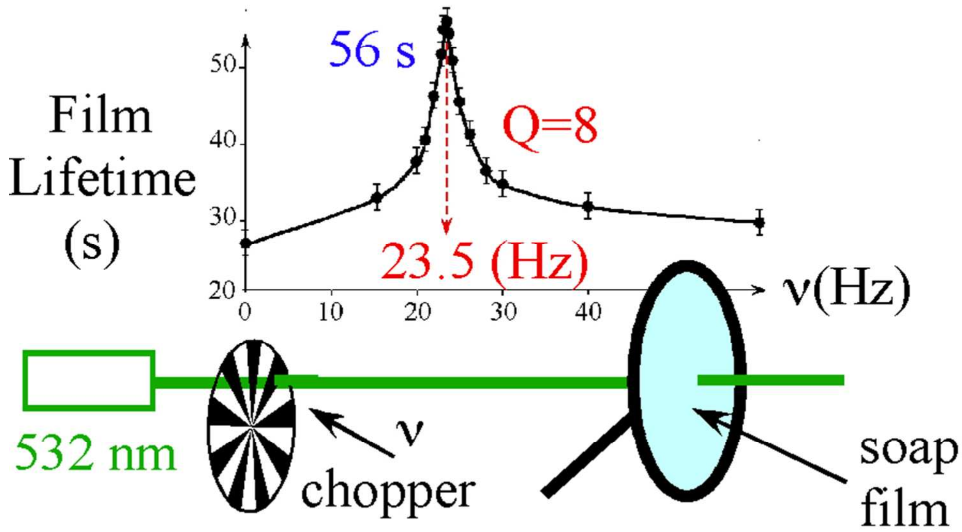

232x137mm (102 x 102 DPI)

Laser induced vibration of a thin soap film.

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We report on the vibration of a thin soap film based on the optical radiation pressure force. The modulated low power laser induces a counter gravity flow in a vertical free standing draining film. The thickness of the soap film is then higher in the upper region than in the lower region of the film. Moreover, the lifetime of the film is dramatically increased by a factor of 2. Since the laser beam only acts mechanically on the film interfaces, such a film can be implemented in an optofluidic diaphragm pump, the interfaces behaving like a vibrating membrane and the liquid in-between being the fluid to be pumped. Such a pump could then be used in delicate micro-equipment, in chips where temperature variations are detrimental and even in biological systems.

1 Introduction

Optofluidics is a research domain that takes advantages of microfluidics and optics to synthesize novel functionalities for applications that include biophotonic systems, lab-on-chip devices, biosensors and molecular imaging[1–6]. One of the key issues in incorporating photonic systems into microfluidic devices is the realization of microvalves and micropumps[6,7]. Most of the vibrating mechanism of the pumping devices reported up to now, mostly relies on a local optical heating that induces a flow[8–12]. This heating may become detrimental when using delicate integrated micro systems or biological devices or cells. On the other hand, the optical radiation pressure can induce a pressure force on air/liquid or liquid/liquid interfaces[13,14]. However, it is quite difficult to bend or deform interfaces using light only. People either use quite high power lasers[13], or low power lasers with liquids having similar surface tensions[15]. Indeed, low power radiation pressure deformation of air/liquid interfaces is hardly noticeable, except under total internal reflection conditions close to the critical angle[16]. Nevertheless, parametric amplification or resonance may dramatically enhance phenomena in general and may thus lead to a higher surface deformation on interfaces. Then, considering a soap film as a model system, since a single laser would act on both air/liquid interfaces, the soap film may then vibrate in a symmetrical manner, like a balloon that inflates and deflates under the influence of the laser. One may wonder which consequences such a vibrating liquid membrane, may induce in the free drainage of the film and whether it then can be adapted to be used as a diaphragm pump in optofluidic devices. Such a pump would be easy to implement, versatile, since it could be adapted to any fluid and even to soft materials, and low cost, since it could be implemented to any chopped light source. The aim of this article is precisely to look for the response of a vertical free standing draining soap film, under the influence of a modulated laser, and to investigate its lifetime and thickness variations.

