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A monolithic and flexible fluoropolymer film microreactor for organic synthesis applications†

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A photocurable and viscous fluoropolymer with chemical stability is a highly desirable material for fabrication of microchemical devices. Lack of a reliable fabrication method, however, limits actual applications for organic reactions. Herein, we report fabrication of a monolithic and flexible fluoropolymer film microreactor and its use as a new microfluidic platform. The fabrication involves facile soft lithography techniques that enable partial curing of thin laminates, which can be readily bonded by conformal contact without any external forces. We demonstrate fabrication of various functional channels (~300 μm thick) such as those embedded with either a herringbone micromixer pattern or a droplet generator. Organic reactions under strongly acidic and basic conditions can be carried out in this film microreactor even at elevated temperature with excellent reproducibility. In particular, the transparent film microreactor with good deformability could be wrapped around a light-emitting lamp for close contact with the light source for efficient photochemical reactions with visible light, which demonstrates easy integration with optical components for functional miniaturized systems.

Introduction

Microfluidic devices, including lab-on-a-chip systems, have been utilized in various areas of chemistry, because of their unique features such as miniaturized reaction volume, extremely large surface-to-volume ratio, and efficient mass and heat transfer capability.[1] The advent of new microfluidic platforms has improved the safety and efficiency not only in bench-scale chemical processes but also in industrial pharmaceutical research where synthesis of libraries of compounds is needed on a milligram scale. Robust and rigid materials such as silicon, metal and glass have generally been employed for the manufacture of microfluidic devices.[2] However, sophisticated fabrication techniques such as etching and micromachining required a highly intensive process and expensive equipment. On the other hand, inexpensive polymers such as poly(dimethylsiloxane) (PDMS) or poly(methyl methacrylate) (PMMA) have also been used, but they are not suitable for application in organic chemical processes due to their low

chemical stability and easy swelling behaviour, although they have been widely used in biological areas due to easy fabrication, high transparency and gas permeability.[3–6] Coating with a resistant material is one way of overcoming the problem.[7,8] However, this intuitive process requires elaborate fabrication steps and careful control of thickness of the coated material.

It is highly desirable to have a thermally and chemically stable polymer material as a matrix of the microfluidic chip that can be fabricated by user-friendly and economic techniques.[9–11] Therefore, fluoropolymer-based materials such as perfluorinated acid (PFA) and polytetrafluoroethylene (PTFE) are quite attractive because they are highly solvent-resistant and thermo-resistant with low friction characteristics.[12,13] However, their very low surface energy and non-adhesiveness make it difficult to seal the channels by interfacial chemical bonding. Several attempts have been made to overcome the problem. DeSimone *et al.* reported a microreactor fabricated with a photocurable, solvent-free, and low viscous perfluoropolyether (PFPE) with urethane dimethacrylate end groups using a soft lithography technique.[12] The PFPE microfluidic chip is highly compatible with popular PDMS-based devices in terms of low surface energy, low toxicity, high elasticity, and high gas permeability. Nevertheless, bonding between thick and rigid laminates was problematic, leading to poor fidelity and inferior flexibility. Moreover, the high cost of the polymer resin limited broad applications of the devices that required more than 10 grams of the polymer for fabrication of a thick plate-type microreactor.[14] In addition, there have been no actual

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† Electronic supplementary information (ESI) available: Detailed fabrication figure of various chip images, controlled chip thickness, pressure resistance, the built-in herringbone mixer pattern in the microreactor and its performance, products, and ¹H-NMR spectrum. See DOI: 10.1039/c4lc00748d

organic reaction studies on fluoropolymer-based microreactors except for simple solvent resistance tests.[15,16]

Herein, we report a facile and economic fabrication of monolithic and flexible fluoropolymer film microreactors with PFPE resin. The reproducibility of the bonding process is highly improved by adapting a flexible film-based fabrication process that facilitates the conformal contact bonding between partially cured laminates with no external force. We demonstrate the versatility of the process by fabricating various functional channels embedded with a herringbone micromixer pattern or a droplet generator. The highly chemical-resistant fluoropolymer film microreactor is utilized for various synthetic reactions under strongly acidic and basic conditions and at elevated temperature. In particular, the transparent film microreactor with high deformability was wrapped around a light bulb for a closer exposure to light, which led to superior performance in photochemical reactions. It is quite possible that this monolithic thin-film chip can readily be integrated with electrodes, heaters, light-emitting diodes, and various electronics for miniaturized systems.

