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Abstract

The realization of miniaturized optofluidic platforms opens up novel potentialities for the achievement of devices with enhanced functionality and compactness. Such integrated systems bring fluid and light together and exploit their micro-scale interaction for a large variety of applications. The high sensitivity of compact microphotonic devices can generate effective microfluidic sensors, with integration capabilities. By turning the technology around, the exploitation of fluid properties holds the promise of highly flexible, tunable or reconfigurable microphotonic devices. We overview some of the exciting developments to date.

1. Introduction

Optofluidics fundamentally aims at manipulating fluids and light at the microscale and leveraging their interaction for creating novel and highly versatile systems. Whereas micro-electromechanical systems (MEMS) and "lab-on-a-chip" communities have made efforts to incorporate optical devices in their micro(fluidic) systems to improve their functionality[1,2], a wide variety of optofluidic devices have been demonstrated recently[3]. Combining fluids and light has produced all sorts of creative devices, such as adaptive optical lenses[4,5] or optofluidic microscopy[6]. New opportunities were undeniably opened up with the recent attempts to synergetically combine both integrated microphotonic devices and microfluidic systems. The potential applications present a dual aspect. Fluids can be used to carry substances to be analysed through highly sensitive microphotonic circuits, in the context of integrated bio-chemical sensing. Conversely, microfluids can be exploited to control microphotonic devices, making them tunable, reconfigurable, and adaptive.

Photonics has evolved towards device miniaturization with the ultimate goal to integrate many optical components onto a compact chip, producing photonic integrated circuits with low cost and higher degrees of functionality. Planar photonic crystals[7], formed from periodic lattices of sub-micrometer air holes inscribed in a slab waveguide, provide a generic platform to realize photonic integrated circuits[8]. The generation of microstructured optical fibres with micrometer air voids[9,10] and the capability of tapering fibres[11] also offer new opportunities to achieve miniaturized optical functions. Nonetheless, control systems should be developed simultaneously to operate such compact devices. In particular, the generation of advanced integrated photonic systems depends on our capability to "miniaturize" tunability. Optical tunability relies on the dynamic modification of the optical properties of a photonic circuit through substantial and local variations in its refractive index. As the spatial scale is reduced in microscopic devices, the necessary range of index modulation becomes higher and challenging to achieve. For instance, a tunability range of $\Delta n \sim 7.5\times10^{-2}$ (7.5×10^{-5}) is required to fully modulate the response of a 10 μm (1 cm) long interferometer at 1.5 μm wavelength.

Since the 1990's, microfluidics has been the subject of concerted research efforts both in academia and industry, especially for biotechnology. Microfluidics found broad application in the "lab-on-a-chip" paradigm: the principle of incorporating large-scale biochemical synthesis and analysis functionalities onto a small chip[12]. Integration offers significant advantages to these systems including minimized consumption of reagents, portability, increased automation and reduced costs. Applications have been found in clinical analysis, drug discovery, small-volume DNA replication and testing[13,14]. The analytical efficiency and throughput of these devices also make them perfectly suited for ambient bio-threat detection, where the local environment is continuously and remotely tested. Integrating monolithic or hybrid optical and optoelectronic devices (light sources, filters, or photodetectors) into lab-on-a-chips[15-18] is a current field of investigation for improving the performance and portability of these systems[1,2].

In addition to the straightforward sensing application of optofluidic systems, microfluidics can provide what an integrated photonic circuit lacks at the micrometer scale: a means to tune and reconfigure microphotonic devices. For that, microfluidics displays some unique properties. Microfluidic laminar flows can efficiently transport various species or nanostructures with desirable optical properties. Those species, that are otherwise difficult to handle, can be brought into targeted locations of a microphotonic circuit. Microfluidics also offers a wealth of ways to control microphotonic devices. The range of index modulation achievable through fluid manipulation is very large and can be induced locally using microfluidic circuitry. Because fluid is a mobile phase, it can be used as a changeable part of a photonic device, which becomes reconfigurable. Liquid/ liquid and liquid/ air flexible interfaces themselves can produce highly adaptive optofluidic devices. Eventually, the specific behaviour of fluids that are confined at the micro-scale can be exploited in a unique fashion (Textbox 1).

We focus here on the latest developments related to the combination of integrated optics and microfluidics by highlighting three main ranges of applications. We first review a new class of optofluidic light sources. Second, we demonstrate how the high sensitivity of integrated microphotonic devices can generate effective and miniaturized fluidic sensors. The last range of application relies on the use of microfluids to control, tune, and reconfigure optical microdevices.

2. Micro-fabrication

Microdevices, such as MEMS, are usually fabricated in silicon or silica, using the well-established micromachining process of microelectronics. Whereas numerous microfluidic systems have been built from those techniques and materials, alternative and cheaper processes, using low cost polymeric materials such as polydimethylsiloxane (PDMS) or polymethylmethacrylate (PMMA), have been developed more recently. PDMS elastomer displays attractive properties like elasticity, optical transparency and biocompatible surface chemistry[19]. Its low Young's modulus has allowed the construction of thin flexible membranes that are exploited to build micro-valves[20] or adaptive lenses[21].

Microfluidic prototyping can be fast and cheap. Soft lithography[22], for instance, relies on the creation of a "hard" master by traditional microfabrication techniques from which a PDMS mould is cast. This mould can then replicate many identical devices easily due to the PDMS low surface affinity that enables separation. Resolution is limited only by the fidelity of the mould[23]; rapidity and economy are enabled by restricting complex fabrication steps to the master step.

