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Real-time optical imaging and tracking of micron-sized particles

Feng Qian *, Qi Song, En-kuang Tien, Salih K. Kalyoncu, Ozdal Boyraz

Advanced Photonics and Devices Laboratory, EECS Department, University of California, Irvine, CA 92697, USA

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ABSTRACT

We report real-time imaging and dynamics monitoring of micrometer predefined and random sized particles by time–space-wavelength mapping technology using a single-detector. Experimentally, we demonstrate real-time line imaging of a 5 μm polystyrene microsphere, glass powder particles and patterns such as fingerprints with up to 5 μm resolution at 1 line/50 ns capture rate. By using the same setup, real-time displacement tracking of micrometer-size glass particles with 50 ns temporal resolution and up to 5 μm spatial resolution is achieved. We also show that existing correlation spectroscopy algorithms can be adopted to extract dynamic information in a complex environment.

1. Introduction

Real-time optical imaging and tracking of submicron particles are attractive approaches for in vitro biological sample imaging and capturing transient properties of target objects in electromechanics. Different laser scanning microscopes including fluorescence or scattering based mechanisms have been proposed and illustrated for obtaining high-resolution optical images [1,2]. Unfortunately, temporal resolutions of the above mentioned laser scanning microscopes are between microsecond and second due to mechanical limitation of scanning methods and data acquisition speed of detector arrays [3]. Recently, wavelength-division-multiplexing (WDM) based confocal microscopy has been demonstrated as a useful tool for optical imaging and detection using space-wavelength mapping technique [4–6]. In addition, time-wavelength mapping can provide unique solution for improving temporal resolution to realize real-time optical measurements [7–9] using a single-detector and single-shot measurement. Time domain profile of ultrafast RF (Radio Frequency) signals can be mapped to wavelength domain; thus, the spectral shape can be retrieved directly into time domain by using a real-time oscilloscope after a dispersive time stretching process [10]. Time-wavelength mapping technique also prevails over the slow-speed conventional spectrometers and allows real-time single-shot measurement of dynamic process [11]. This technique has also recently been implemented to detect highly reflective objects with sub-gigahertz resolution [12,13]. In another field of interest, image correlation spectroscopy has proved to be a powerful tool of measuring dynamic processes and providing spatially resolved transient information in biological systems [14,15]. Analysis of temporal and spatial correlation of image series can provide dynamic information such as diffusion coefficients and velocity vectors by using correlation functions.

In this paper, WDM based time–space-wavelength mapping is demonstrated to integrate space-wavelength mapping and time-wavelength mapping configuration into one system to achieve real-time high-resolution optical measurement. Using this technique, we present real-time optical imaging of a 5 μm polystyrene microsphere, which is extensively employed as size-standards for calibration of the system. As a further proof of concept, fingerprint stains are imaged with up to 200 μm/line spatial resolution and real-time, up to 1 line/50 ns, acquisition rate. We also perform single-shot imaging, measurement of consecutive data points captured in a single measurement, of real-time dynamics of micron-size objects and correlated movements by tracking them in a 20 μm imaging range. The image generated by the time–space-wavelength mapping system is compatible with algorithms developed for image correlation microcopy. Here, we illustrate detection and tracking of objects with 50 ns temporal accuracy by applying the algorithms of correlation spectroscopy.

2. Experimental setup

In this system, WDM essentially reduce the two-dimensional scanning to one-dimensional sample scanning while information along the incident beam is provided by wavelength division map-

* Corresponding author. Address: 325 Engineering Tower, EECS Department, University of California, Irvine, CA, 92697, USA. Tel.: +1 (949) 231 9735; fax: +1 (949) 824 2321.
E-mail address: fqian@uci.edu (F. Qian).

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ping. As shown in Fig. 1, a supercontinuum source is dispersed by the diffraction optics to produce space-wavelength mapping in one spatial dimension. When the laterally dispersed incoming light encounters with the target object, random amplitude modulation is created on the transmitted signal as in Fig. 1. For two-dimensional micron-sized object optical imaging, sample is scanned only in the dimension normal to the incident beam direction while the lateral information (x axis in Fig. 1) is provided by dispersed beam. By comparing the modulated signal with the stored background signal, we can extract the information regarding the position of the object and the density of the scatterers. Imaging and detection of the target object can be realized in real-time by retrieving the single-shot data from the time domain by a detection module of a single-detector and a real-time digital oscilloscope. For particle tracking, dynamic monitoring of micro-particles is achieved by first manipulating the particle moving within 20 μm image frame along the incident beam direction controlled by a piezoelectric stage with the same setup as previously mentioned WDM based system. Transient displacements of the particle induce variation in the temporal waveform due to the amplitude modulation in different wavelengths along the incident beam direction. The trajectory of the particle is recorded and processed using correlation spectroscopy method.

