COMSOL CONFERENCE 2017 BOSTON

Liquid Microlens with Adjustable Focusing and Beam Steering for Single Cell Optogenetics

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MEMS and Nanotechnology 2

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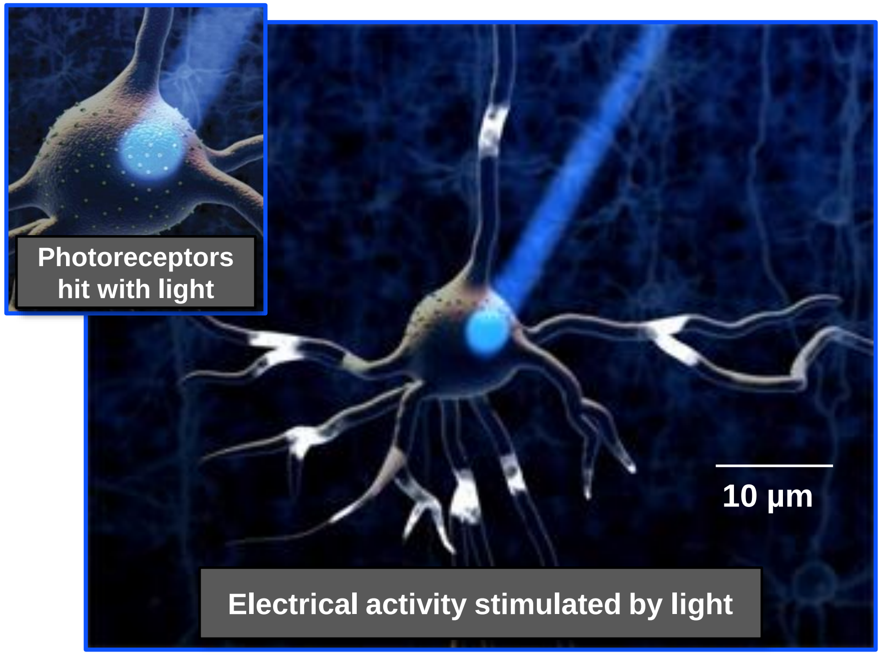
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Motivation and Program Goal

Optogenetics

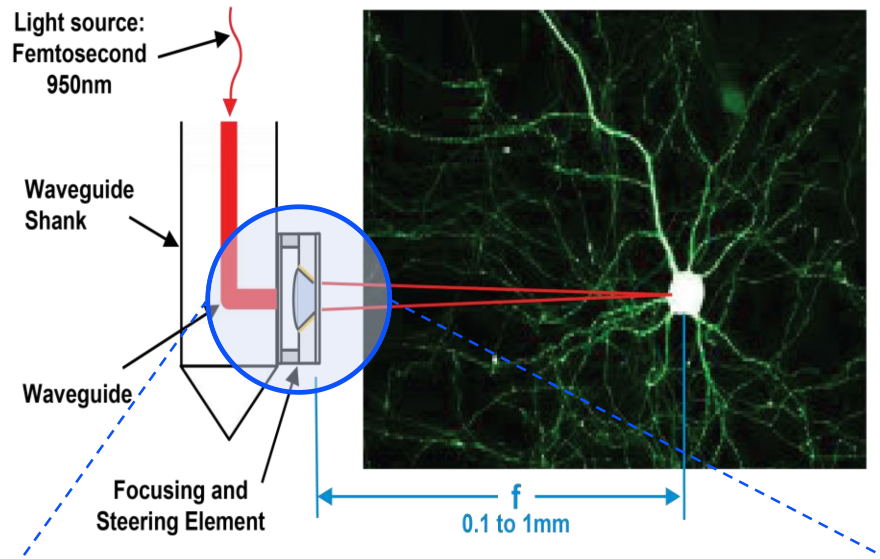
- Electrical activity in neurons stimulated by light



Synthetic Neurobiology Group – Prof. Boyden (MIT)

One of the technology challenges is delivering light down into the brain and enabling single cell resolution

Develop an implantable optical probe with integrated focusing and steering optics



- Initial work on developing an active focusing and steering optical element
  - Focal range: 0.1 – 1 mm
  - Ability to steer over ±5°
  - Focus light to spot ≤10 µm

