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2037-3

# Introduction to Optofluidics

*1 - 5 June 2009*

## Opto-Thermocapillary Actuation of Fluid Interfaces

J.-P. Delville

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# Introduction to Optofluidics

# Opto-Thermocapillary Actuation of Fluid Interfaces

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**Centre de Physique Moléculaire Optique et Hertzienne**
**UMR 5798, Université Bordeaux I, 351 Cours de la Libération**
**F-33405 Talence Cedex, France**

**jp.delville@cpmoh.u-bordeaux1.fr**

Trieste 01-05 June 2009

# Outline

I. Breakthrough experiments

II. Thermocapillary stresses on interfaces

III. Thermocapillary flows

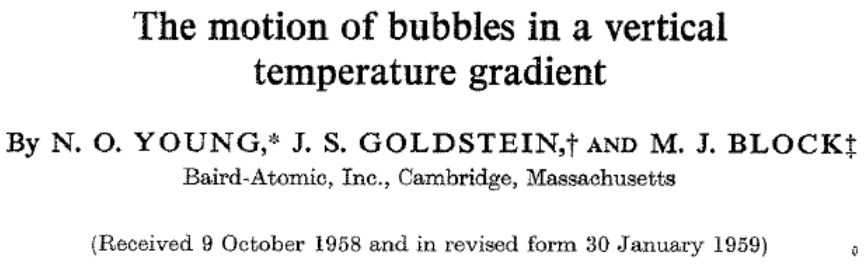
IV. opto-thermocapillary migration/trapping

V. An optical toolbox for digital microfluidics

VI. Concluding remarks

# The very first experiments on drops and bubbles

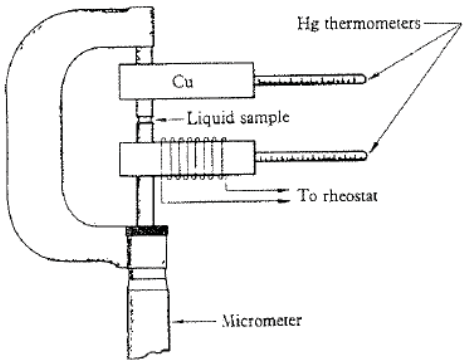
**J. Fluid Mech. 6, 350 (1959)**

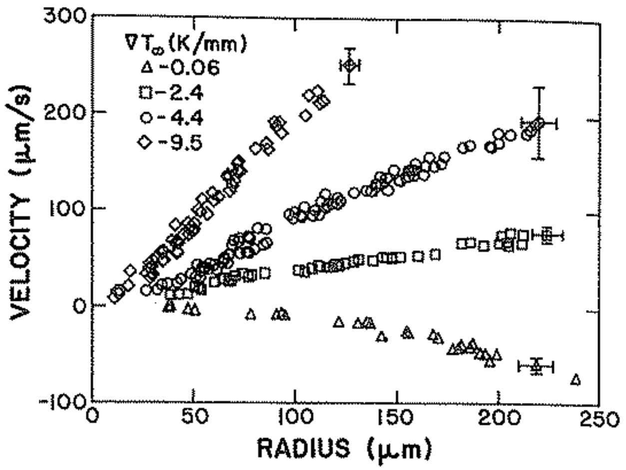


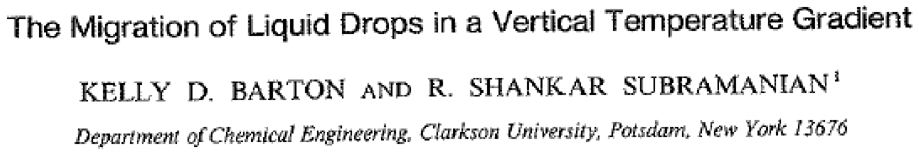
### The motion of bubbles in a vertical temperature gradient

By N. O. YOUNG,* J. S. GOLDSTEIN,† AND M. J. BLOCK‡
Baird-Atomic, Inc., Cambridge, Massachusetts

(Received 9 October 1958 and in revised form 30 January 1959)





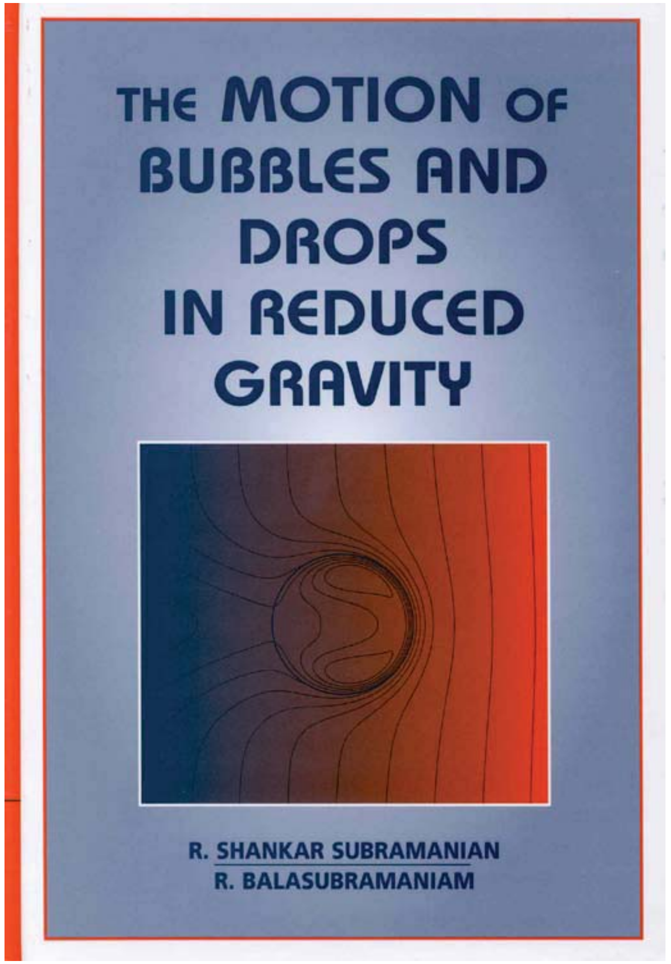


### The Migration of Liquid Drops in a Vertical Temperature Gradient

KELLY D. BARTON AND R. SHANKAR SUBRAMANIAN[1]
*Department of Chemical Engineering, Clarkson University, Potsdam, New York 13676*

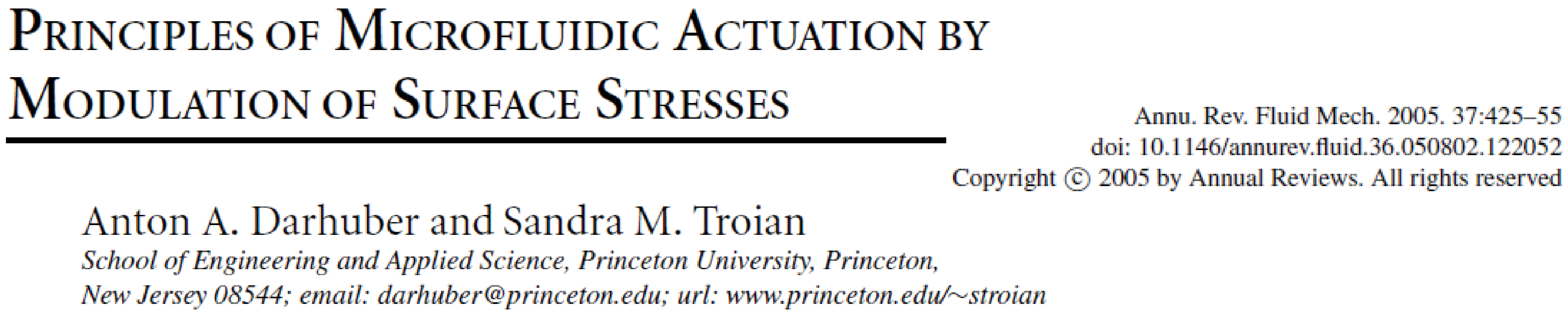
**J. Colloid Interface Sci. 133, 211 (1989)**

**A recent review**



Cambridge University Press,
Cambridge, UK (2001)

# Experiments on films



## PRINCIPLES OF MICROFLUIDIC ACTUATION BY MODULATION OF SURFACE STRESSES

Annu. Rev. Fluid Mech. 2005. 37:425–55
doi: 10.1146/annurev.fluid.36.050802.122052
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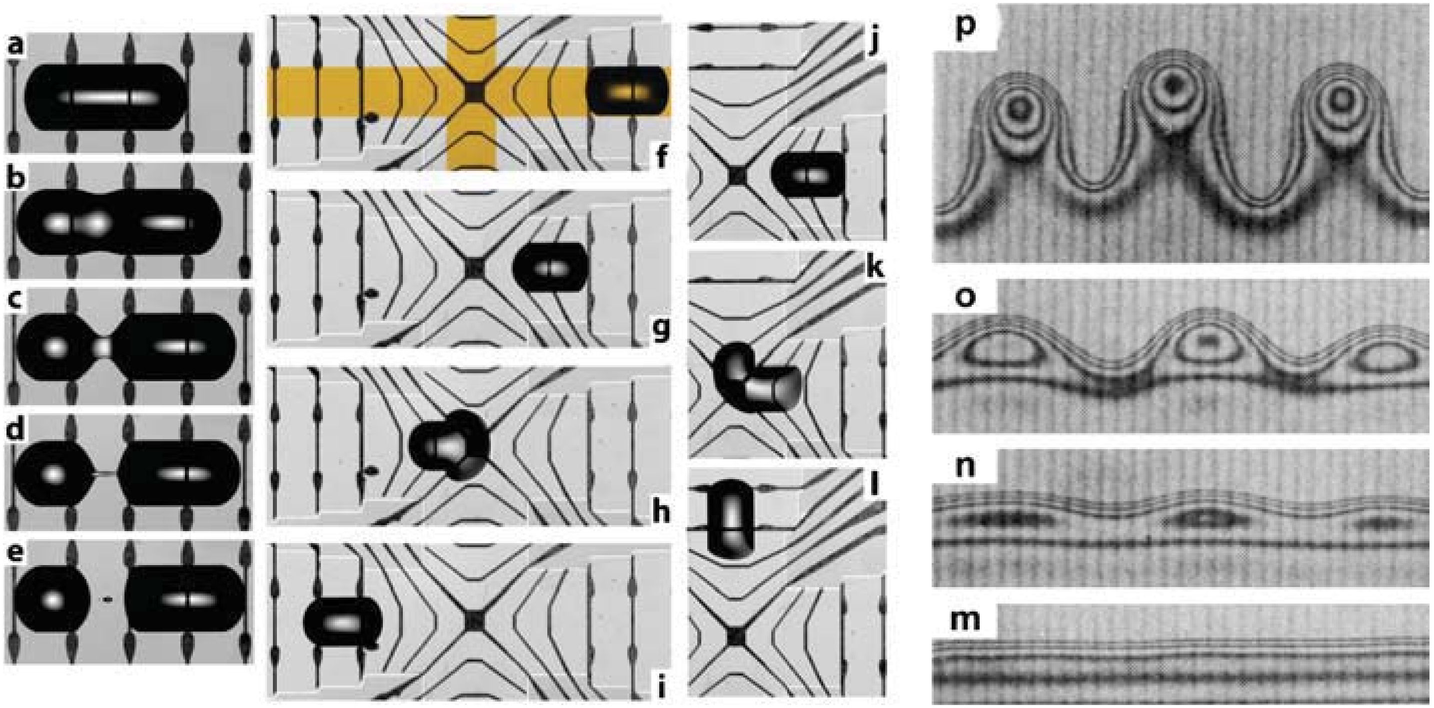
Anton A. Darhuber and Sandra M. Troian
*School of Engineering and Applied Science, Princeton University, Princeton, New Jersey 08544; email: darhuber@princeton.edu; url: www.princeton.edu/~stroian*



**Thermocapillary: splitting** **propelling** **turning** **fingering**

# Thermocapillary flows (L/G and flat interface case)

**Surface tension** $\sigma(T)=\sigma(T_0)\left(1-b\left(T-T_0\right)\right)$ $\longrightarrow$ $\vec{\nabla}T \Rightarrow \vec{\nabla}\sigma$

**Interface** $\left[\cancel{\boldsymbol{T}_2^{hyd}}-\boldsymbol{T}_1^{hyd}\right].\boldsymbol{n}=\cancel{\sigma\kappa}\,\boldsymbol{n}-\vec{\nabla}^s\sigma$ **with** $\boldsymbol{T}_j^{hyd}=-p_j\,\boldsymbol{I}+\eta_j\left(\nabla\,\boldsymbol{u}_j+{}^t\nabla\,\boldsymbol{u}_j\right)$