Experimental setup of the real-time high-resolution optical imaging and particle tracking is shown in Fig. 2. A 20 MHz fiber modelocked laser is used to generate a supercontinuum source with 50 nm bandwidth for imaging experiments. The generated light is then chirped by a grating based dispersion compensation module (1300 ps/nm) and hence time-wavelength mapping is produced. The temporally dispersed supercontinuum is subsequently dispersed in space by using a 600 lines/mm diffraction grating. At point "A" in Fig. 2, an elliptical beam where each position along x axis is mapped to a different color arriving at different times. Then the beam is focused on the sample at point "B" by using microscope objectives OL1 and OL2 (numerical apertures of 0.65 and 0.85 for desired spatial resolution and the high collection efficiency). Polystyrene microspheres with 5 μm diameter and glass particles are used as samples in this experiment. Samples are embedded in a thin polymer film and attached to a cover glass. Sample imaging is performed by monitoring the intensity of the transmitted light from the sample using an InGaAs detector. The presence of particles on the image plane induces amplitude modulation on different wavelengths, which is captured in time domain by a high-speed real-time oscilloscope with 20 GS/s sampling rate. This setup can also be slightly modified for different-sized object imaging such as fingerprint stain imaging. The objectives lens OL1 and OL2 in Fig. 2 are replaced with spherical lenses (f = 100 mm) for fingerprint object imaging.

3. Experimental results and discussion

Imaging capability of the system is evaluated by scanning different-sized objects in one-dimension. As a proof of concept, we first demonstrate 2D imaging of a 5 μm diameter polystyrene microsphere. 2D image of polystyrene microsphere shows that a 5 μm microbead is resolved by the system, Fig. 3a. As a

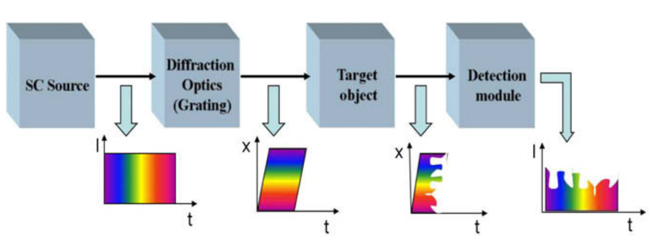

Fig. 1. Conceptual diagram of real-time time–space-wavelength mapping system.

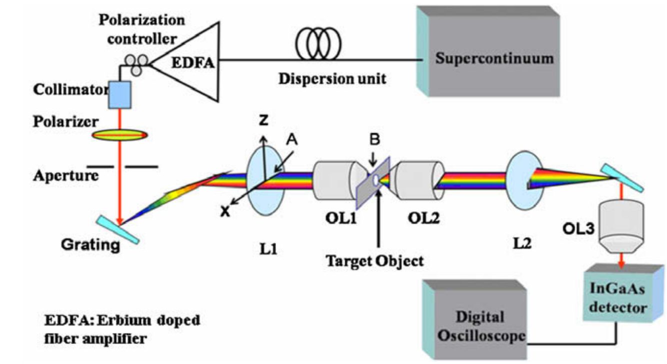

Fig. 2. Experimental setup of real-time high-resolution optical imaging and particle tracking.

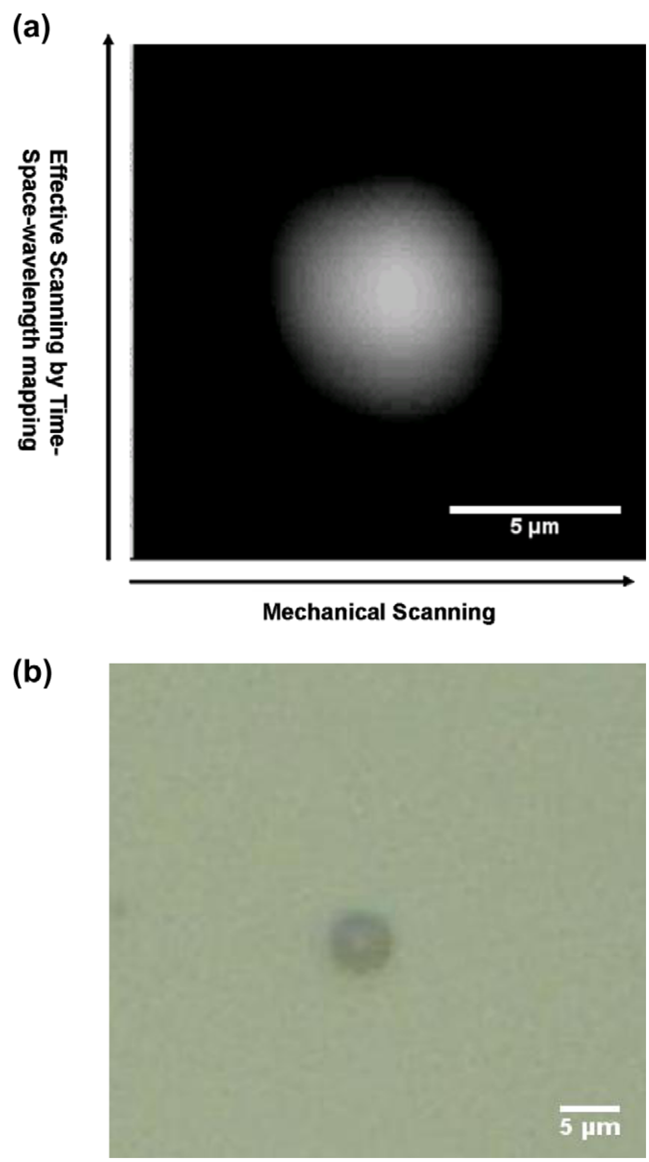

Fig. 3. Imaging of a 5 μm polystyrene microsphere. (a) Image generated by single-shot space–time-wavelength mapping technique, (b) image captured by high-resolution Keyence microscope.