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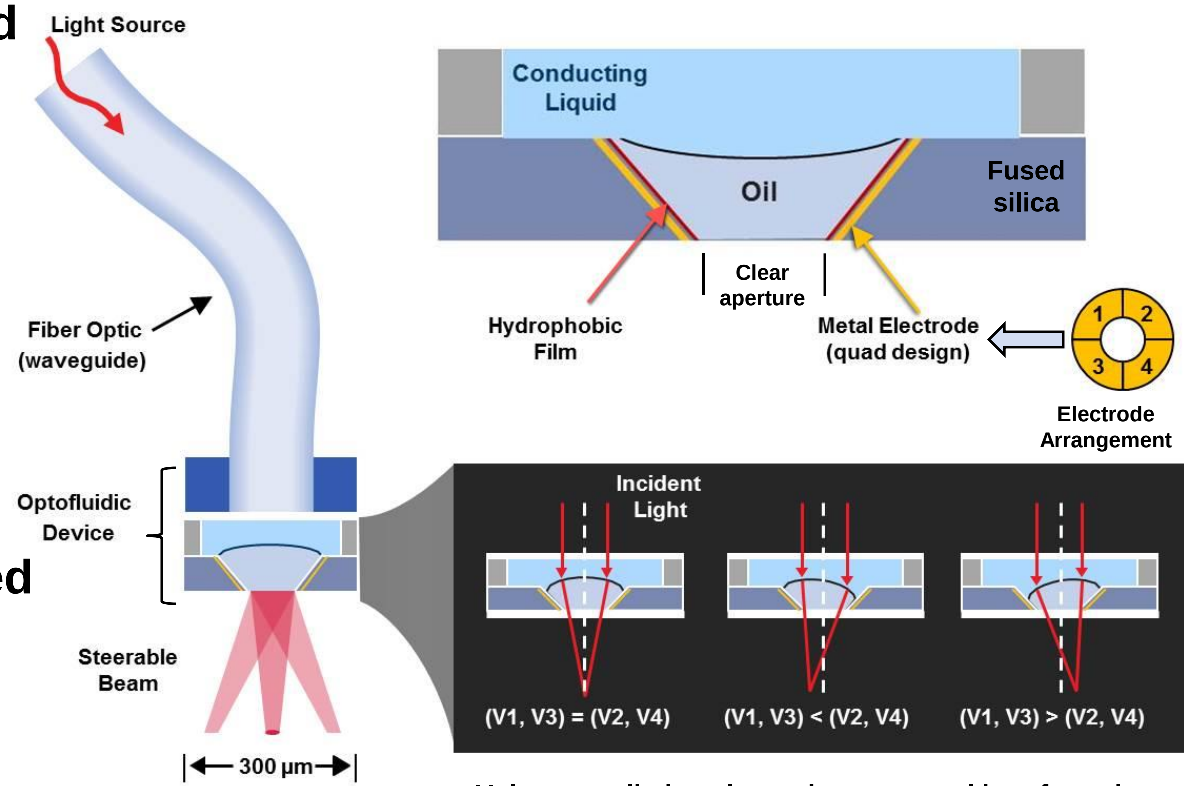
Development of Active Optofluidic Device

- **Integrating focus and steering into single micron-scale liquid lens**
  - Liquid lens formed by interface between two immiscible liquids
  - Electrical control of meniscus shape (Electrowetting)
  - Focus results from different refractive indexes ($n_{oil} > n_{water}$)
- **Beam steering resulting from conical taper etched into fused silica substrate**
  - Quadrupole electrode arrangement along taper wall
  - Geometry allows for the liquid interface to tilt

Liquid Lens Design



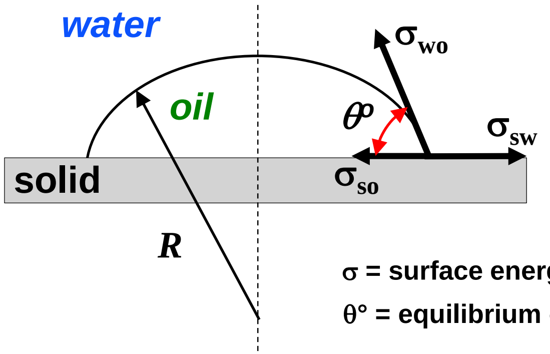
Voltage applied to electrodes to control interface shape

