Electronic Supplementary Information

Field-Effect Pump: Liquid Dielectrophoresis along a Virtual Microchannel with Source-Gate-Drain Electric Fields

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Video S1: Field-effect pumping

Video of Fig. 2(a)-2(h) showing repeatedly pumping of the liquid back and forth between the source and drain electrodes along a virtual microchannel with the dimensions of (L, W, H) = (1500, 50, 50 μm) and the pumping voltage set of (V_S, V_G, V_D) = (45, 100, 85 V). The video is played at 2x speed.

Video S2: Narrowing and tapering of the virtual microchannel with insufficient ΔE^2_{GD}

Video of Fig. 3(a) and 3(b) showing receding of the liquid boundary of a virtual microchannel (designed dimensions of (L, W, H) = (1500, 50, 50 μm)) from the gate electrode boundary because of the insufficient ΔE^2_{GD} with the pumping voltage set of (V_S, V_G, V_D) = (45, 70, 85 V).

Video S3: Repeated pinch-off and replenishment with insufficient ΔE^2_{GD} and large ΔE^2_{DS}

Video of Fig. 3(e) and 3(f) showing repeated pinch-off and replenishment of a virtual microchannel (designed dimensions of (L, W, H) = (1500, 50, 50 μm)) because of the insufficient ΔE^2_{GD} and great ΔE^2_{DS} with the pumping voltage set of (V_S, V_G, V_D) = (45, 100, 230 V). The video is played at 0.5x speed.

Table S1 Field-effect pumping parameters and values along a virtual microchannel with various dimensions and V_D using fixed (V_S, V_G) = (45, 100 V).

L (μm)	W (μm)	H (μm)	V_D (V)	ΔE^2_{DS} (V^2/μm^2)	$\Delta P_{LDEP,DS}$ (Pa)	Q (nL/s)	**Velocity** (mm/s)	**Re**	R (Pa·s/nL)	R_{hyd} [a] (Pa·s/nL)
1000	50	50	65	0.88	301.8	105.0	42.0	2.35	2.87	1.92
			75	1.44	493.8	182.5	73.0	4.08	2.71	
			85	2.08	713.3	259.2	103.7	5.80	2.75	
1500	50	50	65	0.88	301.8	61.5	24.6	1.38	4.91	2.88
			75	1.44	493.8	113.2	45.3	2.53	4.36	
			85	2.08	713.3	154.3	61.7	3.45	4.62	
2000	50	50	65	0.88	301.8	45.6	18.2	1.02	6.62	3.84
			75	1.44	493.8	80.5	32.2	1.80	6.13	
			85	2.08	713.3	117.0	46.8	2.62	6.10	
2000	50	25	65	3.52	1207.1	13.4	10.7	0.40	89.87	30.72
			75	5.76	1975.3	25.7	20.5	0.77	76.92	
			85	8.32	2853.2	36.4	29.1	1.09	78.41	
2000	50	75	65	0.39	134.1	81.2	21.7	1.45	1.65	1.14
			75	0.64	219.5	127.1	33.9	2.27	1.73	
			85	0.92	317.0	179.0	47.7	3.20	1.77	
2000	100	50	65	0.88	301.8	70.8	14.2	1.06	4.26	1.92
			75	1.44	493.8	117.5	23.5	1.75	4.20	
			85	2.08	713.3	168.7	33.7	2.52	4.23	
2000	150	50	65	0.88	301.8	86.7	11.6	0.97	3.48	1.28
			75	1.44	493.8	153.6	20.5	1.72	3.22	
			85	2.08	713.3	222.0	29.6	2.48	3.21	

[a] $R_{hyd} = \frac{12\mu L}{WH^3}$ when neglecting side walls [28].

Pumping pressure $\Delta P_{LDEP,DS}$

The configuration of the designed FEP is shown in Fig. S1. Assuming the liquid (droplet) was initially filled the rectangular source electrode (between 0 and 3). The liquid was then pumped into the gate electrode (between 1 and 4). The gate electrode area A_G is equivalent to $W_S L_1$. The liquid was subsequently pumped a distance x into the drain electrode (between 2 and 5). The cross-sectional view of the device shows the silicone oil (surrounding medium with relative permittivity ε_M) and pumped liquid (relative permittivity ε_L) between the parallel plates. The FEP can be considered as two liquids in three capacitors. The voltage drop mainly occurs across the liquids for every capacitor. The source capacitance includes the capacitance of surrounding medium in the source field C_{SM} and the capacitance of pumping liquid in the source field C_{SL}. The gate capacitance is C_G. The drain capacitance includes the capacitance of surrounding medium in the drain field C_{DM} and the capacitance of pumping liquid in the drain field C_{DL}. The total electric energy U of the system is:

$$U = \frac{1}{2}(C_{SM} + C_{SL})V_S^2 + \frac{1}{2}C_G V_G^2 + \frac{1}{2}(C_{DL} + C_{DM})V_D^2$$

$$= \frac{1}{2}\left(\frac{\varepsilon_o \varepsilon_M W_S (L_1 + x)}{H} + \frac{\varepsilon_o \varepsilon_L W_S (L_S - L_1 - x)}{H}\right) V_S^2 + \frac{1}{2}\frac{\varepsilon_o \varepsilon_L A_G}{H} V_G^2 + \frac{1}{2}\left(\frac{\varepsilon_o \varepsilon_L W_D x}{H} + \frac{\varepsilon_o \varepsilon_M W_D (L_D - x)}{H}\right) V_D^2. \quad \text{(S1)}$$

