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Feature issue introduction: ultrafast optical imaging

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Abstract: This feature issue of *Optics Express* collects 20 articles that report the most recent progress of ultrafast optical imaging. This review provides a summary of these articles that cover the spectrum of ultrafast optical imaging, from new technologies to applications.

Ultrafast optical imaging is essential in understanding the underlying mechanisms of transient phenomena in various systems, ranging from molecular rotations, carrier diffusion, to electric signaling in the brain. To address the great demand for frontier scientific research and industrial applications, various technologies of ultrafast optical imaging have been developed in the past decade, and their modalities have been expanded beyond microscopy and now include tomography, spectroscopy, and cytometry. The emergence of new materials, devices and systems, especially, has accelerated the translation of ultrafast optical imaging technologies from laboratory to practicality. New requirements of practical applications, in return, have also created new concepts for ultrafast optical imaging. This feature issue collected the most recent progress in ultrafast optical imaging, from new technologies to applications, providing a better understanding of these new technologies and inspiring new ideas for ultrafast optical imaging and its applications.

We hope audiences will enjoy these 20 top-level articles that highlight the state of the art in the field of ultrafast optical imaging. We are also thankful to all the authors and reviewers for their great efforts. And we thank very much Carmelita Washington, Dan McDonold, Rebecca Robinson, Sharon Jeffress, and Julie Rovesti from the OPTICA staff for their outstanding work throughout the launch of this feature issue as well as the review and production processes.

Ultrafast laser source is one of the key elements of ultrafast optical imaging systems, and new technologies of ultrafast laser are significantly important for pushing the performance of ultrafast optical imaging. F. Vernuccio et al. [1] utilize a 2-MHz repetition rate ytterbium laser, which

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can generate high-energy (~μJ level) femtosecond pulses at 1035 nm, to produce broadband red-shifted Stokes pulses, covering the whole fingerprint region (400-1800cm^{-1}). This new laser source allows them to perform broadband coherent anti-Stokes Raman scattering (CARS) microscopy. L. Chou et al. [2] demonstrate the control of generating plural few-optical-cycle pulses based on a 24-MHz Chromium:forsterite laser, using which they demonstrate multicolor two-photon tissue imaging by wavelength mixing. Ultrafast fiber laser that features compact design has been a promising laser source for nonlinear optical imaging. Z. Lin et al. [3] report on a 1.7-μm passively mode-locked figure-9 Tm-doped fiber laser that can deliver the dissipative soliton with a 3-dB bandwidth of 20 nm. The spectral bandwidth of this fiber laser can be flexibly tuned with different phase biases by rotating the wave plates. This ultrashort pulse fiber laser at 1.7 μm is anticipated to be useful for in-depth three-photon imaging. In a different scheme of mode-locking, Y. Zhou et al. [4] numerically study the transition from a gain-guided soliton (GGS) to a fully developed noise-like pulse (NLP) in a fiber laser mode-locked by nonlinear polarization rotation, which gains a deeper understanding on the characteristics of mode-locked fiber lasers. Increasing the repetition rate of ultrashort pulses, which is related to the refresh rate when applying for optical imaging, is another hot topic in the field of fiber laser. S. Ou et al. [5] demonstrate a fundamentally mode-locked, GHz-repetition-rate ring cavity Yb-doped femtosecond fiber laser using SESAM mode-locking.

Vibrational spectroscopy is a powerful tool for label-free chemical characterization and non-destructive remote identification of molecules. When applied to microscopy in the life sciences, it can map the concentration of various biological components in cells and tissues. To speed up the imaging acquisition time, spontaneous Raman spectroscopy can be replaced with coherent Raman spectroscopy (CRS), a third-order non-linear process that enhances the signal by several orders of magnitude thanks to the use of ultrashort laser pulses that coherently drive the molecular oscillations in the focal spot. In this special issue, two original articles present novel approaches to CRS microscopy. P. Lin et al. [6] demonstrate how the technique can be employed for volumetric imaging of the chemical bonds in a sample, employing tomographic projection of the sample from different points of view. In particular, their implementation does not require the sample to be rotated, which is a cumbersome and time-consuming approach, as they quickly vary the azimuthal angle of sample illumination by galvanometric mirrors. In the paper by G. Huang at al. [7], a novel technique based on the generation of white-light supercontinuum via nonlinear interaction in multiple thin quartz plates is introduced. It provides the benefits of generating octave-spanning spectra with much higher energy density than using a photonic crystal fiber or a single thick glass plate. This beam is then employed as a broadband pulse for multiplex CRS spectroscopy and imaging across the entire Raman-active region.

