

# Space-Time-Wavelength Mapping Based Electronically Controlled Two Dimensional Optical Tweezing

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**Abstract:** We investigate two-dimensional optical tweezing by space-time-wavelength mapping. We show that by adding a virtually imaged phased array to the proposed setup, force field in a 2D plane can be controlled by time-domain modulation.

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## 1. Introduction

Optical tweezers use forces arising from intensity gradients in a strongly focused beam of light to trap and move micro- and nano-scale objects [1]. We recently proposed a new optical tweezing approach that utilizes space-time-wavelength mapping (STWM) to enable electronic control of optical force fields without the need for mechanical beam steering [2, 3]. In this study we extend the proposed technique to two dimensional electronic control of optical tweezers using a virtually imaged phased array (VIPA) [4–6]. We employ a VIPA to disperse a spectrum in the vertical dimension, while a grating diffracts it in the horizontal dimension, creating a 2D space-wavelength mapping. Through electro-optic modulation in time domain it is possible to manipulate the power spectral density of the spectrum at individual wavelengths, and hence control the 2D intensity landscape – enabling creation of desired intensity gradients that define the 2D force profile. Here we present the analytical framework and sample time-domain waveforms required for generating multiple particle traps, and force configurations for exerting stretching and compressive forces on objects.

## 2. Modeling setup and theory

The proposed setup is shown in Fig. 1. The optical tweezer is driven by a modelocked laser with broad bandwidth and high peak power. Here we assume 150 fs pulses with ~20 kW peak power at 50 MHz repetition rate. The laser beam propagates through a dispersive medium with ~200 ps/nm chromatic dispersion to broaden the optical pulse width to ~4 ns at the full width half max (FWHM) point. Hence, the dispersive propagation creates a time-wavelength mapping where 1 nm wavelength separation corresponds to 200 ps separation in time domain. Dispersed pulses are then passed through an electro-optic modulator to manipulate the power spectral density of the laser as desired, by using RF waveforms. The time-wavelength mapped pulses are then coupled to a diffraction grating with 600 lines/mm groove density to create 1D space-wavelength mapping in the  $x$  direction. The diffracted beam is then dispersed in the  $y$  direction by an air-spaced VIPA with tilt angle  $1.26^\circ$ , thickness 1.5 mm and surface coating reflectivities 1 and 0.98, to produce a 2D space-wavelength mapping. Finally, we use an imaging lens and a 60x microscope objective to generate a  $\sim 25 \mu\text{m} \times \sim 25 \mu\text{m}$  focal spot.

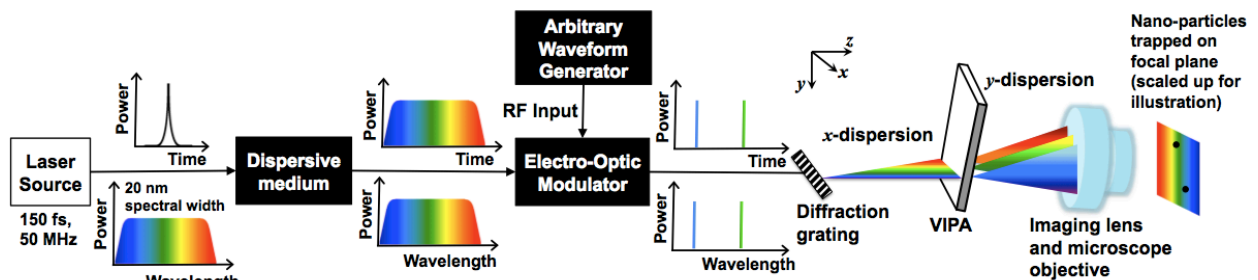


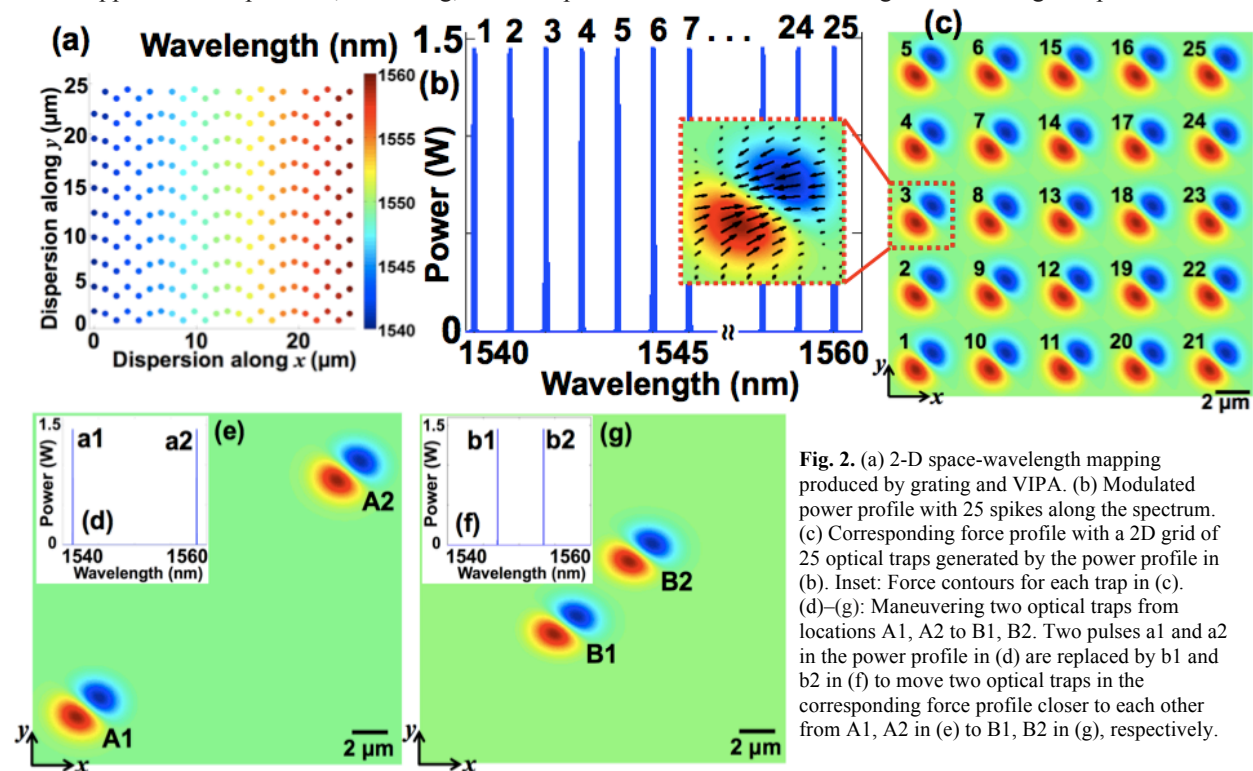
Fig. 1. The proposed experimental setup.