Experimental

Materials

PFPE (Fluorolink MD 700, viscosity 581 cP) was bought from Solvay-Solexis (Milan, Italy); 2-hydroxy-2-methyl-1-phenyl-propan-1-one (Darocur 1173) as a photoinitiator was bought from BASF (Ludwigshafen, Germany), and SU-8 50 photoresists were bought from Microchem (Seattle, USA). Unless stated otherwise, general-use chemicals and solvents were bought from Sigma-Aldrich (St. Louis, USA).

Fabrication of a fluoropolymer film microreactor

Various microchannels with 300 or 500 μm width and 50 μm height were prepared by replication of SU-8 masters which were obtained by a photolithography process on silicon wafers according to a previously reported method[3] (ESI,† Fig. S1). Firstly, the PFPE resin for the fabrication of a microfluidic chip was prepared by mixing Fluorolink MD 700 and Darocur 1173® in a 10:1 weight percent ratio. The low viscous and solvent-free mixture was readily homogenized by a vortexer (M37610-33, Thermo Scientific) for 10 min, and then bubbles were removed by a Rotavapor (R-210 BUCHI). Prior to replication of the microchannel pattern, the SU-8 mold on a Si wafer was treated with chlorotrimethylsilane (CTMS) for 10 min to prevent the adhesion of the fluoropolymer resin (Fig. 1(a)).[17] 1.5 mL of the PFPE mixture was spin-coated (500 rpm, 10 s) on the master to form a coating layer with up to 180 μm thickness and exposed to UV irradiation for only 1 min under nitrogen atmosphere to be solidified in a fully curing manner (Fig. 1(b)). The flexible microchannel part with sufficient mechanical stability to retain the pattern was ripped off from the mold. An alternative PFPE film with 100 μm thickness was made by spin-coating on a flat silicon wafer at 500 rpm for 20 s and was partially cured with UV irradiation for 30 s under nitrogen conditions (Fig. 1(c)). Holes were punched in the
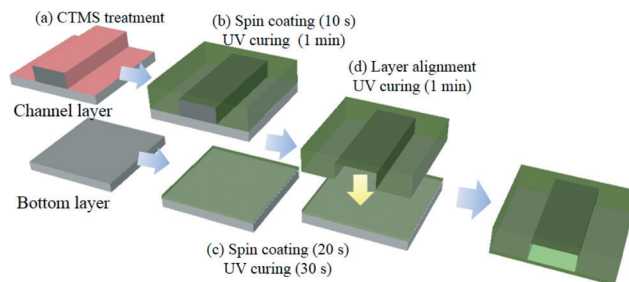

Fig. 1 A scheme for fabrication of a monolithic and flexible fluoropolymer film microreactor: (a) non-adhesive coating on the SU-8 master by chlorotrimethylsilane (CTMS) treatment, (b) spin coating of PFPE resin on the SU-8 master and UV irradiation for curing, (c) spin coating of PFPE resin on a Si wafer and UV irradiation for partial curing, and (d) conformal contact bonding to seal the channel by additional UV radiation for full cross-linking.

inlet and outlet parts of the microchannel using a puncher (Uni-Core 1.2 mm Harris). The freestanding and partially cured laminate with a microchannel pattern was gently placed on another partially cured bottom film layer. Both thin laminates readily became intimate and in conformal contact and then were irradiated by additional UV exposure for 1 min for complete cross-linking, resulting in strong chemical bonding at the interface between films (Fig. 1(d)).