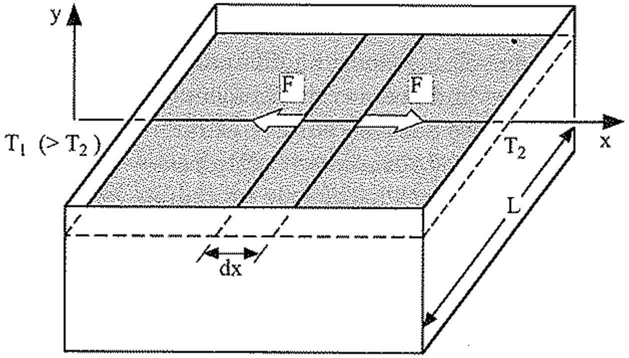
**normal component** $\boldsymbol{n}\cdot\boldsymbol{T}_1^{hyd}\,.\boldsymbol{n}=0$

**tangential component** $-\boldsymbol{t}.\boldsymbol{T}_1^{hyd}\,.\boldsymbol{n}=-\boldsymbol{t}\,.\vec{\nabla}^s\sigma=-\partial\sigma/\partial s=-\left(\partial\sigma/\partial T\right)\cdot\partial T/\partial s$

$$\partial\sigma/\partial s=\frac{dF}{Ldx}=\frac{F\left(x+d\ \right)x-F\left(x\right)}{Ldx}=\frac{\left[\sigma\left(x+dx\right)-\sigma\left(x\right)\right]L}{Ldx}=\frac{d\sigma}{dx}=-b\sigma\left(T_0\right)\frac{dT}{dx}$$

$$\boldsymbol{t}.\boldsymbol{T}_1^{hyd}\,.\boldsymbol{n}=\eta\left(\frac{\partial u_x}{\partial y}\right)_{interface}$$

$$-\boldsymbol{t}.\boldsymbol{T}_1^{hyd}\,.\boldsymbol{n}+\partial\sigma/\partial s=-\eta\left(\frac{\partial u_x}{\partial y}\right)_{interface}-b\sigma\left(T_0\right)\frac{dT}{dx}=0$$



**Bulk: NS Equation** $-\nabla p+\eta\nabla^2\,\boldsymbol{u}_1+\rho\,\boldsymbol{g}=0$

# Thermocapillary flows (L/G and flat interface case)

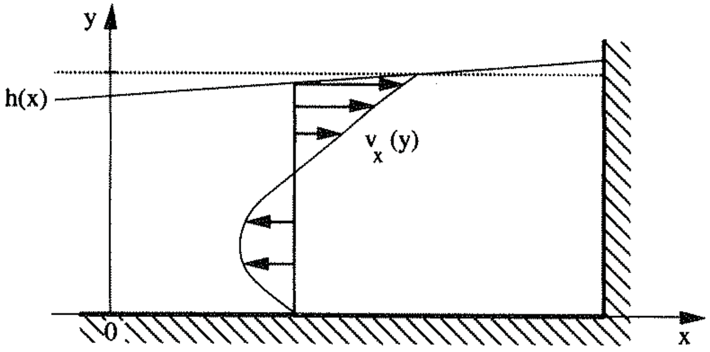
**infinite medium in x and z:**

$$-\cancel{\frac{\partial P}{\partial x}}+\eta\frac{\partial^2 u_x}{\partial y^2}=0 \quad\longrightarrow\quad u_x(y)=-\frac{b\sigma(T_0)}{\eta}\frac{dT}{dx}y$$

$$\frac{\partial P}{\partial y}=\rho g \quad\longrightarrow\quad P=P_{atm}+\rho g(h_0-y)$$

**usually, b>0: flow towards the cold region**

**finite size in x:** $dh/dx \ll 1$



$$P(x)=P_{atm}+\rho g\left(h(x)-y\right)\longrightarrow \frac{\partial P}{\partial x}=\rho g\frac{dh(x)}{dx}$$

**NS:** $$\eta\frac{\partial^2 u_x}{\partial y^2}=\rho g\frac{dh(x)}{dx}$$

**Boundary conditions:** $$\begin{cases}\int_0^{h_0} u_x(y)dy=0\\ u_x(0)=0\end{cases}$$

$$\longrightarrow\quad u_x(y)=\frac{\rho g}{\eta}\frac{dh}{dx}\left(\frac{y^2}{2}-\frac{h_0 y}{3}\right)$$ **and** $$\frac{dh}{dx}=-\frac{3}{2}\frac{b\sigma(T_0)}{\rho g h_0}\frac{dT}{dx}$$

**Flow and interface deformation**

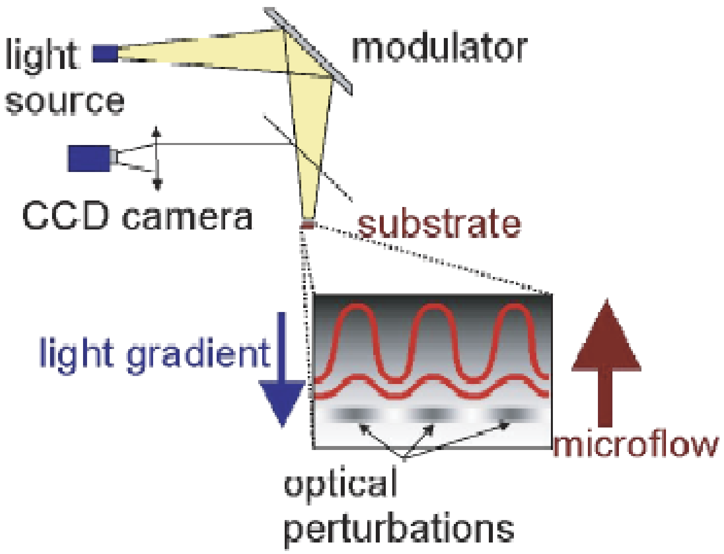
# Laser-Induced thermocapillary interface manipulation and deformations

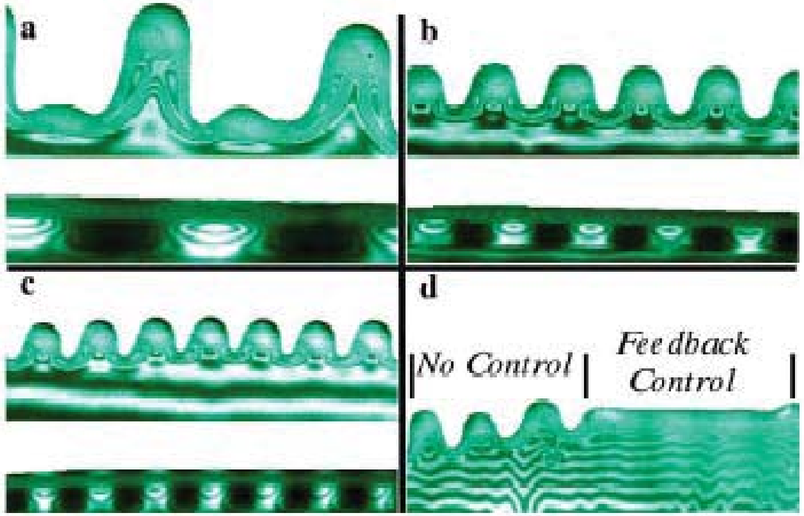
VOLUME 91, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2003

## Optical Manipulation of Microscale Fluid Flow

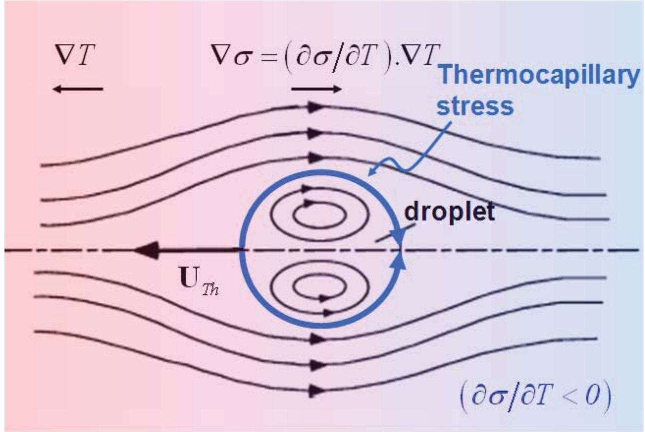
Nicolas Garnier, Roman O. Grigoriev, and Michael F. Schatz
*Center for Nonlinear Science and School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA*

(Received 17 March 2003; published 30 July 2003)





# Thermocapillary migration of drops (I)



## Momentum and energy equations

$$Re\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}.\nabla\boldsymbol{u}\right) = -\nabla p + \nabla^2\boldsymbol{u}, \quad Ma\left(\frac{\partial T}{\partial t} + \boldsymbol{u}.\nabla T\right) = \nabla^2 T$$

**Microfluidics**

$$\begin{cases} Re = \dfrac{\rho u_0 R}{\eta} \ll 1 \\ Ma = \dfrac{u_0 R}{\chi_T} \ll 1 \quad \text{where} \quad u_0 = \dfrac{|\partial\sigma/\partial T|\,|\vec{\nabla} T_\infty|\,R}{\eta} \\ g = 0 \end{cases}$$

$$\longrightarrow \quad \nabla\boldsymbol{u} = 0, \quad \nabla p - \eta\nabla^2\boldsymbol{u} = 0, \quad \nabla^2 T = 0$$

**Boundary conditions at the interface:**
**(prime for the drop)**

$$\begin{cases} \boldsymbol{u}.\boldsymbol{n} = \boldsymbol{u}'.\boldsymbol{n} = \boldsymbol{U}_{Th}.\boldsymbol{n}, \quad \boldsymbol{u}\times\boldsymbol{n} = \boldsymbol{u}'\times\boldsymbol{n} \\ T = T', \quad \boldsymbol{n}.\left(\Lambda_T\nabla T - \Lambda_T'\nabla T'\right) = 0 \\ \left[\boldsymbol{T}^{hyd} - \boldsymbol{T}^{hyd\prime}\right].\boldsymbol{n} - \dfrac{2\sigma}{R}\boldsymbol{n} + \vec{\nabla}^s\sigma = 0 \\ \boldsymbol{u} \underset{r\to\infty}{\to} 0, \quad \nabla T \underset{r\to\infty}{\to} \nabla T_{0\infty} \end{cases}$$

## General solution Stokes/Laplace (Lamb)

$$\begin{cases} \boldsymbol{u} = -\dfrac{R^3}{2}\nabla\left(\dfrac{\boldsymbol{U}_{Th}.\boldsymbol{r}}{r^3}\right) + \dfrac{1}{2\eta}\left(R^2 - \dfrac{r^2}{3}\right)\nabla\left(\dfrac{\boldsymbol{B}.\boldsymbol{r}}{r^3}\right) + \dfrac{2\nabla(\boldsymbol{B}.\boldsymbol{r})}{3\eta r} \\ \boldsymbol{u}' = \nabla(\boldsymbol{U}_{Th}.\boldsymbol{r}) + \dfrac{1}{\eta'}\left(\dfrac{r^2}{6} - \dfrac{R^2}{10}\right)\nabla(\boldsymbol{B}'.\boldsymbol{r}) + \dfrac{r^5}{30\eta'}\nabla\left(\dfrac{\boldsymbol{B}'.\boldsymbol{r}}{r^3}\right) \end{cases}$$

$$\begin{cases} p = \dfrac{\boldsymbol{B}.\boldsymbol{r}}{r^3} + p_0 \\ p' = \boldsymbol{B}'.\boldsymbol{r} + p'_0 \end{cases} \qquad \begin{cases} T = \left(1 + \dfrac{k}{r^3}\right)\boldsymbol{r}.\nabla T_0 + T_C \\ T' = k'\,\boldsymbol{r}.\nabla T_0 + T'_C \end{cases}$$

# Thermocapillary migration of drops (II)

**substitution**

$$\mathbf{B}=0,\quad \mathbf{B}'=-15\eta'\frac{\mathbf{U}_{Th}}{R^2},\quad k'=\left(1+\frac{k}{R^3}\right)=\frac{3}{2+\beta}\qquad\qquad \beta=\Lambda'_{Th}/\Lambda_{Th}$$

**Force** $$\mathbf{F}=\int_S \mathbf{T}^{hyd}.\mathbf{ds}=-2\pi R^2\left[\frac{(2+3\alpha)\eta\mathbf{U}_{Th}}{(1+\alpha)R}+\frac{2(\partial\sigma/\partial T)\nabla T_0}{(1+\alpha)(2+\beta)}\right]\qquad\qquad \alpha=\eta'/\eta$$

**Newton law of motion (invariable liquid properties):**

$$\begin{cases}\left(\dfrac{4}{3}\pi R^3\rho'\right)\dfrac{d\mathbf{U}_{Th}}{dt}=\mathbf{F}=\displaystyle\int_S \mathbf{T}^{hyd}.\mathbf{ds}=-2\pi R^2\left[\dfrac{(2+3\alpha)\eta\mathbf{U}_{Th}}{(1+\alpha)R}+\dfrac{2(\partial\sigma/\partial T)\nabla T_0}{(1+\alpha)(2+\beta)}\right]\\ \mathbf{U}_{Th}(t=0)=0\end{cases}$$