Various microfluidic components, like micro-mechanical valves[20], micro-channels, micro-pumps[24], microfluidic mixers[25], and other elements to handle and control fluids[26] at the micro-scale have been realized. Their large-scale integration[27] onto one chip allows for the construction of dense and functional microfluidic platforms[28]. Microfluidic systems can perform multiple assays simultaneously[27] or sequential procedures of analytical biochemistry through parallel architectures[29].

Microfluidic and microphotonic components can be directly fabricated from the same materials using the same processes, potentially during the same fabrication step; or they can be fabricated separately and post-assembled[2]. However, despite recent demonstrations[30-32], complete integration of both complex platforms is still in a highly developmental stage. Exploration of new optofluidic functionality is the aim of most current investigation. The following three sections highlight some examples of these new modalities.

3. Optofluidic light sources

Typical biochemical analysis relies on bulky, costly and lossy free-space optics carefully coupled through a microfluidic system. Integrated optofluidics could provide photonic integration for lab-on-a-chips impacting on all three of the above limitations[1]. In this context, integrated, planar light sources are essential.

Optofluidic light sources represent an innovative way to integrate an optical source onto a microfluidic system. Those devices use active species dissolved in a liquid solution as the gain medium. A variety of organic dye molecules covering the visible wavelength range are commercially available. Using fluids to "supply optical gain" has several advantages: the gain solution can be delivered through microfluidic channels onto specific locations where the active medium will efficiently interact with the optical modes of the device; dye bleaching effects are avoided by a regenerating continuous flow of dyes through the laser cavity; and most importantly, unlike their solid-state counterparts, liquid dye lasers are inherently tunable.

Since the first demonstration in 2003[33], microfluidic light sources have progressed in terms of functionality, compactness and manufacturing. Various configurations (Fabry-Perot[33,34], microcavities[30,35], Bragg gratings[36,37] or long waveguides[38]) and materials (PDMS[37], SU8 polymer[30,36], thermoplastic[39] or glass[40]) have been explored. Kristensen's group has realized microring-based lasers[35] and distributed feedback microlasers[36] with good performance. The former has a switchable output coupled into an integrated polymer waveguide but is highly multimode. The latter displays narrowband laser operation by exploiting anti-guiding effects and is coupled to waveguides that are defined onto the same polymer layer (Fig. 1). The Bragg grating consists of a series of SU8 micrometer-sized bars, whose spacing is filled by the dye solution. An alternative process based on nano-imprinted thermoplastic has been successfully developed[39]. The technique involves a high-resolution silicon master that could advantageously include nanometer-sized features. Li et al. have realized similar distributed feedback microlasers from a monolithic PDMS layer that is imprinted at once from a polymer stamp[37]. The laser maintains single mode operation while its wavelength is continuously and reversibly tuned over 30 nm by stretching the grating period of the elastomeric chip.

Another class of microfluidic light sources relies on liquid-liquid (L_2) waveguides, where the core and cladding of long optical waveguides are made from two immiscible liquid streams with different index. The two laminar microfluidic streams flow side by side without mixing and produce an optically smooth core/cladding interface. Light emission, collection and propagation all occur within the liquid dye core. These devices possess a high degree of flexibility enabled by the dynamic control of the optical and geometrical properties of the liquid core and cladding. The emission wavelength can be tuned by varying the composition of the liquid core[41]. The output beam size and intensity are changed via the manipulation of the liquid flow rates[38]. Eventually, L_2 waveguides with different dye molecules can be associated in arrays or cascades to generate integrated broadband light sources[42].

The reported optofluidic lasers emit light in the visible range. By exploiting other kinds of dissolved active medium, like quantum dots or colloidal nanocrystals, near-infrared emission could be achieved equally with good performance[43,44]. Note that these lasers are still not stand-alone devices because they usually rely on : (i) external gas pressure source to ensure a microfluidic continuous flow ; and (ii) free-space external pumping lasers. The first issue could be addressed by using emerging integrated techniques to actuate microfluids (see section 5). Regarding the second issue, an internal pumping configuration, in which the pump beam is guided to the chip via an optical fibre, is also possible[34].

Liquid dye microlasers can be tuned by manipulating the cavity conditions (using for instance elastomer to construct the resonator[37]) or the fluids. Changing the dye molecules, the solvent, the dye concentration or the liquid flow rates provide different ways to tune these lasers. However, to benefit from this high flexibility, the capabilities of fast and precise liquid flow control, fluid mixing, switching and delivery of dye solutions should all be carried out onto the one chip. This is possible by integrating micro-valves, micro-pumps, and mixers[30,45]. Galas et al. have demonstrated on-chip tuning of a microring dye laser within 3 seconds[30]. This integrated microfluidic system involved a closed loop based mixer and a micro-pump to adjust the concentration of the nanoliter dye solution and the flow rate. This provides the continuous tuning of both the laser wavelength (over 8 nm) and intensity. Eventually, additional devices can be integrated to increase the degree of functionality of the optofluidic platform[46].

4. Sensor applications

Integrated optics, which can accommodate large arrays of compact optical channels and devices, is highly promising for the integration of robust biochemical sensors with high sensitivity and throughput. A wide variety of optical methods have been used for bio-chemical sensing, such as absorbance, fluorescence, Raman, scattering, refraction or surface plasmon resonance measurements. Integrated optics can be successfully combined with all these schemes[47,2], bringing the unique advantages associated to its planar format. In particular, it has proven useful for directly exciting[48] or collecting[49] (or both[50,51]) particle fluorescence, improving the limit of detection and reducing the probed volumes[51]. Absorbance detection has also benefited from integrated optics[52,53] although this method remains less sensitive and less easily "scalable" than the fluorescence technique. Furthermore, integrated optics enables the direct detection of refractive index changes, Δn, which is label-free and quite versatile as a broad range of physical phenomena influence the effective index of the sensing waveguide: index changes can indicate variations in the chemical composition of the analysed solution or the binding of target molecules with bio-specific receptors coated at the device surface[54]. Reference 47 presents a comprehensive review of the numerous detection principles and instrumental configurations that have been adopted with optical waveguide sensors. We will focus here on selected examples of recent advances in integrated microphotonics that could improve notably some detection schemes.