The resulting force profile depends on the intensity gradient and is given by  $F(r) = \left( \frac{2\pi n_0 b^3}{c} \right) \left( \frac{m^2 - 1}{m^2 + 2} \right) \nabla I(r)$

where  $m = n_1/n_0$  is the relative refractive index of the particle (where  $n_1$  is the refractive index of the particle and  $n_0$  is the refractive index of the surrounding medium),  $b$  is the radius of the particle,  $c$  is the speed of light, and  $r$  is the radial distance from the beam axis [2]. The intensity gradient  $\nabla I(r)$  can be found using expressions for the intensity distribution of a Gaussian beam after passing through a diffraction grating [2] and a VIPA [6].

### 3. Results

The 2D space-wavelength mapping produced by the VIPA and the grating, focused onto a  $\sim 25 \times 25 \mu\text{m}^2$  area is shown in Fig. 2a. By using different RF waveforms, it is possible to manipulate the power profile in accordance with this mapping, to obtain desired intensity gradient and force profiles in 2D space. Any change in the intensity profile in turn creates intensity gradients in the lateral direction. For instance, Fig. 2b shows the modulated power profile with 25 pulses of width  $\sim 80$  ps each, used to obtain the force profile in Fig. 2c., which is a 2D grid of 25 traps, each with  $\sim 10$  pN force hot-spots, in a total area of  $\sim 25 \times 25 \mu\text{m}^2$ . The numbers 1 through 25 link each power spike in Fig. 2b to the corresponding trap in Fig. 2c based on the space-wavelength mapping shown in Fig. 2a. To sustain the depicted rise time of  $\sim 26$  ps, an RF bandwidth of  $\sim 20$  GHz is needed. The inset in Fig. 2b. illustrates the force contours in each trap shown in Fig. 2c. Figs. 2d–2g demonstrate how different power profiles can be applied to maneuver a set of optical traps on the focal plane. When pulses a1 and a2 are applied (Fig. 2d), two optical traps in locations A1 and A2 are produced (Fig. 2e). These two traps can be moved to locations B1 and B2 (Fig. 2g) by changing the power pulses to b1 and b2 in Fig. 2f. This ability to electronically maneuver optical traps in a 2D plane can be applied in compression, stretching, and transportation of cells and other organic and inorganic particles.



**Fig. 2.** (a) 2-D space-wavelength mapping produced by grating and VIPA. (b) Modulated power profile with 25 spikes along the spectrum. (c) Corresponding force profile with a 2D grid of 25 optical traps generated by the power profile in (b). Inset: Force contours for each trap in (c). (d)–(g): Maneuvering two optical traps from locations A1, A2 to B1, B2. Two pulses a1 and a2 in the power profile in (d) are replaced by b1 and b2 in (f) to move two optical traps in the corresponding force profile closer to each other from A1, A2 in (e) to B1, B2 in (g), respectively.

### 4. Summary

We presented techniques for electronically controlled optical tweezing in two-dimensional space using space-time-wavelength mapping. By using time-domain electro-optic modulation, followed by space-wavelength mapping using a grating and a VIPA, STWM can achieve direct control over the entire continuous 2D intensity landscape, and hence is able to manipulate the location, area, size, and polarity of optical force hot-spots as desired.

### 5. References

- [1] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles," *Opt. Lett.*, vol. 11, no. 5, pp. 288–290, May 1986.
- [2] S. Rahman, R. Torun, Q. Zhao, and O. Boyraz, "Electronic control of optical tweezers using space-time-wavelength mapping," *J. Opt. Soc. Am. B*, vol. 33, to be published.
- [3] S. Rahman, R. Torun, Q. Zhao, T. Atasever, and O. Boyraz, "Electronically-controlled optical tweezing using space-time-wavelength mapping," 2015, vol. 9581, p. 95810E–95810E–8.
- [4] P. Metz, J. Adam, M. Gerken, and B. Jalali, "Compact, transmissive two-dimensional spatial disperser design with application in simultaneous endoscopic imaging and laser microsurgery," *Appl. Opt.*, vol. 53, no. 3, p. 376, Jan. 2014.
- [5] M. Shirasaki, "Large angular dispersion by a virtually imaged phased array and its application to a wavelength demultiplexer," *Opt. Lett.*, vol. 21, no. 5, p. 366, Mar. 1996.
- [6] S. Xiao, A. M. Weiner, and C. Lin, "A dispersion law for virtually imaged phased-array spectral dispersers based on paraxial wave theory," *IEEE J. Quantum Electron.*, vol. 40, no. 4, pp. 420–426, Apr. 2004.