Characterization and tolerance test

The dimensions of the microchannels were measured by scanning electron microscopy (SEM, SNE-1500/JEOL) and optical microscopy (SV 32, Sometech). The PFPE microfluidic devices with functional components such as a mixer and a droplet generator were also fabricated with different designs of mold by identical replication and bonding steps. In order to investigate comparative solvent resistance of the cured PFPE under various organic reaction conditions, rectangular pieces of PFPE (1 cm × 1 cm × 1 mm) and PDMS (1 cm × 1 cm × 1 mm) were prepared by pouring into the mold, exposed to UV irradiation for 5 min, and then immersed into various solvents in 10 mL glass vials at room temperature or 60 °C for 12 h. The swelling ratios of fluoropolymer and PDMS were calculated as $100(W - W_o)/W_o$ (W: weight after swelling, W_o: weight before swelling).[18–20] In order to determine the bonding stability of the fabricated microchannels (300 μm × 50 μm × 30 mm), burst pressure was tested by connecting the inlet of the microreactor to a high pressure pump (SP-930D, Younglin, Korea) with an open outlet. Water was injected into the microchannel with a very high flow rate in the range of 0.1 to 10 mL min^{-1}. Then the pressures at which the microchannel part was delaminated by flow-induced force were determined as a measure of bonding strength. Moreover, burst pressures under organic reactions were also measured after performing continuous flow with various kinds of organic solvents (65% nitric acid, 40% methylamine solution and chloroform) for 1 h. In addition, the transparency of the fluoropolymer film (300 μm thickness) was determined by using a UV-Vis absorption spectrometer (NanoDrop 2000c, Thermo Scientific, Korea), which was compared with that of quartz glass (1.2 mm thickness).

Application for organic synthesis under various conditions

To test the fluoropolymer film microreactor under various chemical conditions, we conducted reactions under strongly acidic (nitration of thiophene, pH 1) and strongly basic (Schotten–Baumann amidation of benzoyl chloride, pH 11) conditions at RT and in corrosive organic media (Vilsmeier–Haack formylation) at 100 °C.

Nitration of thiophene[21] was conducted at RT. A solution of nitric acid (65 wt% in H_2O, 50 μL min^{-1}) and a solution of thiophene (0.2 M in acetic anhydride, 50 μL min^{-1}) were introduced into a Y-shaped fluoropolymer film microreactor (300 μm × 50 μm × 50 mm) with or without a built-in herring-bone mixer pattern (30 cm length) using separate syringe pumps (PHD-2000, Harvard). After a steady state was reached, the product was collected for 10 min while being quenched with 1 mL of saturated $NaHCO_3$ aqueous solution. The crude solution was extracted with ether and washed with brine. The extracts were dried over Na_2SO_4 and concentrated.

Schotten–Baumann amidation[22] was conducted using benzoyl chloride and methylamine. A solution of benzoyl chloride (0.1 M in chloroform, 5 μL min^{-1}; 300 μm channel width for continuous phase of benzyl chloride in $CHCl_3$, 100 μm channel width for dispersion phase of methylamine in H_2O) was used for reaction of the two immiscible phases at the interface which were introduced into a T-shaped fluoropolymer film microreactor (50 μm height, 30 cm length) with a droplet generator (300 μm channel width for continuous phase) using syringe pumps at RT. The product was collected for 20 min while being quenched with 2 mL of saturated NH_4Cl aqueous solution. The crude solution was extracted with ether and washed with brine. Then, the extracts were dried over Na_2SO_4 and concentrated.

Vilsmeier–Haack formylation[23] was conducted using a mixture solution of dimethylformamide (13 eq.), phosphoryl chloride (1.35 eq.) (1.47 μL min^{-1}) and N,N-dimethylaniline (1 eq., 0.17 μL min^{-1}). In this reaction, a Y-shaped microreactor (300 μm width, 50 μm height, 55 cm length of reaction part) with two inlets was used. A mixture of dimethylformamide and phosphoryl chloride was infused through the inlet of the fluoropolymer film microreactor (flow rate: 1.47 μL min^{-1}), and N,N-dimethylaniline (1 eq.) was injected to the other inlet (flow rate: 0.17 μL min^{-1}). The product was collected for 20 min while being quenched with 4 mL of H_2O. The crude solution was extracted with ether and washed with brine. Then, the extracts were dried over Na_2SO_4 and concentrated.