Whatever the physical phenomenon used for the detection, integrated optical sensors fundamentally require the interaction between light and the solution of analytes. Some sensors involve evanescent coupling: fluids surround the optical device and interact with its evanescent field. Other sensors exhibit direct coupling: fluids and light are confined into the same locations. The degree of the interaction strongly determines the device sensitivity.

As increasing the optical path length represents one way to raise the light-fluid interaction, many integrated optical sensors are compromised between compactness and sensitivity. Mach-Zehnder interferometers can provide ultra-high resolution detection (Δn~10^{-4}-10^{-8}) but require long interaction lengths (typically 4 cm)[55]. A similar trend is obtained for couplers that exploit simultaneously embedded waveguides and microfluidic channels ($\Delta n<10^{-4}$ for 7.5 mm)[56]. Hollow core anti-resonant reflecting optical waveguides (ARROW) benefit from a high sensitivity due to the direct interaction between fluids and light that are both guided inside the waveguide core[57],[51]. However, the waveguide length should be high enough (~2 cm) for collecting substantial signal modulations[58]. Optical waveguides have been also combined with surface plasmon resonances[59]. They rely on the selective coupling between a dielectric waveguide and a leaky metal-coated waveguide. The narrow dip induced in the transmission spectrum displays ultra-high sensitivity upon fluid index changes (resolution of Δn~10^{-6}) because the evanescent wave at the metal/dielectric interface largely extends in the surrounding liquid. However, relatively high interaction lengths (1.8 mm) are demanded to produce narrow and deep detectable features[60].

By contrast, photonic micro-resonators can produce more compact sensors with reasonably high sensitivity, which does not directly depend on the device footprint. Resonant optical structures dramatically increase the effective length of interaction between the fluid and the optical field that is trapped and built up inside the resonator, beyond its physical length. Furthermore, the magnified optical field intensity can be used to enhance the excitation of surrounding fluorescent molecules[61,62] or the absorbed intensity of the analytes[63], improving the respective signals of fluorescence and absorbance detection methods. The resulting high sensitivities onto compact areas reduce the limit of detection, in terms of sample volumes and analyte concentrations.

Two parameters of the micro-resonator must be maximized to provide high resolution and sensitive detections: the quality factor (Q) of the resonance, which is inversely related to the optical losses, and the slope between extreme transmission states (ideally zero and unity) in the spectrum[64]. Indeed, micro-resonator effective index changes are detected through the monitoring of the resonance wavelength shift or the intensity variation at a fixed wavelength ; narrower resonance linewidths (proportional to $1/Q$) thus improve the sensor resolution by reducing the smallest detectable shift in the resonance. Absorbance, Raman (or fluorescence) schemes, whose sensitivities are proportional to the optical field intensity (or the excitation energy), also benefit from high Q micro-resonators, which ensure effective light storage and field enhancement inside the micro-cavity.

Various micro-resonators with ultra-high Q have been realized in recent years[65-68] (Fig. 2) in aqueous environment[69]. Several optofluidic sensors have been demonstrated, based on micro-cavities coupled to integrated waveguides that serve as the input and output ports. Near the "critical coupling" condition, sharp dips are induced at the resonance wavelengths in the waveguide transmission spectrum[65]. Si micro-disks with moderate Q (5,000) have enabled the detection of fluid index variations down to 10^{-4} for a 10 fL surrounding fluid volume[70]. Polystyrene micro-rings ($Q \sim 20{,}000$) have enabled the detection of glucose concentrations of 0.1% as well as the specific binding of bio-molecules with low mass coverage onto their surface[71]. Ultra-high Q ($>10^7$) microtoroids have monitored unprecedently low concentration of D_2O in water ($1/10^6$ per volume), because of the device capability to detect subtle differences in the water absorption[69]. Resonance linewidths can be decreased further by operating an "active" microcavity in the laser regime, enabling in principle more accurate detection[72]. The coupling of a micro-cavity with another resonator can produce sharp asymmetric (Fano) lines that are also attractive to sensing[73]. The slope in their transmission spectrum is significantly stiffer than for the single microcavity response. These features have been exploited for glucose detection, by combining a microring and a waveguide comprising partially reflecting elements[74].

Bragg gratings provide another kind of resonator structures with sensing capabilities: they usually rely on the spectral shift of the Bragg resonance. Despite recent improvements (cladding etching, management of defect states), Fibre Bragg gratings remain usually quite long (between 500 µm[75] and 4.5 mm[76]). By contrast, 76 µm-short Bragg grating waveguides[77] have been reported to detect index variations of the surrounding fluid as small as 4.10^{-4}, by exploiting gratings that are deeply etched onto the waveguide surface.

