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Design principle for improved three-dimensional ac electro-osmotic pumps

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Three-dimensional (3D) ac electro-osmotic (ACEO) pumps have recently been developed that are much faster and more robust than previous planar designs. The basic idea is to create a "fluid conveyor belt" by placing opposing ACEO slip velocities at different heights. Current designs involve electrodes with electroplated steps, whose heights have been optimized in simulations and experiments. Here, we consider changing the boundary conditions—rather than the geometry—and predict that flow rates can be further doubled by fabricating 3D features with nonpolarizable materials. This amplifies the fluid conveyor belt by removing opposing flows on the vertical surfaces, and it increases the slip velocities that drive the flow.

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I. INTRODUCTION

Microfluidic pumps are crucial components of lab-on-a-chip systems. There is growing interest in exploiting various phenomena of induced-charge electro-osmosis (ICEO) [1,2] due to the lack of moving parts, favorable scaling with miniaturization, tunable local flow control, and low operating voltage suitable for portable or implantable devices. The most advanced technology of this type is based on ac electro-osmosis (ACEO) around micro-electrodes. ACEO was discovered by Ramos *et al.* [3–5], who described steady, time-averaged vortices over a pair of identical, co-planar electrodes applying an ac voltage. Ajdari [6] predicted that breaking spatial symmetry would generally lead to directional flows, and thus to microfluidic pumps. Based on this principle, the first ACEO pumps were built using arrays of asymmetric pairs of planar electrodes, according to the design of Brown, Smith, and Rennie [7,8].

Motivated by ICEO flows around three-dimensional (3D) metal structures [1,2,9], Bazant and Ben [10] predicted that the flow rate of ACEO pumps can be increased by more than an order of magnitude (at the same voltage and minimum feature size) by creating a "fluid conveyor belt" with arrays of nonplanar electrodes. This was validated experimentally by Urbanski *et al.* [11] using gold electrodes with electroplated steps. Current work has optimized the step height in simulations [12] and experiments [13] for this particular class of designs.

In this Rapid Communication, we predict that by modifying the boundary conditions, the fluid conveyor belt can be further amplified and the driving slip velocities increased. We begin by explaining the design principle in simple terms, building on the arguments of Bazant and Ben [10]. We then use the same simulation methods to validate the theory and predict improved robustness and doubling of the flow rate compared to current designs.

II. GROOVED DESIGNS

The motivation behind the discovery of 3D ACEO was to remove the competition between different slip velocities along electrode surfaces, as shown in Fig. 1. ACEO generally drives electro-osmotic slip in opposite directions along different sections of each electrode, and Ajdari's idea is to bias this competition so that one direction "wins." In planar pumps with asymmetric electrodes, symmetry is broken by making one electrode and one interelectrode gap in each pair wider than the other, thus generating slightly more slip in one direction. Though directionality is achieved, a portion of each electrode is "counteracting" in the sense that its surface slip is working against the net pumping [see Figs. 1(a) and 1(b)].

This competition is turned into cooperation in 3D ACEO pumps by raising the productive part of each electrode relative to the counteracting part. The vortices above the counteracting portions are then recessed relative to the bulk fluid. These are "rollers" in the fluid conveyor belt: their tops are moving in the direction of the pumping and are vertically aligned with the productive part of the electrode.

There is a problem with this design, however. Because the sides of the steps are polarizable, the adjacent fluid will have a significant double layer, and there will be a vertical electro-osmotic slip [Fig. 1(c)]. This slip acts *against* the sides of the rollers, slowing them down and reducing the effectiveness of the net pumping [Fig. 1(d)].

In the spirit of Ref. [10], we can improve performance by minimizing this new source of competition. In principle, we could eliminate the vertical slip altogether by making the sides of the steps (but not the tops) relatively nonpolarizable. This should then lead to a more effective fluid conveyor belt and better overall performance [see Figs. 1(e) and 1(f)].