Using the virtual work theorem with W_S equals W_D, the pumping force $F_{LDEP,DS}$ is given by:

$$F_{LDEP,DS} = \frac{\partial U}{\partial \mathrm{x}} = \frac{\varepsilon_o (\varepsilon_L - \varepsilon_M) W_D}{2H} V_D^2 - \frac{\varepsilon_o (\varepsilon_L - \varepsilon_M) W_S}{2H} V_S^2 = F_D - F_S = \frac{\varepsilon_o (\varepsilon_L - \varepsilon_M) W_D}{2H} (V_D^2 - V_S^2). \quad \text{(S2)}$$

The pressure difference between the source and the drain provides the pumping pressure $\Delta P_{LDEP,DS}$ that can be expresses as:

$$\Delta P_{LDEP,DS} = P_{L,S} - P_{L,D} = \frac{F_D - F_S}{W_D H} = \frac{\varepsilon_o (\varepsilon_L - \varepsilon_M)}{2} (E_D^2 - E_S^2) = \varepsilon_{LDEP} \Delta E^2{}_{DS}. \quad \text{(S3)}$$

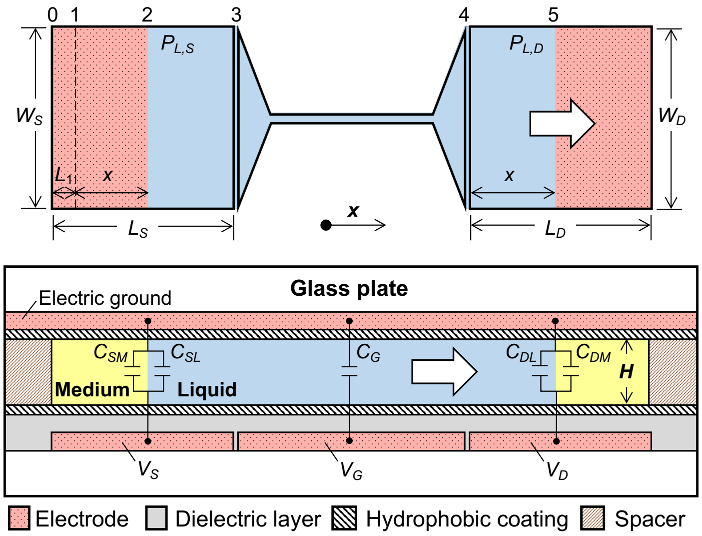
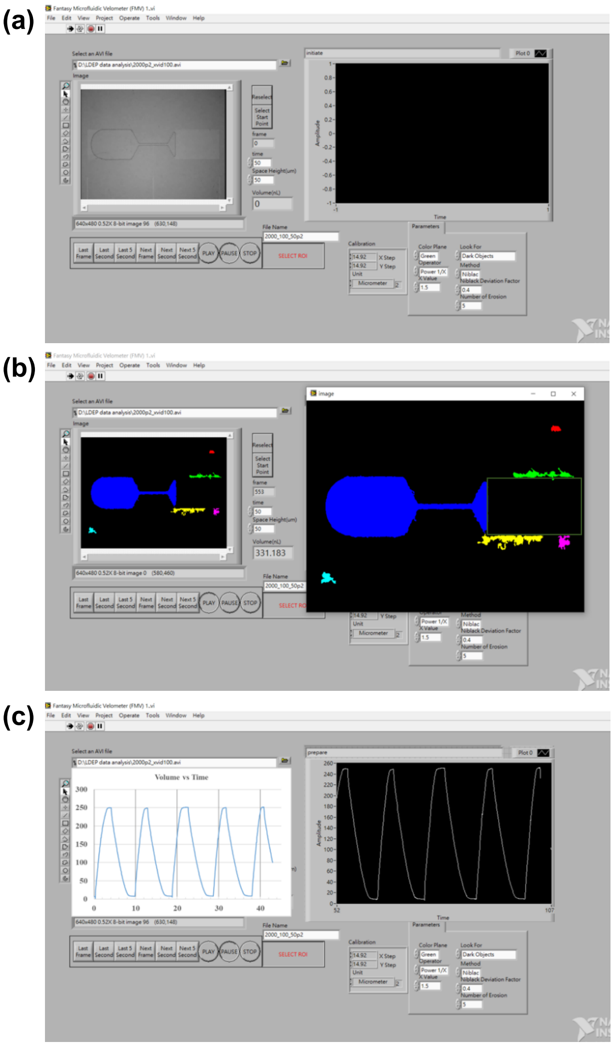


Fig. S1 Configuration of the designed FEP for pumping pressure $\Delta P_{LDEP,DS}$ derivation.