Photochemical cyclization[24] was conducted using a mixture solution (0.1 M in acetonitrile based on the starting compound) including (2E,7E)-1,9-diphenylnona-2,7-diene-1,9-dione as a starting compound, tris(2,2′-bipyridyl)dichlororuthenium(II) hexahydrate (5 mol%), lithium tetrafluoroborate (2 eq.) and N,N-diisopropylethylamine (2 eq.). The solution was introduced into the fluoropolymer film microreactor (300 μm × 50 μm × 88 mm) using a syringe pump (flow rate: 15 μL min^{-1}). After a steady state was reached under irradiation with visible light from a flat 30 W white LED lamp (HV-4-18, Huvit-LED, Korea), the product was collected for 10 min while being quenched with 1 mL of saturated NH_4Cl aqueous solution. The crude solution was extracted with ether and washed with brine. The extracts were dried over Na_2SO_4 and concentrated. The reaction conversion was calculated using ^1H NMR by comparing the integral of the peak between the desired cyclized product (3.87 ppm, 2H) and the starting compound (2.40 ppm, 4H).

Results and discussion

Fabrication of a fluoropolymer film microreactor

Elastic fluoropolymer film microreactors were fabricated by a soft lithography process using commercially available and photocurable PFPE resin. The microchannel was formed by laminating two pieces of the partially cured films that were obtained by spin-coating the low viscosity (581 cP) PFPE polymer on the Si master with a channel pattern and the Si wafer without the pattern. The film thickness was adjusted by controlling the rate and the time of spin coating (refer to ESI,† Fig. S2(a)). For instance, 180 μm and 100 μm thick polymer films were obtained by spinning at 500 rpm for 10 and 20 s, respectively. The absence or presence of a channel pattern (300–500 μm width, 50 μm height) did not make any appreciable difference. Bending angle up to 120 degrees could be maintained as long as the total thickness of the laminated PFPE film was less than 500 μm. This thin film technique for microfluidic devices saves the amount of expensive fluoropolymer needed in fabrication. It also contributes to enhancing the reproducibility and fidelity of the microchannel fabrication process by facilitating conformal and intimate contact bonding between two flexible and partially cured films without requiring any external force for the bonding. Actually, a 5 cm long micro-channel with reliable bonding was fabricated with a thin patterned laminate (180 μm), while the channel with a thick laminate (3 mm) often caused no intimate bonding at several locations under the identical conditions of chemistry and fabrication techniques (refer to the ESI,† Fig. S3). In addition to the thickness, the degree of curing is also very important to form strong covalent bond at the interface. The photocurable PFPE resin required 30 s of UV radiation at least to solidify the viscous phase into a mechanically rigid film. It could easily be detached from the master without damage by pre-treating the mold surface with CTMS to prevent the strong adhesion of the PFPE resin onto the mold, performing the molding step repeatedly up to 20 times. The bonding durability of the PFPE film microreactor was tested by measuring the burst pressure at which the microchannel (300 μm wide, 50 μm high and 5 cm long) was delaminated. The flow rates were increased in the range 0.1 to 10 mL min^{-1} using a high pressure pump to generate the pressure for the delamination. The highest burst pressure was measured at 610 psi which is high enough for the range of flow rates typically encountered in organic synthesis in the film microreactor. Even after 1 h of continuous flow by organic solvents, there was no difference in burst pressure. However, when the partial curing time was further increased from 30 to 40, 50 and 60 s, the

burst pressure gradually decreased to 525, 257 and 160 psi, respectively (refer to the ESI,† Fig. S2(b)). It could be interpreted that the extended UV curing consumed the functional group, thereby reducing the chemical activity of the film surface and presumably leading to the weaker bonding strength. It is worth noting that fully cured PFPE (MD 700) had a modulus of 63.1 MPa at room temperature as reported,[19] which is nearly 30 times higher than 2.4 MPa of PDMS (Sylgard 184).[25] The high mechanical strength preserves the structural integrity of the thin film with microchannel cavity against gravitational force as well as flow-induced force, unlike the PDMS-based film microchannel (500 μm width, 50 μm thickness) that was heavily deformed and clogged by a saggy lid (refer to the ESI,† Fig. S4).