Design provides both focusing and steering in a single optical element

Liquid Lens Interface Physics

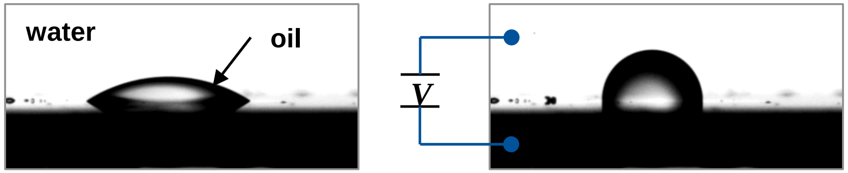
- **Equilibrium drop shape:**
  - Young's eq. $$\sigma_{wo} \cos\theta^0 = \sigma_{sw} - \sigma_{so}$$
  - In-plane radius of curvature
    - $R \rightarrow f(\theta, \sigma_{wo})$
- **Electrowetting:**
  - Wetting properties at the liquid/solid interface modified from an applied electrical field
$$\sigma_{sw}(V) = \sigma_{sw_1} - \frac{1}{2}CV^2$$
- **Goal is to determine R as $f(V)$**
- **Use Numerical simulations to solve:**
  - Equilibrium shape of the liquid interface profile
    - function of voltage and lens cavity geometry

Equilibrium



σ = surface energy (mJ/m²)
θ° = equilibrium contact angle

Electrowetting actuation

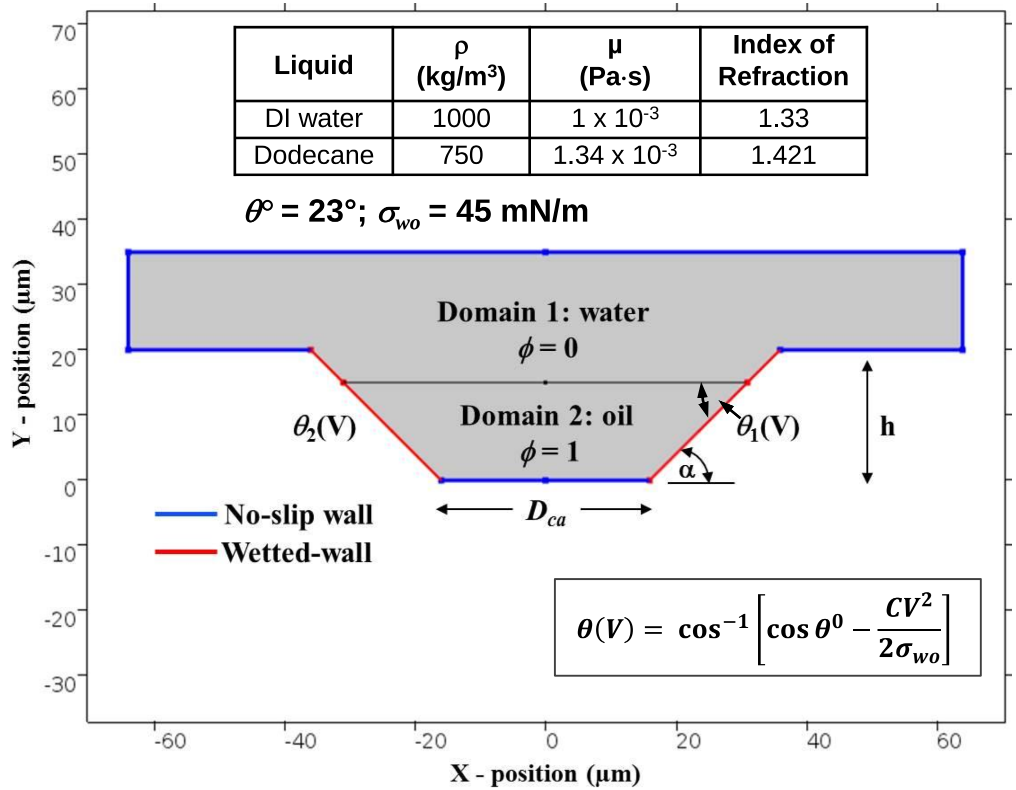


Electrowetting Equation
$$\theta(V) = \cos^{-1}\left[\cos\theta^0 - \frac{CV^2}{2\sigma_{wo}}\right]$$

C= capacitance per unit area
V = voltage

COMSOL Numerical Model

- **Physics:**
  - **2D-Fluid Flow-Multiphase-Laminar two-phase flow-Level set**
    - **Fixed mesh method**
    - **Interface tracked w/additional transport equation**
- **Geometry defined by:**
  - **D_{ca}: clear aperture diameter**
  - **α: taper angle**
  - **h: taper cavity height**
- **Two geometric domains**
  - **Domain 1**
    - **Assigned properties for water**
    - **Level-set function $\phi = 0$**
  - **Domain 2**
    - **Assigned properties for oil**
    - **Level-set function $\phi = 1$**
- **Boundary conditions**
  - **No-slip wall**
    - **for all exterior walls except walls that form taper cavity**
  - **Define $\theta(V)$ at taper walls**