This can be achieved experimentally, for instance, by building the entire step out of a nonpolarizable material and then depositing thin electrodes atop the step and in the recess. Alternatively, one might etch the recesses into the substrate rather than building the steps up from it. Regardless of the fabrication process, we shall henceforth refer to any system whose steps have nonpolarizable sides as "grooved," and any system whose steps have polarizable sides as "plated." Note that a grooved design was originally used to illustrate the fluid-conveyor-belt principle in the context of a fixed-potential ICEO pump [10], but it has never been applied to 3D ACEO pumps, in simulations or experiments. All work has focused on plated designs, and the competition between vertical slip velocities has not been recognized.

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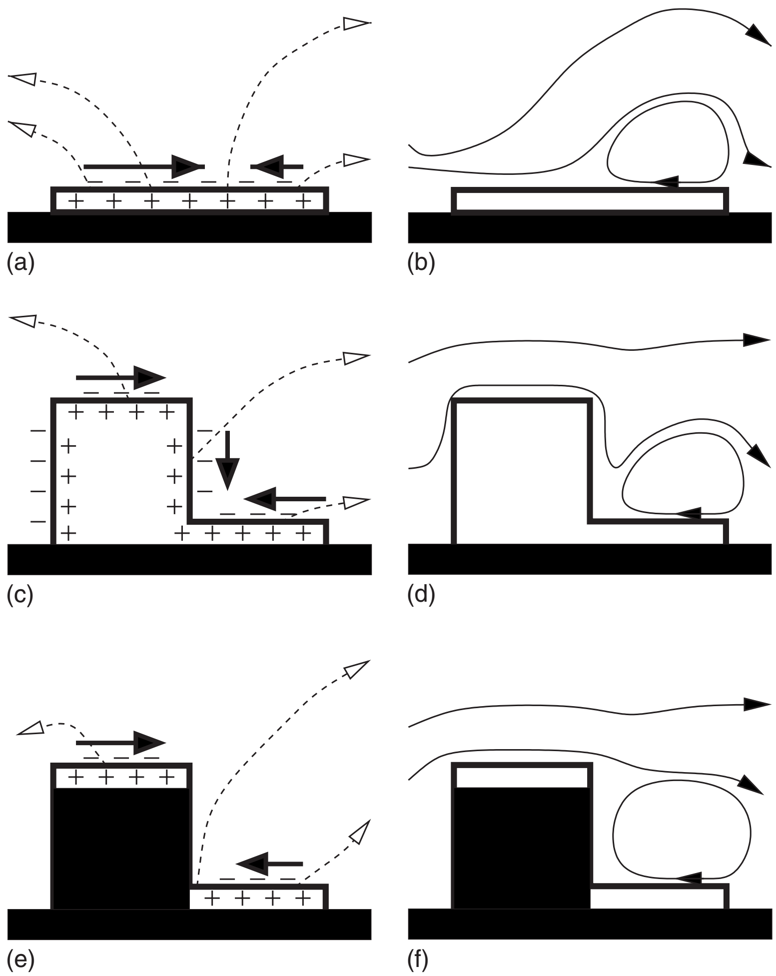

FIG. 1. Design principles for ACEO pumps, shown in 2D cross section. Left: typical in-phase electric field lines (dashed lines) and slip velocities (thick arrows) around one electrode in a periodic array. Right: time-averaged streamlines (solid curves). Top row (a),(b): one electrode in an asymmetric planar array, showing the competition between opposing slips. Middle row (c),(d): the existing "plated" 3D design, which creates a fast fluid conveyor belt. Bottom row (e),(f): our faster "grooved" design, where the electrode is broken into two flat, electrically connected parts, thereby removing counterproductive slip on the side wall.

We have seen how grooved designs offer greater efficiency in the sense that there is less counteractivity in the fluid flow. However, they also offer greater forcing in the form of higher average slip velocities along the raised electrodes. This results from stronger electric fields near the top-left edges of the electrodes, which is precisely where most of the slip is generated.

To explain this difference, we refer again to Figs. 1(c) and 1(e) (though readers might wish to consult Fig. 2 to better visualize the geometry of an electrode pair). In the grooved design, the shortest distance between two electrodes is between the right edge of the recessed part of the left electrode and the left edge of the raised part of the right electrode. In the plated design, the shortest distance is much smaller as the bottom of the vertical side of the right step is itself part of the electrode. However, as a consequence, the *important* electric field lines in the plated design are longer: those starting at the left edge of the raised part of the right electrode must reach much further into the left electrode before terminating.