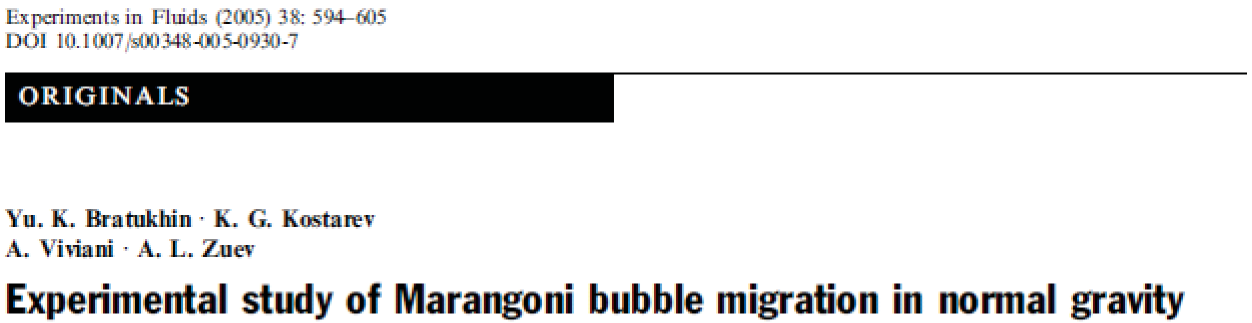
$$\longrightarrow\quad \mathbf{U}_{Th}=-\frac{2R(\partial\sigma/\partial T)\nabla T_0}{(2+3\alpha)(2+\beta)\eta}\left[1-exp\left(-\frac{3}{2}\frac{(2+3\alpha)\eta}{(1+\alpha)\rho' R^2}t\right)\right]$$

**Terminal velocity** $$U_{Th}(t\to\infty)=-\frac{2R(\partial\sigma/\partial T)\nabla T_0}{(2+3\alpha)(2+\beta)\eta}\qquad\qquad (g=0)$$

**with buoyancy**
**and thermal gradient along z**

$$\mathbf{U}_{Th}(t\to\infty)=\frac{2}{3\eta(2+3\alpha)}\left[-\frac{3(\partial\sigma/\partial T)\nabla T_0}{(2+\beta)}R+(\rho-\rho')\mathbf{g}(1+\alpha)R^2\right]$$

# Thermocapillary migration: effect of confinement

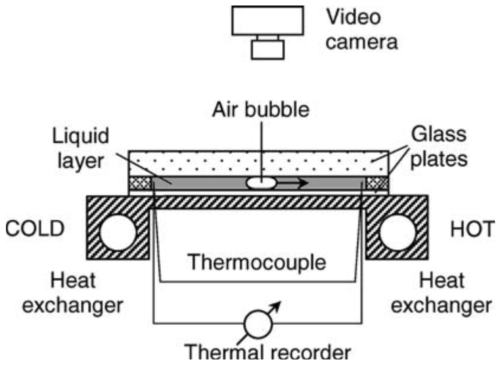


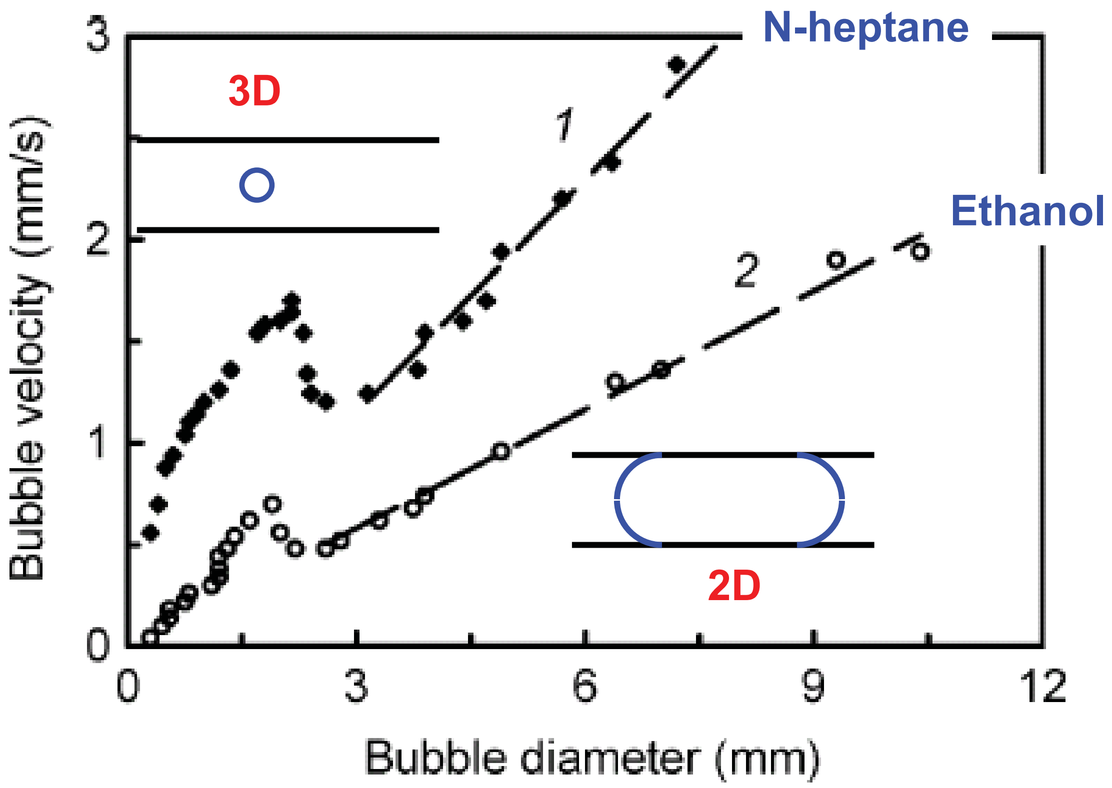
Experiments in Fluids (2005) 38: 594–605
DOI 10.1007/s00348-005-0930-7

**ORIGINALS**

Yu. K. Bratukhin · K. G. Kostarev
A. Viviani · A. L. Zuev

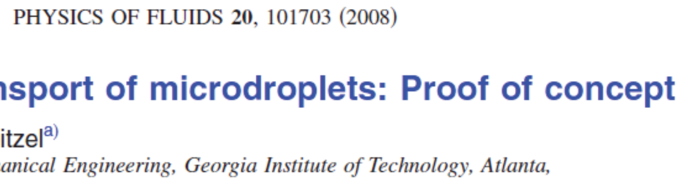
**Experimental study of Marangoni bubble migration in normal gravity**





⟶ **Same behavior, slowing down due to wall friction**

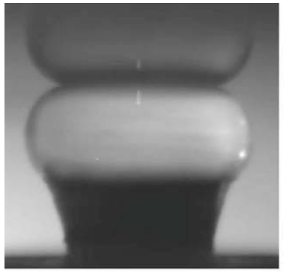
# Thermocapillary levitation



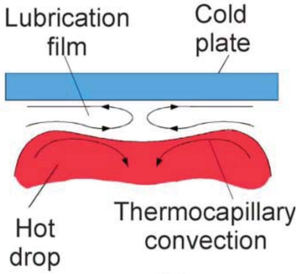
PHYSICS OF FLUIDS **20**, 101703 (2008)

## Optical levitation and transport of microdroplets: Proof of concept

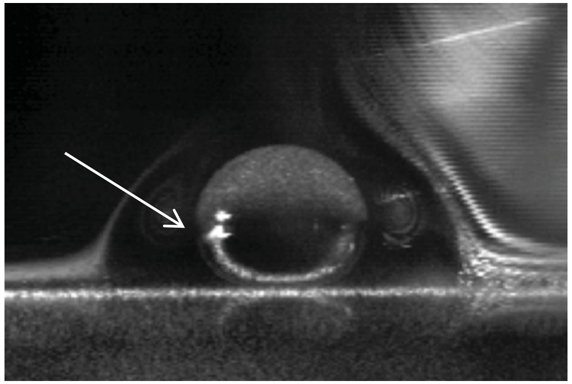
Peter T. Nagy and G. Paul Neitzel[a)]
*George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0405, USA*



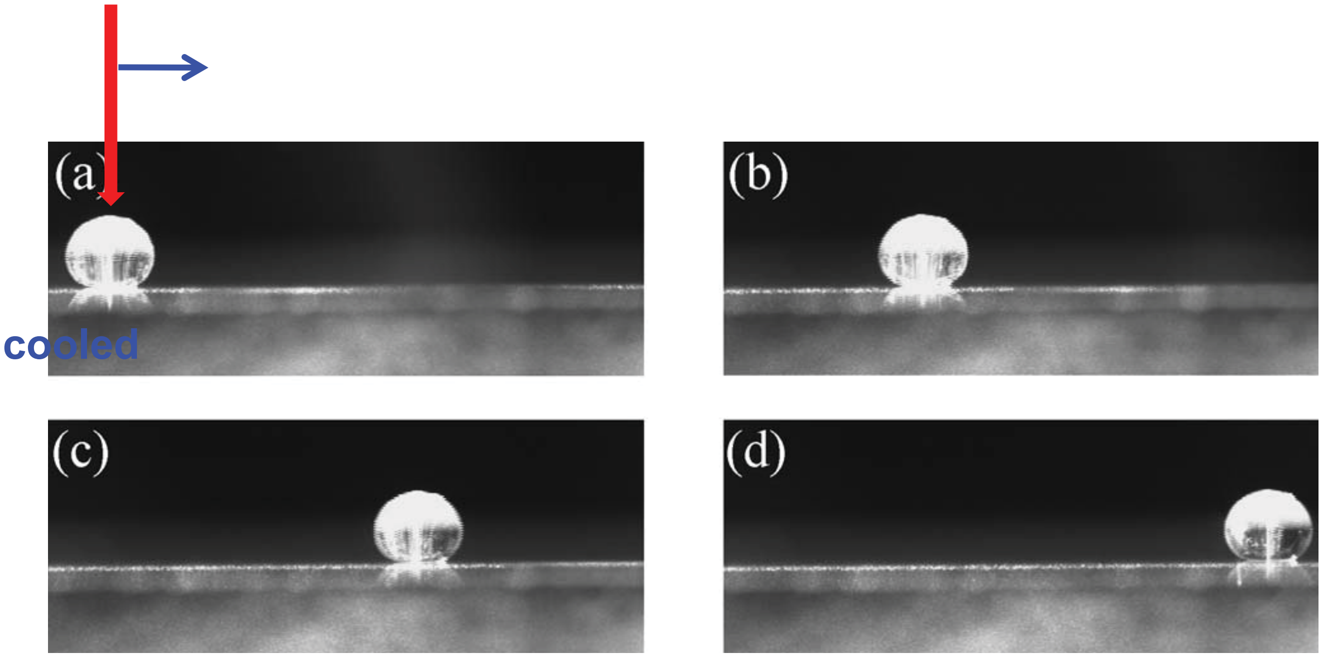
(a)



(b)



CO$_2$ laser



# Thermocapillary trapping of drops by laser

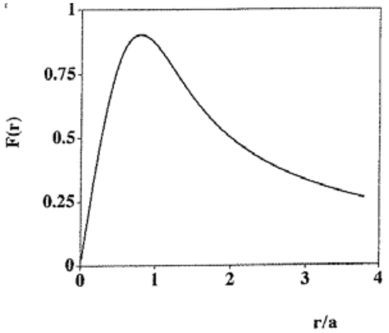
Appl. Phys. B 56, 343–346 (1993)

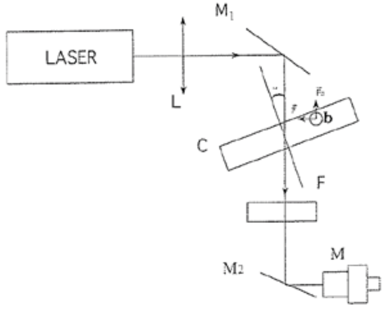
## Laser-Induced Force for Bubble-Trapping in Liquids

