Lab on a Chip

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**HIGHLIGHT**



# Research highlights

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## Two-faced microreactors

Droplet-based microfluidics have found applications in areas ranging from protein crystallization to single-cell studies. The resulting screening assays usually consist of aqueous droplets surrounded by a lipid phase. They benefit from the small droplet volumes (in the order of pl and even fl) and the physical isolation of neighboring droplets from each other by the oil. This effectively renders each droplet an independent biochemical reactor.[1] In most instances, the droplets are used as isolated microbatch reactors. There are only a few exceptions (*e.g.* protein crystallization) that allow for vapor[2] and free interface diffusion[3] as a means of communication between a droplet and its environment.

A novel method that permits controlled communication between a droplet and its neighbor has been developed by Khan and colleagues. In this approach, Barikbin *et al.*[4] enabled the transport of analytes across the interface of two distinct droplets generated *via* microfluidic flow focusing. The droplets, one containing an aqueous solution and the other an ionic liquid (IL) were in contact with each other and surrounded by oil, but did not coalesce. Here, the researchers exploited the tunable properties of the highly polar IL (a type of ionic solution), such as low miscibility with water and no solubility in oil.

Analytes stored in the aqueous compartments, such as ions of gold salt, began to diffuse into the IL phase immediately after generation of these biphasic microdroplets (Fig. 1). They then catalyzed the reaction of a substrate (*e.g.* aryl alkyne) into a visually detectable fluorescent reaction product (a derivative of coumarin). The reaction was confined to the IL compartments, because contrary to the analyte, the substrate and the reaction product dissolved preferentially in the IL. As more of the analyte diffused across the interface, the reaction continued and the concentration (and therefore the intensity) of the fluorescing reaction products increased to saturation. The rate at which the fluorescence signal (or the reaction rate) intensified was found to be a function of the flow-dependent convective mixing inside the droplets. However, the time to signal saturation was independent of the flow conditions, as it was controlled by the total amount of analyte.

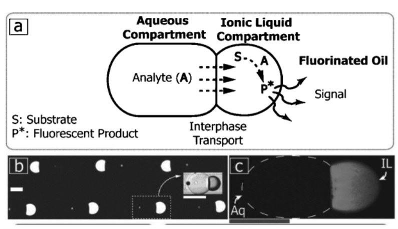


**Fig. 1** Analyte A diffuses from the aqueous side of the biphasic microdroplet into the ionic liquid region (a) and catalyzes the transformation of a substrate chemical S into a fluorescent compound F, (b) and (c). The aqueous compartment is indicated with the dashed line. Figure reprinted with permission from Barikbin *et al.*[4]

After the completion of the reaction, the researchers separated the IL compartments from their aqueous counterparts and collected them for further analysis. This was enabled by introducing obstacles inside the fluidic channels. At relatively low flow velocities ($\sim$1 mm s$^{-1}$), the biphasic droplets passed by the obstructions as single entities, but were decoupled at fourfold higher flow speeds.

This work highlights the use of droplet microfluidics for the dynamic control of chemical reactions and complex chemical assays. It also demonstrates the utility of IL as *de facto* structural elements of microfluidics-based experiments, although this method only allows reactions to proceed in one direction, making the chemical processes irreversible. Still, this technique lends a new dimension to a traditional microfluidic application, opening the path to novel biochemistry and digital microfluidics studies.

## Soft robots

The purpose of early microfluidic devices has been to transform bench-top scale experiments into micro- or chip-scale studies, thereby saving reagents, cost and time, and exercising more control over individual experimental parameters and kinetics.[5] Recently, however, there has been a growing interest in utilizing microfluidics not only for lab-on-a-chip reactors and factories, but for constructing autonomous, active field robots.

A conceptual example of this approach has now been developed by Whitesides and colleagues, who engineered a set of

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soft machines capable of camouflage. In an effort to create a synthetic system mimicking the color-changing behavior of certain animals, Morin *et al.*[6] fabricated elastomeric devices with tunable color, pattern and surface temperature (IR signature). These devices contained dense microfluidic networks that could be filled with different liquids, changing color or pattern and, when pressurized, becoming mobile.[7] The structures (10 cm × 10 cm in size, with several hundred μm wide channels) were generated from poly(dimethylsiloxane) (PDMS) using standard photo- and soft lithographic techniques and were reinforced with flexible, biodegradable Ecoflex sheets.