Analysis of flow rate *Q*

The recorded video AVI files were analyzed with a LabVIEW software we developed with the NI Vision Assistant module (National Instruments) as shown in Fig. S2. As shown in Fig. S2(a), in the software window, we first imported a video for analysis and also entered some key parameters, including the gap size between parallel plates, counting time and file name of the exporting excel spreadsheet. We then selected the desired counting area (region of interest), shown as a green rectangle covering the drain area in Fig. S2(b), for computing the liquid volume variation in the drain and started the program. The user can choose either drain or source area to compute the liquid volume variation.



(a)

Select an AVI file: D:\LDEP data analysis\2000p2_xvid100.avi
initiate
frame: 0
time: 50
Space Height(um): 50
Volume(nL): 0
640x480 0.52X 8-bit image 96 (630,148)
File Name: 2000_100_50p2
Calibration: 14.92 X Step, 14.92 Y Step
Unit: Micrometer 2
Color Plane: Green
Operator: Power 1/X
X Value: 1.5
Look For: Dark Objects
Method: Niblac
Niblack Deviation Factor: 0.4
Number of Erosion: 5

(b)

Select an AVI file: D:\LDEP data analysis\2000p2_xvid100.avi
frame: 553
time: 50
Space Height(um): 50
Volume(nL): 331.183
640x480 0.52X 8-bit image 0 (580,460)
File Name: 2000_100_50p2
14.92 Y Step
Unit: Micrometer 2
Power 1/X
X Value: 1.5
Method: Niblac
Niblack Deviation Factor: 0.4
Number of Erosion: 5

(c)

Select an AVI file: D:\LDEP data analysis\2000p2_xvid100.avi
prepare
640x480 0.52X 8-bit image 96 (630,148)
File Name: 2000_100_50p2
Calibration: 14.92 X Step, 14.92 Y Step
Unit: Micrometer 2
Color Plane: Green
Operator: Power 1/X
X Value: 1.5
Look For: Dark Objects
Method: Niblac
Niblack Deviation Factor: 0.4
Number of Erosion: 5

Fig. S2 LabVIEW software developed with the NI Vision Assistant module (National Instruments) to analyze the flow rate *Q* from the recorded video AVI files. (**a**) Importing file and inputting parameters. (**b**) Selecting region of interest for volume variation analysis. (**c**) Exporting data and plot.

After analyzing the imported video, the software generated an Excel file and a plot of the pumping volume versus time as shown in Fig. S2(c). In this example, there were five pumping cycles in the imported video and the slope of every rising segment of the curve represented the flow rate Q of the liquid flowing into the drain reservoir. The average volume flow rate is calculated by averaging all the volume flow rates.

FEP wiring

The wiring configuration of the designed FEP is shown in Fig. S3. The wiring electrodes were connected to the electrodes via a narrow region as a flow stopper adjacent to the electrodes. The width of the narrow region should be minimized to increase the aspect ratio of the local electric field for a reduced LDEP force to avoid liquid pumping on the wiring electrodes [18]. In our design, the narrow region with a width of 15 μm was small enough to efficiently stop the liquid flow toward the connecting wires whereas supplying adequate voltage to the thin gate electrode (widths 50, 100 and 150 μm). Because the gate electrode had the greatest voltage, the position of the narrow region may influence the geometry of the virtual microchannel. As shown in Fig. S3, when the connecting wire connects the gate electrode from the center (shown 1), the virtual microchannel may slightly deform at the narrow region. The concern can be addressed by placing the narrow region at the converging (shown 2) or diverging (shown 2’) portion.

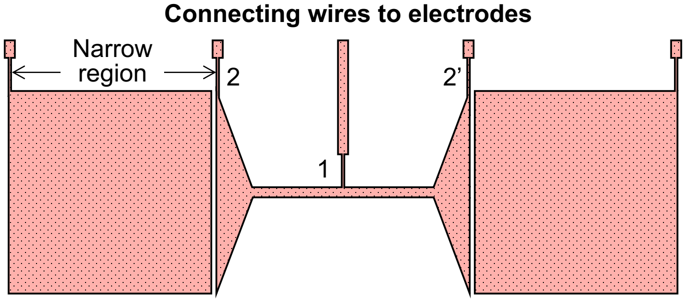


Fig. S3 Wiring configuration of the designed FEP. The connecting wires providing driving voltage to the electrodes with a narrow region as a flow stopper adjacent to the electrodes to prevent liquid pumping toward the connecting wires. For the gate electrode, the connecting wire can be placed at the center (shown 1) or at the conversion or the diversion portion (shown 2 or 2’).