Liquid	ρ (kg/m³)	μ (Pa·s)	Index of Refraction
DI water	1000	1×10^{-3}	1.33
Dodecane	750	1.34×10^{-3}	1.421

θ^o = 23°; σ_{wo} = 45 mN/m

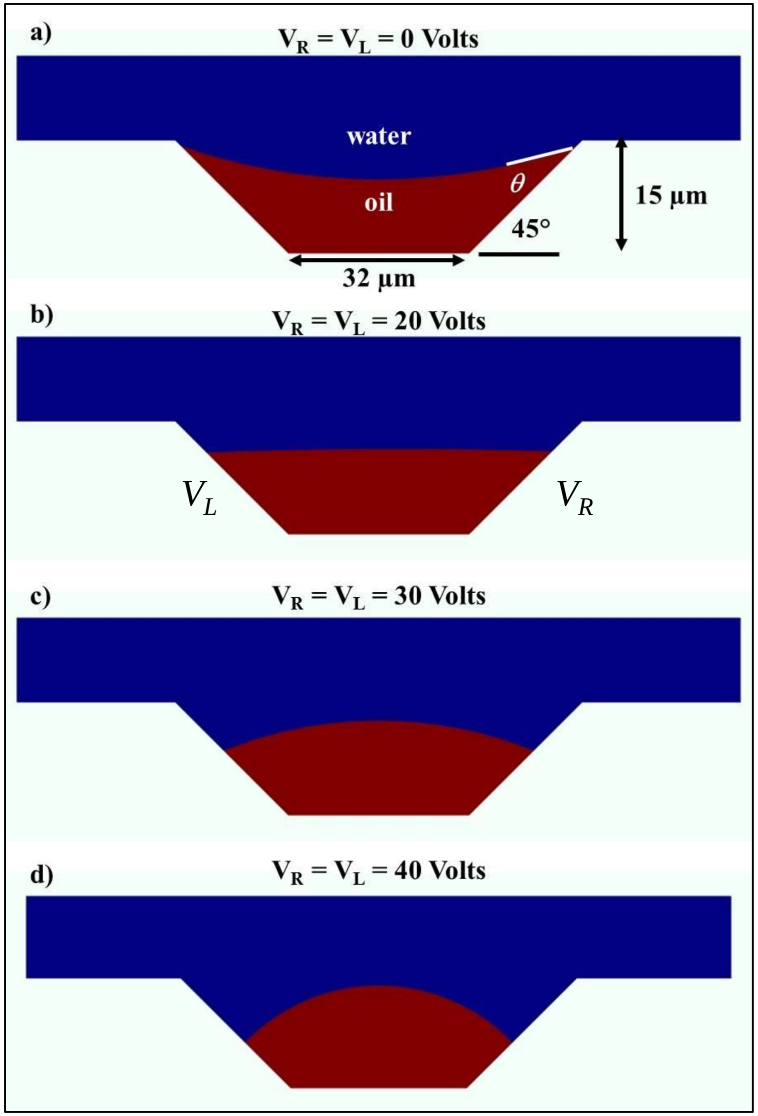
$$\theta(V) = \cos^{-1}\left[\cos\theta^0 - \frac{CV^2}{2\sigma_{wo}}\right]$$