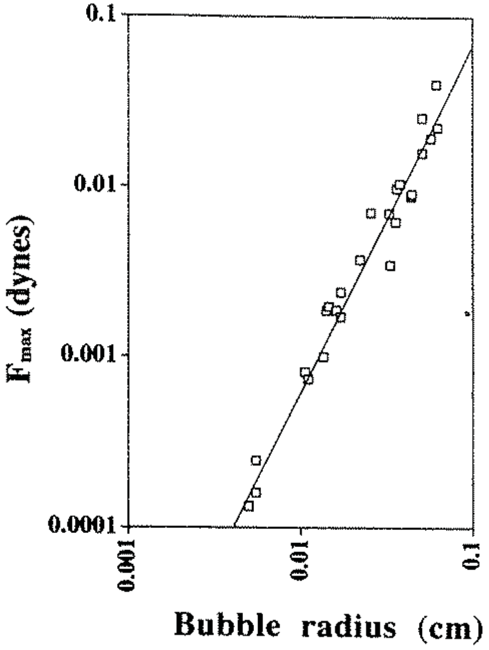
A. Marcano O., L. Aranguren
Centro de Física, Instituto Venezolano de Investigaciones Científicas, Caracas 1020A, Apartado 21827, Venezuela (Fax: +58-2/5011148)

$$\vec{F} = \int_S P\vec{n}\,dS = \int_V \vec{\nabla}\left(P_{atm} - \frac{2\sigma}{R}\right)dV$$

$$\approx -\frac{8\pi}{3}R^2\frac{\partial\sigma}{\partial T}\vec{\nabla}T$$



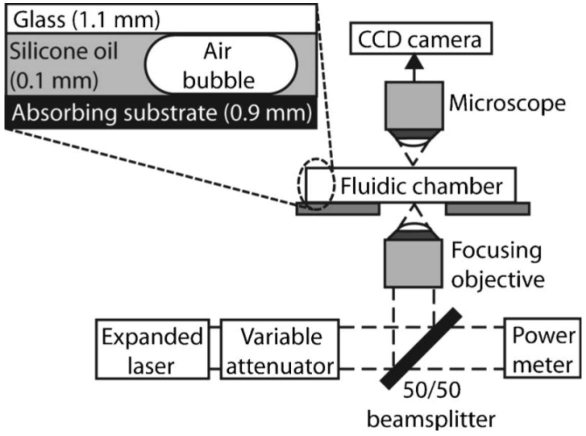


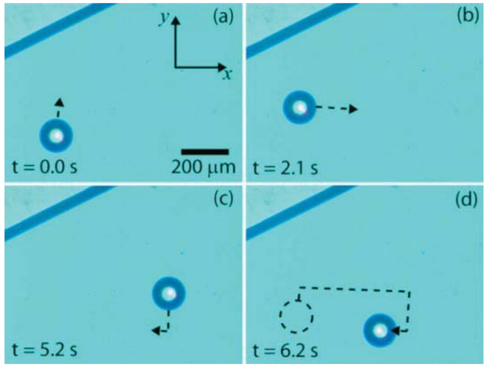


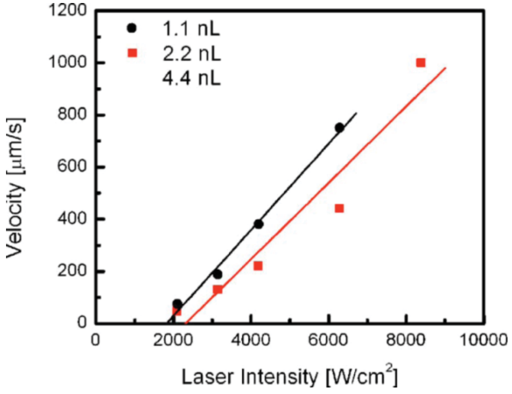
APPLIED PHYSICS LETTERS 91, 074103 (2007)

## Optically actuated thermocapillary movement of gas bubbles on an absorbing substrate

Aaron T. Ohta, Arash Jamshidi, Justin K. Valley, Hsan-Yin Hsu, and Ming C. Wu[a]
*Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, California 94720 and Berkeley Sensor & Actuator Center, University of California, Berkeley, California 94720*





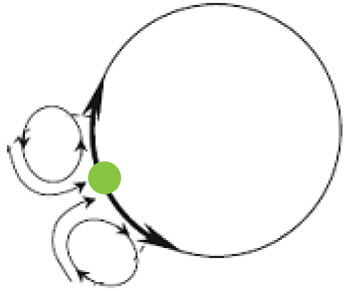


# Thermocapillary pushing and coalescence

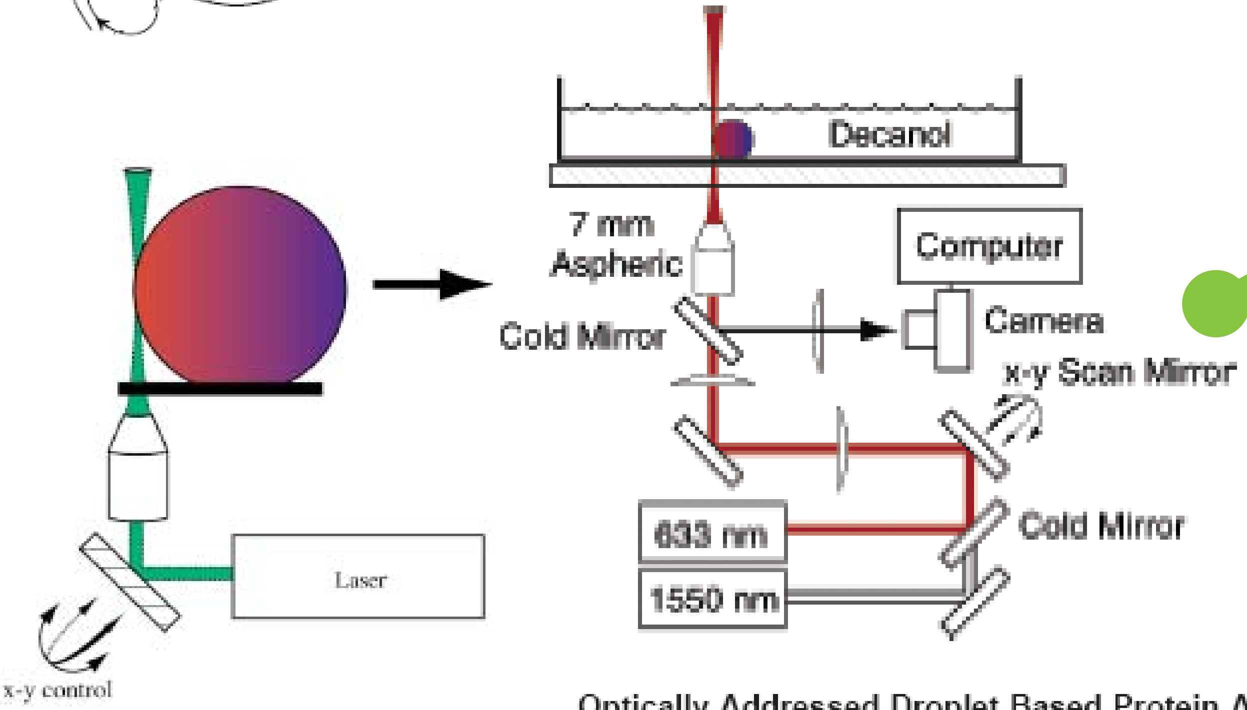
APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 13 27 SEPTEMBER 2004

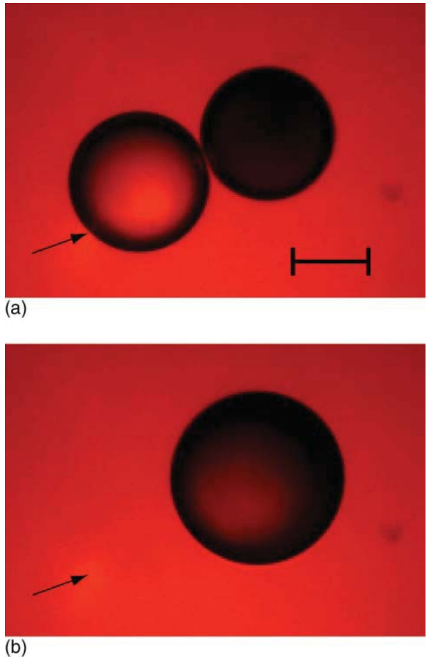
## Optical microfluidics

K. T. Kotz, K. A. Noble, and G. W. Faris[a)]
*Molecular Physics Laboratory, SRI International, 333 Ravenswood Avenue, Menlo Park, California 94025*



$$\sigma(T)=\sigma_0\left(1+\frac{(\partial\sigma/\partial T)_0}{\sigma_0}\nabla T\right)$$





Optically Addressed Droplet-Based Protein Assay **(JACS 2005)**

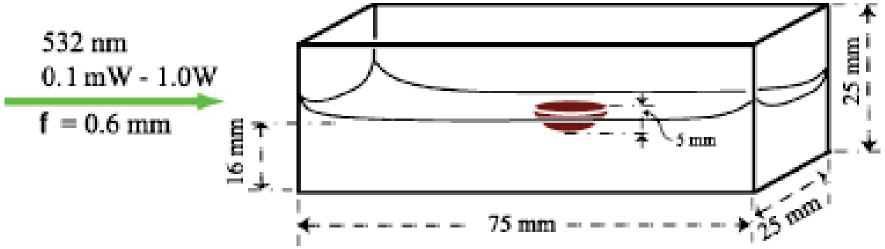
Kenneth T. Kotz, Yu Gu, and Gregory W. Faris*
*Molecular Physics Laboratory, SRI International, 333 Ravenswood Avenue, Menlo Park, California 94025*

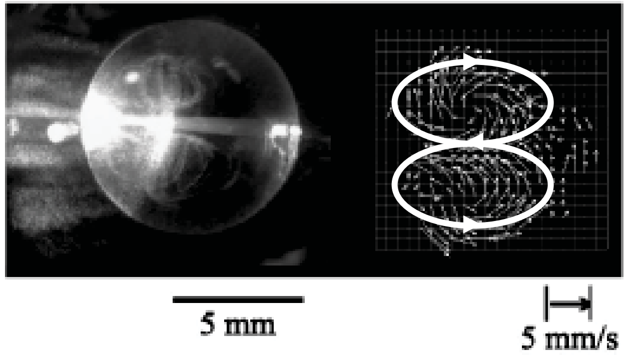
# Thermocapillary-Induced Droplet Motion

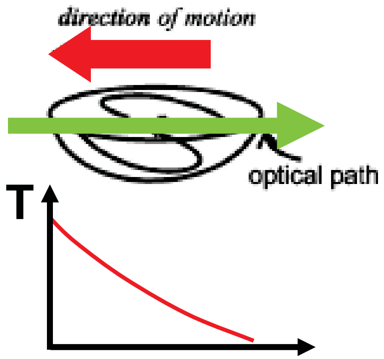
PHYSICAL REVIEW E **70**, 046301 (2004)

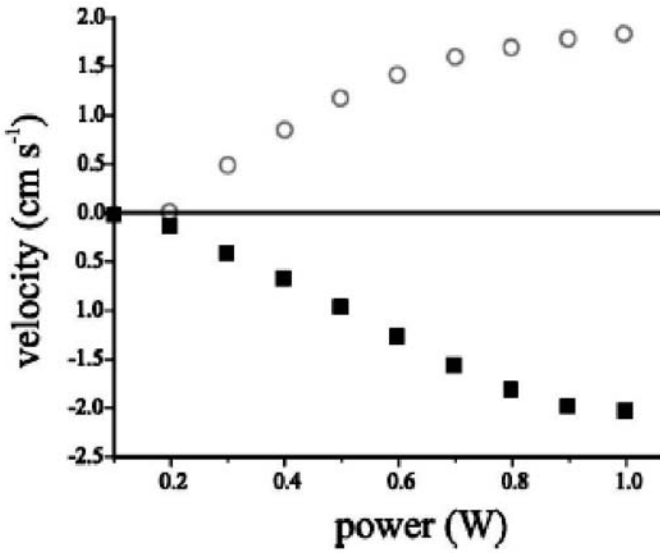
**Forward and backward laser-guided motion of an oil droplet**

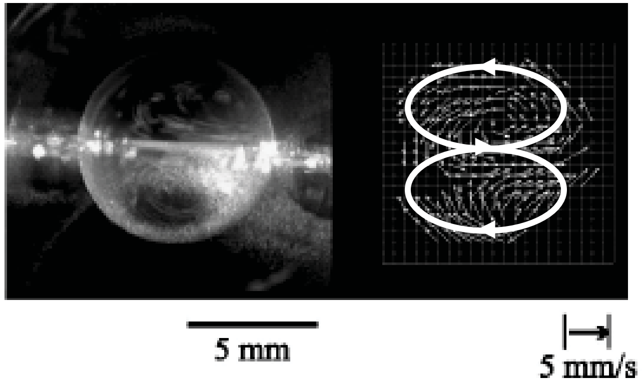
Sergei Rybalko,* Nobuyuki Magome, and Kenichi Yoshikawa
*Department of Physics, Graduate School of Science, Kyoto University & CREST, Kyoto 606-8502, Japan*