Thus the important electric fields in the grooved design are stronger because their field lines are shorter. This has another important consequence: the time dependence for ACEO flows is controlled by the dominant time scale for diffuse-layer charging at the driving electrode surfaces. This is given by $\tau = \lambda L / D$ [14], where L is the length of the electric field lines at the driving surfaces (λ is the Debye screening length and D is an ionic diffusion constant). The grooved design will therefore have a shorter characteristic time scale, and so its optimal frequencies will be higher than those of the plated design.

III. NUMERICAL SIMULATIONS

For numerical work, we employ the low-voltage, thin-double-layer model that has become standard in ACEO studies [4–6,9,13] and has been found to predict qualitative trends seen in experiments [9,11,13]. We solve the time-averaged equations [5,13] for the steady response to a periodic driving potential $Ve^{i\omega t}$ (where successive electrodes are 180° out of phase). The polarizable electrode surfaces are modeled as completely blocking (i.e. there are no Faradaic reactions), and all other surfaces are modeled as perfectly insulating. The pump is assumed to consist of a long, linear array of identical electrodes, so periodic boundary conditions surrounding a single electrode pair are employed. The resulting equations are solved using the commercial finite element package COMSOL Multiphysics 3.2b (COMSOL, Burlington, MA). To focus on the impact of boundary conditions on the side walls, we study only the simplest geometry in which the electrode half-widths and interelectrode gaps all have the same length. This is not a drastic restriction since we still achieve pumping velocities that are within a few percent of those generated by the optimal geometries found by Olesen using the same model [12].

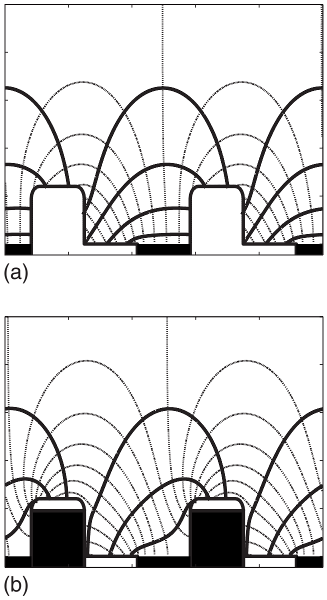

FIG. 2. Numerical solutions of the electrical equations for identical plated (a) and grooved (b) geometries. The thin, dotted curves are equally spaced ($0.1V$ apart, where V is the peak applied voltage) contours of the in-phase potential; thick, solid curves are representative electric field lines. Each case was simulated at its respective optimal driving frequency. The electrode corners are rounded for improved convergence.

One set of numerically computed electric fields and fluid flows are shown in Figs. 2 and 3, and the results are as predicted in Sec. II. The grooved design has stronger electric fields along the raised electrodes, resulting in 60% stronger average slip velocities. Moreover, the grooved design does not suffer the strong "dip" seen in the streamlines of the plated design. The two effects combine to yield average pumping velocities that are about twice as fast. This is not as dramatic as the difference between stepped and flat geometries, but is still quite significant.

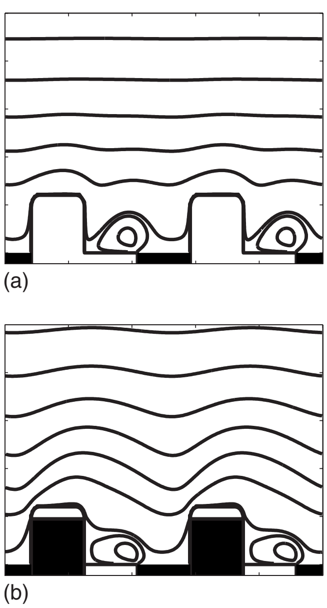

FIG. 3. Numerical solutions of the time-averaged fluid flow equations for the plated (a) and grooved (b) designs from Fig. 2. The curves are time-averaged streamlines.