Dielectric material properties

Solid	ε	t (nm)
SiO_2	3.9	500
Hydrophobic film	2.1	85

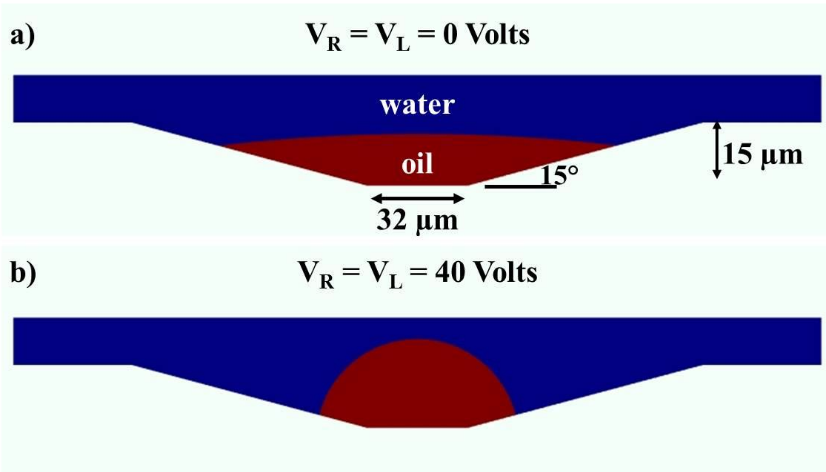
Simulation Results for Uniform Voltages

- **Model parameters**
  - D_{ca} = 32 µm
  - α = 45°
  - h = 15 µm
  - Voltage sweep = 0 – 40 V
    - $V_L = V_R$
  - $\theta°$ = 23°
  - σ_{wo} = 45 mN/m
- **Results:**
  - Contour plots for volume-of-fraction data, *vof* = 0.5
  - Liquid interface is concaved at 0 V
    - Liquid lens has negative optical power
  - Liquid interface becomes convex (positive) at ~18 V
  - Working voltage range from 18 to 40 V



Comparing Different Lens Cavity Geometries

$\alpha = 15°$

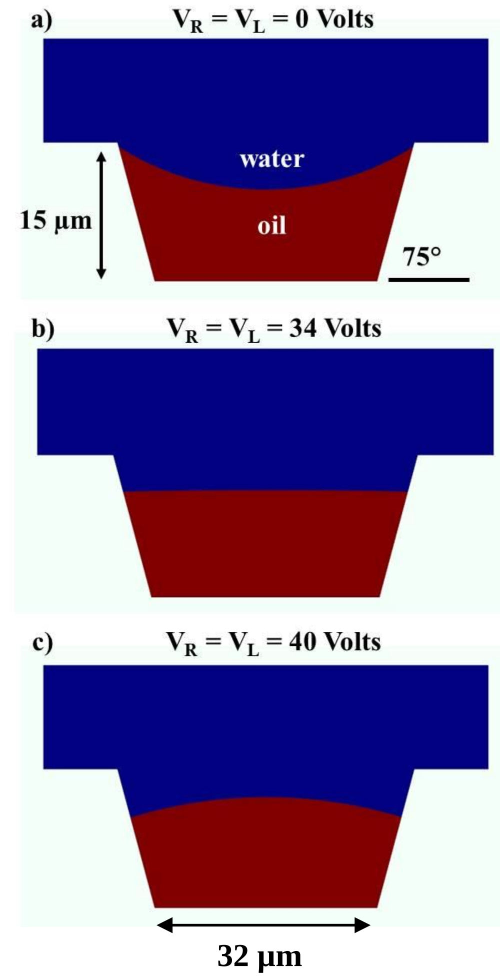


- **Liquid interface convex at 0 V for 15° taper design**
  - **Lens will have always positive optical power**

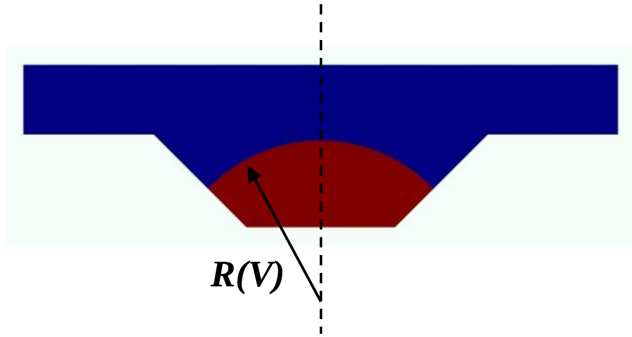
Taper Angle α	Voltage for Positive Optical Power	Voltage Dynamic Range (ΔV)
15	0	40
45	18	22
75	34	6