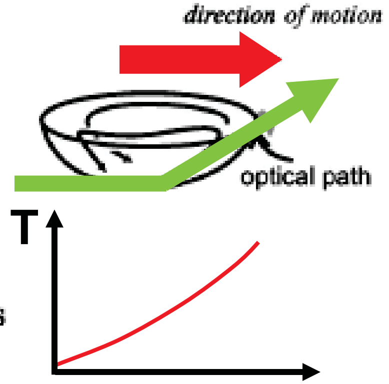












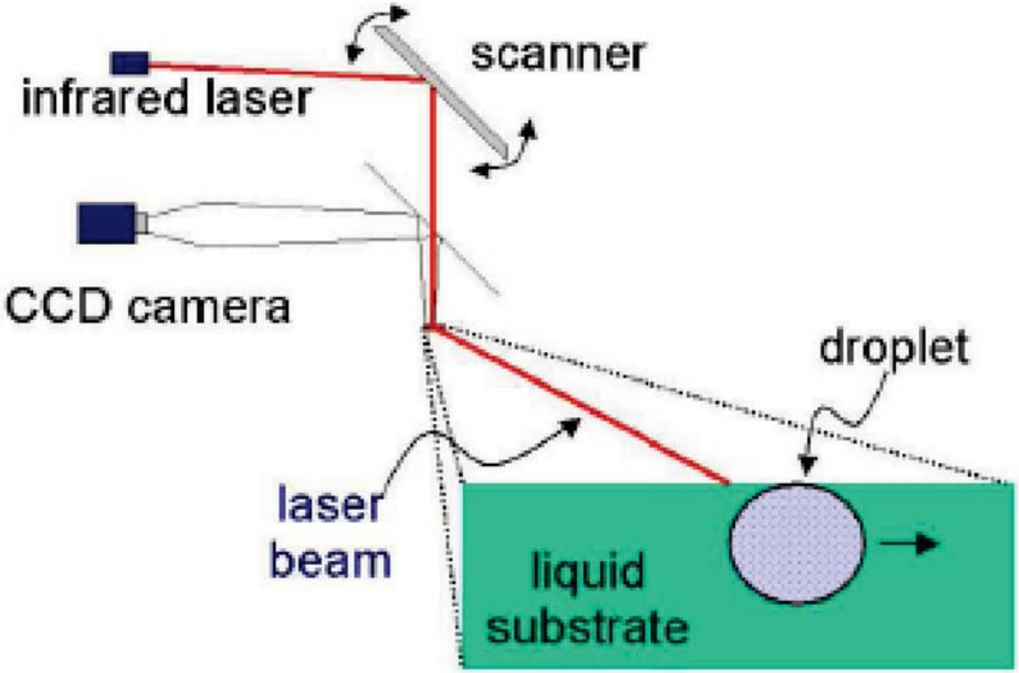
# Chaotic mixing in microdroplets

PAPER www.rsc.org/loc | Lab on a Chip

*Lab Chip*, 2006, 6, 1369-

## Chaotic mixing in microdroplets

Roman O. Grigoriev,*[a] Michael F. Schatz[a] and Vivek Sharma[b]



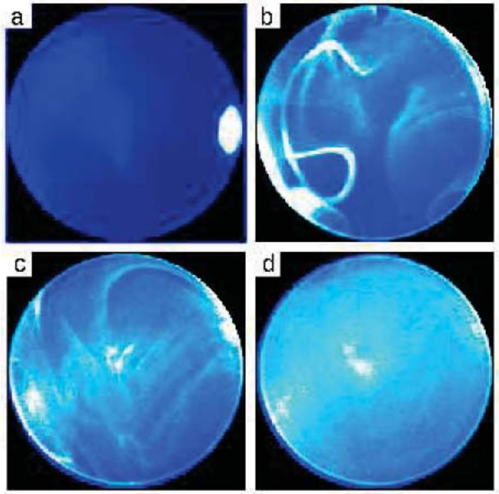


Figure 9: Video images illustrating optically controlled driving of an aqueous microdroplet along a path that periodically changes direction. (a) A 10 nanoliter droplet dyed with fluorescent microspheres is merged with a 4.5 microliter (1.02 mm diameter) undyed droplet. The combined droplet is subsequently driven repeatedly along a square path with side length 3.5 mm and imaged after changing directions (b) 4 times (c) 12 times and (d) 20 times (for a total path length of 7 cm).

## OPTICALLY CONTROLLED MIXING IN MICRODROPLETS

Roman O. Grigoriev* and Michael F. Schatz†
Center for Nonlinear Sciences and School of Physics
Georgia Institute of Technology, Atlanta, GA 30332-0430

American Institute of Aeronautics and Astronautics

# Optical microfluidics in microchannels ?

1) Device for fast production (kHz, 1-10mm/s)

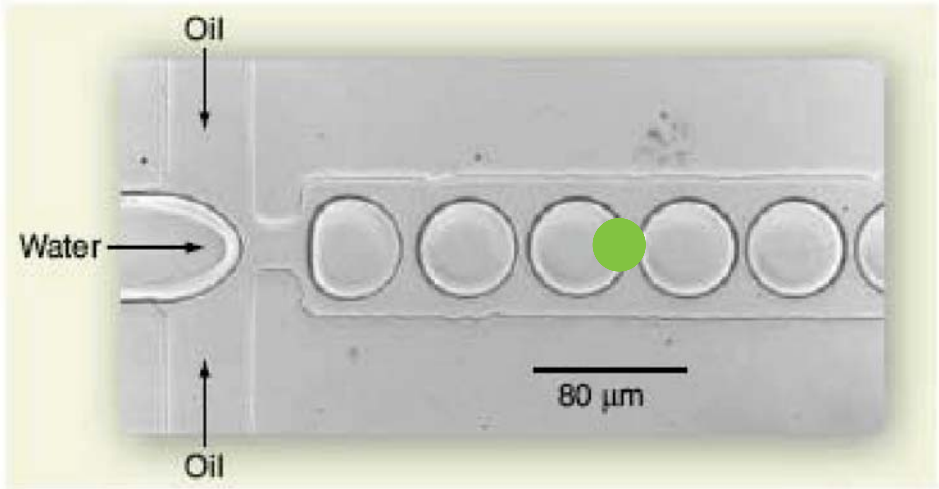
2) Strong Stability of permanent regimes

Tuning parameters fast?

3) Stiffness of Circuits

strong dependence of functions on µC geometry

difficulties in building some functions (sorting, mixing, fusion,…)



?

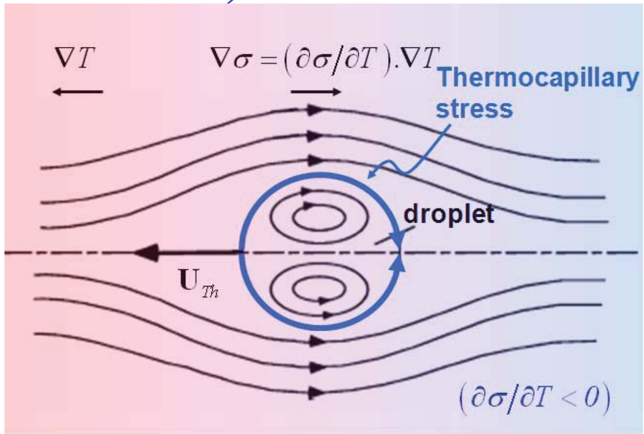
1) Optical trapping: $n_w<n_o$, ~ 1-10 pN

2) Radiation pressure: large surface tension: $n_w<n_o$, ~ 1-10 Pa

3) Thermocapillary actuation: $\sigma(T)=\sigma_0\left(1+\frac{(\partial\sigma/\partial T)_0}{\sigma_0}\nabla T\right)$ , $\approx$ *0.1-1 µN !*

# Thermocapillary-induced large scale flows

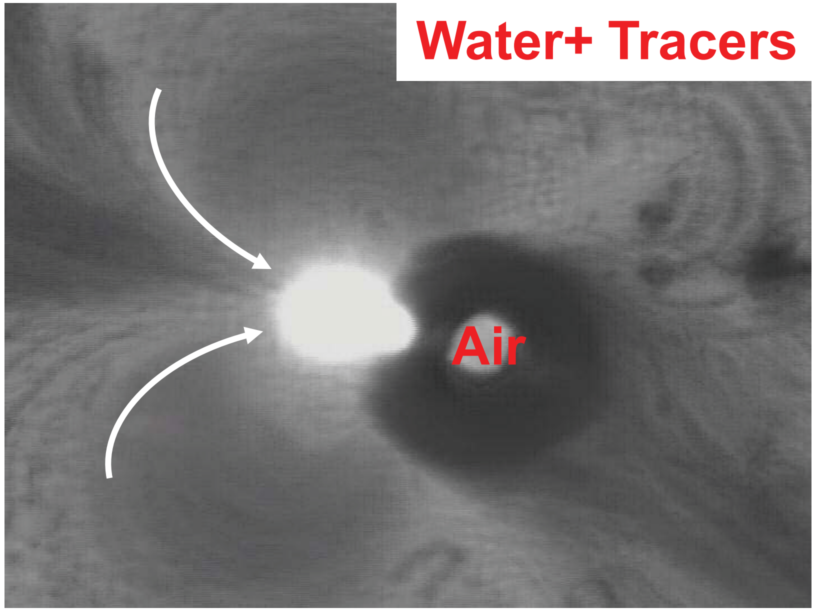
$$\sigma(T) = \sigma_0 \left( 1 + \frac{(\partial\sigma/\partial T)_0}{\sigma_0} \nabla T \right) \quad \Rightarrow \quad \textit{Induced velocity } U \propto -R(\partial\sigma/\partial T)\nabla T$$



**$H_2O$+ Dye (0.1% Wt) / Air bubble (20 µm)**

**Laser $Ar^+$**

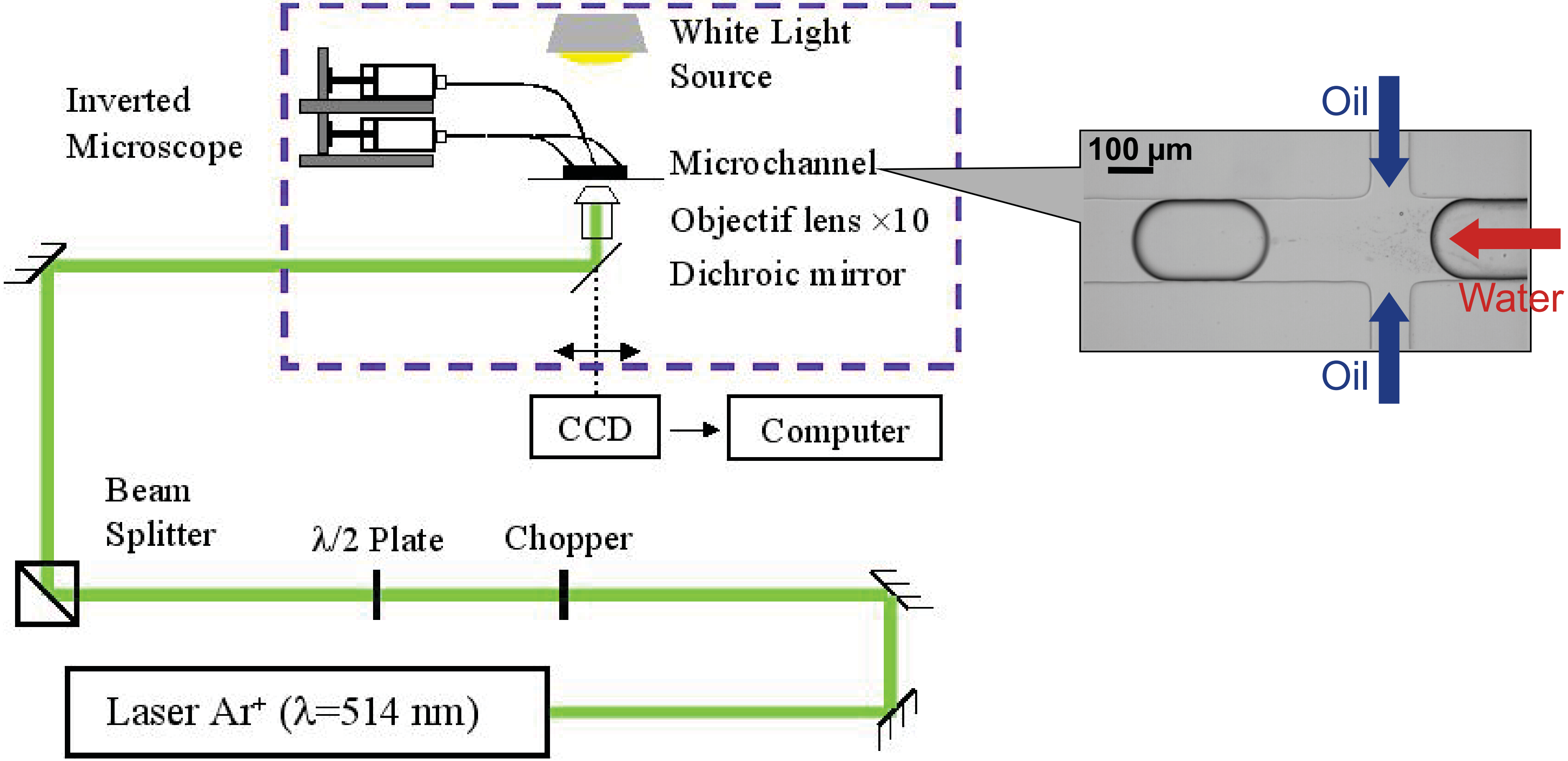
**25fps**



***Thermocapillary Force ≈ 0.1-1 µN !***

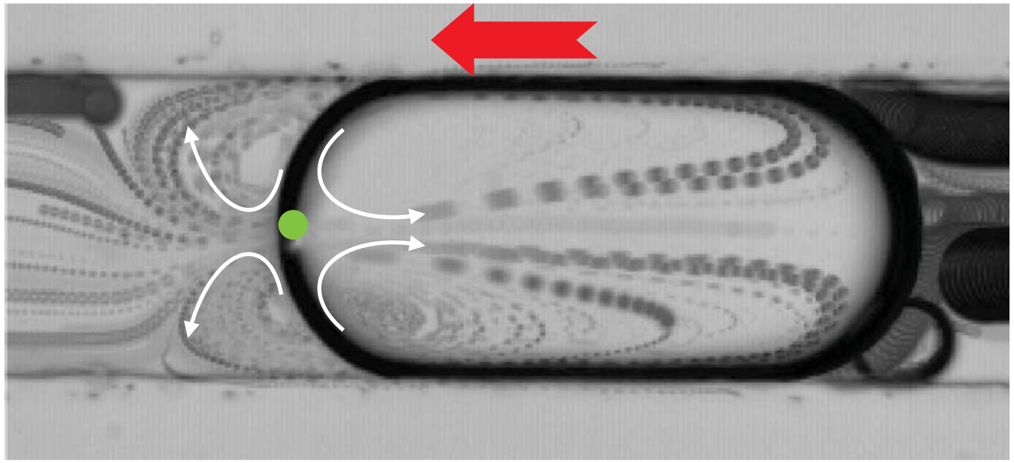
C. Baroud et al., Phys. Rev. E 75, 046302 (2007)

