chemistry. Femtosecond chemistry, the science that studies chemical reactions on ultrafast timescales, was developed mostly using Ti:Sa lasers. This research earned Ahmed H. Zewail the Nobel Prize for Chemistry in 1999. Recently, the sophistication of coherent control has grown significantly, and devices to control the spectral phase and amplitude of ultrafast pulses have now been developed. Other applications include nonlinear physics, terahertz generation, micromachining that requires the cutting, drilling and scribing to be free of undesirable thermal effects, and multiphoton microscopy.

Multiphoton microscopy takes full advantage of the high power, short pulsewidth and wide wavelength tunability of Ti:Sa lasers to enable high-contrast and high-resolution *in vivo* imaging of living deep tissues. This technique is based on the two-photon absorption of dyes and the extended tunability of Ti:Sa lasers, thus allowing the use of various dyes with distinct absorption spectra and chemical properties. Multiphoton absorption is highly dependent on the laser peak power, and hence on the pulse duration. By focusing an ultrafast pulse train to a tight focal spot, one can selectively generate two-photon absorption in a small sample volume, greatly enhancing the spatial resolution of the image in all three dimensions while also reducing the background signal from the out-of-focus regions of the sample.

Although Ti:Sa technology is now fairly mature, it is interesting to note that Ti:Sa oscillators are still limited principally by the green pump source. Other ultrafast lasers such as chromium-doped colquiriites (for example, Cr:LiSAF) are more suitable for direct diode pumping than Ti:Sa, but have not been commercially successful due to their lower average powers and reduced tunability. Fibre lasers have recently attracted much attention for their average power scalability and turn-key operation, but are much less tunable than Ti:Sa and do not produce very short pulse durations. Looking to the future, for ultrafast applications such as micromachining and terahertz generation, in which neither tunability nor the shortest pulses are required, fibre lasers will have an important role. However, for research and spectroscopy in which flexibility in wavelength, pulse duration and power are essential, the Ti:Sa laser will continue to be the source of choice for a significant period of time. ❐

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