When $\alpha \leq \theta°$ liquid lens will always be a focusing element

$\alpha = 75°$



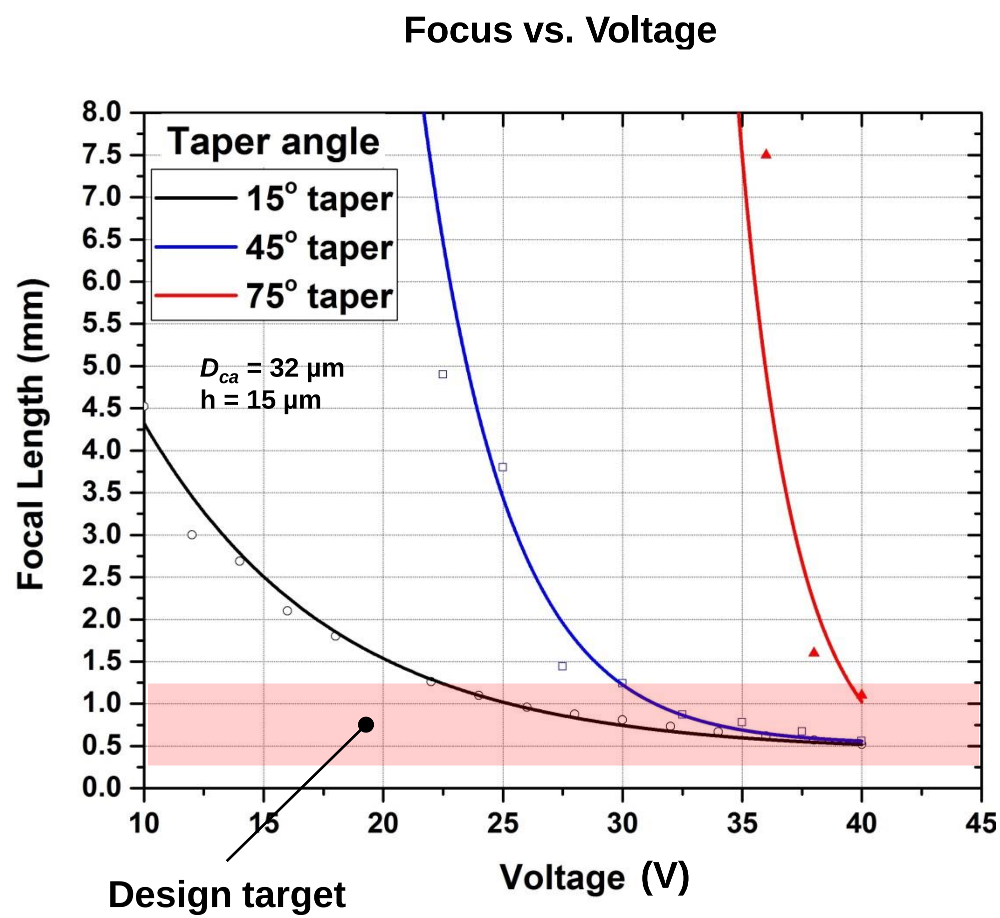
Determine Focus vs. Voltage



- *R(V)* determined from volume of fraction data (*vof*)
- Focal length calculated using Lens Maker Eq.

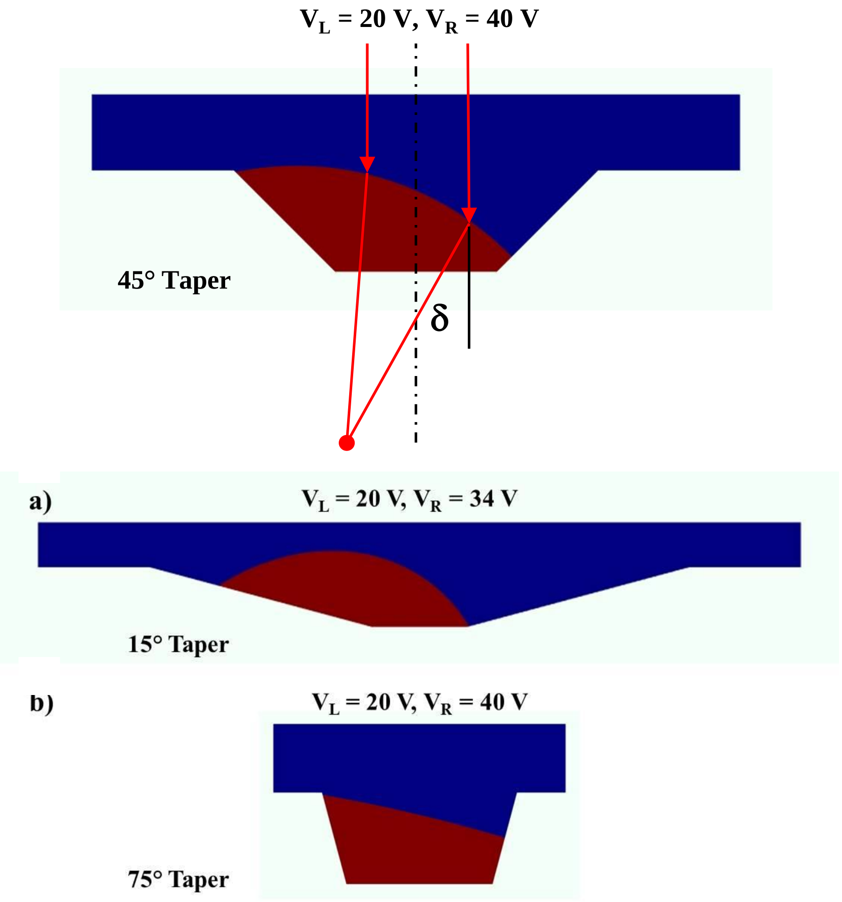
$$\frac{1}{f} = \frac{n_o - n_w}{n_w}\left(\frac{1}{R(V)}\right)$$