Despite their good performance, the sensitivity of the above micro-resonators and more generally of evanescent-wave sensitive devices is intrinsically limited by the restriction of the fluid-light interaction over the short penetration depth ($\sim\lambda$) of light in the fluid, at the device surface. Having the analysed solution directly located inside the optical resonator should provide more efficient sensors. A compact and integrated 50 µm-long refractometer device has been demonstrated, in which a microfluidic channel containing the solution to analyse, forms the optical cavity[78] (Fig. 3). The use of two integrated Bragg grating reflectors and collimating elements generate low-loss Fabry-Perot modes exhibiting narrow linewidths (<0.02 nm). This has enabled the detection of index variations down to 2.10^{-3}, mainly limited by the set-up detection accuracy.

Because fluids generally display smaller refractive index than the solid materials used to build the devices, increasing fluid-light interaction implies the confinement/ guidance of light in the low index regions, which is unusual. This can be achieved through interference effects, as involved in hollow ARROWs or photonic crystal structures. Planar photonic crystal cavities can be engineered to concentrate light in their nanometer sized air pores, where analytes can be directly introduced. Their ultra-small mode volumes offer a promising platform for high spatial resolution detection, enabling single molecule sensing. Photonic crystal lasers[79] and passive microcavities[80] have been reported as highly sensitive potential sensors with dense integration capabilities[81]. Slot waveguides[82], which consist of two close and parallel waveguides, represent another innovative geometry to maximize the overlap between light and fluids. Light tends to concentrate and propagate in the ultra-narrow spacing (~50 nm) managed between the waveguides, which can be filled with low index solutions of analytes. High *Q* (27,000) microcavities have been fabricated from this technology[83] and appear highly promising for sensitive detections.

Besides the realization of both compact and effective sensors, planar micro-photonics displays integration capability. Arrays of waveguides can provide multipoint detection[47,2], possibly useful for single particle detection[84]. Furthermore, multiple sensors with different operating ranges can be constructed on a single chip[48,81] to respond simultaneously to different analytes. Fibre optic sensors and microstructured fibres provide also a great promise for integration of multiple sensing channels onto lab-on-a-chip systems[85].

5. Tunable/ reconfigurable optical devices

The range of index modulation provided by microfluid manipulation (Δn~0.5-1) is much higher than those traditionally offered by electro-optic[86] (Δn~10^{-3}) or thermal[87] effects

(Δn~10^{-2}). This should translate into the achievement of both ultra-compact and tunable devices. More generally, three main characteristics of fluids can be exploited to control and produce flexible optical devices: fluid mobility, adjustable fluid index (upon composition) and fluid-based interfaces. Various adaptable optofluidic devices have been demonstrated, using one or more of these specificities.

Fluid infused photonic crystals and microstructured optical fibres

Photonic crystals and microstructured optical fibres comprise air voids that can be reversibly filled with different kinds of microfluids[88]. This gives rise to fluid/ light interactions, possibly enhanced through fiber tapering[11], which highly modify the device optical properties. Upon fluid actuation, the infused devices can demonstrate not only on/off switching functionality but also a continuous tuning of their properties.

Mach et al. have realized tunable optical filters based on microstructured fibres including a core index grating surrounded by six micrometer holes infused with fluids[89]. The filter relied on the selective coupling of the core mode to a cladding mode that becomes leaky when fluid has high index. By moving dynamically different fluid plugs along the fibre, both the wavelength and the extinction ratio of the filter were independently adjusted. Alternatively, fluids themselves can form adaptive Bragg gratings for tunable optical filtering[90]. Fluid gratings were created by infiltrating the cladding holes of microstructured fibres with periodically spaced microfluidic plugs. This filter was spectrally tuned by thermally changing the period of the mobile fluid grating.

Infiltrating photonic crystal lattices with fluids is particularly attractive because of the potential for dispersion engineering. 2D photonic crystals tuned with fluids were explored optically by Domachuk et al. in photonic crystal fibres (PCFs)[91]. PCFs employ a periodic matrix of air inclusions in silica extending uniformly along their length. Probed transversely, they present stop-bands whose wavelength positions vary with the refractive index of fluid residing within the PCF voids. Thermal displacements of fluids in a transverse PCF provided dynamic optical reconfigurability with a response of 1.8 s.

Further functionality is possible by integrating a planar photonic crystal with a microfluidic layer capable of individually addressing single lattice elements. This enables completely reconfigurable photonic crystal defect structures for confining light and creating adjustable optical paths in a photonic integrated circuit. As a first step, a photonic crystal waveguide transmission was controlled through localized diffusion of fluid into its structure[31] (Fig. 4). The alternate pumping of water and saline provided 20 dB modulations within tens of seconds. This method allows targeted, high refractive index change (Δn=0.11) as opposed to modulation across the structure, as with liquid crystals[92] or micromechanical approaches[93]. This local tunability relies on a two level microfluidic system bonded to the photonic structure, delivering fluids on the scale of 100 nm[31].

The currently high switching times of the reported devices could be substantially reduced by using integrated, non-pressure fluid actuation approaches[94], like electrokinetics or electro-wetting, which rely on charge manipulation via patterned electrodes. Electro-wetting[95] is favourable as it involves surface tension manipulation, the dominant force on the microfluidic scale (Textbox 1). Millisecond fluid actuation timescales are achievable[89,96]. Other emerging methods involve optically induced actuation via photo-thermal nano-particles[97] or via light scattering in nano-structure induced birefringent microgears[98].

Fluid based reconfigurable interfaces

Harnessing of microfluidic interfaces, which have proven useful for biochemistry[99], provides us with another means to control integrated optical devices and to realize adaptive optical functions[4,5]. Microliquids form flexible and controllable interfaces with either air, solid or other kinds of (im)miscible liquids. On the one side, this provides a sharp and large index contrast that can be tuned through fluid manipulation. On the other side, the interface shape and location can be readily controlled at the microscale, where the usual macroscopic effects of gravity are overcome by surface tension (Textbox 1).