For organic syntheses, a small amount (about 1.8 g) of the PFPE precursor was used and a low-cost (~US$ 1.0 resin per reactor) monolithic and flexible microfluidic device with a 5 or 50 cm long microchannel was prepared by assembling a set of transparent fluoropolymer film microreactor (Fig. 2(a)) with a rectangular microchannel (Fig. 2(b)). A metal frame with screw holes was used for tube connections into the inlet and outlet of the microreactor so as to prevent leakage (refer to ESI,† Fig. S5). These thin film techniques can be utilized to embed various functional structures in the microchannel. An example is shown in Fig. 2(c) for a built-in staggered herringbone mixer pattern (30 mm length) on a fluoropolymer microchannel (50 mm length). The mixing efficiency of the mixer structure was experimentally demonstrated by generating a chaotic flow from two laminar flows of dye solutions at a low flow rate of 10 μL min^{-1} (refer to the ESI,† Fig. S6), which is consistent with the reported result.[26] Another example is an X-shaped junction for a droplet generator, which produces a two-phase droplet in a continuous-flow manner. Water droplets in toluene were generated with toluene as a continuous medium (Fig. 2(d)), which was made possible due to organic solvent resistance and surface hydrophobicity that are offered by the fluoropolymer.

Application for organic synthesis under various conditions

To evaluate the performance of the fluoropolymer film microreactor under various chemical conditions, we carried out 3 types of well-known organic syntheses under harsh conditions as model reactions.

Mono-nitration of thiophene was chosen first to test the durability of the film microreactor under strongly acidic aqueous nitric acid (65% HNO$_3$, pH 1) with acetic anhydride (pH 1) as solvent (Fig. 3). In this reaction, two types of Y-shaped microreactor (300 μm wide, 50 μm high, 50 cm long reaction part) with or without a built-in staggered herringbone mixer pattern (30 cm long) were used. The microreactor with the mixer pattern produced a 100% conversion and 93% yield of product with only 10 s of reaction time at a total flow rate of 100 μL min^{-1}: ^{1}H NMR (300 MHz, CDCl$_3$) of 2-nitrothiophene δ 7.98–7.90 (m, 1H), 7.60–7.52 (m, 1H), 7.12–7.03 (m, 1H) ppm; ^{1}H NMR (300 MHz, CDCl$_3$) of 3-nitrothiophene δ 8.34–8.27 (m, 1H), 7.68–7.62 (m, 1H), 7.40–7.33 (m, 1H) ppm (ESI,† Fig. S8). The microreactor without the mixer pattern showed a lower conversion of 70%. Intrinsic advantages of the chemical-tolerant microreactor such as excellent heat conduction with a high surface–volume ratio completed the nitration of thiophene at room temperature in a short time without leakage and delamination problems. Note that this highly exothermic nitration reaction generally required a low-temperature cooling bath (−10 to 0 °C) and a long reaction time.[21]
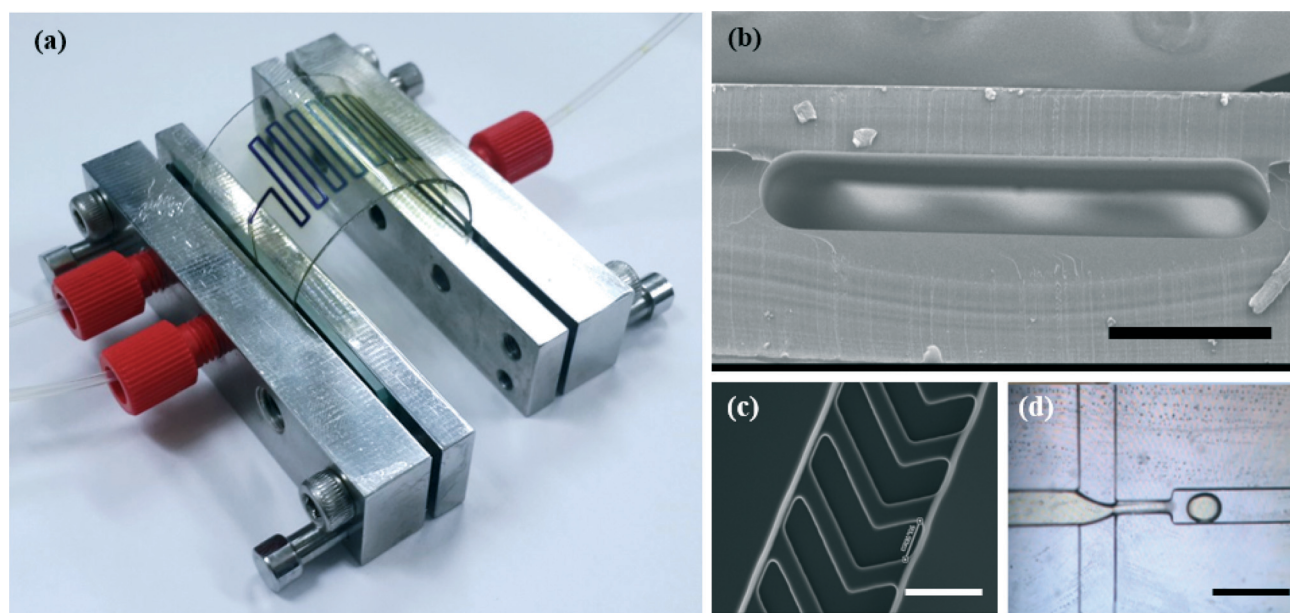

