Hydrodynamic Metamaterials: Nanofabricated Arrays
to Steer, Refract and Focus Streams of Biomaterials

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Abstract:
We show that it is possible to direct particles entrained in a fluid along trajectories much like rays of light in classical optics. A nanostructured, asymmetric post array forms the core hydrodynamic element and is used as a building block to construct nanofluidic metamaterials and to demonstrate refractive, focusing and dispersive pathways for flowing beads and cells. The core element is based on the concept of deterministic lateral displacement where particles choose different paths through the asymmetric array based on their size: particles larger than a critical size are displaced laterally at each row by a post and move along the asymmetric axis at an angle to the flow, while smaller, sub-critical particles move with the flow. We create compound elements with complex particle handling modes by tiling the core element using multiple transformation operations: we show that particle trajectories can be bent at an interface between two elements and that particles can be focused into hydrodynamic jets using a single inlet port. Although particles propagate through these elements in a way that strongly resembles light rays propagating through optical elements, there are unique differences in the paths of our particles as compared to photons. The unusual aspects of these modular, nanofluidic metamaterials form a rich design toolkit for mixing, separating and analyzing cells and functional beads on-chip.

Summary of Research:
Generally the term metamaterial describes structured periodic features designed to achieve performance beyond that of conventional materials. Although typically defined in electromagnetics, we apply the broader definition to nanofluidics and design a nanostructured media that enables the motion of particles across non-mixing streamlines and along trajectories different from the bulk fluid flow. For example, two birefringent elements can be connected in series in order to change the angle of a particle’s trajectory through the metamedia. Alternatively, the $+\alpha$ and $-\alpha$ elements can be stacked to create a particle focusing element. If the $-\alpha$ element lies on top of the $+\alpha$ element, the new metamaterial element, denoted as $+F$, focuses particles—continuously creating a hydrodynamic particle jet. The $+F$ focusing element does not act as a lens, focusing particles to a single point, but instead focuses particles to a line. Particles above a critical radius will thus be actively focused to a line as they move down the channel, while those below a critical size will simply move unfocused. This characteristic is reminiscent of axicon optical elements used to create “non-diffracting” bessel beams over finite distances. Unlike light rays, which exit the focal line and continue on to project a ring for collimated incident light, particles in a focusing nanofluidic metamaterial element do not cross the centerline but continue forward entrained in the fluid flow. The $+F$ element is able to attain a rapid increase in local particle concentration along the centerline. The element demonstrates full removal of all bumping mode particles from the remaining flow and has potential applications for continuous flow concentration of rare biological species. Creating a hydrodynamic jet...
usually requires carefully balancing flows across three input channels, but using the focusing element we are easily able to concentrate particles into a jet from only a single inlet reservoir. The concentration is remarkably compact and is completed in distance of only \(5/2\) channel widths for the angle shown of \(\alpha = 1/5\).

This work was done in collaboration with Keith Morton, Jim Sturm and Steve Chou at Princeton University.