The use of fluids to form the cladding part of an optical device provides a simple way to produce a reconfigurable component. Tunability of the device response is obtained by changing the fluid composition hence the index contrast of the fluid/solid interface. On this basis, microfluidic-based optical switches[100] as well as gradual optical attenuators[101] have been demonstrated. Levy et al. have realized more sophisticated tunable optical micro-filters[32]. Their architecture includes a PDMS microfluidic network that is bonded onto a silicon microring-based device. In this structure, the on-chip mixing of two liquids with different indexes provides the accurate adjustment of the refractive index in the surrounding of the optical filter, inducing the fine tuning of both the filtered wavelength (over 2 nm) and the associated transmission (down to –37 dB).

Water/air meniscus display high index contrasts (Δn=0.33) that have been exploited to create compact microfluidic interferometers[102]. The spectrally modulated response of the device arises from the interaction of a single optical beam with the meniscus (Fig. 5). A relative phase shift is induced between the two sections of the beam, after they have propagated in air or water across the 10 µm-microfluidic channel. The extinction ratio can be tuned by moving the meniscus location in front of the beam. A compact and planar embodiment of this concept has been recently demonstrated[103]. Other functionalities, like beam steering, can be achieved by controlling the shape of water/air interfaces with electro-wetting[104].

Unlike solid boundaries, liquid/liquid interfaces form optically smooth boundaries and can be reshaped at will. Whitesides' group has demonstrated a reconfigurable L_2 optical waveguide composed of a thermal gradient across a liquid flowing in a microfluidic channel[105]. Light is guided through the index contrast provided by the thermal difference between the core and the cladding streams. The output intensity and numerical aperture can be adjusted by changing the relative flow rates or the temperature contrast. The control of the particle diffusion at the interface between laminar microfluidic streams with different composition and hence refractive index has also been exploited to construct tunable optical splitters and wavelength filters[106]. The generation of concentration gradients across laminar streams using microfluidic networks can produce complex index profiles that are exploitable to tune optical devices[32].

Fluids can eventually incorporate all sorts of optically attractive elements, like silica microspheres. Silica microspheres can act as lenses at the micron scale and can be accurately manipulated within fluids using optical tweezers[107]. The device in Ref. 108 displays a planar optical channel sectioned by a microfluidic channel, in which an optically trapped microsphere is displaced in front of the beam. The optically adjustable interaction between the sphere and the signal beam provides beam-steering effect and eventually optical attenuation in the device transmission. A waveguide based integrated platform could make the most of this effect to construct optically actuated routers[103].

More generally, optical tweezers is of high interest for optofluidic devices to trap or actuate micro-elements within fluids[98,109], possibly on-chip, using integrated microlasers[110] or intense microstructured optical fields[111]. Optoelectronic tweezers[112] represent another innovative technique to manipulate in parallel numerous (~ 15000 / mm^2) diluted microparticles. It combines the use of unpatterned biased electrodes and the projection of optical images focused onto a photoconductive layer. This creates a dense and virtual network of microparticle traps whose pattern can be reconfigured with a high resolution.

6. Future outlook

Optofluidic integration holds many promises for, on the one hand, highly sensitive integrated sensors and, on the other, photonic devices with novel functionalities.

Current investigation into optofluidic integration is still in a very formative stage. Most research thus far has approached optofluidics from a standpoint of enhancing photonic device functionality. Optofluidics provides many avenues of enhancement as outlined in this article. An obvious progression is further integration of more sophisticated microfluidic platforms and fluid motivation techniques. Further utilization of fluid chemistry including liquid crystals or optically non-linear fluids will enable dynamically reconfigurable photonic devices with very broad ranges of operations. Novel modalities will also derive from the exploitation of water-soluble nanocrystals, quantum dots or gold nanoparticles[113]. Those species can be easily handled and delivered with high spatial accuracy through microfluidic circuitry; they can efficiently interact with optical signals and be optically manipulated. Their unique properties are attractive to both novel optofluidic devices and integrated sensors with enhanced sensitivity.

Optofluidics is a broad field with many applications across disciplines. With current research only in its infancy, many opportunities exist across the field for creating novel devices and elegant solutions.

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Author information

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Figure Legends

Figure 1. **Optofluidic laser. a**, Scanning Electron Micrograph of the distributed feedback laser, whose emission is coupled into integrated waveguides (left down side). **b**, Close-up of the polymer resonator walls that form the Bragg grating. **c**, L-I curve of the optically pumped laser. **d**, Typical laser spectrum. *From Ref [36] Baslev, S. et al. Opt Express **13,** 344 (2005).*

Figure 2. **Optical micro-cavities for bio-sensing.** Scanning Electron Micrographs of various microcavities, which can be used as effective biosensors due to their low optical losses and high compactness. **a,** Suspended Polystyrene microring (*Ref [74] Chao, C.Y. et al. Appl. Phys. Lett. **83,** 1527, 2003*) **b**, Silica suspended microdisk (*Ref [66] Kippenberg, T. J. et al. Appl. Phys. Lett. **83,** 797, 2003*) and silica microtoroid obtained after a reflow process of the miscrodisk (*Ref [68] Armani, D. K. et al. Nature **421,** 925, 2003*) **c**, Silicon on insulator microring (*Ref [86] Almeida, V. R. et al. Nature **431,** 1081, 2004*) **d**, Planar photonic crystal in a InGaAsP membrane (*Ref [79] Loncar, M. et al. Appl. Phys. Lett. **82,** 4648, 2003*).