The soft machines were simple to operate. Flowing an aqueous dye solution through the microfluidic channels caused the machine to either stand out or blend into the background. For example, a machine placed on a red surface was filled with a red dye solution to blend in. When this soft robot was pressurized in a particular manner, it moved across different substrates. Depending on the color and the pattern on the substrate, the researchers replaced the initial solution with a different dye to alter the appearance of the machine. The red-colored machine became easy to spot against a layer of grey rocks, but it was camouflaged again after replacing the red dye with a grey solution. The same behavior was demonstrated in the IR-spectrum by adjusting the temperature of the solution. Thus, a soft machine noticeable in the IR spectrum can be masked in the visible range and *vice versa*. Since the body of the robot is made of PDMS and Ecoflex, which are transparent to a wide range of wavelengths, the machine could also be visualized with fluorescent dyes.

The present work serves as an introduction to mobile soft robots with an ability to camouflage. This type of device could potentially be used in defense applications, *e.g.* to transport cargo without being detected. Alternatively, it could be used as a signaling beacon for studies of animals capable of bioluminescence, mimicry or camouflage. Currently, however, the soft machines are controlled *via* external inputs, which confines them to the laboratory. To render this type of device useful, it will be necessary to include on-chip components, such as heating/cooling modules and reservoirs prefilled with different liquids. Future soft machines should also contain on-chip sensors capable of detecting environmental parameters, such as brightness and temperature, and providing this information to an integrated control unit.

## Liquids as metamaterials

Metamaterials are synthetic materials with properties not found in nature, such as negative or gradient index of refraction and particular electromagnetic bandgaps, *etc.*[8] Optofluidics is an emerging field that aims to combine the study of optics with microfluidics. One of the goals of optofluidics is to engineer metamaterials inside microfluidic channels, by propagating light through fluids under certain flow conditions.

To this end, Liu and colleagues studied the behavior of light in an optofluidic waveguide at low Peclet numbers (Pe). This allowed them to observe light interference patterns and other effects of diffusion between the core and sheath flows in a flow-focusing setup. Yang *et al.*[9] fabricated a simple PDMS device with a single long flow focusing channel and filled it with ethylene glycol (core flow) and deionized water (sheath flow). The incoming light from an argon ion laser was initially confined to the core flow, since its index of refraction was higher than that of water and PDMS. However, at low flow rates and low Pe ($\leqslant 0.001$) the core and sheath fluids mixed with each other *via* diffusion, which led to inhomogeneities in the optical medium where the changes in the refractive index occur on a scale similar in size to the wavelength of light. A gradient in the index of refraction was generated both along the direction, as well as perpendicular to the flow, causing the light to refract at different locations in the channel and to form interference patterns (Fig. 2a).

The presence of multiple focal points of light was also observed in the core flow. The focusing period (distance between two foci, Fig. 2b) increased along the channel. The first period was dependent on the absolute and the relative magnitude of the core flow, such that it increased whenever the core stream widened. Reducing the core flow rate, for example, allowed a more efficient diffusive mixing and, hence, resulted in widening of the core flow near the channel input.

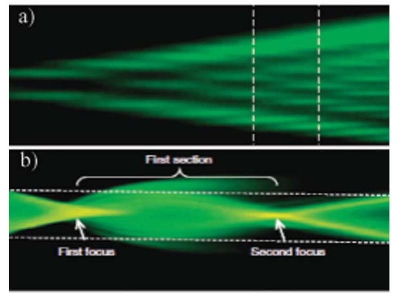


**Fig. 2** Experimental images of an optofluidic waveguide showing the interference pattern (a) and two focal points (b). The dashed lines in (b) outline the 15 μm wide core flow. Figure adapted and reprinted with permission from Yang *et al.*[9]

The light patterns observed in this study are unique to metamaterials consisting of miscible liquids, where the observed dielectric properties have not previously been achieved in synthetic solids. Furthermore, the gradient in dielectric properties is readily tunable in two dimensions simply by altering the fluid flow rates. Likely applications include signal routing and information coding. In addition, by employing a coaxial capillary setup, a third dimension could be added to the gradient. This could potentially lead to particle trapping applications similar to Holographic Optical Trapping.

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