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2 Experimental set-up

The experimental set up is sketched in figure 1. A vertical free standing draining soap film supported by a glass frame experiences a modulated radiation pressure force from a chopped green solid state laser also called ”modulated laser” in the following (Cristal Laser, P = 100 mW, attenuated to P = 2 mW, waist w = 300 μm, $\lambda = 532$ nm). Although much more accurate techniques exist to measure thin film thickness variations[17], we use the interference fringes in transmission from two continuous wave (CW) low power He-Ne lasers (Mlles Griot, P = 1 mW, w = 400 μm, $\lambda = 633$ nm and $\lambda = 543$ nm respectively), in order to measure the absolute film thickness[18]. These lasers will be called ”probe beams” in the following. The film thickness is deduced from the relative position of the intensity maxima and minima of the transmission of the two lasers, with an absolute precision of the order of 10 nm. Indeed, this technique is quite easy to handle, versatile and fast acquisition times can be obtained.

We have checked that when the solid state laser is not modulated or is not applied, the lifetime and the drainage curve of the liquid film are exactly alike. Thus, the influence of the two low power CW probe beams on the film dynamics could be neglected. The modulated beam was attenuated below 2 mW in order to avoid any deformation of the film interfaces due to higher laser power such as thermal or Marangoni effects[17,19].

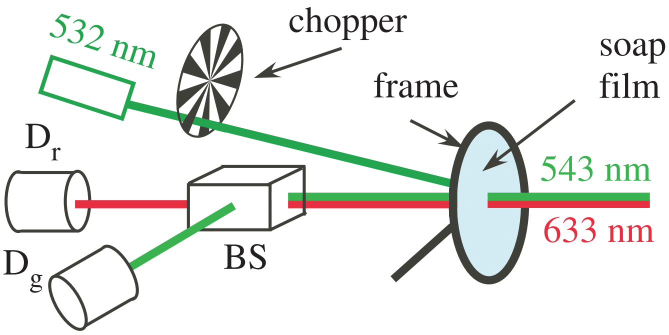

Fig. 1 Experimental set up. Laser light from a 532 nm -2 mW solid state laser deforms a vertical free standing thin soap film. The film thickness is measured from the transmission interferences of two low power lasers with different colors ($\lambda = 633$ nm and $\lambda = 543$ nm). BS: beam splitter, Dg and Dr: photodiodes detecting green and red light respectively.

The glass frame sustaining the film is a 3 cm diameter toroidal ring. The glass rod diameter is 5 mm. The soap solution is composed of a well-known surfactant SLES (Sodium Lauryl Ether Sulfate, Cognis), 0.1% v/v in pure water, below the critical micellar concentration (CMC). Immersing the frame in the soap solution makes the film. The frame is then placed vertically in front of the lasers. The film is centered on the modulated beam. The temperature is controlled to $T = 20.0 \pm 0.2$°C, as well as the air humidity to $50\% \pm 5\%$. The two transmitted probe laser signals are recorded on two photodiodes and then registered on a computer. The acquisition rate can be changed from 1 ms to 0.1 s.

3 Results

3.1 Dynamical response

Let us first investigate the dynamical response of the film under a sudden laser excitation. To that purpose, we have switched the laser on and off with a mechanical shutter. We have recorded the response of the film (thickness variation) via the intensity transmitted by the probe laser beams, as can be seen in figure 2. First of all, one can notice that there is a mechanical response of the film under laser excitation. The film gets thinner as the laser is switched on and thicker as the laser is switched off, as can be expected from the usual radiation pressure force[13,14]. One has to note that both interfaces are bended due to the radiation pressure. When the laser is on and not modulated, the soap film experiences a permanent extra stress that leads to a tiny deformation hardly noticeable on the global drainage curves. The stress is released when the laser is off.