Fig. 2   (a) A full set of monolithic and flexible fluoropolymer film microreactor with metal frame connection for chemical reaction. (b) Cross-sectional view of the film microchannel with 300 μm width (scale bar: 100 μm). (c) Herringbone mixer pattern in the film microchannel (scale bar: 200 μm). (d) Droplet generator made by a fluoropolymer film microreactor (scale bar: 200 μm).
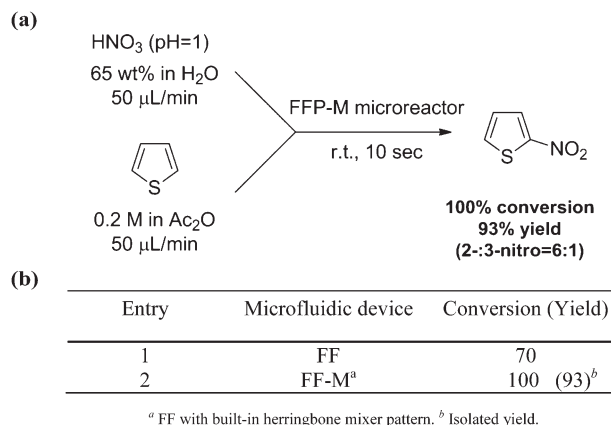
(a)

HNO₃ (pH=1)
65 wt% in H₂O
50 μL/min

FFP-M microreactor
r.t., 10 sec

0.2 M in Ac₂O
50 μL/min

100% conversion
93% yield
(2-:3-nitro=6:1)

(b)

Entry	Microfluidic device	Conversion (Yield)
1	FF	70
2	FF-M[a]	100 (93)[b]

[a] FF with built-in herringbone mixer pattern. [b] Isolated yield.

Fig. 3 (a) Scheme for mono-nitration of thiophene by a fluoropolymer film microreactor (300 μm wide, 50 μm high, 30 cm long mixer pattern in a 50 cm long microreactor) under concentrated nitric acid at room temperature. (b) Conversion comparison between a plain fluoropolymer film microreactor (FF) and a fluoropolymer film microreactor with a herringbone mixer pattern (FF-M).