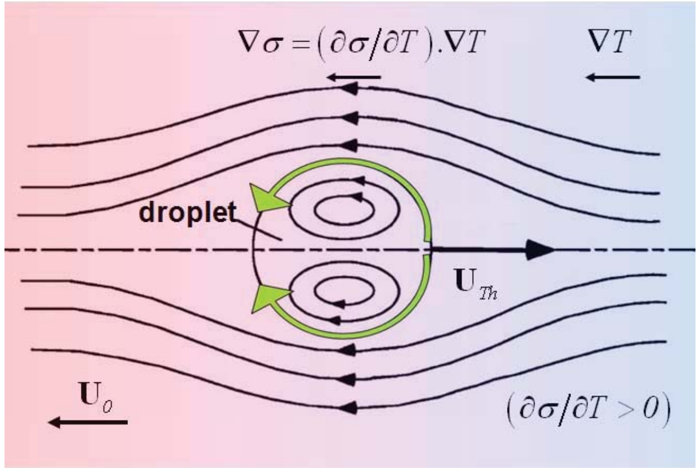
# Experimental setup



**Water + Dye (1/1000 Wt)**
**Hexadecane + Surfactant (2% Wt>CMC): $\partial\sigma/\partial T>0$**
**Microchannels: PDMS@Glass; Thickness: 50µm**

# Thermocapillary coupling in a microchannel





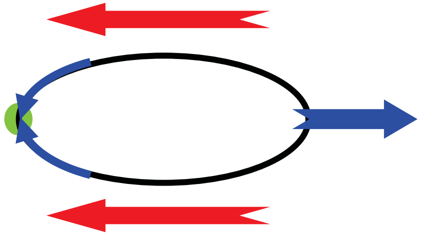
$Q_W$=0.01µl/min et $Q_O$=0.1µl/min; 200 fps; P=100 mW
sec=(140 x 35)µm$^2$; Tracers : toner (ø~1µm)

**Thermocapillary vortices inside and outside (U~1cm/s)**

**(Oil velocity: 500 µm/s)**

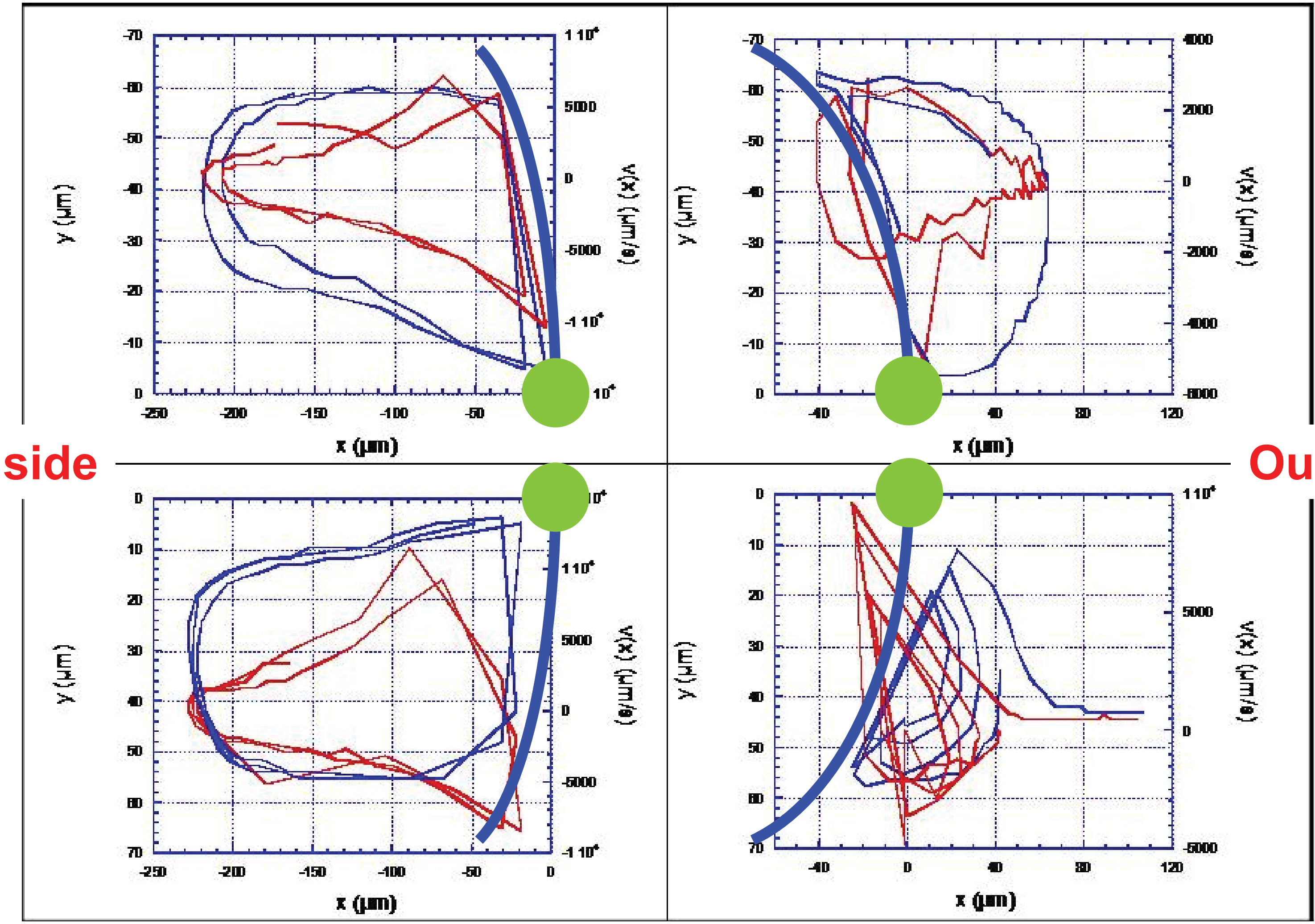
**Vorticity → $\partial\sigma/\partial T>0$ (linked to $C_{Surfactant}$>CMC)**

**$\partial\sigma/\partial T>0$ → Drop blocking by the laser**



# Vortex Analysis

**Tracer trajectories: Δt = 0,005 s between two points**



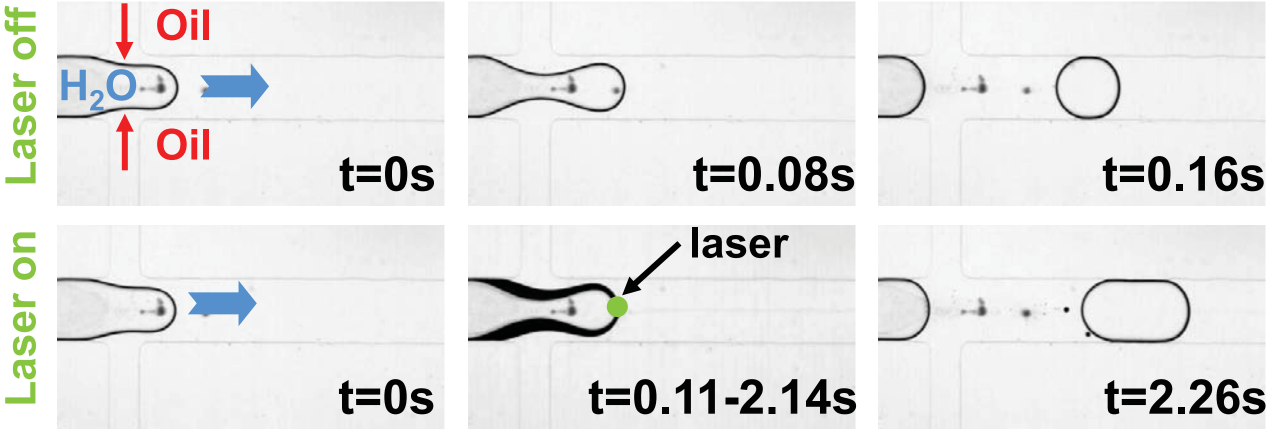
**Inside**

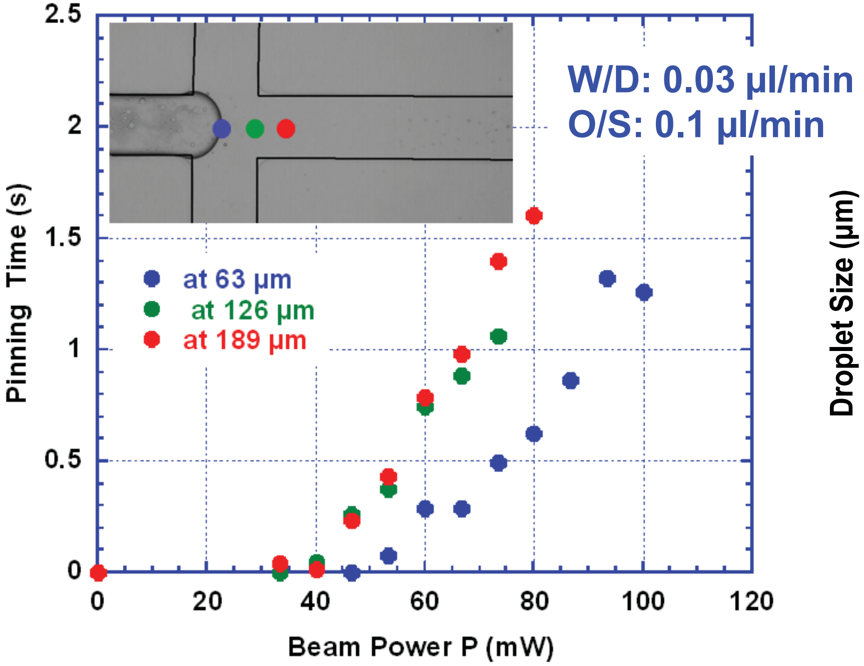
**Outside**

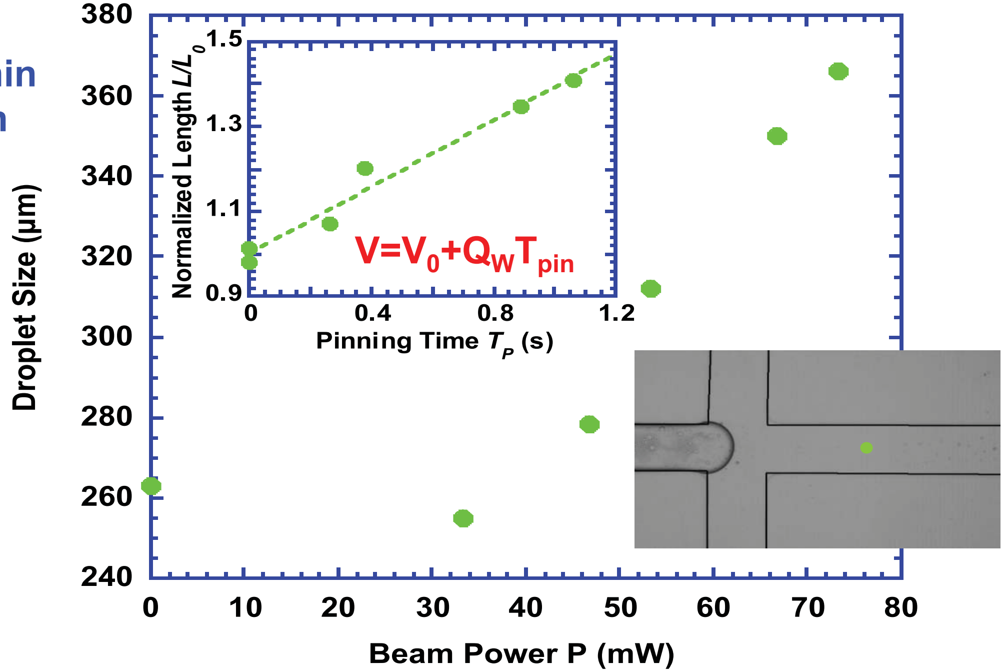
$v_{max}$ (1.2 cm/s) → Close to the laser spot: max thermocapillary coupling