Moreover, when the modulated laser and the CW lasers are not perfectly aligned, one can see, when switching on the modulated laser, a tiny bump and then a dip in the film thickness versus time, meaning that we can easily generate travelling waves on the film interfaces. Typically, when the laser is switched on, the time response of the film is 0.1 s with a thinning of 20 nm. The reverse effect is observed when the laser is switched off, with the same characteristics (see figure 2). Since the CW probe lasers are always applied on the film, they may have a little effect on the absolute thickness of the film but not on the relative variation (drainage curve), as mentioned previously. Indeed the effects we discussed are tiny deformations. However could they modify the flow inside the film or even reverse it by modulating them?

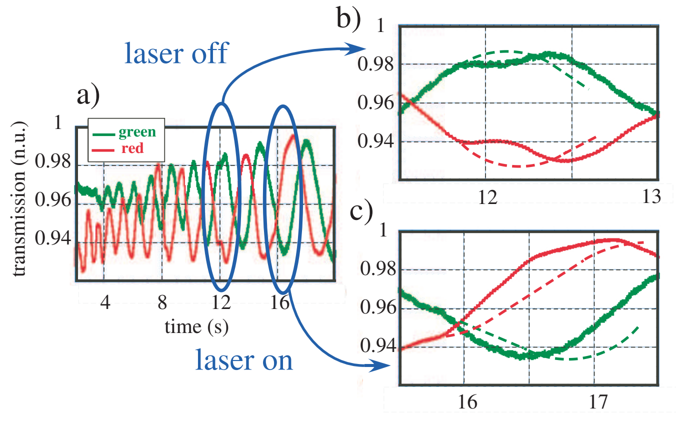

Fig. 2 Deformation of the film interfaces. Interference transmission fringes during the drainage of the film, while the modulated laser is switched on and off several times (a). n.u.: normalized unities. Zoom on the fringes for two specific cases (b), laser off and (c), laser on). The dotted lines are a prolongation of the evolution of the fringes without the applied perturbation. We estimate that the interface deformation is of the order of 20 nm when the laser is either on or off.

3.2 Resonance

Since the time response of the soap film is of the order of 0.1 s, the optimal modulation frequency should be of the order of ten Hz. This is also the typical resonance frequency range of soap film vibrations excited by acoustic waves[20–22]. Let us chop the beam at a low frequency and look at the lifetime of the film, i.e. the time before its rupture. Such a response is sketched on figure 3. One can see a quite sharp resonance around a frequency of 23.5 Hz. The quality factor of the resonance is equal to $Q = 8$, which seems to be rather high for such a mechanical system. Outside the resonance, at high frequencies, the film does not experience the modulation and thus sees a CW excitation. At low frequencies, below resonance, the film reaches a steady state before experiencing the following excitation, as for figure 2.

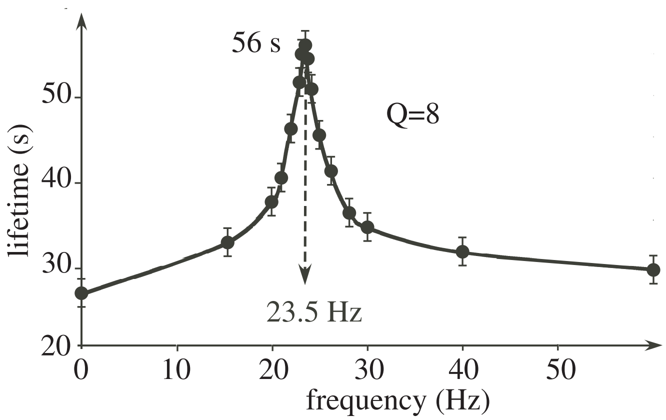

Fig. 3 Lifetime of the film versus modulation frequency. A resonance behaviour of the lifetime of the film for around a 23.5 Hz frequency modulation of the laser beam is evidenced. The quality factor Q equals 8. The lifetime of the film is more than doubled at resonance.