Pump-probe (also called transient-absorption) microscopy is another label-free imaging technique to image cells and tissues. As a contrast mechanism, it does not employ the previously mentioned Raman response of vibrational levels, but rather the electronic absorption of a pump pulse and the subsequent absorption or emission of a photon at the probe frequency. D. Grass et al. [8] employ this technique to obtain relevant biomarkers to distinguish healthy melanin, a natural pigment found in human skin, from its disaggregated form. Another highly flexible and cost-efficient detection scheme based on a conventional photodiode and a USB oscilloscope with MHz bandwidth that deviates from the commonly used lock-in setup and achieves benchmark sensitivity has been demonstrated by R. Schwarzl et al. [9]. Such 2-D imaging performance of their transient absorption microscope enabled the studies on micro-crystalline molecular thin films. The aforementioned pump-probe imaging can be used to record ultrafast transient dynamics on a femtosecond time scale of repeatable phenomena. When it comes to non-repeatable events, single-shot ultrafast imaging methods must be employed. Q. Zhu et al. [10] in their contribution to this special issue demonstrate a novel technique, called frequency-domain-integration sequential

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imaging (FISI), capable of recording 12 thousand billion frames per second with a resolution of more than one hundred lines per millimeter in the spatial dimension of the image plane.

One very illustrative application is ultrafast x-ray imaging (UXI) specifically in imaging the laser-driven shock wave interactions with micro-voids in the ablator layer of the fuel capsules that compress the fuel pellet – one of the major obstacles of deploying inertial confinement fusion (ICF) as a potential source of abundant and clean energy as demonstrated by D. Hodge et al. [11]. Such kind of UXI detection will help to minimize the high- and low-frequency variations of the captured images by incorporating principal component analysis (PCA) and image alignment for flat-field correction, in addition to a transport-of-intensity (TIE) based method to yield insight into how defect-bearing ablator materials alter microstructural feature evolution, material compression, and shock wave propagation on ICF-relevant time scales. Also for the shock wave study, J. Mur et al. [12] demonstrate multi-frame multi-exposure shock wave velocity measurement for all in-plane directions of propagation, which is based on a custom-built illumination system allowing multiple illumination pulses within each frame at multi-MHz frame rates and at up to 200 MHz illumination pulse repetition frequency at sub-nanosecond pulse durations. For material science, by using optical four-wave mixing (FWM) process, T. Purz et al. [13] perform rapid multiplex ultrafast nonlinear microscopy for material characterization, and assess the quality of advanced materials through measurement of their nonlinear response, exciton dephasing, and exciton lifetimes, allowing a higher accuracy than that of current prevalent techniques. Another two-dimensional image was reconstructed using a moving mirror to scan the line-sensor field-of-view (FOV) across the target, to achieve an efficient 2D 0.26 Mpixel time-correlated single-photon counting (TCSPC) imaging system based on a line-scanning architecture by E. McShane et al. [14]. The system benefitted from the high fill-factor, active area, and large dimension of an advanced CMOS single-photon avalanche diode (SPAD) array line-sensor for TCSPC imaging and locating objects obscured in scattering media - specifically to locate a series of discrete point sources of light along an optical fibre submerged in a highly scattering solution.

Increasing the speed of label-free optical imaging by modifying established imaging techniques' basic design and approach is highly demanded in this field. W. Zou et al. [15] eliminate scanning to accelerate material inspection. They use a single-pixel approach based on a virtually imaged phased array in combination with a time-stretch-based wavelength-to-time readout system to achieve 7.6 MHz frame rates. L. Xu et al. [16] also use time-stretch principles in a dual optical frequency comb approach to ranging. In it, signals are down-sampled to manage the acquisition bandwidth challenges that accompany imaging at high speeds. G. Lin et al. [17] take steps toward developing simpler approaches to camera-based detection of ultrasound-modulated optical tomography. Using a coaxial interferometric design, the proposed system offers simplicity and improves stability. In the meanwhile, compressed ultrafast photography (CUP) has aroused tremendous attention in increasing the speed of optical imaging. However, the high compression ratio induced by large sequence depth brings the problem of low image quality in image reconstruction, preventing CUP from observing transient scenes with fine spatial information. C. Jin et al. [18] demonstrate an efficient image reconstruction algorithm with multi-scale (MS) weighted denoising based on the plug-and-play (PnP) based alternating direction method of multipliers (ADMM) framework for multi-channel coupled CUP (MC-CUP), named the MCMS-PnP algorithm. H. Huang et al. [19] demonstrate a novel noniterative end-to-end deep learning-based framework for compressive imaging. In comparison to existing approaches, they extend the pipeline by co-optimizing the recovery algorithm with optical coding as well as cascaded high-level computer vision tasks to boost the quality of the reconstruction. To improve the quality of phase image of living biosamples, J. Zhao et al. [20] propose a deep convolutional neural network (DCNN) with a weighted jump-edge attention mechanism, namely, VDE-Net, to

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realize effective and robust phase unwrapping. Using the trained VDE-Net, they show that an unseen wrapped phase image of a living red blood cell (RBC) can be successfully unwrapped.

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