- Parameters for tuning focus length:
  - Lens geometry
  - Liquids (index of refraction)
  - Voltage (electrowetting effect)

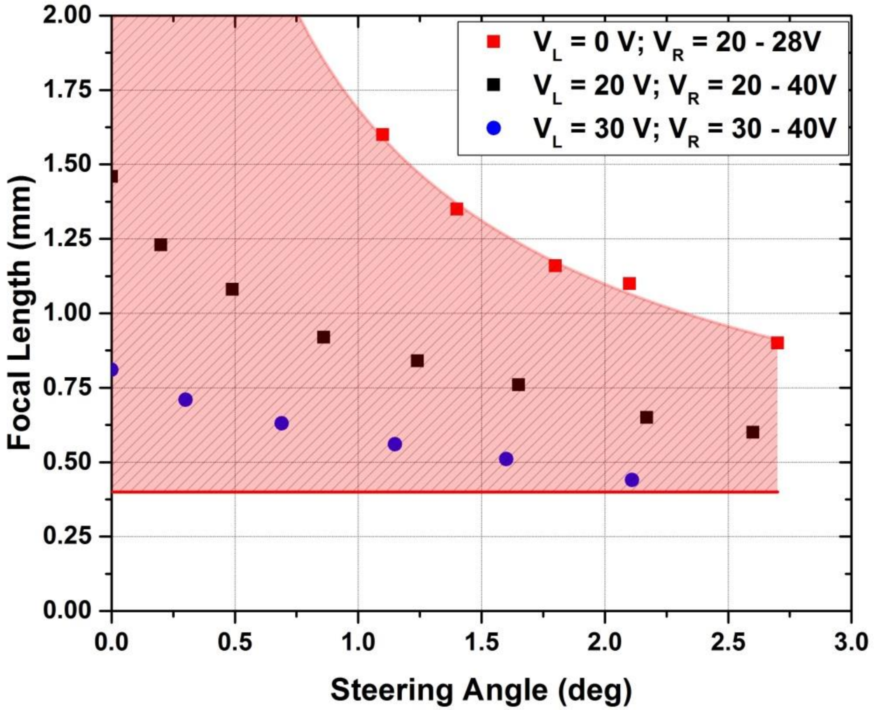


Beam Steering

- **Appling different voltages to each side wall results in liquid interface tilting**