In order to get some more physical insights, one can try to modify the film stiffness. For example, above the CMC, the film structure is changed by miscellar stratification[17]. The film should be stiffer. We have thus observed an increase of the resonance frequency by increasing CMC (for example 25 Hz at 2 CMC). One can also tune the bulk viscosity and the surface shear viscosity by adding some glycerol[23]. The damping coefficient of the film increases, leading to a decrease of the resonance frequency (22 Hz for 5 wt% glycerol added). The quality factor also decreases to $Q = 5$. These results are globally in qualitative agreement with what have been observed with acoustic studies[21,22]. Here the amplitude of the vibrations are much lower than for acoustic waves. In their case, they observed with the naked eye the white light interferences due to the film thickness to evidence the vibrating modes, which is not possible here. However, they are two main differences between acoustic excitation and laser excitation. First the acoustic excitation is induced via a loudspeaker in order to have a uniform vibration. Here, the excitation is point like. Second, bending or antisymmetric modes[24,25] are preferentially excited with acoustics[22] whereas symmetric or squeezing modes are observed here, mainly because the radiation pressure acts on both air/liquid interfaces symmetrically.

According to these studies one would also expect a lower resonance frequency for a frame with higher dimensions. However, we find an increase of the resonance frequency (for example 33 Hz for a 4 cm diameter frame). Actually the studied film is a free vertical standing film whereas experiments with sound induced vibrations used horizontal films. The modulated laser has to counterbalance gravity. The effect of gravity is even more disturbing with a larger frame since the liquid volume excited by the modulated laser is higher, leading to a higher resonance frequency. It follows that the resonance frequency can thus be adapted to the physico-chemical properties of the liquid film and to the geometry of the frame.

4 Drainage curves

Since the soap film lifetime can be dramatically increased, one could wonder how the drainage curves and the film thickness are then modified under a modulated excitation. We have moved the probe beams in order to measure the film thickness at 3 different positions (see figure 4). First we probed the film in the middle of the frame where the modulated laser hits the film, then 0.75 cm above and 0.75 cm below, away from the edges of the frame. In the absence of the modulated laser, one gets usual drainage curves[23,26,27] with a t^{-1} dependence in the middle and on the upper part of the film, t being the time. Gravity and evaporation are the two main mechanisms governing the drainage. In the lower part of the film, due to the presence of the meniscus and related to the accumulation of liquid by gravity, the power law thinning is smoother with a $t^{-0.5}$ law.

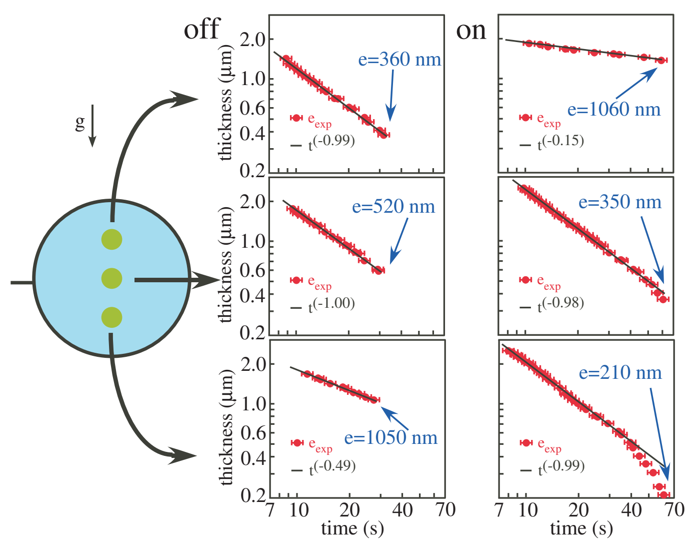

Fig. 4 Drainage curves of the film without and with the laser modulation, at resonance. Thickness evolution of the film versus time at the top, middle and bottom of the frame, without and with the laser modulation, on a log-log scale. The laser modulation frequency equals 23.5 Hz. The red points are experimental values together with the error bars due to the statistic, each measurement being performed three times. The black solid line is a power fit. The absolute precision on the power law is 0.03.