Secondly, Schotten–Baumann amidation[22] of benzoyl chloride was selected to perform the reaction under extremely basic conditions of neat aqueous methylamine solution (40 wt% MeNH₂, pH 11) as shown in Fig. 4(a). The film microreactor (50 μm height, 30 cm length) with a T-shaped droplet generator (300 μm wide channel for continuous phase of benzyl chloride in CHCl₃, 100 μm wide channel for dispersion phase of methylamine in H₂O) was used for interfacial reaction between the two immiscible phases. After 50 s of reaction time (total flow rate: 10 μL min⁻¹), the desired amide product was obtained with 98% yield: ¹H NMR (300 MHz, CDCl₃) δ 7.80–7.70 (m, 2H), 7.55–7.39 (m, 3H), 5.30 (s, 1H), 3.02 (d, *J* = 5.1 Hz, 3H) ppm. It is demonstrated that the fluoropolymer film microreactor can be used not only for a corrosive reaction under extremely basic conditions but also for a two-phase reaction with organic solvent without any leakage or observable degradation. Thirdly, in order to confirm the thermal stability of the film microreactor at elevated reaction temperature, Vilsmeier–Haack
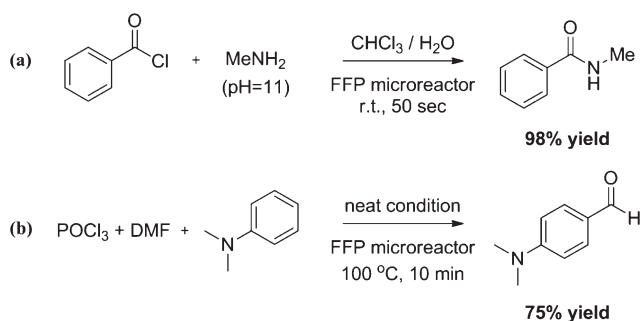
formylation in corrosive organic medium was carried out at 100 °C. In this reaction, a Y-shaped microreactor (300 μm wide, 50 μm high, 55 cm long reaction part) with two inlets was used. A mixture of dimethylformamide and phosphoryl chloride was infused through the inlet part of the fluoropolymer microreactor (flow rate: 1.47 μL min⁻¹), and *N*,*N*-dimethylaniline (1 eq.) was injected into the other inlet part (flow rate: 0.17 μL min⁻¹). As shown in Fig. 4(b), the reaction for 10 min at 100 °C successfully produced the desired formylated product with 75% yield: ¹H NMR (300 MHz, CDCl₃) δ 7.86 (2H, *J* = 8.1 Hz, d), 7.25 (2H, *J* = 8.1 Hz, d), 2.58 (s, 3H), 2.41 (s, 3H) ppm, which is compatible with a previous report.[23] In addition, the chemical durability of the fluoropolymer film microreactor was also proven with the absence of any observable defects in the inner surface of the microchannel when continuously infused by 65% nitric acid, 40% methylamine solution and chloroform up to 1 h, respectively (refer to the ESI,† Fig. S7). Furthermore, in order to confirm the long-term chemical stability, the UV-cured fluoropolymer pieces were immersed for 12 h in typical organic solvents such as DMF, THF, benzene, hexane, chloroform and trichloroethylene. Not much swelling occurred in most cases (less than *ca.* 5 wt% at room temperature and less than *ca.* 10 wt% at 60 °C), revealing much superior chemical stability to conventional polymers such as PDMS (refer to the ESI,† Table S1).

(a)

+ MeNH₂
(pH=11)

CHCl₃ / H₂O
FFP microreactor
r.t., 50 sec

98% yield

(b) POCl₃ + DMF +

neat condition
FFP microreactor
100 °C, 10 min

75% yield

Fig. 4 Two schemes of chemical reactions carried out in a fluoropolymer film microreactor. (a) Schotten–Baumann amidation reaction at room temperature by a T-shaped droplet generator (300 μm wide channel for continuous phase, 100 μm wide channel for dispersion phase, 30 cm length of reaction part). (b) Vilsmeier–Haack formylation reaction at 100 °C by a Y-shaped microreactor (300 μm wide, 50 μm high, 55 cm long).
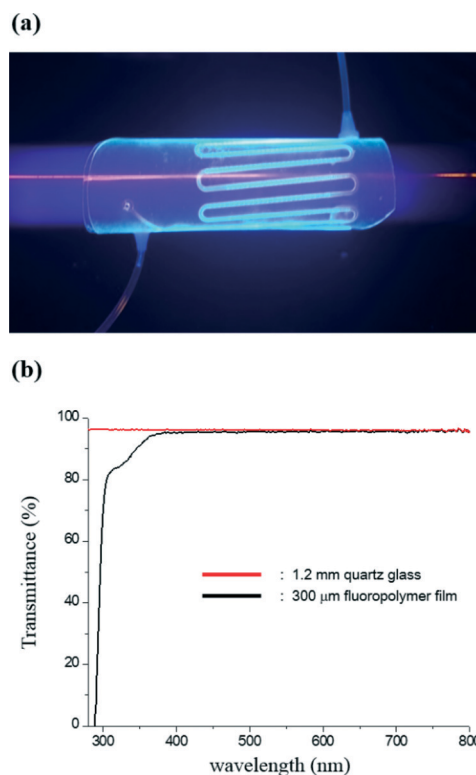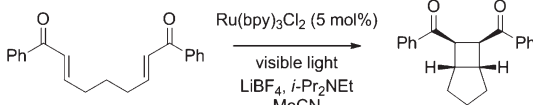

(a)

(b)

Fig. 5 (a) Fluoropolymer film microreactor wrapping a cylindrical LED lamp. (b) Comparison of UV-Vis transmittance spectrum between quartz glass (1.2 mm thickness) and a fluoropolymer film microreactor (300 μm thickness).