Figure 3. **Refractometer. a**, Schematic cross-section of the Bragg grating-based refractometer. **b**, Top view micrograph of the final device that is integrated onto a planar environment. **c**, Experimental spectra of the generated optical resonance for different fluid refractive index inside the channel. *From Ref [78] Domachuk, P. et al. Appl. Phys. Lett. **88,** 093513 (2006).*

Figure 4. **Optofluidic integrated platform. a**, Schematic representation of a two-level microfluidic network bonded onto a planar photonic crystal device. **b**, Scanning Electron Micrograph of the planar photonic crystal waveguide that displays a central row of holes

selectively filled with fluids. **c**, Transmission of the photonic crystal waveguide with its central holes successively filled with water or $CaCl_2$. *From Ref [31] Erickson, D. et al. Opt. Lett.* ***31,*** *59 (2006).*

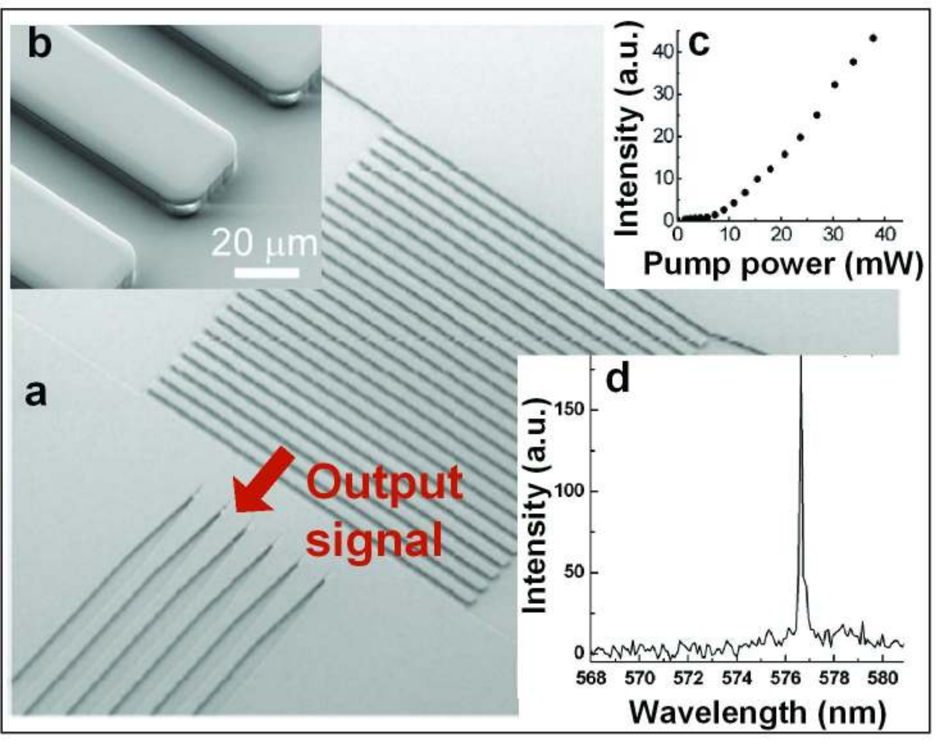
Figure 5. Microfluidic single beam interferometer. a, Schematic cross-section view of the device, which relies on the interaction between a single beam and an air/water meniscus. **b**, Top view micrograph of an integrated version of the device, with the meniscus and the optical channels combined onto a planar platform. **c**, Tuning of the device response in transmission when the meniscus is moved across the beam; the corresponding 1, 2, 3 and 4 locations of the meniscus relatively to the signal beam are represented schematically in cross-section. **d**, Tunable depth of the response versus the location of the meniscus for both experiments (black squares) and numerical simulations (dotted line). (d) *From Ref [102] Grillet, C. et al. Opt. Express* ***12,*** *5440 (2004)* and *Ref [103] Monat, C. et al. Proc. SPIE Optics and Photonics,* ***6329,*** *4, August 13-17 2006, USA.*

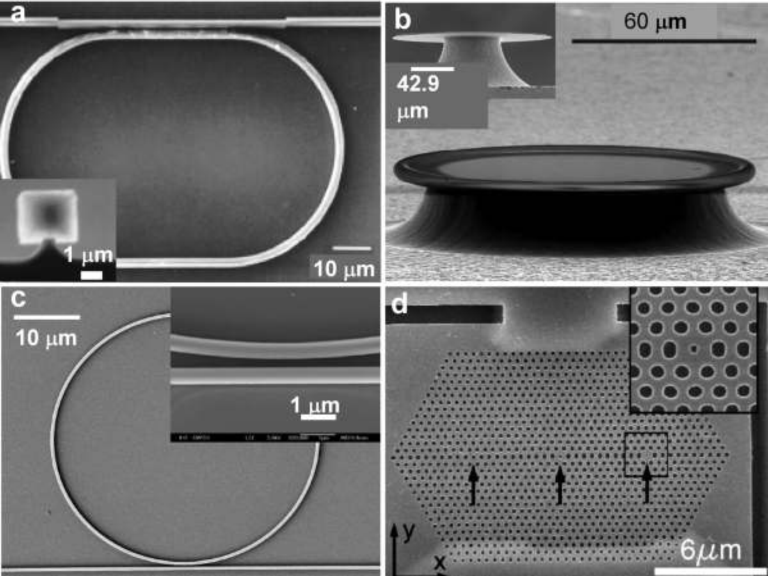
Textbox 1. The physics of microfluidics

The dynamics of fluids on the micro scale obey the governing equations of fluids on the macro scale, the Navier-Stokes equations. However, micro-flows exhibit characteristic behaviours unique to their scale of confinement:

- Laminar flow: For flows confined on the micron scale, viscous forces in the fluid dominate over inertial forces, damping non-linearity. Thus, micro flows are never turbulent and always laminar.
- Diffusion driven mixing: As a consequence of the previous point, a lack of turbulent flow means that all mixing is driven by diffusion of species, providing design challenges in making microfluidic mixers that produce homogenous output in a compact space.
- Capillarity: Surface tension at the phase boundary of a fluid dominates over the viscous forces inside the fluid. In fact, surface tension is one of the strongest forces on the micron scale, by several orders of magnitude. It can be utilized to introduce a fluid into a void but similarly renders the same fluid difficult to remove.