In the presence of the modulated laser, the situation is dramatically changed. As already shown in see figure 2, the lifetime of the film is increased by more than a factor of 2. One can see from figure 4, the thinning power law in the middle of the film is unchanged, only the final thickness decreases strongly, due to the longer lifetime (about 35% thinner). In the bottom of the film, the power law changes from $t^{-0.5}$ to t^{-1}, although at the end of the drainage, there is a small departure from this power law. The final thickness also decreases strongly (about 80% thinner). Indeed, the liquid feeding of this zone from the upper region is dramatically reduced. Contrarily, at the top of the film, the power law changes from t^{-1} to $t^{-0.15}$. The final thickness significantly increases by nearly a factor of 3, and the film hardly drains in this region.

5 Discussion and applications

The drainage evolution is thus globally reversed with an exchange between the top and bottom of the film. Let us try to investigate the flows inside the film. At the beginning of the drainage, the film is thicker in the bottom of the film than at the top (see figure 4). When the laser switches on, it creates a little dip on both sides of the film, flushing the liquid outward. On the bottom of the film the excess of liquid is evacuated down towards the meniscus, due to gravity (see figure 5). On the top of the film the liquid runs uphill, and experiences a new laser flush while it runs downhill towards the center of the film. The liquid cannot drain towards the meniscus, it thus accumulates in the upper region of the film, only submitted to evaporation. One thus gets a film that is thinner in the lower region than in the upper region.

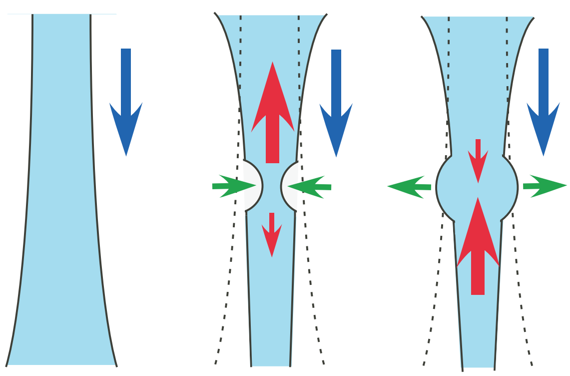

Fig. 5 Influence of the laser on the interfaces (green arrow), flow of the liquid in the film (red arrow) and influence of gravity (blue arrow). The deformations are exaggerated. Left drawing and doted line: free standing draining film. Other drawings: laser on-laser off cycle. In the upper part of the film, the effect of gravity is hidden by the effect of the laser, leading to a an inflation in the upper zone.

The effect is amplified at the end of the drainage. Since the film is thinner at the bottom, the pressure is higher. When the laser switches on the liquid at the center flushes uphill. When the laser switches off, the liquid flows from the lower region toward the center (see figure 5). The liquid is thus pumped from the lower zone towards the upper zone. The pressure difference is indeed acting as a valve. We have been able to make the flow run uphill[8] with a pure mechanical effect. This effect could also explain the departure of the t^{-1} power law of figure 4 of the thickness evolution in the lower part of the film. In that region, the liquid is drained downhill due to gravity and flushed uphill due to the pumping effect.

Since micrometer size valves[28,29] and photoinduced valves[30] have already been demonstrated, this optofluidic pump can be readily implemented for practical applications. These applications are of course non limited to liquid films with air/liquid interfaces. It could be used in soap films deposited on a substrate, but also more generally in liquid/liquid interfaces with different optical indexes. It could also be helpful in controlling and regulating the water density or water flow in biological and cell applications. It can even be implemented for liquid core/polymers cladding waveguides[31]. It can thus become the dynamical element in optofluidic devices for drug and food flow delivery in in-vitro cell culture. Besides, since the modulated laser is a very low power laser (2 mW output power), low consumption cheap diode laser or even natural light from the sun can also be used, this optofluidic pump would be of valuable help in remote areas with difficulty in energy supply[32,33], where people can rely on solar energy.