Tracer velocity in oil : 480µm/s → weak compared to $v_{max}$

# Optical valve († configuration)





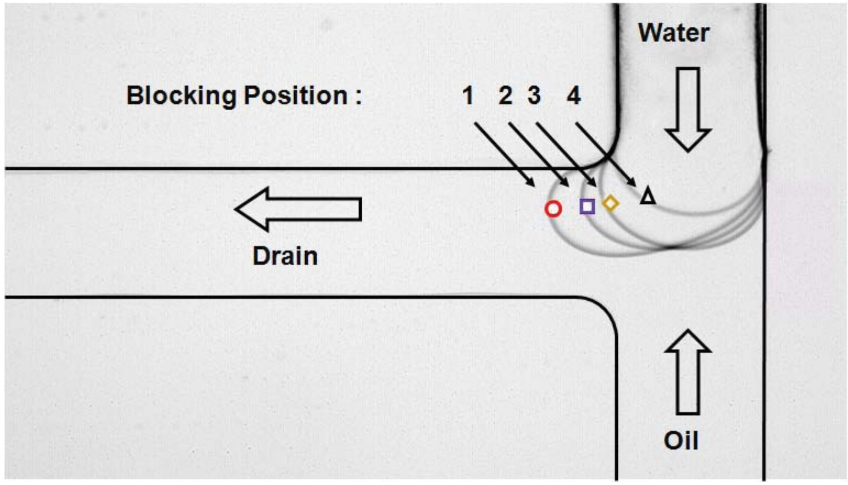


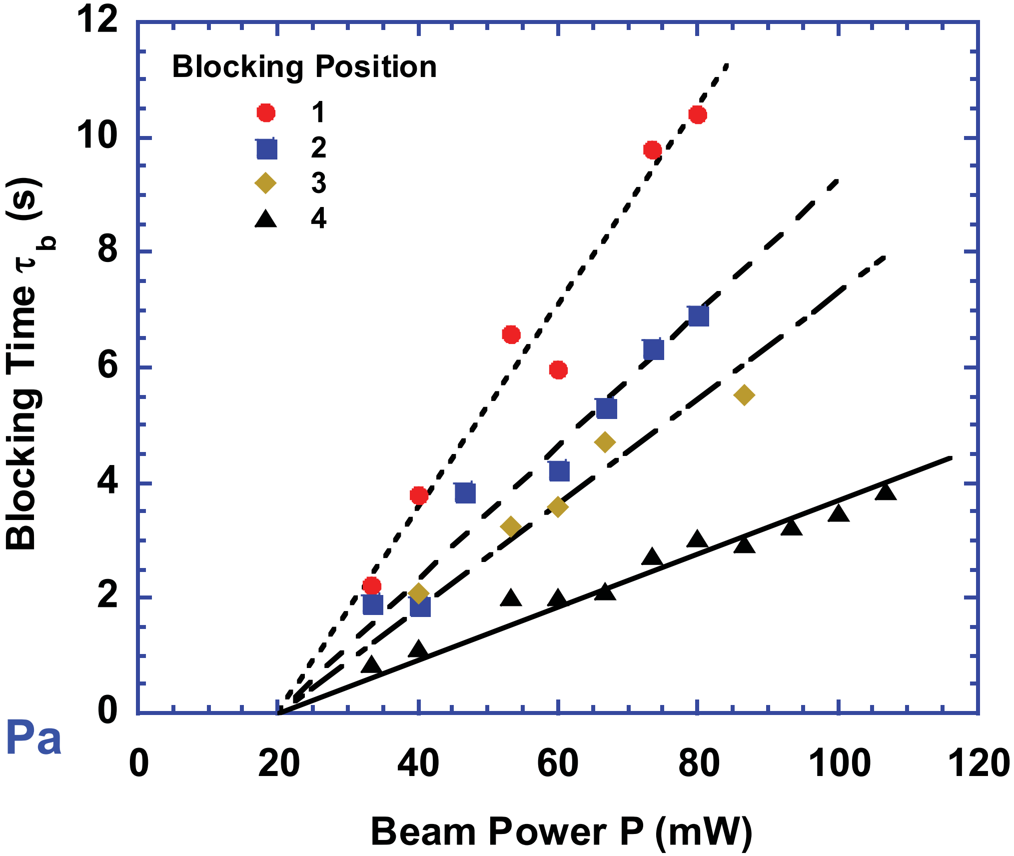
$V=V_0+Q_W T_{pin}$

→ actuation of the drop size and the emission frequency

C. Baroud et al., Phys. Rev. E 75, 046302 (2007)

# Optical valve (T configuration)

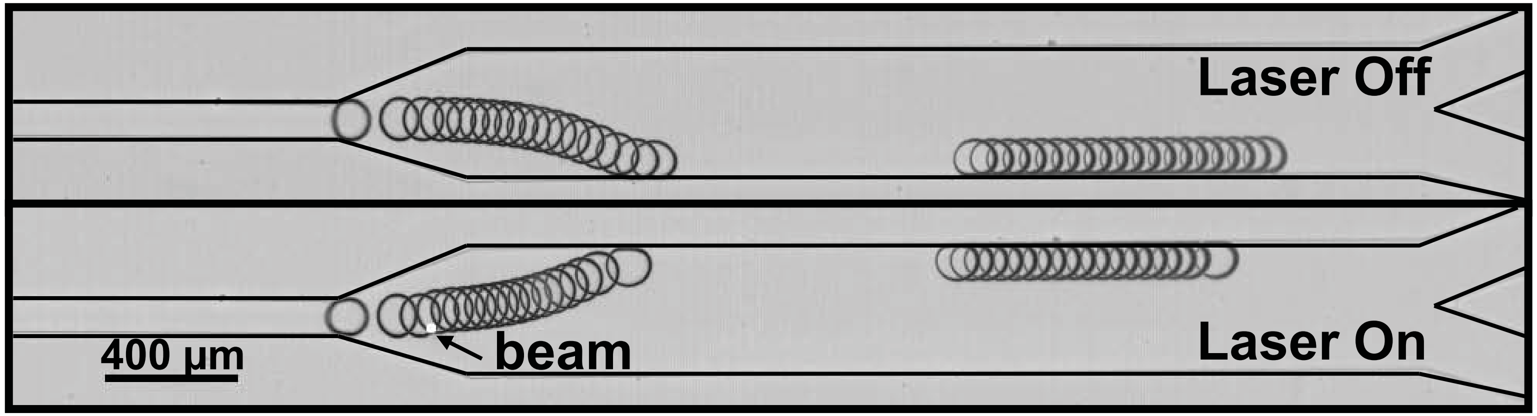




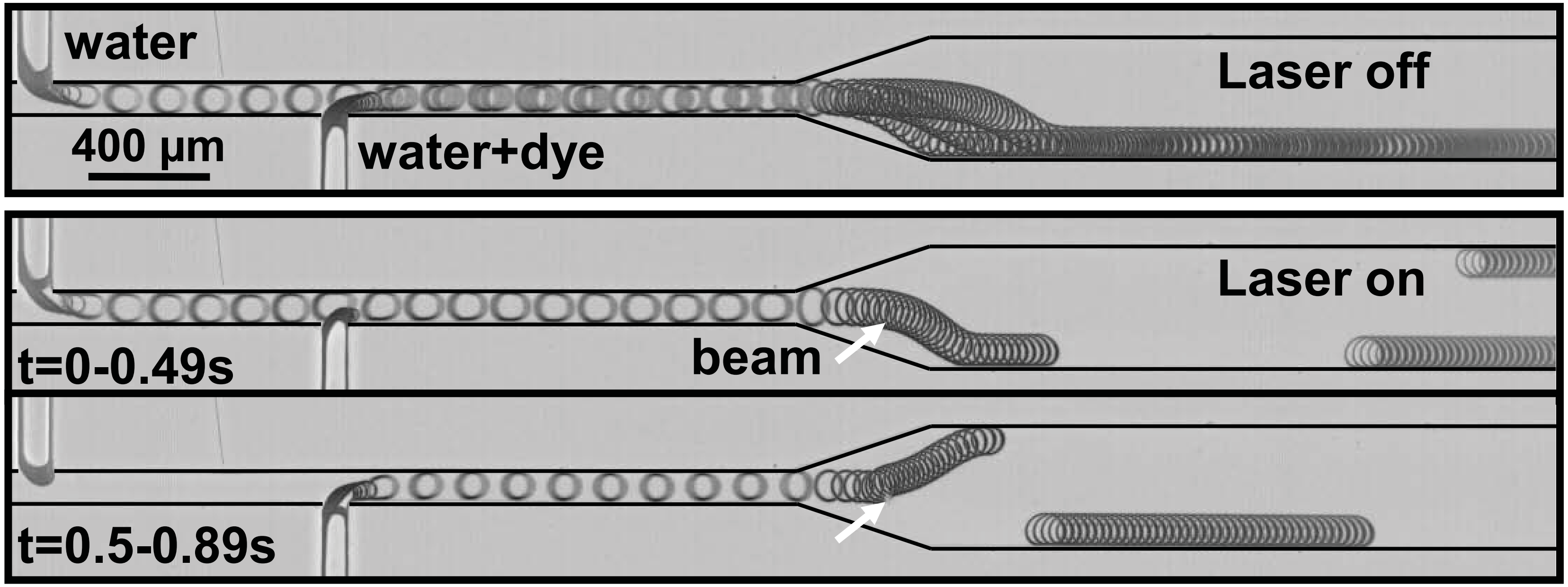
**channels 100 mm wide.**
**$Q_{oil}$ = 0.05 mL/min and $P_{water} = 2.3\ 10^3$ Pa**
**$\omega_0$ = 2.6 µm.**

C. Baroud et al, Lab. Chip 7, 1029 (2007)

# Drop Switching



# Drop Sorting



→ see M. Robert de Saint Vincent talk

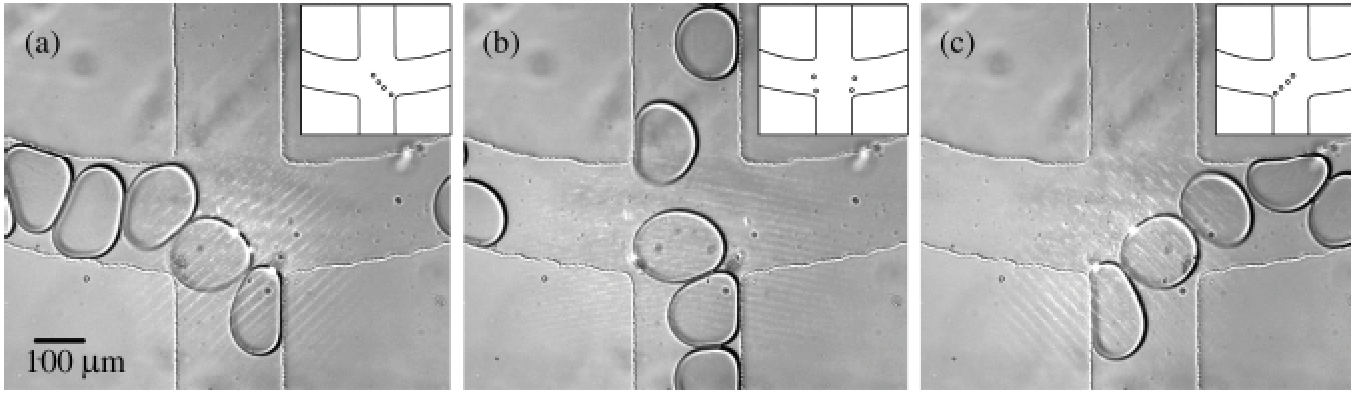
M. Robert de Saint Vincent et al, APL 92, 154105 (2008)

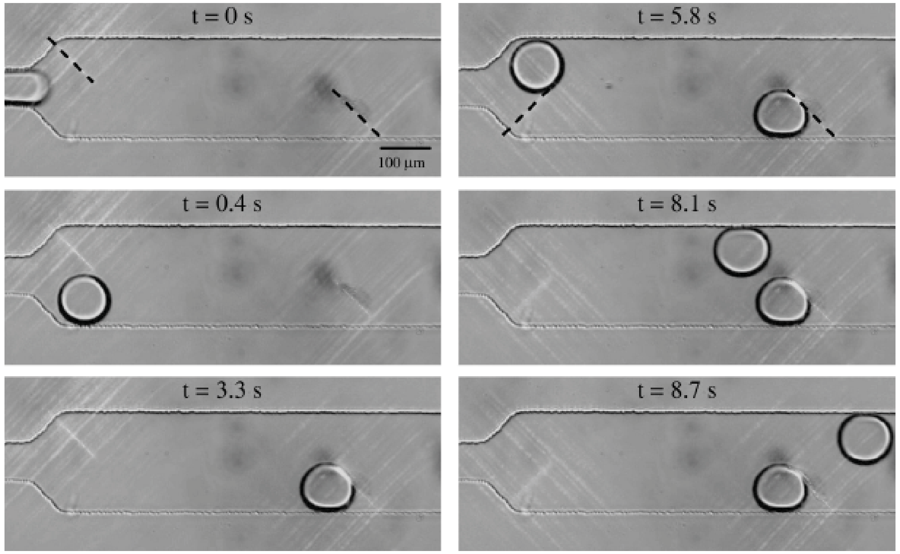
# Holographic control of droplet routing