The above characteristics of micro-flows constrain the design of optofluidic components and microfluidic devices in general. However, these effects may also be utilized to create novel structures (such as L_2 waveguides) or highly efficient actuation mechanisms (electro-wetting). Indeed, the nature and engineering of these effects is a topic of ongoing research in fundamental microfluidics.


b
20 μm
c
Intensity (a.u.)
Pump power (mW)
a
Output signal
d
Intensity (a.u.)
Wavelength (nm)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c
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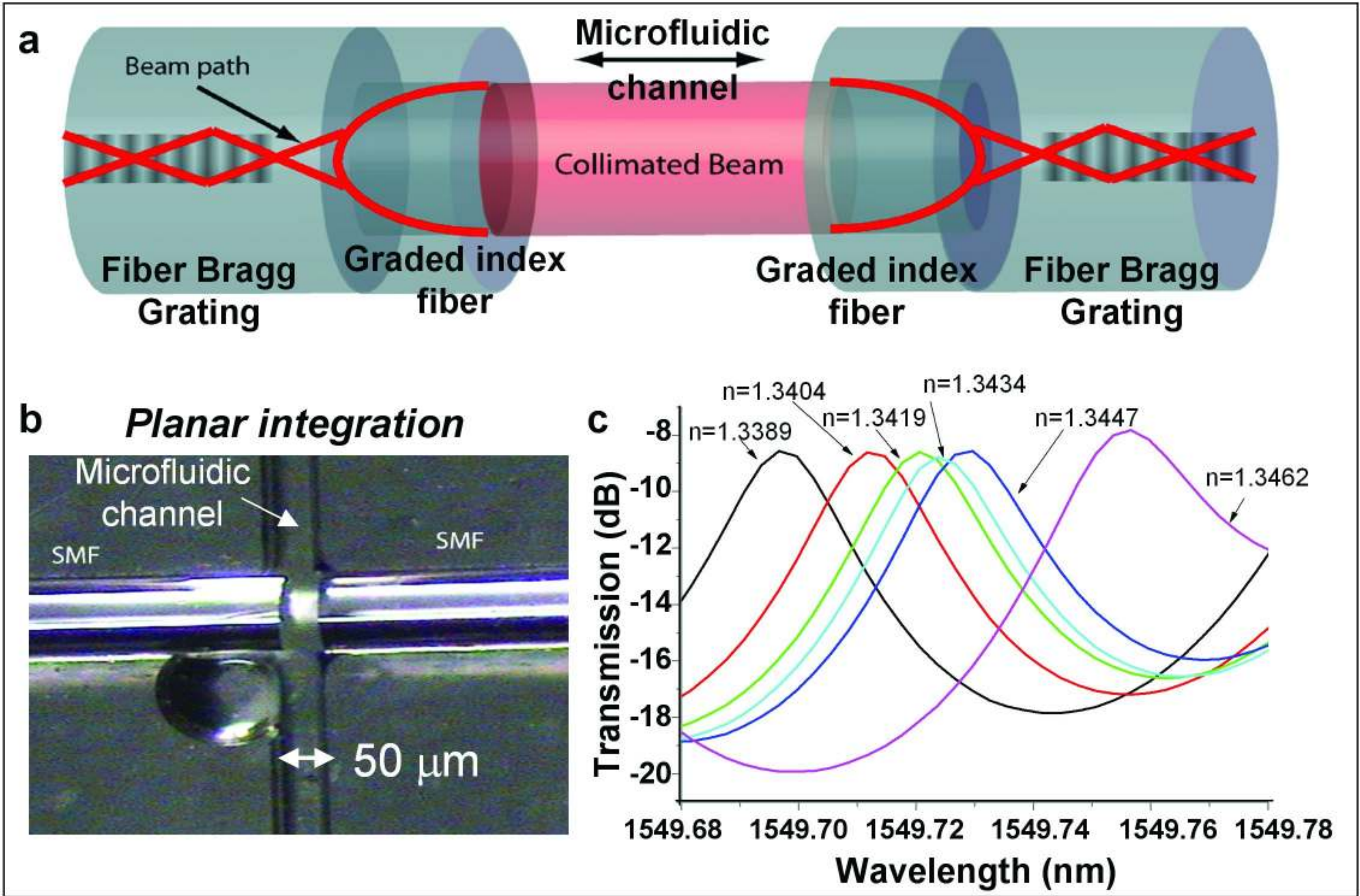
d
y
x
6μm