6 Conclusions

We have experimentally shown that even a low power laser can dramatically change the dynamical behaviour of a liquid draining film. The action of a modulated laser beam on a vertical soap film flushes the liquid upstream, creating then a bottle neck that reverse the liquid flow from downhill to uphill. This results in a dramatic increase of the lifetime of the film for a given resonance frequency. The power law drainage time evolutions and the final thickness of the film are also strongly changed.

Such an optofluidic diaphragm pump can be readily implemented in practical devices. For example, such a modulated laser light can be directly shined on the membrane of biological cells to pump liquid inside or outside the cell and may thus find applications in dermatology to remove angioma or in ophthalmology to remove floaters. Since the action of the laser only leads to tiny mechanical vibrations, there would be no biocompatibility problems when used in for biomedical and neuronal applications[34,35]. Besides, since the optical power is very low, there would not be any problem of photothermal damages[36–38] due to the laser radiation.

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References

1 D. Psaltis, S. R. Quake, C. Yang, Developing optofluidic technology through the fusion of microfluidics and optics. *Nature* 2006, 442, 381-386
2 C. Monat, P. Domachuk, B. J. Eggleton, Integrated optofluidics: a new river of light. *Nat. Photonics* 2007, 1, 106-114
3 Y. Fainman, L. P. Lee, D. Psaltis, C. Yang, *Optofluidics fundamentals, devices and applications*, McGraw-Hill, Montreal, 2010
4 X. D. Fan, I. M. White, Optofluidic microsystems for chemical and biological analysis. *Nat. Photonics* 2011, 5, 591-597
5 H. Schmidt, A. R. Hawkins, Photonics integration of non-solid media using optofluidics. *Nat. Photonics* 2011, 5, 598-604
6 L. Pang, H. M. Chen, L. M. Freeman, Y. Fainman, Optofluidic devices and applications in photonics, sensing and imaging. *Lab. Chip.* 2012, 12, 3543-3551
7 L. Chen, S. Lee, S. Choo, E. K. Lee, Continuous dynamic flow micropumps for microfluidic manipulation. *J. Micromech. Microeng.* 2008, 18, 013001
8 M. K. Chauhury, G. M. Whitesides, How to make water run uphill. *Science* 1992, 256, 1539-1541
9 G. L. Liu, J. KIm, Y. Lu, L. P. Lee, Optofluidic control using photothermal nanoparticles. *Nat. Mat.* 2006, 5, 27-32.
10 F. M. Weinert, J. A. Kraus, T. Franosch, D. Braun, Microscale Fluid Flow Induced by Thermoviscous Expansion Along a Traveling Wave. *Phys. Rev. Lett.* 2008, 100, 164501
11 D. A. Boyd, J. .R. Adelman, D. G. Goodwin, D. Psaltis, Chemical Separations by Bubble Assisted Interphase Mass-Transfer. *Anal. Chem.* 2008, 80, 2452-2456
12 J. S. Danou, G. Baffou, D. McCloskey, R. Quidant, Plasmon assisted optofluidics. *Acs nano* 2011, 5, 5457-5462
13 A. Ashkin, J. M. Dziedzic, Radiation Pressure on a Free Liquid Surface *Phys. Rev. Lett.* 1973, 30, 139-142
14 A. Ashkin, Applications of laser radiation pressure *Science* 1980, 210, 181-188
15 A. Casner, J. P. Delville, Giant Deformations of a Liquid-Liquid Interface Induced by the Optical Radiation Pressure. *Phys. Rev. Lett.* 2001, 87, 054503