APPLIED PHYSICS LETTERS **93**, 034107 (2008)

## Thermocapillary manipulation of droplets using holographic beam shaping: Microfluidic pin ball

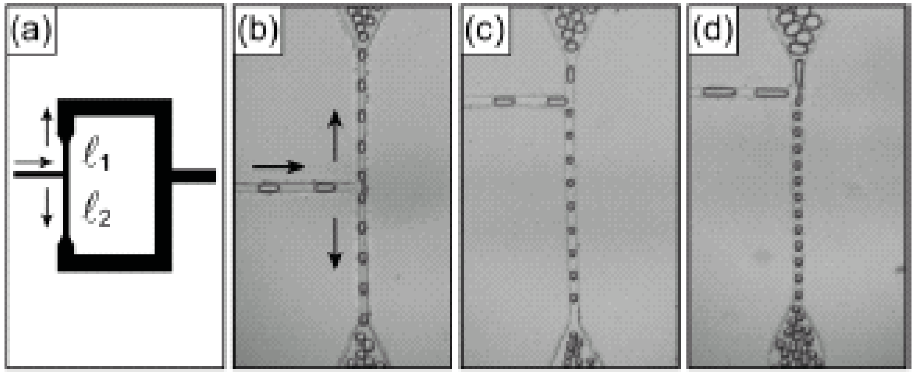
Maria Luisa Cordero,[1] Daniel R. Burnham,[2,3] Charles N. Baroud,[1,a)] and David McGloin[2,b)]
[1]*LadHyX and Department of Mechanics, Ecole Polytechnique, 91128 Palaiseau cedex, France*
[2]*Electronic Engineering and Physics Division, University of Dundee, Nethergate, Dundee DD1 4HN, United Kingdom*
[3]*SUPA, School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS, United Kingdom*





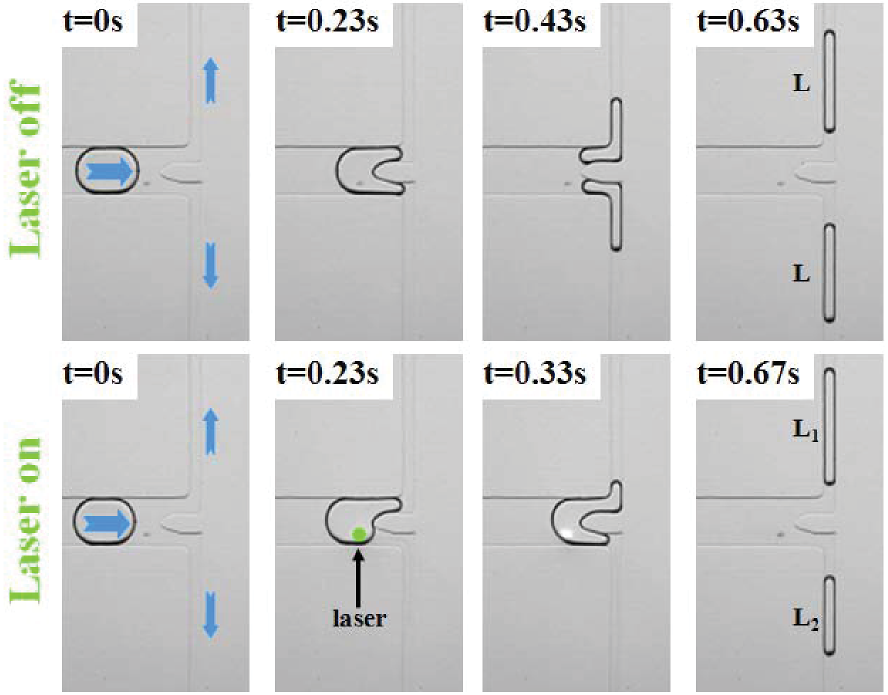
M. L. Cordero et all. APL 93, 034107 (2008)

# Optical asymmetric divider

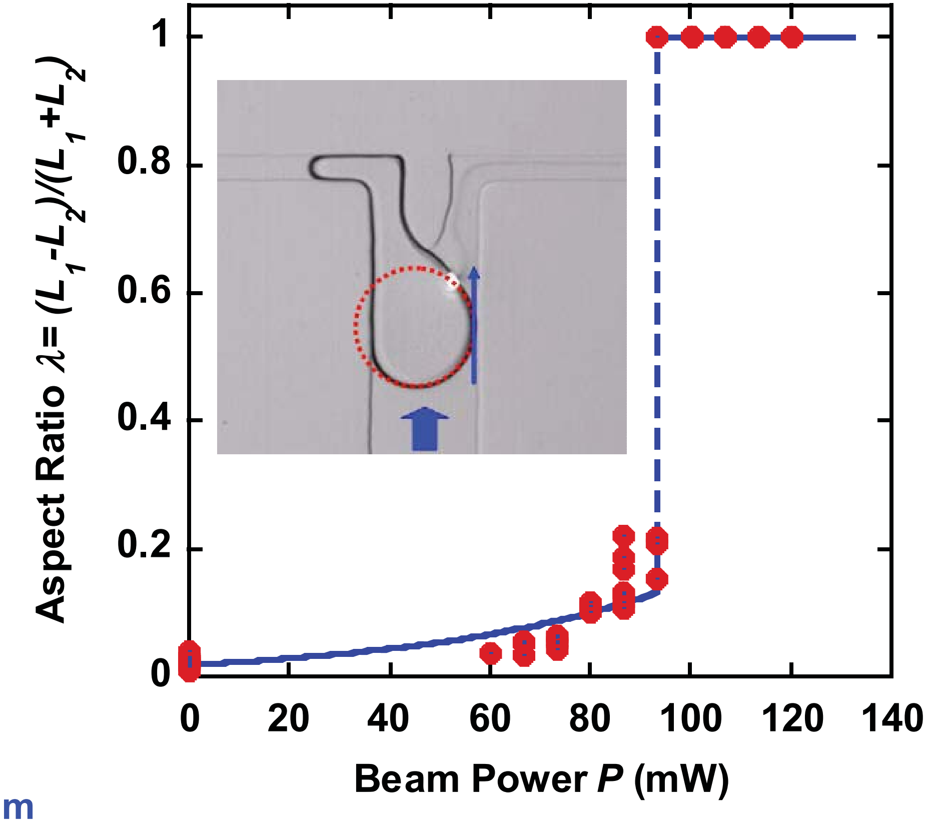


**Drop volume ratio = $l_1/l_2$**

D. R. Link et al, PRL 92, 054503 (2004)



**W/D: 0.02 µl/mn, O/S: 0.2 µl/mn, P=94 mW, $\omega_0$=5.2µm**



C. Baroud et al, Lab. Chip 7, 1029 (2007)

# Thermocapillary Stresses Induced Jetting?

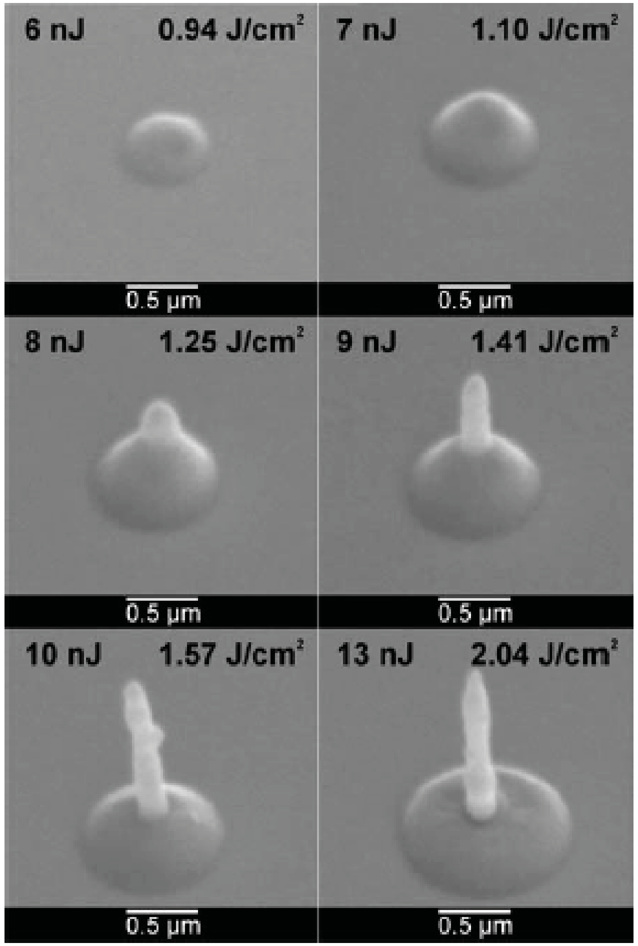
Appl. Phys. A 79, 879–881 (2004)
DOI: 10.1007/s00339-004-2590-5
Applied Physics A
Materials Science & Processing

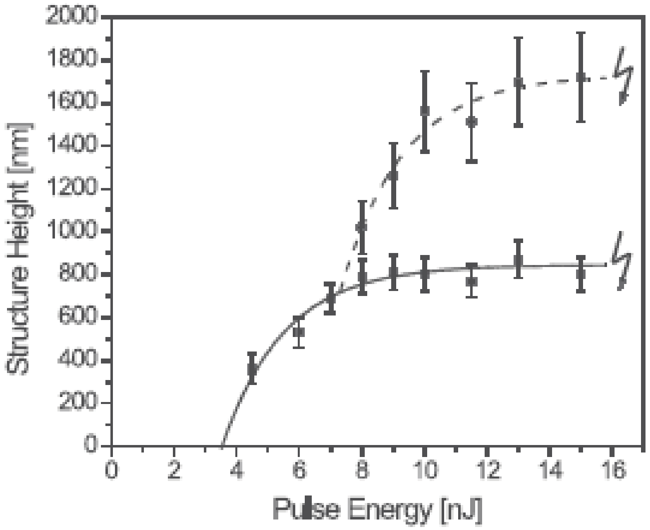
F. KORTE
J. KOCH
B.N. CHICHKOV✉

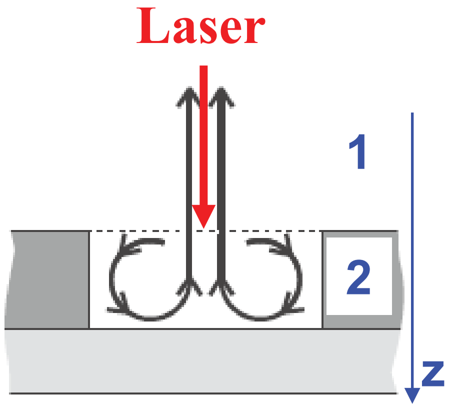
**Formation of microbumps and nanojets on gold targets by femtosecond laser pulses**

Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany

## 1 kHz, 0.9 mJ, 30 fs, 800 nm

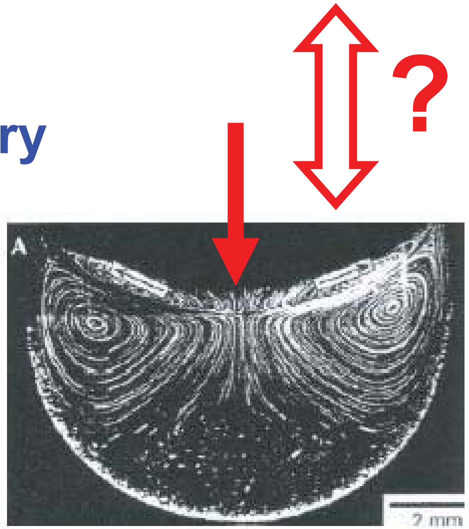






## Stationary Thermocapillary Deformation

$$h_{Th} \propto (\eta_1 - \eta_2)\frac{\partial \sigma}{\partial T} T_E$$



(Marangoni eddies in a weld pool)

# Concluding Remarks

**Focusing thermocapillary stresses on fluid interfaces**

→ An optical toolbox for flowing droplets in microchannels
(force in the range of the several nN)

**Further questions and developments**

→ Several mechanisms remain unclear (coalescence)
→ Quantitative descriptions are difficults
→ What are the final performances?
→ Are they sufficiently robust for contactless microfluidics

**A final dream**

→ Can we couple RP effects and thermocapillary stresses to build and drive a « total optical lab on a chip »?