a
Beam path
Microfluidic
channel
Collimated Beam
Fiber Bragg
Grating
Graded index
fiber
Graded index
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Fiber Bragg
Grating
b
Planar integration
Microfluidic
channel
SMF
SMF
50 μm
c
n=1.3389
n=1.3404
n=1.3419
n=1.3434
n=1.3447
n=1.3462
Transmission (dB)
-8
-10
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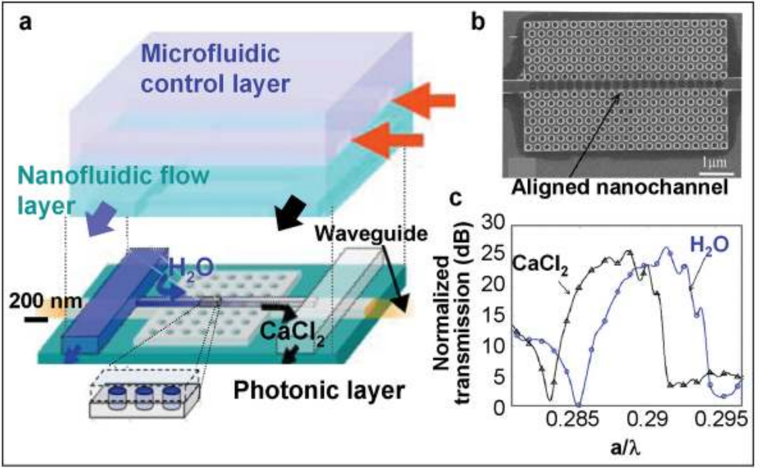
1549.78
Wavelength (nm)


a
Microfluidic control layer
Nanofluidic flow layer
Waveguide
H2O
200 nm
CaCl2
Photonic layer
b
1μm
Aligned nanochannel
c
Normalized transmission (dB)
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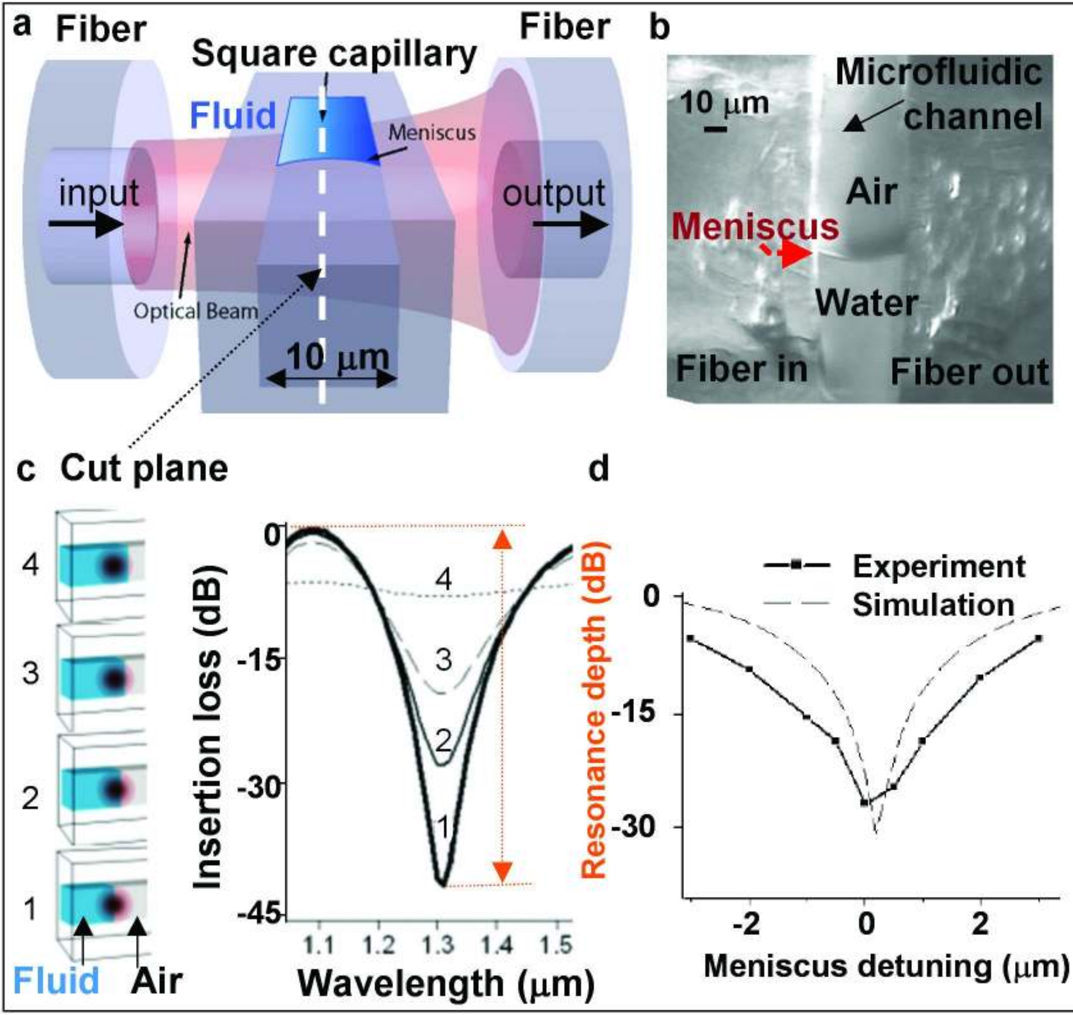
25
20
15
10
5
0
CaCl2
H2O
0.285
0.29
0.295
a/λ


a
Fiber
Square capillary
Fiber
Fluid
Meniscus
input
output
Optical Beam
10 μm
b
Microfluidic channel
10 μm
Air
Meniscus
Water
Fiber in
Fiber out
c
Cut plane
4
3
2
1
Fluid
Air
Insertion loss (dB)
Resonance depth (dB)
Wavelength (μm)
d
Experiment
Simulation
Meniscus detuning (μm)