- **Focus and steering map for:**
  - D_{ca}: 32 µm
  - α: 15°
  - h: 15 µm

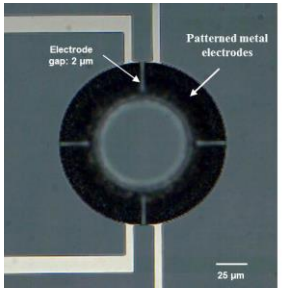


- **2.7° steering angle translates to ~24 µm focal spot shift**

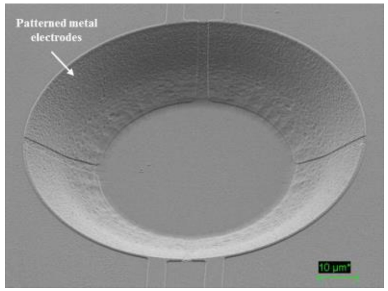
Experimental vs. Simulation

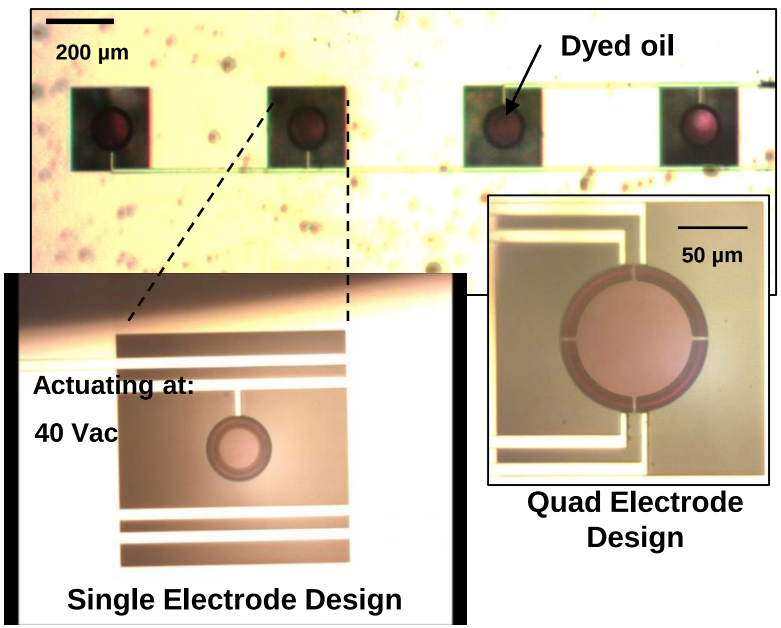
- **Using Lincoln's state-of-art fabrication facilities**
  - **Fabricated 45° tapered liquid microlenses***
  - **Novel grayscale lithography process developed**
- **Developed optical measurement techniques for small aperture lenses**

Microscope Image after Metal Electrode Patterning



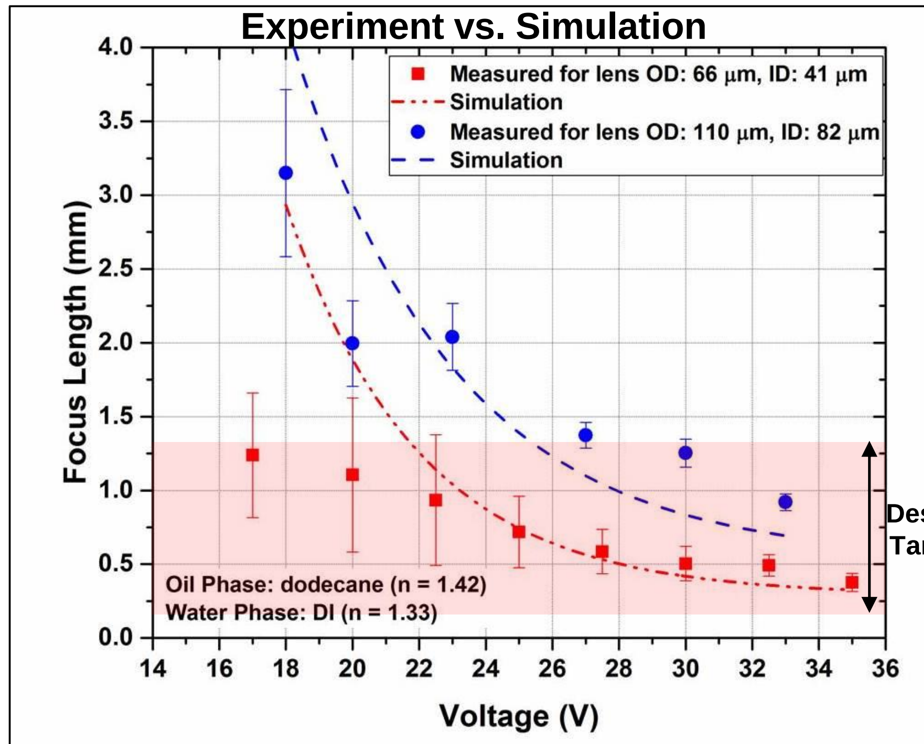
SEM after Metal Electrode Patterning





Quad Electrode Design

Single Electrode Design



*Shaun Berry, et. al., "Fluidic microoptics with adjustable focusing and beam steering for single cell optogenetics," Opt. Express 25 (14), 16825-16839 (2017).

Summary

- **This work has led to the successful demonstration of micron-sized liquid lenses that combined both focusing and steering**

- **Developed a useful simulation tool for liquid optics and have combined it with fabrication**

- **Establishing an optofluidics center of excellence with capabilities:**
  - **Simulation (optical and fluidic)**
  - **Fabrication**
  - **Testing and evaluation**

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Thank you

Questions?

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