16 O. Emile, J. Emile, Low-Power Laser Deformation of an Air-Liquid Interface. *Phys. Rev. Lett.* 2011, 106, 183904
17 J. Emile, O. Emile, Mapping of the Marangoni effect in soap films using Young's double-slit experiment. *EPL* 2013, 104, 14001
18 J. Emile, F. Casanova, G. Loas, O. Emile, Swelling of a foam lamella in a confined channel, *Soft Matter* 2012, 8, 7223
19 S. Chandrasekhar, *Hydrodynamic and hydromagnetic* Dover, New-York, 1981
20 E. B. Tylor, Sound vibrations of soap film membranes. *Nature* 1877 16, 12-12
21 L. Bergmann, Experiments with vibrating soap membranes. *J. Acoust. Soc.Am.* 1956, 28, 1043-1047
22 A. Boudaoud, Y. Couder, M. Ben Amar, Self adaptation in vibrating soap films. *Phys. Rev. Lett.* 1999, 82, 3847-3850
23 S. Berg, E. A. Adelizzi, S. M. Troian, Experimental Study of Entrainment and Drainage Flows in Microscale Soap Films. *Langmuir* 2005, 21, 3867-3876
24 P. Sens, C. Marques, J. F. Joanny, Hydrodynamics modes of viscoelastic soap films. *Langmuir* 1993, 9, 3212-3218
25 C.-Y. D. Lu, M. E. Cates, Hydrodynamic modes of soluble surfactant films. *Langmuir* 1995, 11, 4225-4233
26 R. J. Braun, A. D. Fitt, Modelling drainage of the precorneal tear film after a blink. *Math. Med. Biol.* 2003, 20, 1-28
27 S. N. Tan, Y. Yang, R. G. Horn, Thinning of a Vertical Free-Draining Aqueous Film Incorporating Colloidal Particles. *Langmuir* 2010, 26, 63-73
28 V. Studer, G. Hang, A. Pandolfi, M. Ortiz, W. F. Anderson, S. R. Quake, Scaling properties of a low-actuation pressure microfluidic valve. *J. Appl. Phys.* 2004, 95, 393-398
29 C. Murray, D. McCoul, E. Sollier, T. Ruggiero, X. Niu, O. Pei, D. Di Carlo, Electro-adaptive microfluidics for active tuning of channel geometry using polymer actuators. *Microfluid. nanofluid.* 2013, 14, 345-358
30 F. Benito-Lopez, R. Byrne, A. A. Raduta, N. E. Vrana, G. McGuiness, D. Diamond, Ionogel-Based Light-Actuated Valves for Controlling Liquid Flow in Microfluidic Manifolds. *Lab. Chip.* 2010, 10, 195-201
31 P. Fei, Z. Chen,Y. Men,A. Li, Y. Shenac, Y. Huang, A compact optofluidic cytometer with integrated liquid-core/PDMS-cladding waveguides *Lab Chip*, 2012, 12, 3700-3706
32 L. Jiang, M. Mancuso, Z. Lu, G. Akar, E. Cesarman, D. Erickson, Solar thermal polymerase chain reaction for smartphone-assisted molecular diagnostics *Sci. Rep.* 2014, 4, 4137
33 S. Lee, V. Oncescu, M. Mancuso, S. Mehta, D. Erickson, A smartphone platform for the quantification of vitamin D levels *Lab Chip*, 2014, 14, 1437-1342
34 M. A. Unger, H. P. Chou, T. Thorsen, A. Scherer, S. R. Quake, Monolithic microfabricated valves and pumps by multilayer soft lithography. *Science* 2000, 288, 113-116
35 J. W. Park, H. J. Kim, M. W. Kang, N. L. Jeon, Advances in microfluidics-based experimental methods for neuroscience research. *Lab. Chip* 2013, 13, 509-521
36 E. K. Scackmann, A. L. Fulton, D. J. Beebe,The present and future role of microfluidics in biomedical research. *Nature* 2014 507, 181-189
37 V. VanDelinder, G. D. Bachand, Photodamage and the importance of photoprotection in biomolecular-powered device applications. *Anal. Chem.* 2014, 86, 721-728.
38 B. Dura, Y. Liu, J. Voldman, Deformability based microfluidic cell pairing and fusion, to be published in *Lab on a Chip* DOI 10.1039/CALC00303A