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Single-particle analysis with 2D electro-optical trapping on an integrated optofluidic device: supplementary material

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This document provides supplementary information to "Single-particle analysis with in-plane electro-optical trapping on an integrated optofluidic device," https://doi.org/10.1364/OPTICA.5.001311. Here, we describe the fabrication details of the novel 2D ABEL trapping device. We also describe the schematic of planar optical setup with interconnected feedback electronics. A full length description of the feedback control electronics is presented. Additionally, we provide the video of the trapping event for visualization.

DEVICE FABRICATION

The devices were created on top of a 100 mm, <100> oriented Si substrate, with the alignment designed for proper facet cleaving on the four edges of the chip. Six alternating dielectric layers of SiO_2 (n=1.47) and TA_2O_5 (n=2.107) were then sputtered over the whole wafer, by Evaporated Coatings Inc., to thicknesses of 265 nm and 102 nm respectively, forming the ARROW layer stack, which acts as the substrate in subsequent fabrication steps. The hollow optofluidic liquid core channels are 6 μm tall and start at a width of 12 μm near the fluid reservoirs placed at the corners of the chip. These channels then taper to a width of 6 μm near the trapping region. The total length of these fluid channels is 4.25 mm. The channels were formed by first defining them using standard lithography procedures for SU-8, and then hard baking the layers at a maximum temperature of 250^0C to withstand further processing. A self-aligned pedestal was defined by using reactive ion etching to etch through the sputtered ARROW stack and then approximately 3 μm deep into the underlying silicon substrate. The purpose of the pedestal is to improve the structural integrity of the hollow cores in the subsequent sacrificial etch process. Once the pedestal is defined, a 6 μm thick PECVD oxide layer was deposited over the wafer using a low stress deposition recipe to reduce potential core cracking. Excitation and collection waveguides were then patterned using typical lithography procedures involving a nickel hard mask and etched with an RIE etcher to create 3 μm tall rib waveguides. The rib waveguides are 5.6 μm wide and run from the chip edge to interface with the liquid core optofluidic waveguides. The original SU-8 cores used to define the liquid core structures were exposed at the corners of the chip by removing the oxide with buffered hydrofluoric acid. The wafer was then placed in a strong acid to remove the SU-8, hollowing out the liquid core channel. After completion of the microfabrication steps, individual chips were cleaved from the wafer to a size of 10 mm x 10 mm.

EXPERIMENTAL SETUP

At first, the laser (HeNe [633nm], Newport) light was split into four different paths using 50:50 beam splitters (Thorlabs) as shown in Fig. S1. After that, all the four paths were carefully sent through an optical chopper wheel (Thorlabs) to achieve the devised excitation pattern. The chopper wheel was operated by a chopper driver (Thorlabs) which was externally triggered (1 kHz square wave) using a function generator (Agilent). The chopper driver adjusts the wheel rpm in a way which optically modulates (on/off) all the four paths at the triggered frequency (1 kHz). However, due to the relative positions of the four paths at different chopper slots, Z_1 and Z_2 is alternately (180° out of phase) excited which is true for X_1 and X_2 as well. Moreover, the excitation pairs ($Z_{1/2}$ and $X_{1/2}$) are 90°shifted relative to each other. All the four modulated excitation