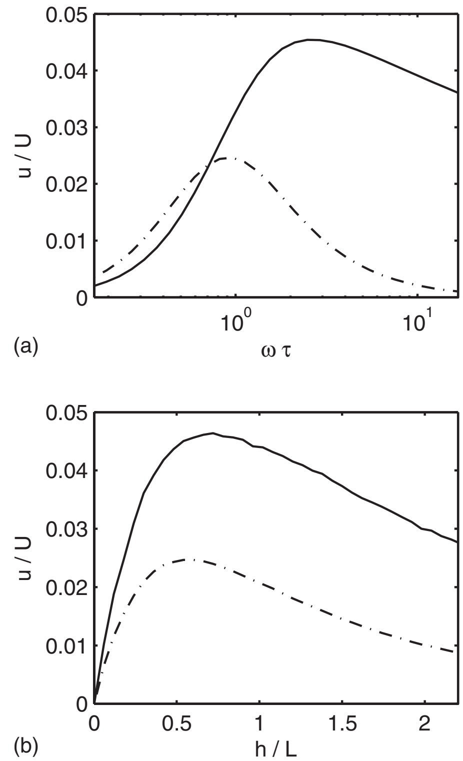

FIG. 4. The dependence of the simulated average pumping velocity on ac frequency ω (a) and step height h (b) for the grooved (solid curves) and plated (dotted curves) designs shown in Fig. 3. We follow standard practice [10,13] in nondimensionalizing lengths using the minimum electrode gap width L, frequencies using the inverse $1/\tau$ of the RC time defined earlier, and velocities using $U = \epsilon V^2/\eta L$ (ϵ is the solution's permittivity, V is the peak electrode voltage, η is the dynamic viscosity).

Figure 4 shows the results of two brief, parametric studies. They clearly demonstrate that across a wide range of step heights and driving frequencies, the grooved design is significantly faster. Moreover, as predicted at the end of Sec. II, we see that the ideal operating frequencies are higher in the grooved case. Indeed, when the frequency is plotted on a logarithmic scale [Fig. 4(a)], the shorter characteristic time scale causes the grooved velocity curve to be shifted to the right. This results in a crossover frequency below which the plated design is faster. However, this occurs well below the optimal frequencies, so is unlikely to be important in practice.

Figure 4(a) also reveals another important advantage of the grooved design: its performance curve is much less sharply peaked around its optimal operating frequency than that of the plated design. This can be explained in terms of the flow efficiency. At high frequencies, only the double layers near the edges of the electrodes have time to charge, so these will be the only places with significant slip velocities. The left edge of the raised portions of the electrodes will still generate more positive slip in the grooved design because, as described above, the corresponding electric field lines are shorter. However, the same reasoning (and Fig. 2) allows us to conclude that the electric field lines emanating from the right edge of the recessed parts of the electrodes will be *longer* in the grooved case, leading to weaker negative slip. The bigger negative slips and smaller positive slips in the plated design lead to much bigger vortices which reach well above the electrodes. This impedes the bulk fluid flow, drastically reducing the efficiency. In contrast, the flow in the grooved designs look very similar at high and low frequencies. Note that this may help to reduce the poorly understood flow reversal that can sometimes be observed in plated designs [11,13].

This difference in the sharpness of the performance curves suggests that the grooved design is more robust and may be less sensitive to geometric or electrical changes in operational systems. This is especially important since the physics behind ACEO is not completely understood, so our theoretical predictions for optimal geometries and driving frequencies need to be checked experimentally as in [13].

Finally, note that the streamlines in Fig. 3 are more curved above the grooved electrodes than above the plated electrodes, giving the impression that the plated design might gain an advantage in very narrow channels. However, the grooved design always maintains a significant advantage in slip velocity and minimized slip competition. Further numerical work shows that the grooved design remains about twice as fast as the corresponding plated design across the entire range of channel heights.

IV. CONCLUSION

We have predicted that altering the fabrication process for 3D ACEO pumps can have a major effect on the fluid-conveyor-belt mechanism and the driving slip velocities. In particular, designs whose 3D features have nonpolarizable vertical sides should outperform those with polarizable side walls. We have explored this hypothesis numerically and have found that the grooved design could potentially double the pumping velocity of existing plated devices. The improved performance comes without having to increase the applied voltages, while at the same time being more robust to engineering and prediction errors. Our design principle could therefore have a significant impact on various lab-on-a-chip applications.

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