Table 1 Photochemical cyclization in the fluoropolymer film microreactor (300 μm wide, 50 μm high, 88 cm long reaction part) under various distances from a flat LED light source

Entry	Reactor	Reaction time (min)	Temperature (°C)	Distance from the light (cm)	Conversion[a] (%)
1	Flask	30	r.t.	5	68
2	Flask	30	70	—	<5
3	FF microreactor	1	r.t.	30	30
4	FF microreactor	1	r.t.	5	80
5	FF microreactor	1	r.t.	0.5[b]	100
6	FF microreactor	1	0	0.5[b,c]	98

[a] The reaction conversions were obtained by ^{1}H NMR. [b] The FF microreactor was attached to the surface of the light source. The reaction temperature was checked during the reaction and maintained at r.t. by a cooling fan. [c] A cooling jacket as well as a cooling fan was used to maintain the temperature at 0° C.

Photochemistry application

In general, the radiation absorption for photoreaction conversion is directly affected by the distance between the light source and the reaction medium. Therefore, we envisaged that facile deformability of the film microreactor would be effectively applied for photochemical reaction in a visible wavelength region. The optically transparent fluoropolymer film with no absorbance in the visible light range (380 to 780 nm), as confirmed by UV-Vis transmittance spectrum in Fig. 5(a), allowed us to achieve the closest proximity to the light source by wrapping the cylindrical light lamp as shown in Fig. 5(b). The effectiveness of the fluoropolymer film microreactor (300 μm wide, 50 μm high, 88 cm long reaction part) was tested by conducting a reaction of photochemical cycloaddition using visible light from a flat 30 W white LED lamp in comparison to a conventional flask reaction. Generally, a shorter distance between the light source and the reactor led to a higher reaction conversion as shown in Table 1, which is consistent with the reported result.[24] In particular, in the case of a 5 cm distance from the light source, the film microfluidic device delivered a conversion of 80% for the [2 + 2] photochemical cyclized product in 1 min, whereas the conventional flask yielded a 66% conversion in 30 min of reaction time (entries 1 and 4). It is apparent that the reactants in the shallow (50 μm high) and long (88 cm long) microchannels as well as high optical transparency of the thin fluoropolymer led to highly efficient exposure to radiation.

The proximity contact to the light source at a distance of 0.5 cm gave the product in full conversion in 1 min of retention time (flow rate: 15 μL min⁻¹) at room temperature (entry 5): ^{1}H NMR (300 MHz, CDCl₃) 7.85–7.58 (m, 4H), 7.55–7.25 (m, 8H), 3.92–3.80 (m, 2H), 3.35–3.15 (m, 2H), 2.25–1.95 (m, 2H) ppm (ESI,† Fig. S9). The reaction also showed similar conversion (98%) when the reaction was carried out at 0 °C by placing an ice cooling jacket at the opposite side of the irradiated part, proving high photochemical efficiency of the film reactor with a negligible thermal effect (entry 6). It is pointed out that this thin film microreactor provides a photochemical platform alternative to conventional glass microreactors as well as falling film reactors where an efficient light irradiation is needed.[27]

Conclusions

In summary, we have developed a monolithic and flexible fluoropolymer film microreactor with chemical resistance as a new platform for microchemical applications. The excellent deformability and high chemical activity of partially cured laminate films allowed conformal and intimate contact bonding in a reproducible and cost-saving manner, enabling fabrication of functional microchannels embedded with either a herringbone micromixer or a droplet generator. The performance of the fluoropolymer film microreactors with excellent chemical stability was demonstrated by conducting various organic reactions under both extreme acidic and basic conditions (pH 1 and pH 11) as well as at elevated temperature. Moreover, it was found that the transparent and flexible thin microreactor was useful as an efficient photochemical platform for close proximity to a flat or curved light source, which suggests its utilization for miniaturization and integration of the reaction systems.

Acknowledgements

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