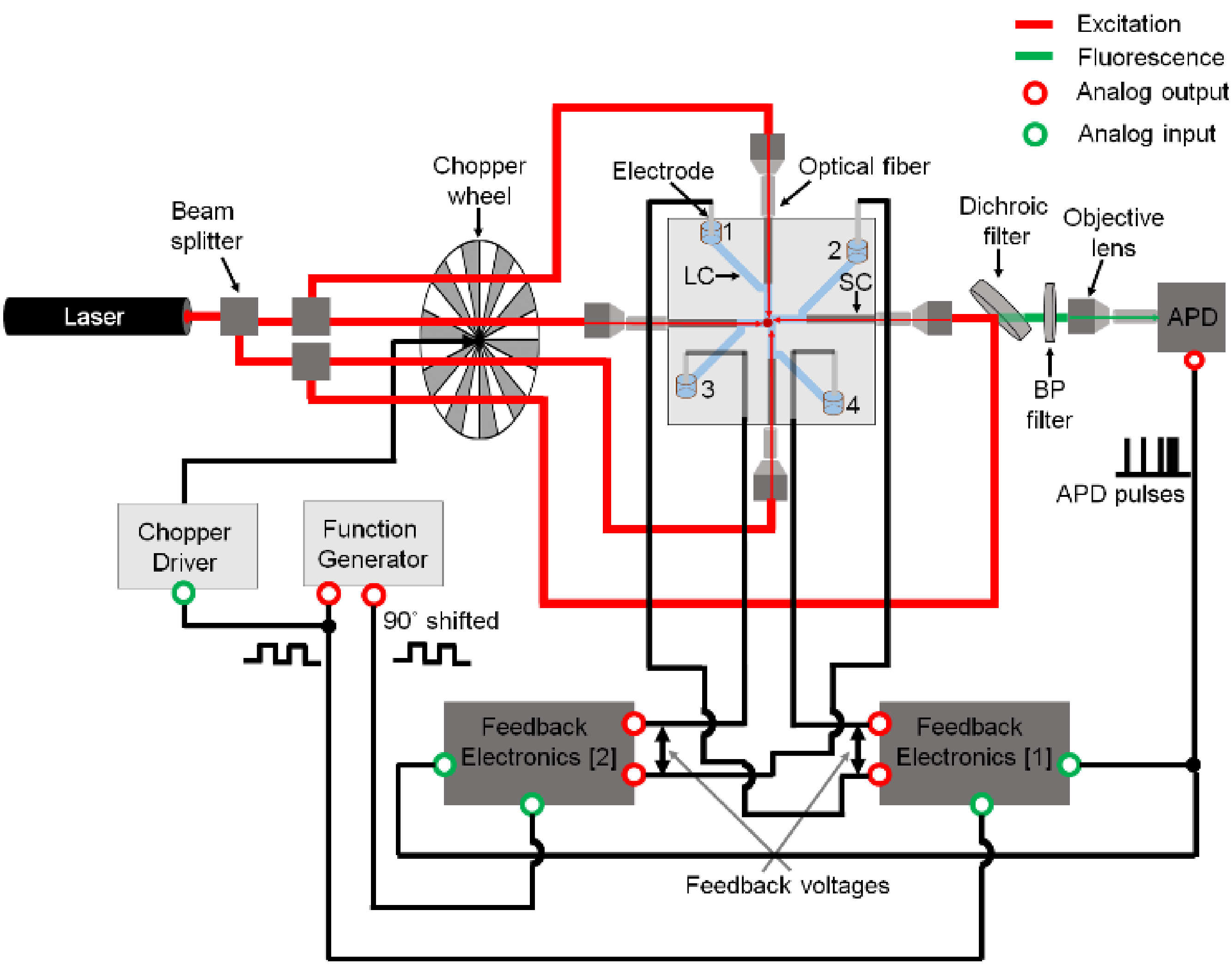

Fig. S1. Schematic of experimental setup for novel 2D ABEL trap.

light beams were then coupled into single mode fibers (Newport) to launch light into the device using objective lenses (Newport). One of the SC waveguide was used for both excitation and fluorescence collection using a dichroic filter as shown in Fig. S1. The fluorescence signal was further filtered using a BP filter (Omega Optical) and sent to the APD using connectorized multi-mode fiber (Thorlabs).

FEEDBACK CONTROL ELECTRONICS

Two identical electronic circuits (assembled in two different boxes) were used in this experiment to generate feedback voltages depending on the particle position. Each of the electronic boxes has two inputs which are the reference chopper signal and generated APD pulses. Based on the two inputs, the electronic boxes output feedback voltages which is applied to the device via Ag-AgCl electrodes immerged into the fluidic reservoirs. In this case, electronic box1 was synced with the combined excitation cycle of Z_1 and Z_2 and applies the feedback voltage across reservoirs 1and 4 which limits particle movement in X direction. In case of electronic box2, the reference chopper signal is nothing but a 90˚ shifted square wave (w.r.t the reference chopper signal of box1) generated using the function generator which mimics the actual optical modulation of X_1 and X_2. Electronic box2 applies the feedback voltage across reservoirs 2 and 3 which counteracts particle movement in Z direction. The APD signal was split and fed to both the electronic boxes using BNC cables and T splitter.

Each of the electronic boxes consists of an up/down counter, digital to analog converter (DAC) and amplifier stage. The functionality of the electronic boxes can be divided into three major sections. The first part is responsible to generate all the necessary timing signals to synchronize the chopper signal, counter and APD pulses. The second section comprises of an 8 bit counter (256 count levels) and DAC. The counter is initialized and set to the mid-point (127) which is referred as the base value. The counter counts up (adds up the number of incoming APD pulses) for the first half of the chopper cycle (Z_1/X_1) whereas counts down (subtracts the next incoming APD pulses) for the second half of the chopper cycle (Z_2/X_2). At the end of the chopper cycle, the counter sends the final counter value to the DAC which converts the digital counter value into corresponding analog value. The final component of the electronics is a low power voltage amplifier stage. This part amplifies the analog signal converted by the DAC. The electronic boxes facilitate user defined gain adjustment via a gain control knobs. Furthermore, the polarity and magnitude of the generated feedback voltage depends on the final counter status. If the end cycle counter value is greater than the base value ($C_X/C_Z>127$) then the electronic box generates a voltage of certain polarity which pushes the particle in a specific direction ("up" for box1, "right" for box2) whereas if the end cycle counter value is smaller than the base value ($C_X/C_Z<127$) then the electronic box generates a voltage of opposite polarity which pushes the particle in the opposite direction ("down" for box1, "left" for box2). The electronic boxes have polarity control switches which allows the user to manually correct the voltage polarity if necessary. The magnitude of the generated voltage is proportional to the relative difference between the final counter value and counter base value (abs [C_Z/C_X-127]). Additionally, the electronic boxes have an offset knob, an adjustment of which can compensate for unequal optical power within a SC waveguide pair (Z_1 and Z_2 for box1 whereas X_1 and X_2 for box2). At the very beginning of respective chopper cycles, each electronic box applies the feedback voltage and resets respective counter to their base value.